

People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research



Course Materials for Third-Year Bachelor's Degree Students

Field of Study: Science and Technology

Discipline: Mechanical Engineering

Specialisation: Mechanical Design and Construction

Maintenance

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Academic year: 2025/2026
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Preface

The course "Maintenance" is a semester-long teaching unit offered in the fifth semester of the third-year Bachelor's degree program in Mechanical Engineering. It employs a progressive pedagogical approach to provide students with both theoretical and practical skills necessary for professional engineering roles in industry.

Ensuring the long-term viability of industrial equipment is a critical strategic concern for company competitiveness and broader economic development. As demands for availability, reliability, and safety increase, maintenance has become central to modern industry. Maintenance has transitioned from basic corrective tasks to a proactive discipline integrating technical, managerial, and economic aspects.

The course pursues two primary objectives. It offers a structured introduction to fundamental maintenance concepts, such as definitions, typologies, methods, and terminology. Additionally, it provides students with analytical tools to understand and manage maintenance processes across various industrial sectors.

Upon completing this course, students will demonstrate the ability to:

- Master standardized vocabulary and foundational concepts in industrial maintenance;
- Identify and apply maintenance strategies tailored to specific equipment;
- Analyze challenges associated with operational safety and industrial risk prevention;
- Optimize maintenance costs across the entire asset lifecycle.

The course is organized into sequential chapters that address the maintenance process from equipment design through decommissioning. Each chapter provides a concise, structured overview of maintenance methods and technologies for complex systems. This resource is intended for future managers and engineers dedicated to safety, cost control, and risk prevention during both design and operational phases.

This course provides students with comprehensive training in industrial maintenance and reliability engineering.

Introduction

The competitiveness and sustainability of a production unit depend largely on its ability to guarantee the continuous, reliable, and safe operation of its equipment. In this context, dependability has become a key discipline in modern industrial engineering. Dependability is defined as the science of managing system failures. It includes the knowledge, assessment, prediction, and control of failures throughout the equipment's lifecycle.

Dependability rests on four complementary attributes. First, reliability measures a system's ability to perform its required function under defined conditions and over a certain period. Second, maintainability describes how easily a system can be restored to working order after a failure. Third, availability is the probability that a system will perform its function at a given time. Fourth, safety guarantees the absence of unacceptable risks to people, property, and the environment.

Beyond these concepts, dependability stands as its own discipline. It uses rigorous methods to evaluate these attributes qualitatively and quantitatively. It gives engineers the tools needed to anticipate failures, optimize interventions, and improve industrial system performance.

Within this framework, industrial maintenance is vital for boosting installation performance. Maintenance is much more than simple upkeep. It has become a strategic function that directly helps control operating costs, reduces production downtime, and ensures operator safety.

Course Material Organization

This handout covers the maintenance of industrial systems in a progressive and structured manner according to the National Programme Framework 2021–2022 presented in Appendix 1, through six chapters:

- Chapter 1: General Aspects of Maintenance: This chapter introduces the basic principles of maintenance, defines the key concepts related to dependability attributes, and clarifies the standardized terminology and definitions fundamental to understanding the field.
- Chapter 2: Different Forms of Maintenance: This chapter explains the various maintenance policies, describes the types and levels of maintenance, and details common operations performed on industrial systems, providing concrete examples to illustrate their application.
- Chapter 3: Maintenance Organization: This chapter analyzes different maintenance management systems, outlines key operational maintenance functions, and introduces the use and benefits of Computerized Maintenance Management Systems (CMMS) in optimizing maintenance activities.
- Chapter 4: Equipment Monitoring and Logistics Function: This chapter covers methods for monitoring equipment condition, managing asset information, and organizing

maintenance logistics, emphasizing the relationship between asset knowledge and maintenance efficiency.

- Chapter 5: Reliability and Maintenance: This chapter explores the connection between maintenance and reliability, discusses key reliability functions and indicators, and explains how to model and evaluate the maintainability of repairable systems.
- Chapter 6 covers Failure Mode, Effects, and Criticality Analysis (FMECA). It details the chapter's objectives, traces the history, explains relevant standards, outlines the methodology, and includes an applied case study.

The handout begins with this introduction and closes with a general conclusion that highlights key achievements from all chapters and explores current trends and future perspectives in industrial maintenance.

Chapter 1 General aspects of maintenance

1 Chapter 1: General aspects of maintenance

1.1 Introduction

Companies are becoming more aware of the economic and operational impacts of failures in production systems. In the past, maintenance was often viewed only as a source of costs. Today, it is recognized as an important function that directly affects system availability, reliability, and safety. According to the EN 13306 and IEC 60300 standards, maintenance is part of a broader approach to dependability, together with reliability, maintainability, and safety.

This change is mainly due to the increasing complexity of equipment degradation processes. As a result, the lifetime of industrial systems is difficult to predict and is usually treated as a random variable. In such conditions, failure management cannot rely only on actions taken after a failure occurs. However, because the economic benefits of preventive maintenance are not always easy to measure, many companies still rely mainly on corrective maintenance strategies.

Maintenance plays a key role from the design stage and throughout the entire life cycle of industrial systems. Its main objective is to keep equipment in a condition that allows it to perform its required function safely and efficiently. When maintenance is poorly planned or poorly adapted to the system, it can lead to reduced reliability and availability, as well as increased risks for people, equipment, and the environment. For this reason, maintenance should be considered as a structured and essential function within the organization.

In this context, this chapter introduces the basic concepts related to systems, failures, and dependability, in accordance with standard definitions. It explains the role of maintenance in industry, its main objectives, and its principal forms. The aim is to provide students with the fundamental knowledge needed to understand industrial maintenance and to highlight the technical and organizational challenges involved in implementing an effective maintenance system.

1.2 System Concept

A **system** is a set of elements that interact to perform one or more functions in a given environment.

In engineering, a system can be electrical, hydraulic, mechanical or programmable, or a combination of these technologies. For complex industrial installations, it is useful to think in a hierarchy {Villemeur, 1988 #1}:

parts → components → subsystems → elementary systems → overall system.

This hierarchical view helps engineers analyze failures and maintenance actions at the right level.

Table 1-1 System Characteristics (Villemeur, 1988)

Ref	Characteristic	Description
1	Functions (missions)	Main and secondary missions of the system.
2	Structure	Components, their roles, and their connections.
3	Operating conditions	normal and degraded modes, start/stop, standby
4	Usage conditions	Inspections, tests, maintenance tasks, procedures.
5	System environment	operators, auxiliary systems, ambient conditions and hazards

1.3 Failure, Fault, and Breakdown

In reliability analysis, error, fault, and failure represent a causal chain that moves from a human mistake to an internal system state deviation and, finally, to an observable service interruption for the user.

1.3.1 Error (breakdown)

An error is a difference between a measured, observed, or computed value and the true or specified value [IEC 191-05-24]. An error can exist while the required performance is still satisfied, but it may evolve into a failure if it increases. Errors can be:

- Intermittent: disappear without intervention.
- Transient: difficult to detect and reproduce.
- Latent: present but not yet visible in operation.

1.3.2 Fault

A fault is an abnormal condition or defect that exceeds acceptable limits and can lead to a failure. A fault is a state that can last for a short or long time, unlike a failure, which is an event (Fig.I.1).

When a failure occurs, the system enters a failed state which is the result of one or more faults. Faults can exist during operation, in standby, or when the item is demanded. Typical examples of faults in mechanical systems are:

- Cracked gear teeth.
- Excessive bearing wear.
- Misalignment of shafts.

1.3.3 Failure

According to NF EN 13306, a failure is the cessation of the ability of an entity to perform a required function. Catastrophic failures occur suddenly and affect the entire system

A failure is related to a required function. The function is specified together with a performance requirement. A failure occurs when the function cannot be performed or has a performance that falls outside the performance requirement.

Example: Shutdown valve: According to the performance requirement, the maximum closing time of a shutdown valve shall be no longer than 15 seconds. A failure of the closing function occurs when the closing time exceeds 15 seconds.

A failure is an event that occurs at a specific point in time. The failure may be developed gradually or occur as a sudden event

1.3.4 Relationship Failure, Fault and Error

A fault is an internal defect, an error is a visible deviation, and a failure is the loss of the required function. All failures originate from faults or errors, but not all faults or errors immediately cause failures (Fig.1.1).



Figure 1-1 Relationship between Fault, Failure, and Breakdown (schematic diagram to be created in vector form, English labels)

Table 1 illustrates the distinctions between failure, fault, and error, providing concrete examples and drawing on authoritative sources from standards and scientific literature (IEC 60050-191; (El Hami & Radi, 2011)Villemeur, 1988 #1(Netes, 2016)}(Leitao-Junior, Freitas, Vergilio, Camilo-Junior, & Harrison, 2020).

Table 1-2 Relationship Failure, Fault and Error with example

Attribute	Definition	Characteristics	Examples
Error (Performance deviation)	A deviation in the output or behavior of a function from its intended performance, which still meets required performance criteria.	Can exist without causing immediate failure; may propagate into a failure if uncorrected.	- Slight deviation in sensor reading within tolerance. - Temporary timing mismatch in software that does not trigger a crash. - Minor misalignment in a mechanical system that does not

			impair operation.
Fault (internal problem)	An abnormal condition or defect within a system that may lead to a failure.	Persistent state that can last for varying durations; may or may not immediately cause a failure.	- Broken wire in a circuit. - Corrupted memory in a control unit. - Wear of a mechanical component that may lead to malfunction.
Failure (function lost)	The event in which an entity ceases to perform a required function.	Occurs at a specific point in time; results in the system entering a failed state.	- A motor stops working during operation. - A software module crashes while running. - A power supply fails when requested.

1.4 Dependability

According to IEC 60300 (Navas, Sancho, & Carpio, 2019), *dependability is the ability to perform as required, when required, serving as an umbrella term for attributes like reliability, availability, and maintainability, encompassing the quantitative and qualitative factors that allow a system, product, or service to operate as desired and continue to do so over time.*

Dependability encompasses:

- Understanding, evaluation, prediction, measurement, and control of failures.
- Maintaining functional performance; It covers the factors: Reliability, Availability, Maintainability, Supportability, Safety, Confidentiality (See the Fig. I.2).

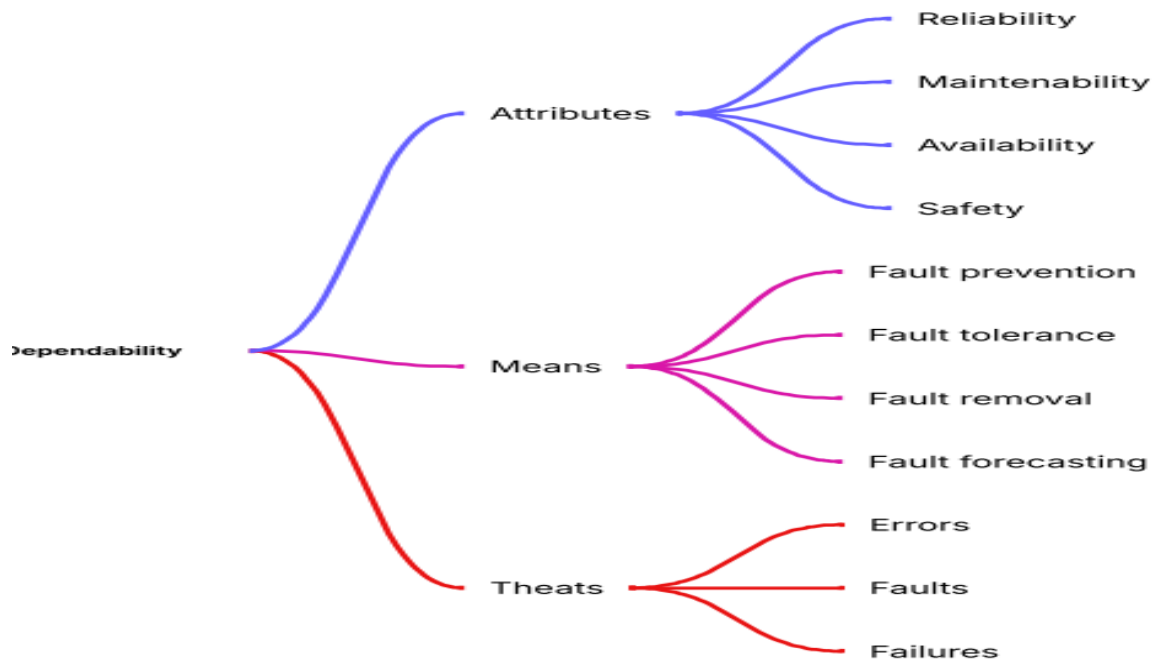


Figure 1-2 Dependability analysis (Attributes; Means; Threats)

The diagram presented by Fig. I.2 concisely illustrates that achieving a dependable system—characterized by high Availability, Reliability, and other attributes—requires the application of a combination of means (Prevention, Tolerance, Removal, and Forecasting) to mitigate the inevitable threats (Faults, Errors, and Failures).

This framework is universally applicable across engineering domains where trustworthiness is critical, including:

- Aerospace: flight control systems
- Healthcare: medical devices
- Finance: banking transaction systems
- Industrial Automation: nuclear power plant controls
- Cloud Computing and Data Centers

It establishes a common language for engineers, architects, and evaluators to design, assess, and communicate about the dependable systems that underpin everyday life.

1.4.1 History

- The entire discipline of FMDS/RAMS originated from Reliability and Safety considerations.
- These considerations were introduced by the aerospace industry in the 1930s, driven by the ambition to achieve human flight.
- By the 1950s, reliability and safety had become essential components of aeronautical and spacecraft engineering, with statistical techniques already in use. The Failure Mode and Effects Analysis (FMEA) tool, which facilitates reliability and safety assessments, was developed in the 1940s.
- In the 1960s, Boeing enhanced this tool, resulting in the development of Failure Mode, Effects, and Criticality Analysis (FMECA).
- Beginning in the 1970s, additional tools such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and Probabilistic Risk Analysis (PRA) were introduced and remain in use today. These techniques were subsequently adopted by industries such as oil and gas, rail, and chemical sectors.
- In the 1980s, formal consideration of maintainability and availability was introduced. The rail industry, along with the aerospace industry, demonstrated significant interest in these techniques.
- Since 1990, FMDS/RAMS (Failure Mode and Effects Analysis/Reliability, Risk, and Safety Management) has emerged as a distinct discipline, with dedicated specialists. Within organizations, these professionals are responsible for planning, implementing, and validating FMDS-related activities using appropriate concepts, methods, tools, and parameters.

The analysis of literature standards IEC 60300 (Hadeif, 2015; Navas et al., 2019; Villemeur, 1988) (Joglar, 2016) provides a framework for dependability, defining RAMS as:

1.4.2 Dependability attributes

1.4.2.1 Reliability (*R*)

Definition: The probability that an item (product, system, etc.) will perform its required function for a specified period under given conditions.

$$R(t) = \Pr (\text{Entity non failing in } [0, t])$$

In industry, reliability targets are often written in technical specifications, sometimes with penalties if they are not reached. For a mechanical system, high reliability means few unplanned stoppages during the planned service period (El Hami & Radi, 2011).

1.4.2.2 Maintainability (*M*)

Definition: The ease and speed with which an item can be maintained, serviced, inspected, or repaired to restore it to its operational state.

$$M(t) = \Pr (\text{Entity repaired in } [0, t])$$

The maintainability is crucial to achieving high availability based in the steps include: (i) Allocate maintainability targets to subsystems, (ii) Analyze tasks and resources (tools, spare parts, skills). and (iii) Define corrective actions and standard procedures. Good maintainability helps increase system availability and reduces maintenance costs.

1.4.2.3 Availability (*A*)

Definition: The ability of an item to be in a state to perform its required function at a given instant or over a specified period, considering both reliability and maintainability.

$$A(t) = \Pr (\text{Entity non – failing at instant } t)$$

In practice, high availability requires: (i) Reliable design (few failures), (ii) Efficient maintenance (short repair time), and (iii) Appropriate logistics (spare parts, tools, personnel).

1.4.2.4 Safety (*S*)

Definition: The freedom from unacceptable risk to people, the environment, or other assets, achieved through hazard identification, analysis, and control throughout the item's life cycle.

The mathematical expression of safety is as follows:

[$S = \Pr(\{\text{Entity avoids critical or catastrophic events under specified conditions}\})$]

Safety does not always increase when reliability increases. A highly reliable device can still be dangerous if its rare failures create severe accidents in the overall system.

To summarize the four key dependability attributes, the following Fig.I.3 provides a concise overview (Joglar, 2016).

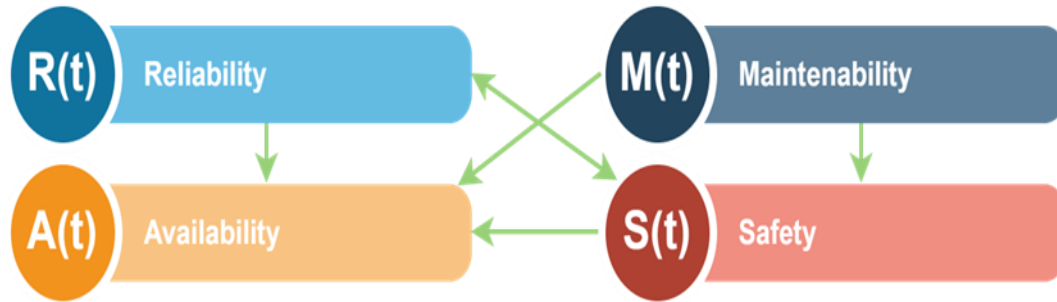


Figure 1-3 Dependability Attributes (RAMS)

1.4.2.5 Additional Attributes

- Supportability/Safety: Support services throughout the life cycle.
- Confidentiality: Absence of unauthorized information disclosure

1.5 Importance of Maintenance in Industry

Maintenance is essential in industry because it helps ensure safety, availability, quality, and steady economic performance, as highlighted in international standards and academic literature Bouabid, 2024 #10}. More and more, it is seen as a strategic function that boosts competitiveness and supports risk management, rather than just a set of repair tasks (See the Fig.I.4).

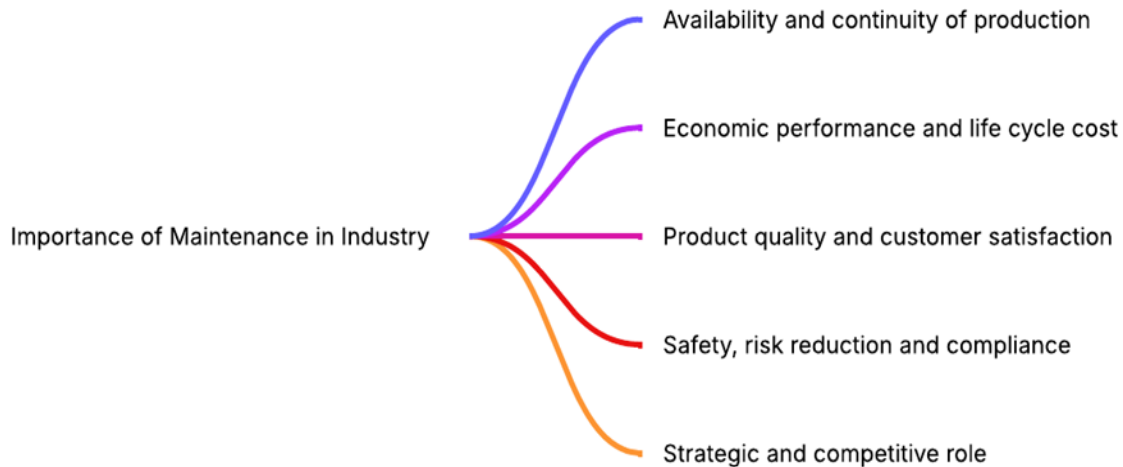


Figure 1-4 Importance of Maintenance in Industry

1.5.1 Availability and continuity of production

Dependability management standards, such as IEC 60300-3-11, define maintenance policies, such as Reliability-Centred Maintenance (RCM), to keep equipment and structures safe, available, and cost-effective.

Building on these standards, research in manufacturing shows that poor maintenance leads to equipment downtime, more stoppages, and lower production, while good maintenance helps keep production steady (Jonsson, 1999).

1.5.2 Economic performance and life-cycle cost

IEC 60300-3-10 on maintainability explains that, for long-life products, operation and support costs can exceed the initial purchase cost. Good maintainability and maintenance reduce life-cycle costs by making repairs easier and faster.

Asset management standards like ISO 55000 (Standardization, 2014) emphasize that maintenance is a key tool for optimizing asset performance throughout the life cycle, reducing unplanned downtime, and controlling maintenance and operating budgets in a measurable way.

1.5.3 Product quality and customer satisfaction

Research shows that companies with integrated, long-term maintenance plans see better quality improvement, prevention, and manufacturing capabilities than those that do not treat maintenance as a strategic priority (Chopra, 2021).

Other studies show that poor maintenance can lower product quality and process capability. Good maintenance, on the other hand, leads to stable processes and fewer defects, which improves customer satisfaction and helps avoid legal or reputational issues (Jonsson, 1999).

1.5.4 Safety, risk reduction and compliance

RCM and dependability standards say that maintenance policies should be chosen based on how failures could affect safety and operations. This shows that maintenance is a key way to prevent accidents and major incidents. (Dhillon, 2006)

Asset management and maintenance frameworks also treat maintenance as a means of managing risks. This includes identifying asset-related risks early, setting priorities, and demonstrating compliance with safety and environmental rules (Bouabid, Hadeif, & Innal, 2024).

1.5.5 Strategic and competitive role

ISO 55000 and related research explain that maintenance should be part of a strategic asset management approach rather than a separate technical function. This helps organizations make better decisions, increase returns on assets, and become more competitive.

Studies in manufacturing show that companies that integrate maintenance into their overall strategy and planning benefit from better preventive maintenance, higher quality, and improved manufacturing capability. These advantages lead to stronger market performance (Dhillon, 2006; Nikolopoulos, Metaxiotis, Lekatis, & Assimakopoulos, 2003).

1.6 Objectives of Maintenance Management

Maintenance management is essential for aligning technical activities with organizational strategic, financial, and human resource policies. The primary objective is to ensure operational continuity, equipment reliability, cost efficiency, and adherence to relevant standards. Although some organizations continue to use a run-to-failure approach, the majority emphasize preventive maintenance rather than corrective actions to prolong asset lifespan, minimize unplanned downtime, and enhance overall system reliability (IEC 60300-3-11; NF EN 13306).

Resource constraints frequently limit the implementation of comprehensive maintenance strategies. In these situations, Computerized Maintenance Management Systems (CMMS) facilitate the planning, monitoring, and optimization of preventive tasks, thereby increasing efficiency and transparency in maintenance operations (Wireman, 1994) (Mohd Noor, Mazlan, & Amrin, 2021).

An effective maintenance program requires a balance between corrective (reactive) and preventive (proactive) activities. Accordingly, maintenance departments should address the

following eight core objectives, which are widely recognized in industry and maintenance standards(Dhillon, 2006; El Hami & Radi, 2011; Joglar, 2016):

1. **Cost Control and Budget Optimization** Maintenance managers are required to allocate resources efficiently across both planned and unplanned tasks, maintaining budgetary discipline while ensuring flexibility for unforeseen emergencies. Strategic decisions regarding repair versus replacement, outsourcing, and spare parts inventory should be based on sound economic analysis.
2. **Regulatory Compliance** Adherence to local and international regulations, such as OSHA, EPA, FERC, and FDA, is essential. Achieving compliance necessitates systematic inspections, verification of safety devices, comprehensive documentation, and continuous asset monitoring in accordance with health, safety, and environmental standards.
3. **Proactive maintenance planning** facilitates uninterrupted equipment operation and reduces costly downtime. Strategic scheduling addresses urgent requirements and enhances resource allocation, which contributes to operational stability.
4. **Maintaining the safety of assets**, including boilers, compressors, and mechanical systems, is essential. Regular inspections, thorough staff training, and rigorous adherence to safety regulations help prevent workplace accidents and ensure compliance with safety standards (e.g., IEC 61508).
5. **Minimizing equipment failure** and downtime is achieved through the integration of preventive, predictive, and condition-based maintenance strategies. These approaches enable maintenance teams to substantially reduce both the frequency and severity of equipment breakdowns. Timely fault detection and effective repair are critical for minimizing operational disruptions.
6. **Reliable maintenance** extends the equipment's useful lifespan. Well-implemented maintenance plans enhance reliability, availability, and maintainability, which are core components of the RAMS framework as defined in IEC 60300 and ISO 55000.
7. **Improving product quality** is achieved through proper machine maintenance, resulting in higher-quality outputs with fewer defects and rework. This approach enhances customer satisfaction and reduces scrap rates.
8. **Continual improvement of maintenance policies, procedures, and interdepartmental coordination fosters** enhanced communication, reduces inefficiencies, and promotes the adoption of best practices throughout the organization.

1.7 Conclusion

This maintenance course is for third-year mechanical engineering students. It introduces the course's general framework. The module is part of dependability, which is the study of failures and the reliability of systems. In this context, maintenance refers to the activities carried out to prevent failures or restore systems to working order.

System failures occur randomly. In this context, dependability refers to a system's ability to perform as expected over time. Maintenance involves actions taken to prevent or address failures. This chapter clarifies the purpose of the maintenance function in industrial systems, particularly in ensuring system reliability, which is the probability that a system operates without failure for a specific period, and safety, meaning the system operates without causing unacceptable risk.

To meet this objective, the chapter introduces essential concepts. These include system definitions, the relationships among error, fault, and failure, system configurations, dependability attributes, and maintenance goals.

This chapter provides an overview of the subject. The next chapter focuses in detail on maintenance. It will cover definitions, policies, tasks, and hierarchical levels.

Chapter 2: Different forms of maintenance

2 Chapter 2: Different forms of maintenance

2.1 Introduction

In the current competitive industrial environment, organizational performance depends not only on equipment design and quality but also on maintaining reliability, availability, and safety over time.

Maintenance, previously regarded as a support function or cost center, is now recognized as a strategic activity that directly contributes to competitiveness, risk management, and lifecycle optimization of industrial assets. Effective maintenance reduces production downtime, improves product quality, enhances safety, controls operating costs, and extends equipment lifespan.

Modern maintenance management seeks to balance corrective (reactive) and preventive (proactive) maintenance while adhering to budgetary, regulatory, and organizational constraints. International standards such as NF EN 13306, IEC 60300, and ISO 55000 emphasize standardizing terminology and integrating maintenance into a comprehensive asset management framework focused on reliability, availability, and risk control. Maintenance is a technical and economic necessity for the sustainable performance of mechanical and industrial systems.

Upon completing this chapter, students will be able to:

- Master standardized terminology by understanding and applying official definitions to ensure precise technical communication in professional contexts;
- Analyze maintenance policies by identifying initiating events and corresponding methods;
- Distinguish among maintenance strategies, including: (i) corrective maintenance, (ii) systematic preventive maintenance, and (iii) condition-based preventive maintenance;
- Select appropriate maintenance policies based on equipment criticality.
- Classify interventions according to maintenance levels and operations, ranging from simple adjustments to complete overhauls.

This chapter addresses standardized definitions, maintenance policies and strategies, maintenance operations, and maintenance levels. Mechanical students of these concepts are essential for mechanical engineers, as it forms the foundation for subsequent study of system reliability, operational safety, condition-based maintenance, and industrial asset management.

2.2 Maintenance Terminology and Standard Definitions

Standardizing maintenance terminology is essential for ensuring a common understanding among industrial, academic, and regulatory stakeholders. This section presents the most widely accepted definitions, primarily from EN 13306 and IEC standards, along with key scientific references.

2.2.1 Maintenance

According to the European standard EN 13306:2017, maintenance is defined as: « The combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. » (13306, 2017).

This definition underscores the comprehensive scope of maintenance, encompassing not only technical interventions but also organizational and decision-making aspects throughout the system's lifecycle.

Consistently, IEC 60050-192 (International Electrotechnical Vocabulary – Dependability) offers a similar definition: « Maintenance is the combination of all actions carried out to retain an item in, or restore it to, a state in which it can perform its required function. » (IEC-60050-192, 2016)

Both definitions highlight that the primary goal of maintenance is the system's functional capacity, irrespective of the methods used.

- Based in this definition, the keys concepts are issued:
- Maintain: Preventive actions on functioning systems
- Restore: Corrective actions after performance loss

Specified state: Target operational criteria must be predefined and measurable.

So, for the company, this "*good maintenance*" should therefore translate into "*fewer breakdowns*", "*less expenses*", "*more availability*" of the production tool, "*more quality of service provided to the user*", better security, etc.

The maintenance function is often described in the literature as comprising two main categories: predominantly technical activities and predominantly managerial activities (see Figure 1.1).

2.2.2 Maintainability

According to (IEC-60050-192, 2016), maintainability is defined as: « Ability of an item, under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources».

Maintainability is therefore an intrinsic property of the system, closely linked to its design and operating environment.

2.3 Foundational Concepts of Maintenance Policy Analysis

There are four basic concepts for analyzing and classifying maintenance strategies (Bouabid et al., 2024; Chanter & Swallow, 2008; Dhillon, 2006; Kelly, 1997; Mobley, 2011):

2.3.1 Maintenance Triggering Events

These refer to the origin or rationale for initiating maintenance actions. Maintenance triggers are specific reasons or signals that start the maintenance process. Examples include a scheduled maintenance date (a planned time to perform maintenance), detection of abnormal behavior through built-in system checks (self-diagnosis), sensor data such as unusual vibration or temperature readings from equipment, measurements indicating that parts are worn, or the actual breakdown (failure) of a component. These events determine when and what kind of maintenance is needed.

2.3.2 Associated Maintenance Methods

Each triggering event corresponds to a specific maintenance approach. The main categories are: Systematic Preventive Maintenance (maintenance performed at set time intervals or after a specified amount of machine use), Condition-Based Preventive Maintenance (maintenance performed when sensors or inspections indicate a problem or wear), and Corrective Maintenance (maintenance performed only after equipment has already failed). These strategies align with the definitions in (13306, 2017; 14224:, 2016).

2.3.3 Primary Maintenance Operations

These operations include technical actions designed to preserve or restore system functionality, such as the following:

- Inspection procedures
- Functional testing protocols
- Troubleshooting and fault localization
- Repair and restoration procedure,

2.3.4 Associated Support Activities

In addition to primary operations, maintenance encompasses several ancillary tasks intended to enhance performance, safety, or asset value. These tasks include:

- Equipment upgrades and modernization
- Renovation and refurbishment
- Implementation of new installations, including construction or retrofitting
- Safety upgrades and compliance measures

2.3.5 Application and Importance

This terminological and conceptual framework serves as a foundational reference for two critical dimensions in industrial maintenance:

- The use of standardized language across all stakeholders: design teams, production departments, service providers, and maintenance engineers
- The development and deployment of Computerized Maintenance Management Systems (CMMS) or Enterprise Asset Management (EAM) platforms to digitize, monitor, and optimize maintenance processes

By clearly defining the nature of maintenance activities and their organizational context, this structure helps ensure coherence, traceability, and operational efficiency throughout the asset lifecycle. (Wienker, Henderson, & Volkerts, 2016).

These four basic concepts for maintenance and their classifications (Kelly, 1997) are presented by the Fig.2.1.

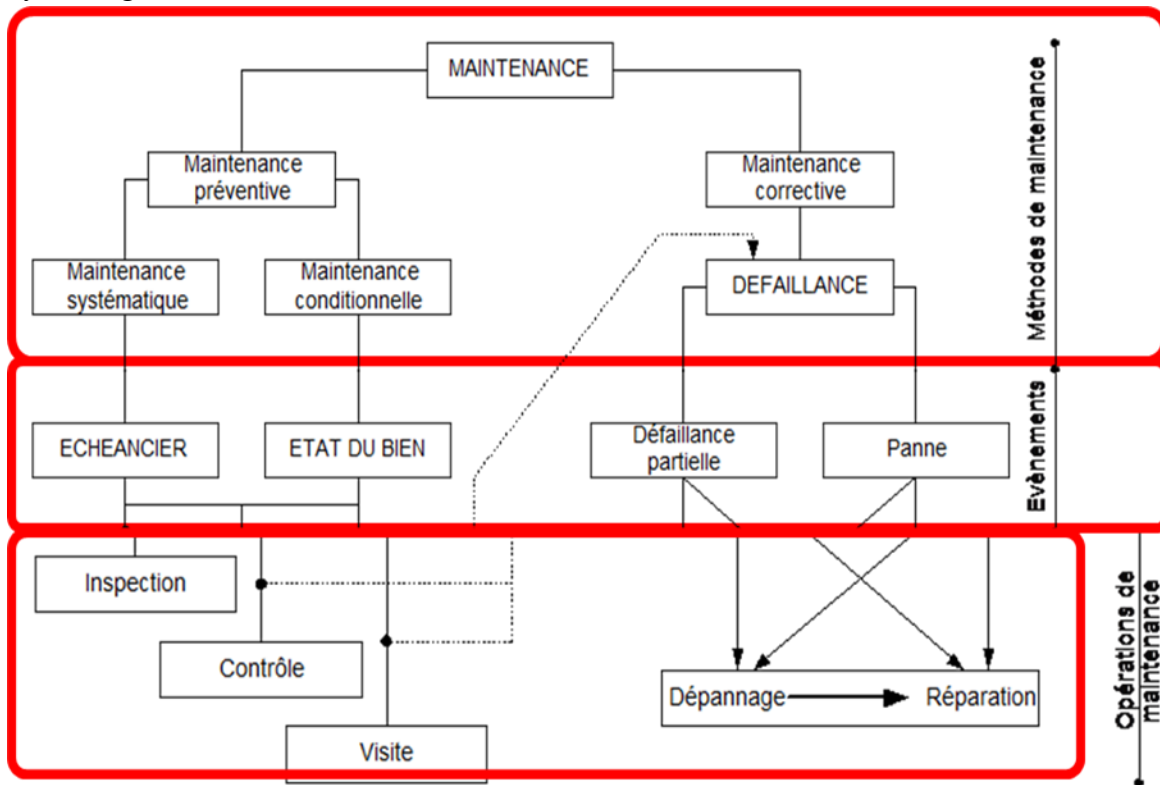


Figure 2-1 Maintenance Policy Analysis

2.4 Classification of Maintenance Strategies (policies)

The selection of a maintenance method is conducted in accordance with the company's maintenance policy and requires management approval to ensure consistency with other objectives and guidelines. The following factors must be considered:

Management's stated objectives:

- The operational behavior of equipment
- Costs associated with production loss
- The overarching maintenance strategy
- Costs incurred by maintenance activities
- Conditions for the application of each method
- Understanding of equipment operation and characteristics

Maintenance activities are categorized based on event triggers, intervention methods, and system objectives.

2.4.1 Corrective Maintenance

According to NF EN 13306; the corrective maintenance is « Maintenance carried out after fault recognition and intended to restore an item into a state in which it can perform a required function. » (13306, 2017) (see the Fig. 2.2).

Similarly, AFNOR X60-010 defines corrective maintenance as: “*Maintenance carried out after the occurrence of a failure (partial or total). Given its random nature, tasks related to this type of maintenance are reactive and generally unplanned.*”

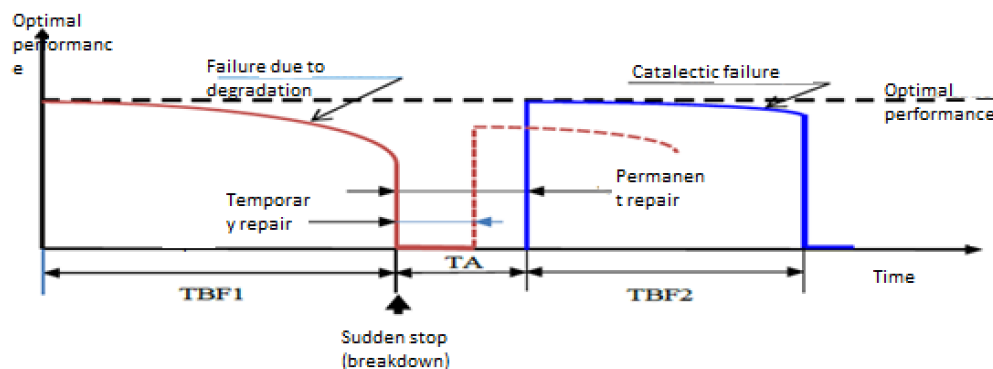


Figure 2-2 Principle of corrective maintenance

2.4.1.1 Nature and Scope of Corrective Maintenance

Corrective maintenance is inherently reactive, as it is only triggered by the appearance of a failure or performance loss. This type of maintenance is commonly referred to as breakdown

maintenance and is essential in any industrial environment where unplanned downtime must be addressed promptly.

The core activities involved in corrective maintenance include:

- Anomaly detection and reporting
- Failure localization and root cause diagnosis
- Repair and component replacement
- Functional testing and recommissioning
- Documentation of intervention (often using CMMS systems for traceability)

The intervention report is essential for updating reliability and availability databases and tracking maintenance costs and failure modes over time.

2.4.1.2 Factors Affecting Effectiveness

The efficiency of corrective maintenance actions depends on several key factors:

- Maintainability of the equipment (ease and speed of repair)
- Skill level and availability of maintenance personnel
- Organization and responsiveness of the maintenance logistics chain (spare parts, tools, access)

Any weakness in these areas can lead to extended downtimes, increased operational costs, and loss of production efficiency(Y. Wang, Deng, Wu, Wang, & Xiong, 2014).

2.4.1.3 Curative vs. Palliative Actions

Corrective maintenance does not necessarily imply a complete repair of the asset. In many cases:

- A partial failure may degrade performance without completely halting operation.
- Deferred repair may be chosen for logistical or strategic reasons.
- Temporary fixes (also known as troubleshooting or palliative actions) are implemented to restore partial functionality until a full intervention can be scheduled.

In this context, curative maintenance refers to complete restoration, whereas palliative maintenance consists of interim actions that reduce failure impact or delay more extensive work (see the Fig 2.3).

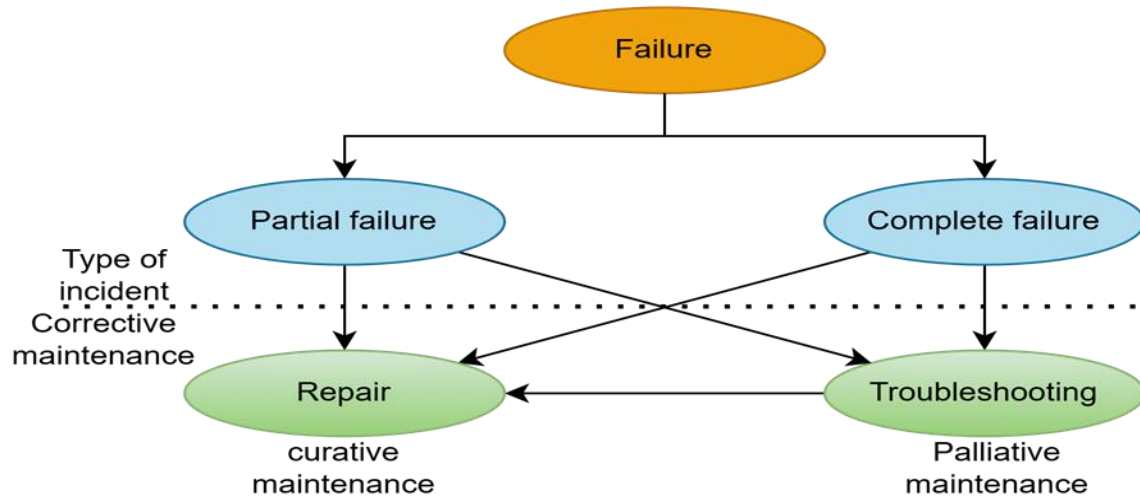


Figure 2-3 typically illustrates both types within the corrective maintenance category

Corrective maintenance is indispensable in all maintenance systems, but it must be strategically limited through proactive policies (preventive, predictive) to avoid costly and frequent interventions. Nevertheless, its structured application, supported by proper documentation, analysis, and logistical preparedness, ensures that when failures do occur, downtime and cost are minimized. (Mobley, 2011; Y. Wang et al., 2014).

2.4.2 Preventive Maintenance

According to EN 13306, preventive maintenance is maintenance performed at set intervals or in accordance with defined criteria to reduce the likelihood of failure or functional degradation of an item (13306, 2017). This category includes: (i) Systematic maintenance, (ii) Condition-based maintenance, and (iii) Predictive maintenance.

In this context, maintenance is carried out according to predetermined criteria to reduce the risk of failure for an entity or a decline in service quality. There are two main types of preventive maintenance:

2.4.2.1 Systematic Preventive Maintenance (time-based maintenance)

Definition: according to (13306, 2017): “Maintenance carried out at predetermined time intervals or after a defined number of operating units, without prior inspection of the asset’s condition.” See the Fig. 2.4.

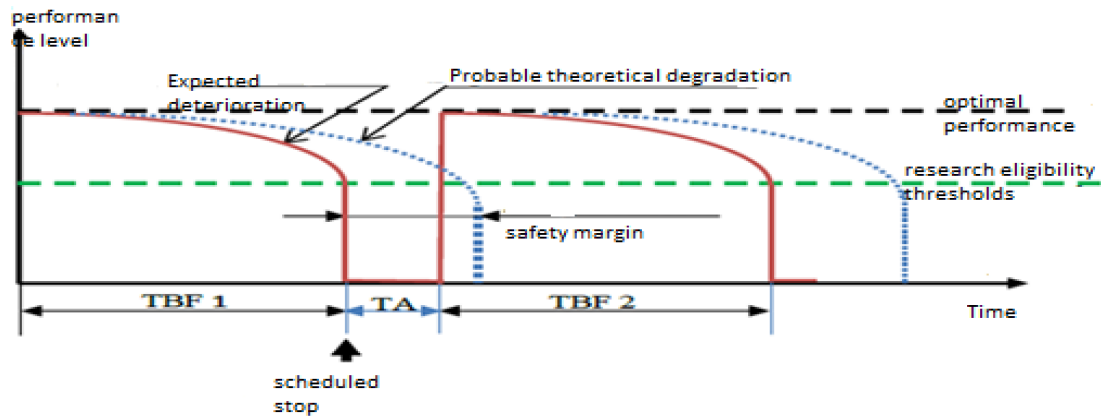


Figure 2-4 Principle of systematic preventive maintenance

This maintenance strategy aims to keep the system working as it did at first. Its goal is to maintain the system's original performance. It is best for components in Category A of the ABC failure-cost curve. In these cases, a failure could have serious economic or operational effects, but replacements are not expensive (see the Fig. 2.5). (Joglar, 2016)

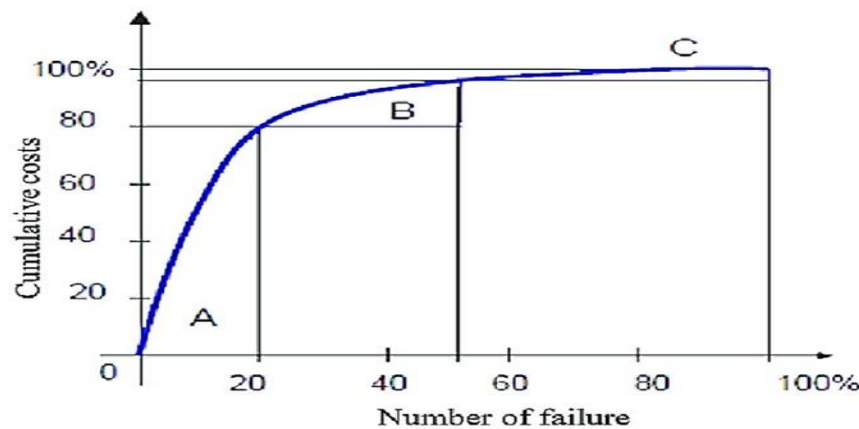


Figure 2-5 ABC Cost Curve

Typical examples include:

- Replacement operations: examples include replacing oil, bearings, filters, and seals.
- Adjustment tasks: examples include pressure calibration, alignment, and clearance adjustments.

The Fig. 2.6. shows the systematic preventive intervention (Ipsi). It is done at fixed intervals (T). During each cycle, parts or fluids are replaced, regardless of condition. This means maintenance happens on a set schedule, not based on the asset's condition. (Mahfoud, El Barkany, & El Biyaali, 2016).

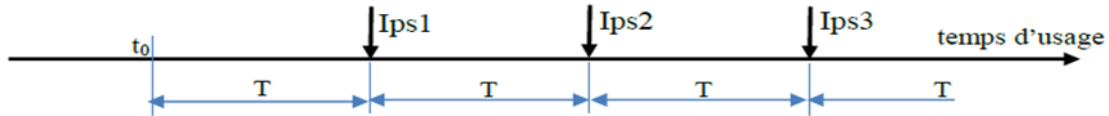


Figure 2-6 Systematic preventive intervention

Table 2.1 details the preventive maintenance frequencies and criteria, and

Table 2-1 Preventive Maintenance Frequencies and Criteria (Mahfoud, El Barkany, & El Biyaali, 2016)

T Value	Nature of systematic actions	T selection criteria
Short Period 1/2 day to one week	- Active monitoring - Preventive inspection, rounds - Standing instructions / Station duties	- Supplier recommendation - Experience - Empirical practices
Medium Period $T = k * MTBF$ (1 week to 1 year)	- Standard module or component replacement - Specific actions on a "fragile" component	- Regulatory requirements - Manufacturer recommendation - T optimized via calculations, testing, or experience
Long Period 1 year to 10 years	- Limited overhaul, general decennial review - Periodic shutdowns, annual outages	- Regulatory requirements - Empirical (T linked to operational constraints: e.g., annual holidays)

the ABACABAD method is used to define intervention frequencies and planification for greater detail.

The ABACABAD method

The ABACABAD method: Since the intervention frequencies are known, the next step is to plan them. This planning can be done following a geometric progression with a common ratio of x :

$$t_i = t_{i-1} * X \quad \text{Eq. 2-1}$$

Example with $x=2$:

Table 2-2 The ABACABAD method for systematic preventive intervention (Frequencies)

Tasks	Frequencies
A	$t_1 = t_{i-1}$
B	$t_2 = 2 t_1$
C	$t_3 = 2 t_2$
D	$t_4 = 2 t_3$

Thus, the planning is carried out as follows:

Table 2-3 Tasks performed of The ABACABAD method for systematic preventive intervention

Tasks	Tasks performed	Visitor information sheets
t_1	A	1
$2 * t_1$	A+B	2
$3 * t_1$	A	
$4 * t_1$	A+B+C	3
$5 * t_1$	A	
$6 * t_1$	A+B	
$7 * t_1$	A	
$8 * t_1$	A+B+C+D	4

Example:

The maintenance manager must establish an intervention checklist for construction equipment and schedule the four tasks.

Table 2-4 Example of the ABACABAD method for systematic preventive intervention

N°	Tasks		T(h)
A	Vérifier le boulon de tenue du godet	Check the bucket retaining bolt	1100
B	Changer huile du moteur	Change engine oil	2000
C	Remplacer le filtre à huile	Replace the oil filter	4200
D	Changer l'huile de la boîte de vitesse	Change the gearbox oil	7900

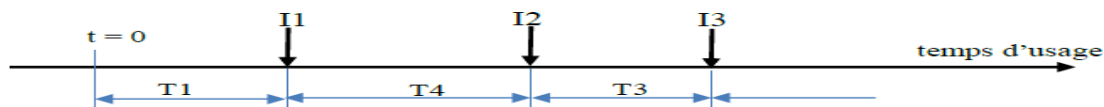
2.4.2.2 Condition-Based Preventive Maintenance (CBM)

Triggered when parameters exceed thresholds (e.g., vibration, temperature, oil quality). This approach suits equipment that is monitored by non-destructive methods and is costly to replace. The core idea is to replace components only when signs of aging or wear jeopardize functionality (El Hami & Radi, 2011; Sakib & Wuest, 2018).

The main challenge is setting the interval T. T depends on the failure risk. MTBF is the average time between failures (See **Fig. 2.7**). The maintenance interval is given by:

$$I_n - I_{n-1} = k \times \text{MTBF} \quad \text{Eq. 2-2}$$

(where $k < 1$) With: I_i : intervention; $T_1 \neq T_2 \neq T_3$

**Figure 2-7** Intervention of Condition-Based Preventive Maintenance (CBM)

Characteristic graph of Conditional Preventive Maintenance:

This refers to monitoring, through periodic measurements or in real time using sensors, of a deterioration up to the alarm threshold that triggers a conditional preventive intervention (denoted I_{pc}). The response time is the period between the alarm threshold being reached and the completion of preparation and scheduling for the intervention (see Fig. 2.8).

Sensor measurements commonly include temperature, pressure, vibration, mechanical play, oil condition, and electrical values such as voltage or current.

Reference Standards: ISO 17359 (Condition Monitoring), ISO 13379 (Diagnostics), IEC 61508

(Safety-related systems)

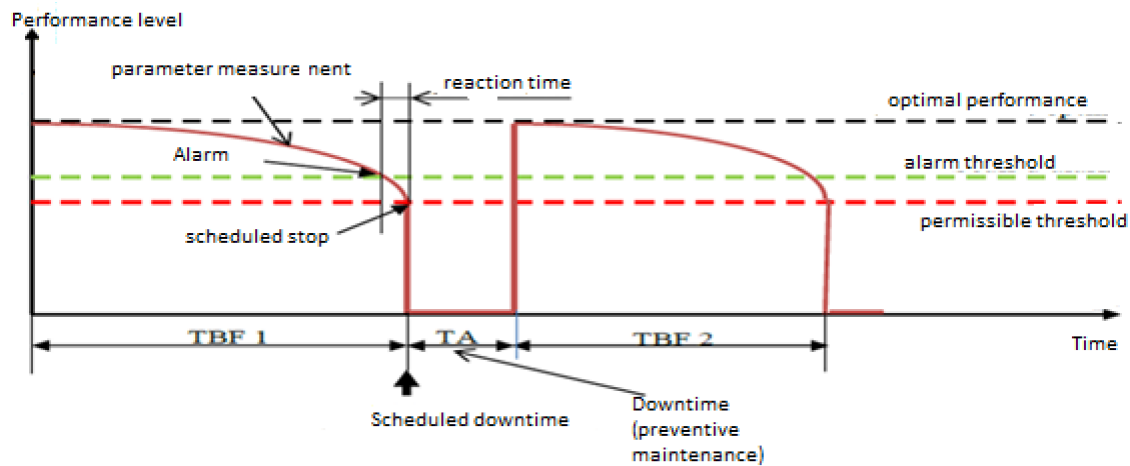


Figure 2-8 Characteristic graph of Conditional Preventive Maintenance

CBM based on various technics or method can be led to the maintenance tasks; the Table 1 and Fig. 2.9 provides descriptions of these methods (Bouabid et al., 2024; Sakib & Wuest, 2018).

Table 2-5 Type of conditional preventive maintenance: (Bouabid et al., 2024; Sakib & Wuest, 2018)

Ref	Type	Description
1	Vibration Analysis	This diagnostic tool evaluates vibrational signatures of rotating assets such as motors and pumps. Deviations from established vibration baselines can reveal misalignment, imbalance, or component degradation, facilitating preemptive corrective actions.
2	Thermography	This approach uses infrared imaging to detect thermal anomalies in equipment components. Elevated temperatures may indicate developing electrical or mechanical defects, supporting predictive maintenance decisions.
3	Oil Analysis	This procedure involves laboratory examination of lubricants for contaminants and wear particles. Assessing lubricant condition enables the detection of internal wear processes and informs maintenance scheduling.

4	Ultrasonic Testing	This inspection method uses sensors to detect high-frequency acoustic emissions beyond human hearing. Ultrasonic signatures correlate with equipment issues, such as bearing degradation or fluid leaks, enabling early fault identification.
5	Electrical Testing	By measuring insulation resistance and current continuity, maintenance personnel can identify conditions such as insulation breakdown or short circuits. This reduces the likelihood of major electrical failures.



Figure 2-9 (a) Oil Analysis, (b) Vibration Analysis, (c) Ultrasonic Testing and (d) Thermography

Rationale for Implementing Condition-Based Maintenance): A Structured Approach

Implementing CBM requires a systematic approach aligned with organizational goals. Following these steps (presented by the figure 1) ensures a smooth transition and maximizes the benefits of real-time monitoring (Dhillon, 2006; Sakib & Wuest, 2018):

- 1) **First, identify assets that benefit most from CBM.** Focus on critical machinery causing major downtime or high repair costs. Not every asset needs CBM, so prioritize wisely.
- 2) **Select sensors based on the conditions to monitor,** like vibration or temperature. Ensure they fit your machinery and deliver accurate, real-time data.
- 3) **Integrate with Monitoring Systems:** Connect sensors to a centralized monitoring platform, such as a Computerized Maintenance Management System (CMMS). This integration enables efficient data collection and analysis, providing maintenance teams with comprehensive visibility into asset health.
- 4) **Analyze Data in Real Time:** Establish condition thresholds based on collected data. When monitored parameters exceed these thresholds, the system should generate maintenance alerts. Continuous real-time monitoring facilitates early detection of issues, thereby reducing the risk of costly equipment failures.

- 5) **Train your team to interpret CBM data and respond promptly.** Ensure they know the tools and understand system insights.
- 6) **Implement Incrementally:** Initiate a pilot program with a limited number of critical machines. Evaluate outcomes, refine implementation processes, and progressively expand CBM deployment to additional assets as improvements in operational efficiency and reduced downtime are observed.



Figure 2-10 Implementing of Condition-Based Maintenance

2.4.3 Predictive Maintenance

Like condition-based preventive maintenance, predictive maintenance depends on current asset conditions. Predictive tasks, including routine monitoring, are ideally performed in real time. They can be performed both offline and online (Bouabid et al., 2024). Predictive monitoring aims to reduce failures and equipment wear. It does this through data collection, data analysis, and measurement of variables and performance parameters. After analysis, you can assess the condition of your assets (K. Wang, 2016).

The predictive maintenance practices provide some of the smartest and most useful maintenance tools today, such as condition-monitoring software. These tools keep the manager informed about all equipment activity (24/7). They provide diagnoses and accurate data to support strategic planning. Corrective and preventive tasks are then scheduled purposely, not randomly (Dhillon, 2006; Liu, Li, & Yan, 2024).

The stages discussed are illustrated in the accompanying figure by the P-F Curve. The P-F Curve is named for its focus on monitoring conditions associated with known failure modes,

specifically between the point of potential failure detection (P) and functional failure (F). Accurate failure prediction through early detection depends on implementing an appropriate predictive maintenance strategy (K. Wang, 2016).

As the curve declines from left to right, machine performance, represented on the y-axis, deteriorates. The severity of machine failure increases over time, as indicated on the x-axis, and associated symptoms become more readily detectable. However, although symptom detection becomes easier at this stage, it typically coincides with imminent downtime and increased costs, since the damage is often irreparable. Unfortunately, this coincides with impending downtime and increased costs, as the damage is irreparable.

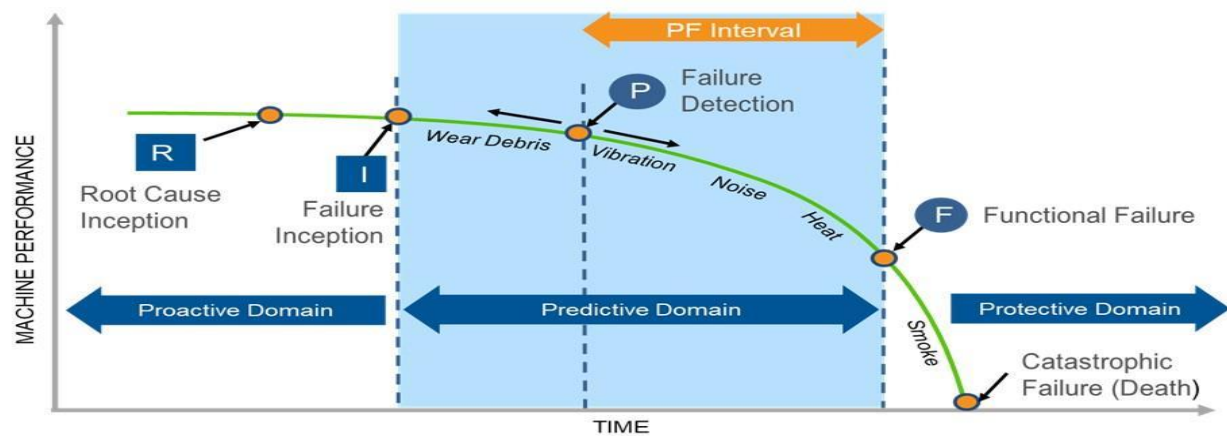


Figure 2-11 Predictive maintenance domain

2.4.4 Proactive Maintenance (Pre-Failure Detection (Root Cause))

Combining predictive and preventive maintenance enables a proactive strategy. By analyzing machine data, you can identify and fix faults before failures occur (Bouabid et al., 2024).

Since wear and tear are unavoidable, proactive maintenance emphasizes machine reliability and minimizes downtime. This approach helps managers allocate resources when needed. Implementing a proactive maintenance plan not only increases efficiency but can also extend the lifespan and reliability of machines (Do, Voisin, Levrat, & Iung, 2015; Leitao-Junior et al., 2020).

Proactive Maintenance is not tied to a schedule. Instead, it uses insights from ongoing data analysis to target common failures with interventions based on calculated probabilities.

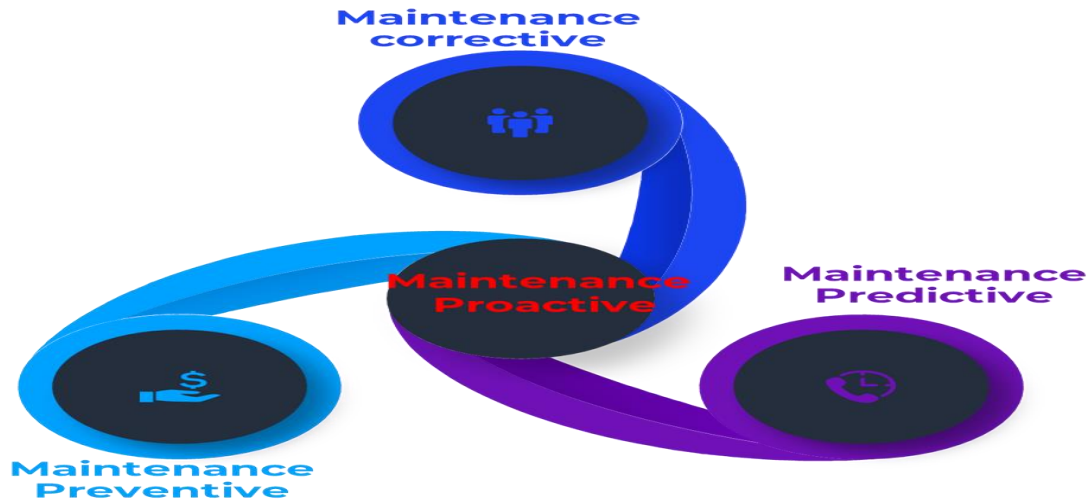


Figure 2-12 Proactive Maintenance

2.5 Maintenance Policy Selection

The **Fig.2.12** presents the choice of the most suitable maintenance type for a given situation generally depends on (Leitao-Junior et al., 2020) type and criticality of failure (random, cyclical, wear-based):

- Direct and indirect maintenance costs
- Technical staff capability
- Availability of spare parts and diagnostic tools
- Asset life cycle strategy and production planning

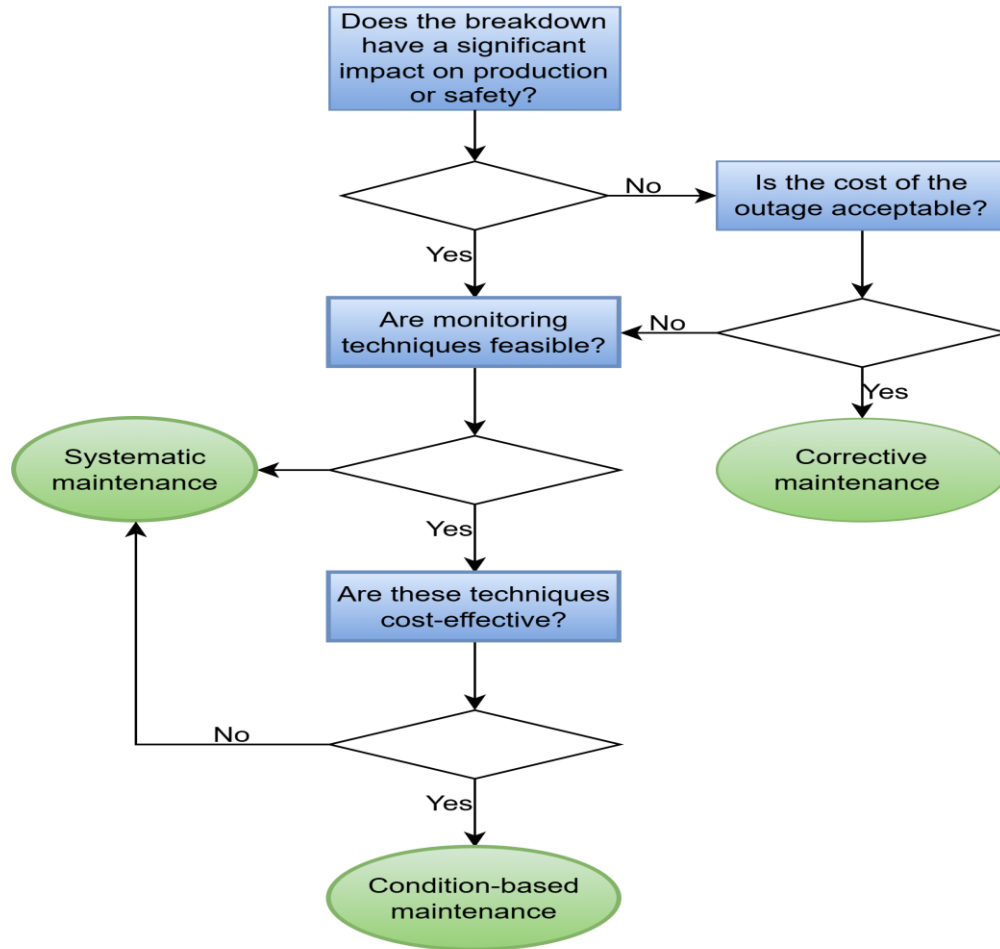


Figure 2-13 Maintenance Policy Selection Process

Note: The goal is not only to fix failures, but to plan interventions that prevent them, reduce costs, and increase productivity.

This course content has been built to serve as a technical foundation for mechanical engineering students, and aligns with international norms in reliability engineering, maintenance planning, and asset management. Advances in technologies (vibration analysis, infrared thermography, oil and debris analysis) combined with smart sensors and IoT, have redefined industrial maintenance. Predictive maintenance now anchors modern reliability strategies (Bouabid et al., 2024).

Predictive maintenance relies on early detection of failures, ideally at the start of the P–F curve. Early detection slashes repair costs, limits downtimes, and curbs catastrophic risk.

However, early detection poses a decision-making challenge: Weak signals (e.g., wear particles detected through oil analysis) can create uncertainty about when to intervene. Such signals may

raise doubts, leading maintenance teams to hesitate and delay action, even though the equipment appears to be functioning normally. As a result, intervention might be delayed until signals become more obvious—at which point the machine is much closer to functional failure. This hesitation can undermine the effectiveness of predictive maintenance(Chopra, 2021).

At the same time, proactive maintenance has developed as a complementary approach to predictive maintenance. While predictive maintenance focuses on early failure detection, proactive maintenance targets eliminating the root causes of failures, including: (i) contamination control, (ii) lubricant quality, and (iii) control of operating conditions.(Mohd Noor et al., 2021; K. Wang, 2016)

Unlike predictive maintenance, which detects symptoms, proactive maintenance addresses the factors that cause degradation. By working together, these strategies provide both early warnings and long-term reliability improvements, aiming to significantly reduce failure frequency by tackling the dominant causes (Pareto's 80/20 principle: 20% of causes account for 80% of failures).

2.5.1 Complementarity of Maintenance Policies

However, it would be a mistake to consider proactive maintenance as a standalone solution. This is because some failures are not related to contamination or lubrication and can only be detected by specific predictive techniques.

In practice, proactive maintenance addresses the fundamental causes of degradation by enabling early detection of emerging failures. And, Predictive maintenance targets remaining failure modes not eliminated by proactive measures, focusing on timely detection. Both approaches depend on monitoring physical parameters. They can be driven by common indicators (KPIs, trends, alert thresholds).

Given the overlap in purpose and method, integrating both approaches within a comprehensive Condition-Based Maintenance (CBM) strategy constitutes the most effective approach.

Together, proactive maintenance reduces the likelihood of faults while predictive maintenance limits their progression toward functional failure. This combined approach allows for optimizing the timing of interventions along the P-F curve, minimizing the overall lifecycle cost, increasing asset reliability and availability, and improving technical decision-making.

CBM, unlike time-based maintenance, intervenes only when measurable indicators indicate action is needed.

2.6 Maintenance operations

2.6.1 Corrective maintenance operations

2.6.1.1 Troubleshooting

Troubleshooting involves taking physical actions to temporarily enable faulty equipment to operate until full repair is completed (13306, 2017)

Troubleshooting has no specific application requirements. Knowledge of equipment behavior and failure modes is not essential, though it can save time. Troubleshooting operations are often short but frequent. Therefore, maintenance departments, aiming to reduce costs, try to organize troubleshooting activities. Some maintenance indicators (used to measure effectiveness) account for troubleshooting.(Kelly, 1997)

Thus, troubleshooting applies to continuously operating equipment, where production demands prohibit visits or interventions during shutdown periods.

2.6.1.2 Repair

Repair its actions taken to restore a faulty item's required function (EN 13306: April 2001). Repair may be applied either immediately after an incident or failure, after troubleshooting, or after a conditional or systematic preventive maintenance activity.

Note: Repair is a permanent action. The repaired equipment must

2.6.2 Preventive maintenance operations

2.6.2.1 Inspections

Inspections it's the conformity checks carried out by measuring, observing, testing, or calibrating the significant characteristics of an asset. In general, the inspection can be carried out before, during, or after other maintenance activities (13306, 2017)

Inspections do not have to use pre-set data. In maintenance, staff commonly perform this task during rounds.(Mobley, 2011)

Examples include inspecting fire-fighting equipment, accident-prevention measures, and the condition of slings and ropes. These inspections usually use basic tools and do not require equipment stops.

2.6.2.2 *Visite*

monitoring tasks carried out at set intervals as part of preventive maintenance. These tasks follow a preset list and may require dismantling components and equipment, resulting in downtime. An inspection can also result in corrective maintenance.(Kelly, 1997)

Examples:

- periodic inspection of elevators in residential buildings,
- periodic inspection of the engine components of a transport vehicle,
- periodic inspection of the electrical and mechanical equipment of lifting equipment in an assembly hall.

2.6.2.3 *Controls*

Controls are used to verify conformity to pre-established data, followed by a formal assessment. This process may include information sharing and a subsequent decision, such as acceptance, rejection, or postponement. Similar to site visits, these controls can lead to corrective maintenance actions.(Phogat & Gupta, 2017)

For example, the electrical insulation level of a low-voltage installation may be checked against the NFC15-100 standard.

Additional examples include verifying the play in a mechanical joint against technical drawing specifications and measuring the brush length of a rotating DC machine in accordance with the maintenance methods department's specifications. The frequency of checks may remain constant during the equipment's normal operating phase or become variable, increasing as the equipment enters its wear phase. In large automated systems, control hardware is integrated into the equipment's operating process through on-site data capture, followed by data formatting and processing in measurement units.(Kelly, 1997)

Examples of such integration include continuous automated monitoring of a refining unit's operation, centralized vibration monitoring of rotating machinery in a rolling mill, and centralized temperature monitoring in a heat treatment plant.

Monitoring operations, including checks, visits, and inspections, are essential for tracking the evolution of an asset's actual condition. These activities may be conducted continuously or at predetermined or unpredictable intervals, determined by elapsed time or the number of units used.

For example, an inspection of transport equipment may be conducted annually, whereas a visit to a motor-compressor is scheduled every three hundred operating hours. In the first instance, frequency is based on elapsed time; in the second, it is based on a unit of use, specifically the operating hour.

2.6.3 Other operations

2.6.3.1 Revision

Revision refers to all examinations, controls, and interventions performed to safeguard the asset against major or critical failures for a specified period or number of usage cycles.

Depending on the scope of work, a distinction is made between partial and general overhauls. Both types of overhauls require the removal of various sub-assemblies.

The term 'revision' should not be confused with visits, checks, or inspections.

Both general and partial overhauls are classified as fourth-level maintenance operations (see the following paragraph).

2.6.3.2 Standard exchanges

Standard exchanges involve replacing a used part, component, or sub-assembly with an identical item. The replacement may be either new or refurbished, as long as it meets the manufacturer's guidelines. The customer is charged a price determined by the refurbishment cost. (Lee & Scott, 2009)

2.6.4 Related maintenance activities/ Improvement maintenance

When improving capital goods by modifying, changing, or transforming them, the goal is to boost equipment performance. As a result, this may lead to increased reliability through fewer interventions, higher staff safety, improving maintainability (enhancing accessibility to subsystems and components with elevated failure risk), and other benefits. (Joglar, 2016; Wijeratne, Perera, & De Silva, 2014). The following operations are mentioned:

2.6.4.1 Renovation

Renovation may follow a general overhaul and can involve a standard exchange. Typical renovation activities include the following:

- Complete inspection of all components
- Complete dimensional correction or replacement of deformed parts,
- Verification of component characteristics, as applicable,
- Repair of faulty parts and sub-assemblies.

2.6.4.2 Reconstruction

Reconstruction is an action following the dismantling of the main asset and the replacement of assets that are nearing the end of their service life and/or should be systematically replaced." The primary objective of reconstruction is to extend the useful life of an asset beyond its original life.

This process requires replacing vital parts with original or equivalent new components. Unlike an overhaul, reconstruction may include modifications or improvements. Reconstruction can be accompanied by modernization or other modifications that may enhance availability, efficiency, safety, and other operational parameters.

Caution is advised regarding the reconstruction method known as 'cannibalization,' which involves extracting serviceable components from decommissioned assets with uncertain remaining lifespan for use as spare or replacement parts. The advisability of this approach should be carefully evaluated.

2.6.4.3 Modernization

Modernization involves replacing equipment, accessories, and software with subsystems that incorporate technological advancements not present in the original product, thereby improving usability. Modernization may be implemented during renovation or reconstruction projects.

2.7 Maintenance level

During asset operation, maintenance activities are performed through various tasks, both repetitive and occasional. These activities are typically categorized into five distinct maintenance levels (Joglar, 2016).

The following **Fig 2.14** outlines the responsibilities associated with each level of maintenance:

- Production staff;
- Maintenance personnel, considering the required qualifications for each task;
- Company staff or subcontractors;
- A combination of the above roles.



Figure 2-14 Maintenance level

A successful maintenance system depends on defining maintenance levels in the organization. Monchy (2) and Nakajima (5, 6) describe five levels based on task complexity and required resources. The following table explains these levels (Joglar, 2016; Kelly, 1997; Lee & Scott, 2009; Mobley, 2011).

Table 2-6 Presentation of maintenance levels (Joglar, 2016; Kelly, 1997; Lee & Scott, 2009; Mobley, 2011)

Description	Actors	Tools	Example
1st level			
Simple actions are basic operational tasks performed on elements that are directly and safely accessible using support equipment already provided within the property. These actions do not require installing or replacing any equipment.	Local operator	Light tools as defined in the instructions for use	Preventive maintenance tasks include condition monitoring rounds, daily lubrication, manual operation of mechanical parts, reading condition values or units of use, testing lamps on the control panel, purging filter elements, and checking for filter fouling. Corrective maintenance tasks include replacing bulbs, making adjustments, and replacing worn or damaged parts on simple, accessible components.
2nd level			
Intermediate actions involve simple procedures or the use of supporting equipment, which can be either integrated or external to the property. These actions are straightforward to use or implement.	Authorized technician (of average qualification) on site	Light tools as defined in the instructions for use	Preventive maintenance tasks include checking parameters on operating equipment with integrated measurement devices, performing simple adjustments such as pulley or pump-motor alignment, inspecting switching devices, including sensors, circuit breakers, and fuses, verifying safety devices, lubricating equipment at scheduled intervals, and replacing filters in inaccessible areas. Corrective maintenance tasks involve replacing components through standard exchanges, such as fuses, belts, and air filters, as well as replacing braids, stuffing boxes, and related parts. Troubleshooting procedures require consulting flowcharts to guide system restarts and component replacements. During corrective maintenance, individual or damaged wear parts are replaced using

			standard exchange methods, including rails, slides, rollers, chains, fuses, and belts.
3rd level			
Advanced operations require complex procedures and/or the use of portable support equipment. These can include tasks such as fault identification and diagnosis, replace functional components, or perform minor mechanical repairs, which are more involved or technical in nature.	Specialized (qualified) technician, on site or in a maintenance facility.	With the procedures, detailed information, and support equipment provided in the maintenance instructions. (devices) measurement, test bench, control, etc.)	Examples of preventive maintenance include checks and adjustments using external measuring devices and scheduled preventive maintenance visits. complex equipment; ignition and combustion control (boilers); intervention by Preventive maintenance also involves recording technical parameters of asset condition using data from individual measuring equipment, such as fluid or matter sampling. Examples of corrective maintenance include diagnosis, repair of refrigerant leaks in refrigeration units, reinstallation of thermal insulation, replacement of components via standard exchange without specialized tools (such as PLC boards, cylinders, pumps, motors, gears, or bearings), and troubleshooting production equipment using individual measurement and diagnostic methods.
4th level			
Operations whose procedures involve mastery of a particular technique or technology and/or the implementation of specialized support equipment.	Maintenance tasks should be performed by a technician or specialized team, following all general or specific maintenance instructions relevant to their role.	A specialized maintenance workshop, staffed by trained personnel, is equipped with general tools (mechanical, electrical, cleaning equipment, etc.) and, if applicable, measuring benches and required working standards. Personnel use all	Examples of preventive maintenance include partial or general overhauls that do not require complete dismantling of the machine, vibration and lubricant analyses, infrared thermography, and recording technical parameters using collective measurement tools and data analysis. Additionally, a workshop technician may overhaul a pump after preventive removal to ensure detailed inspection and repair. Similarly, corrective maintenance examples include compressor valve replacement, low-voltage cable head replacement, on-site pump repair following

		general or specific documentation during tasks.	a failure, and troubleshooting production equipment using advanced measurement or diagnostic tools such as PLC programming and control systems.
5th level			
Operations whose procedures involve know-how, using specific techniques or technologies, processes, and/or equipment, and industrial support. (renovation, reconstruction, or repair work)	This type of operation is carried out by the manufacturer or by a specialized service provider or company.	With the use of support equipment specified by the manufacturer and closely related to the manufacturing process, the company's attention to these operations becomes evident.	With the use of support equipment specified by the manufacturer and closely related to the manufacturing process, the company's attention to these operations becomes evident.

2.8 Conclusion

Contemporary industrial performance depends on a systemic approach to maintenance integrated into the broader asset management strategy. No single maintenance policy ensures the reliability and availability of complex systems. Instead, an optimal level of technical and economic control is achieved through a rational and hierarchical combination of corrective, preventive, predictive, and proactive approaches.

Proactive maintenance addresses the root causes of failures before they cause degradation. Predictive maintenance uses data analysis and condition monitoring to anticipate failures before they cause functional impact. Although corrective maintenance is reactive, it remains essential for decision-making, especially for equipment with low criticality or unpredictable performance.

Modern maintenance engineering builds on this integrated approach and is grounded in risk management, lifecycle optimization, and the maximization of operational availability. It employs methodologies from reliability engineering, dependability engineering, probabilistic analysis, and economic engineering.

Ultimately, maintenance functions as a strategic lever for continuous improvement, supported by systematic measurement, analysis, and rational decision-making.

Chapter 3: Maintenance Organizations

3 Chapter 3: Maintenance Organizations

3.1 Introduction

In accordance with EN 13306, maintenance includes all technical, administrative, and organizational actions intended to maintain or restore an asset to a state enabling it to perform its required function. In this context, maintenance is an essential function of the production system, with a direct impact on equipment availability, installation reliability, and cost control.

This chapter is devoted to the study of maintenance organization in industrial systems. It presents the components of a maintenance system, including organizational, methodological, and operational aspects, as well as the steps for developing an effective maintenance plan. The approach adopted is part of the logic of physical asset management, as defined by ISO 55000.

An important place is given to Computerized Maintenance Management Systems (CMMS), (CMMS), which today constitute a central tool for managing maintenance activities. The main functionalities of the CMMS are analyzed and linked to reliability, maintainability, and availability (RMA) indicators to provide a global and operational understanding of the performance of industrial systems.

Educational objectives

- At the end of this chapter, the student will be able to:
- Understand the organization of an industrial maintenance system;
- Identify key maintenance functions and policies.
- Explain the role of a CMMS in managing maintenance;
- Link maintenance actions to RMA indicators

3.2 Maintenance system

A comprehensive maintenance system relies on three complementary pillars. The first pillar involves organizational functions that structure activities, including role distribution, resource management, planning, and intervention coordination. The second pillar comprises methodological approaches that facilitate the selection and optimization of maintenance strategies based on equipment criticality, including corrective, preventive, conditional, and predictive methods, with a focus on reliability and cost control. The third pillar comprises specialized information technology tools, such as Computerized Maintenance Management Systems (CMMS), which provide traceability, historical tracking, performance analysis, and support the continuous improvement of maintenance actions (see these elements in Fig. 3.1)(Chanter & Swallow, 2008; Dhillon, 2006; Kelly, 1997).

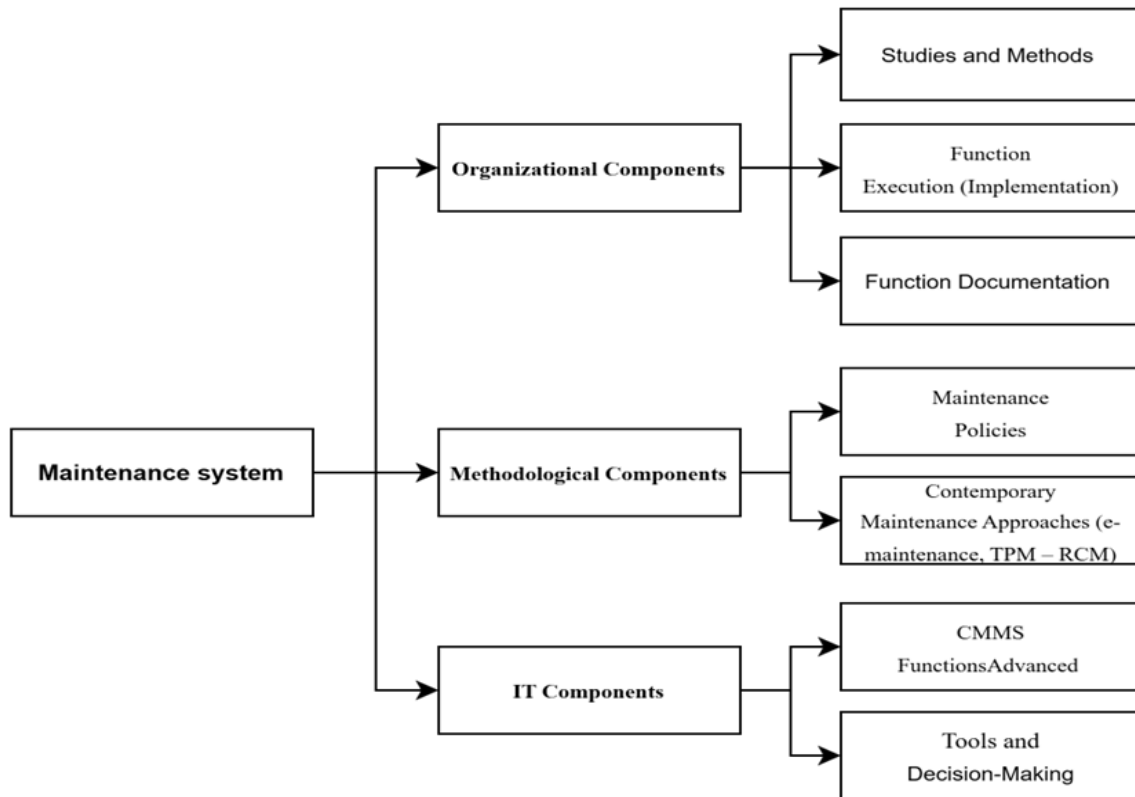


Figure 3-1 Elements of maintenance system

3.2.1 Organizational components

The organizational structure of maintenance management generally involves three main functions, which guide the activities and tasks necessary for success:

3.2.1.1 Studies and methods function

This function focuses on optimizing tasks based on the criteria of the chosen maintenance policy. The main tasks include carrying out technical studies. These studies focus on system improvements, participation in the design of new construction with an emphasis on maintenance, and accident analysis. Their aim is to propose corrective actions and safety instructions.

He manages preparation and planning by first establishing the necessary instruction sheets, then creating documentation for all types of interventions, and finally preparing schedules for preventive interventions and supplies. It carries out economic and financial studies, such as supply management to optimize the use of raw materials, analysis of maintenance costs, breakdown costs, and operating costs, and participates in the drafting of specifications to ensure that the systems meet the requirements for maintainability and reliability.

3.2.1.2 *Execution function (implementation)*

This role needs solid experience and a strong understanding of different technologies. Key tasks include installing machinery and equipment, training staff to use them, and ensuring hygiene and safety rules are followed.

He manages schedules and service calls, including finding the cause of hardware problems. He also coordinates maintenance work, restarts equipment after repairs, and keeps track of materials like spare parts and tools.

3.2.1.3 *Documentation function*

This function works alongside the other two. It creates and updates the inventory of equipment and facilities. It also maintains current technical, historical, and economic records and ensures that supplier documentation, technical data, and safety information remain up to date.

3.2.2 **Methodological components**

Methodological elements encompass strategies and policies adopted to perform maintenance, ranging from traditional reactions to modern predictive systems:

3.2.2.1 *Maintenance policies*

This section covers several types of maintenance policies, including the following:

- **Corrective maintenance** occurs after a failure and includes palliative (temporary fixes) or curative (permanent solutions) actions.
- **Preventive maintenance:** Perform actions aimed at reducing the probability of failure. This category includes the following types:
 - o **Systematic preventive maintenance** consists of scheduled tasks based on time or usage, replacing components regardless of wear.
 - o **Conditional or predictive preventive maintenance** uses criteria like vibration or oil analysis to trigger action. Predictive maintenance tracks these changes to delay and schedule repairs.
 - o **Ameliorative maintenance** targets root causes by diagnosing faults and applying suitable solutions.

For more information about these policies, refer to Chapter 2.

3.2.2.2 Contemporary approaches to maintenance

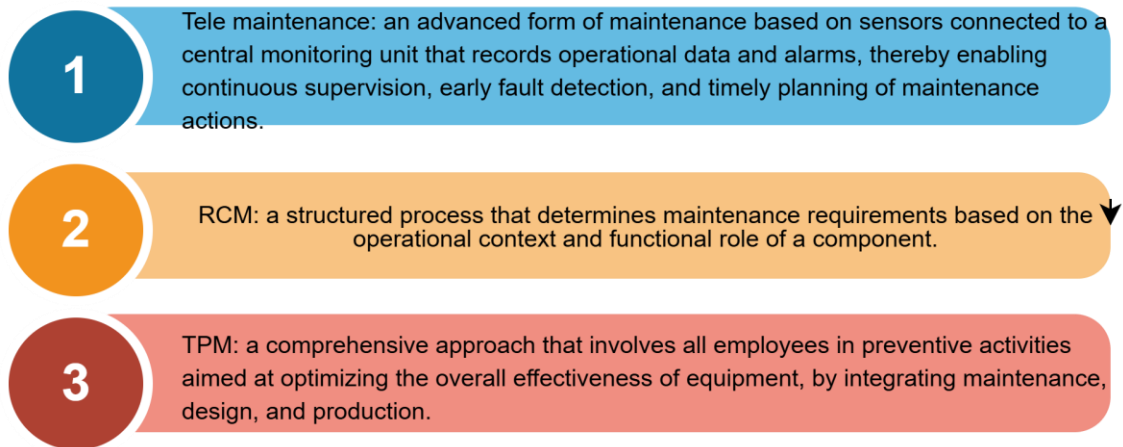


Figure 3-2 Contemporary approaches to maintenance

a) E-maintenance

Remote maintenance consists of monitoring, diagnosing, and, when needed, assisting with maintenance interventions, enabled by sensors and communication infrastructure (industrial networks, the internet, 4G/5G, VPNs, etc.)(Bouabid et al., 2024; Liu et al., 2024).

Working principle (typical chain)

- 1) Equipment sensor installation: vibration, temperature, pressure, flow rate, electrical intensity, etc.
- 2) Data acquisition: programmable logic controllers (PLCs, devices for automating equipment), data acquisition modules (hardware for capturing sensor data), and IoT gateways (edge gateways that collect device data for transmission).
- 3) Local processing (also called edge processing): filtering, indicator calculations such as RMS (root mean square) vibration, average or maximum temperature, drift (changes over time), and initial detection of anomalies.
- 4) Transmission to a central unit: supervision server (oversees equipment), SCADA (Supervisory Control and Data Acquisition system), IoT platform (system for managing IoT data), or CMMS/EAM (Computerized Maintenance Management System/Enterprise Asset Management).
- 5) Perform monitoring and alarm generation: define thresholds, track trends, apply rules (IF...THEN), or use predictive models.
- 6) Decision & planning: generation of alerts, creation of work orders (OT), preparation of parts, and planned intervention.

- 7) Remote support: diagnostic guide, video conferencing, and AR (augmented reality) assistance in some cases.

Types of tele-maintenance

- 1) Surveillance (monitoring): observation of the state, alarms, trends.
- 2) Diagnosis: likely identification of the cause (misalignment, cavitation, rolling...).
- 3) Assistance: remote expert support during troubleshooting (procedures, settings).
- 4) Tele-intervention (rarer and framed): remote action on parameters (e.g., reset, change of setpoint) — highly controlled in security.

Advantages and limits

Advantages and limits are presented by the **Table 3.1**

Table 3-1 Benefits and limits of e-maintenance

Benefits	Limits
-Early detection of drifts less sudden failures. -Intervention better prepared MTTR reduction (repair time). -Less travel saves time/costs. -Traceability of alarms and data better reliability.	-Cybersecurity (VPN, network segmentation, access rights). -Quality of the sensors and installation (incorrect assembly = false alarms). -Data management (too many alarms = 'alarm fatigue'). -Need for skills (vibration analysis, data, instrumentation).

b) Total Productive Maintenance (TPM – Total Productive Maintenance)

TPM is a global approach to continuous improvement aimed at maximizing equipment efficiency by involving all stakeholders: production, maintenance, methods, quality, safety, etc. The central idea: machine performance is not only about maintenance (Do et al., 2015; Joglar, 2016).

Objectives

Achieving zero failures, zero defects, and zero accidents represents the ideal objective. Improving Overall Equipment Effectiveness (OEE) or Synthetic Rate of Return (TRS) requires attention to key factors, including availability (addressing breakdowns and stops), performance (optimizing speed and minimizing micro-stops), and quality (reducing rejects and managing alterations).

The 'pillars' TPM (classical vision)

Even if the variants exist, we often find the following key pillars of the approach:

- 1) Autonomous maintenance (AM): operators responsible for basic care (cleaning, inspection, simple lubrication, tightening).
- 2) Planned Maintenance: preventive and condition-based, organized by maintenance.

- 3) Focused Improvement (Kaizen): reducing losses such as recurring breakdowns and micro-stops.
- 4) Maintenance Quality: Prevent defects by controlling machine settings and correcting drifts.
- 5) Training & skills: operators + technicians.
- 6) Early Equipment Management: ensure maintainability is integrated from the point of purchase or modification.

Safety and Environment: integrated safety in compliance with TPM standards.

Concrete examples in the workshop

- 1) Begin with the implementation of operator checklists (daily): levels, leaks, and abnormal noises.
- 2) Next, include standard cleaning alongside inspection, ensuring cleaning serves as inspection.
- 3) After inspections, implement “tagging” of anomalies: red label = to be corrected, yellow = to be monitored.
- 4) Finally, conclude each shift with short performance meetings (5–10 min): TRS losses, quick actions.

Advantages & Limits

Advantages and limits of TPM are presented by the **Table 3.2**

Table 3-2 Benefits & Limits of TPM

Benefits	Limits
-Fewer micro stops and drifts (often invisible to maintenance alone). -Best basic discipline (cleanliness, lubrication, standards). -Shared reliability culture: the operator becomes 'guardian' of his machine.	-Risk of confusion: the operator is not a maintenance technician (clear boundary). -Need for simple standards, training and allocated time. -Demanding approach in management (monitoring, animation, indicators).

c) Reliability Centered Maintenance (RCM – Reliability Centered Maintenance)

The RCM is a structured process that determines what to maintain, how to do it, and how often, based on: (i) the operational context (actual conditions of use), (ii) equipment functions (roles or purposes of the equipment), and (iii) consequences of failures (impacts when equipment fails).

We do not apply preventive maintenance everywhere: we select the most suitable maintenance strategy based on assessed risks and the potential impact of equipment failures (Bouabid et al., 2024; K. Wang, 2016).

General logic (typical steps)

- 1) Define the context and boundaries of the system (describe what the system includes and its operating environment).
- 2) Define the expected functions (specify what the equipment is designed to do or the services it must provide).
- 3) Define functional failures (how it may no longer perform its function).
- 4) Identify failure modes (the specific causes or mechanisms that could lead to a failure).
- 5) Study the effects and especially the consequences (examine safety issues, impact on production, and costs related to possible failures).
- 6) Choose a management policy for each mode:
 - a. Conditional maintenance (monitoring)
 - b. Planned replacement/restoration (if age-dependent and justified)
 - c. Detection tests (failure finding) for hidden functions (e.g., security)
 - d. Corrective (run-to-failure) if consequence acceptable
 - e. Modification/ improvement (if no task is effective)

Advantages & Limits

Advantages and limits of RCM are presented by the **Table 3.3**

Table 3-3 RCM Highlights & Limits/ Conditions for success

RCM Highlights	Limits/ conditions for success
-Prioritizes security and criticality. -Avoids unnecessary tasks (over maintenance) and replacements "by habit". -Promotes state maintenance when it is effective (vibration, temperature, oil). - Very relevant for critical systems (fire pumps, compressors, continuous production).	-Request for data and skills (analysis, feedback). -Process heavier at the start (analysis workshops), but profitable on critical equipment. -Requires data entry discipline (history, fault coding, parts consumed).

Simple example (pump)

- Mode : degraded bearing.
- Effective detection : vibration + temperature + trend.
- RCM Action: conditional monitoring + thresholds + planned intervention before breakage.

Quick comparison (when to use what?)

Remote maintenance: when you have sensors and want to diagnose/plan remotely (ideal for multiple sites or equipment difficult to access). Whereas, TPM: when you want to improve the overall performance of lines by involving production + maintenance (micro-stoppage reduction, culture). Also, RCM: when you want to build an optimal strategy based on risk and context, especially on critical equipment.

Example (pump):

Mode: Degraded bearing. Indicates increased vibration, possible misalignment, or wear. Action: Inspect bearing for signs of surface damage, lubrication failure, or looseness. Initiate a corrective plan based on findings.

Effective detection: vibration + temperature + trend.

RCM Action: conditional monitoring + thresholds + planned intervention before breakage.

Quick comparison (when to use what?)

Remote maintenance is ideal when you have sensors and want to diagnose or plan remotely, particularly for multiple sites or equipment that is difficult to access. In contrast, TPM is suitable when the goal is to improve overall line performance by involving production and maintenance, focusing on micro-stoppage reduction and culture. Meanwhile, RCM is effective when used to develop an optimal strategy tailored to risk and context, especially for critical equipment.

3.2.3 Computer components

IT components are usually centralized in a Computerized Maintenance Management System (CMMS), which is essential for gathering, processing, and utilizing the vast data generated by maintenance activities.

3.2.3.1 CMMS functions

CMMS software enables the creation of a dedicated database to manage assets, inventory, suppliers, corrective and preventive interventions, work orders, procurement, financial evaluations, and maintenance metrics (Sakib & Wuest, 2018; Wienker et al., 2016).

CMMS modules are structured to streamline work by coordinating preparation, planning, scheduling, initiation, and monitoring of maintenance activities.

3.2.3.2 Advanced tools and decision making

- Expert systems improve maintainability by facilitating fault diagnosis and reducing downtime. They duplicate specialized knowledge within a knowledge base and use an inference engine to draw conclusions from current information in a fact base.
- Building on expert systems, Decision Support Software such as "PREVENT PLUS" is designed to help in choosing the optimal maintenance policy. It uses reliability data (e.g., failure dates, Weibull modelling) and economic inputs (costs of failures vs. costs of preventive changes) to determine the optimal time to intervene and calculate the expected gain.

To illustrate how these elements work together, imagine the maintenance system as a vehicle. In this analogy, the organization is the model defining the roles and teams needed to build and operate it; the methodology serves as the roadmap and driving manual detailing how and when to use and maintain the vehicle; and the IT components (CMMS) represent the sophisticated dashboard, diagnostic system, and navigation tools needed to plan, track, and optimize each trip efficiently.

3.3 Operational functions of maintenance

Maintenance functions fall into three main functions. These functions interact to manage and improve maintenance activities in a company. **Fig. 3.3** of the sources shows these three functions (Sullivan, Pugh, Melendez, & Hunt, 2010; Zhou et al., 2024).

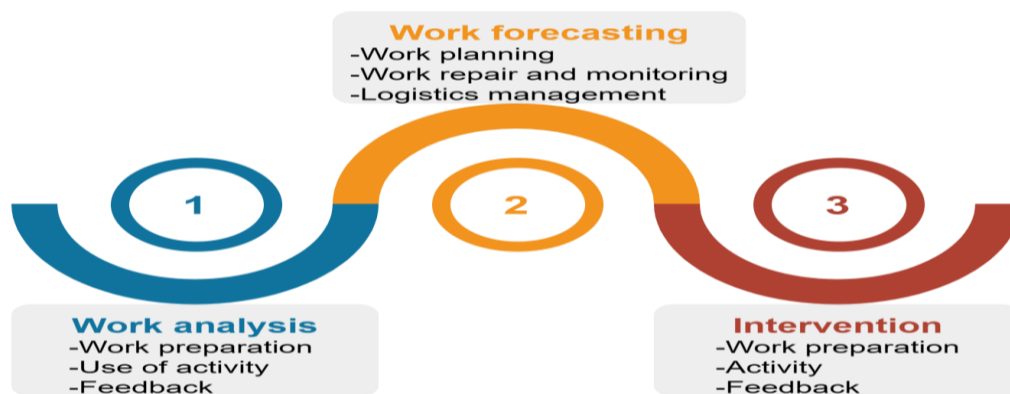


Figure 3-3 The operational functions of maintenance

These three operational functions of maintenance are:

3.3.1 Function Methods

The Methods function always focuses on improving maintenance. The main actions involved are: know, analyze, predict, plan, and improve. The main tasks for this function are:

- Preparation of the work.
- Exploitation of activity feedback.
- This function shares policies, guidelines, and projects to be carried out.
- This function is the main source of documents.
- The Methods office manages the technical activities and proposes improvement actions.
- The Methods office participates in the design of new works while accounting for maintenance.
- This team investigates workplace accidents to identify safety measures and ways to prevent and resolve issues.

The methods office bases its work largely on documentation. This includes the Technical Equipment File (DTE) and the historical equipment file.

3.3.1.1 The Technical Equipment File (DTE)/ machine file

The effectiveness of intervention preparation by the maintenance methods office and team performance in the field depends on complete and reliable knowledge of the equipment to be maintained. This knowledge must cover the material's origin, technology, performance, constitution, and technical diagrams and documents (mechanical, electrical, pneumatic, hydraulic, etc.).

- The DTE aims to centralize and provide all necessary information to preparers and stakeholders. This enables them to prepare, secure, and execute maintenance operations under good conditions. The DTE is generally structured into two or three parts:
- The information folder includes all documents provided by the manufacturer, such as specifications, plans, instructions, procedures, part lists, and conditions of use, as well as information negotiated during purchase and acceptance.
- The internal file is created, standardized, and updated by the maintenance methods office. It follows the equipment inventory code and contains internal adaptations (ranges, instructions, feedback, improvements, modifications, etc.).

The maintenance plan outlines the organization of maintenance actions: preventive maintenance, checks, inspections, conditional maintenance, and other planned tasks.

3.3.1.2 The historical equipment file

The historical file is a chronological inventory of all failures and corrective interventions on the equipment. It covers a sufficiently representative period. This file serves as the machine's real health record, covering the period from commissioning, the start of structured monitoring, or a reference date, through to the current operating date.

Analyzing this history allows the use of information both qualitatively and quantitatively. Qualitative data includes the nature of the breakdowns, the conditions, and the probable causes. Quantitative data includes frequencies, durations, and costs. This analysis helps identify recurring breakdowns and implement targeted improvements by addressing root causes.

3.3.2 Fonction Ordonnancement (Ordonnancement, Logistique et Approvisionnement)

The scheduling function involves organizing maintenance interventions over time. It focuses on planning, coordinating, and synchronizing activities. The main missions of this function are as follows:

- Work planning (preventive and corrective).
- Distribution and follow-up of the work (launch).
- Management of logistical means (supply).

- Scheduling consists of planning when and where staff, equipped with the necessary tools and materials, will perform tasks in coordination with other activities.
- The scheduler manages requests for corrective work and preventive work plans.
- The scheduler ensures coordination with the other maintenance functions.
- The scheduler establishes the schedules for preventive interventions and supplies.

3.3.3 Fonction Réalisation (Exécution – Mise en œuvre)

The Realization function concerns the actual execution of the works planned by the methods and ordered by the scheduling. Action verbs are performed, checked, and reported. The main missions associated with this function:

- Corrective interventions.
- Preventive interventions.
- Other assigned tasks.
- Provision of activity feedback.
- This function also includes installing machinery and equipment.
- The Realization function manages scheduling and maintenance interventions, including the establishment of failure diagnoses.
- It coordinates maintenance interventions and equipment, and manages material resources, including spare parts and tools. (Parts, tools).

3.4 Steps to developing an effective maintenance plan

The development of an effective maintenance plan follows a structured process, generally broken down into logical phases, that begins with documenting the equipment and ends with follow-up on interventions (Mobley, 2011).

This process, presented in Fig. 3.4, encompasses the development of the plan and comprises four fundamental steps: receiving equipment and documentation; selecting the maintenance type; planning; execution; and monitoring (Kelly, 1997; Mobley, 2011).

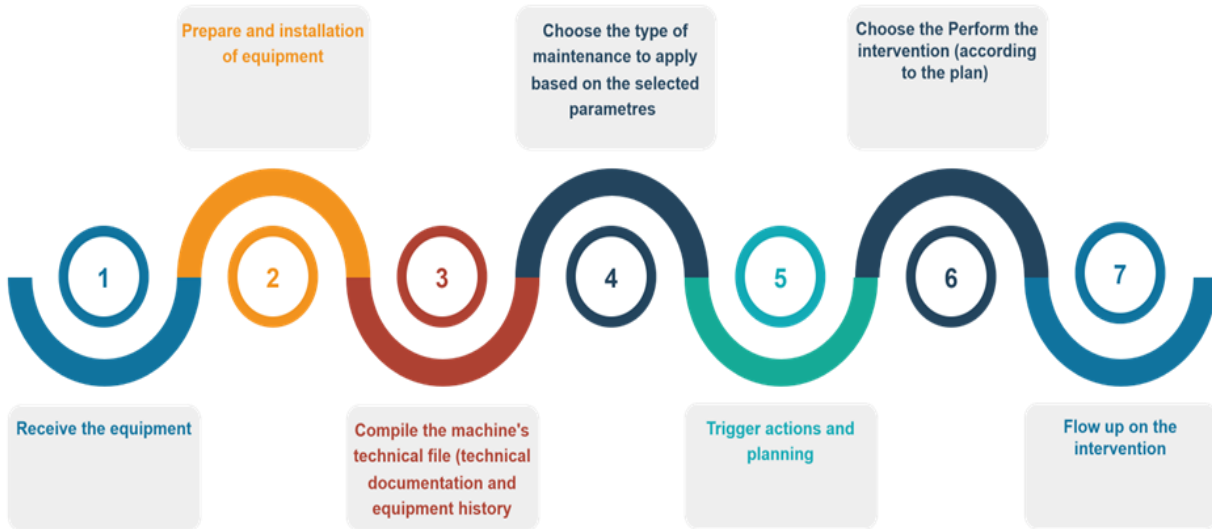


Figure 3-4 Processus d'élaboration d'un plan de maintenance efficace

3.4.1 Acquisition and Documentation of Equipment

This initial phase involves preparing the technical environment for the maintenance system: (i) Receiving the equipment, (ii) Installing the equipment, and (iii) Creating the machine file, which contains technical documentation and equipment history.

3.4.2 Choice of Maintenance Policy

Once the material is documented, decide which approach to use for each piece of equipment. Choose the maintenance type according to the selected parameters. This can be systematic, conditional, corrective, or maintenance of improvement.

3.4.3 Planning (Maintenance Plan Proper)

Planning interventions depends on the type of equipment maintenance chosen:

- For systematic maintenance, once the maintenance type is selected, plan the intervention according to a pre-established schedule.
- If conditional maintenance is necessary, first measure key parameters of the property's condition, then plan the intervention if a degradation threshold is reached.
- If improving maintenance, specify the improvements made and plan the intervention.
- If corrective maintenance is necessary, the failure must be detected and diagnosed before planning the intervention.

3.4.4 Execution and Monitoring

The final phase concerns the application of established plans and the updating of knowledge for the future:

- First, execute the intervention as planned, then monitor the following indicators: Availability/failure rate, MTBF, MTTR, schedule compliance (%), Maintenance cost (preventive/corrective), Rework rate (returns after intervention), and Out-of-stock parts rate.
- Once the intervention is complete, follow up by integrating feedback: the results are fed back into the process, creating a feedback loop that updates the technical file and informs subsequent decisions.

Then, analyze recurring failures (Pareto + RCA), adjust frequencies and ranges (too much/not enough), eliminate the 'bad causes' (alignment, lubrication, design), and capitalize on it: update methods and training.

3.5 Computerized Maintenance Management Systems (CMMS)

3.5.1 Role of CMMS in Modern Maintenance Engineering

A CMMS is software that helps engineers plan, monitor, and improve maintenance. In mechanical engineering, CMMS ensures equipment reliability, availability, and optimal lifecycle performance. It does more than record actions; CMMS creates a structured decision-making framework using technical and operational data.

From an engineering perspective, the use of CMMS reduces unplanned failures and production downtime, extends equipment service life, and improves the coordination of maintenance teams and resources. By systematically collecting maintenance data, CMMS enables engineers to analyze failure patterns, optimize maintenance intervals, and support reliability-oriented strategies. This section is informed by the following references, which provide additional information (Mohd Noor, Mazlan, & Amrin, 2021; Sakib & Wuest, 2018; Wang, 2016; Wienker et al., 2016).

3.5.2 Functional Scope of a CMMS

A CMMS enables engineers to manage and automate maintenance tasks across a wide range of physical assets, including industrial machinery, mechanical systems, production lines, buildings, and material-handling equipment. Assets are typically organized in a hierarchical structure, which reflects the physical decomposition of systems and subsystems. This structure facilitates fault localization, intervention planning, and performance monitoring.

Dashboards and performance indicators provide mechanical engineers with a clear, real-time overview of asset condition, work order status, maintenance costs, and equipment availability.

This enhanced visibility enables more informed decision-making, directly linking maintenance actions to system behavior, degradation mechanisms, and operational constraints.

3.5.2.1 CMMS as a Decision-Support Tool

CMMS is now more than just a tool for managing operations. It has become a valuable decision-support system for maintenance engineers. By using both historical and real-time data, engineers can spot common failure patterns, assess maintenance results, and help move from corrective to preventive, condition-based, and predictive maintenance. This focus on data aligns with modern reliability engineering methods and international standards such as ISO 55000 and IEC 60300.

3.5.2.2 Evolution and Industrial Deployment

CMMS was first created for industrial use between the 1970s and 1990s to help manage more complex systems and improve maintenance control. Over time, CMMS has changed a lot, especially with the rise of Software-as-a-Service (SaaS) models. These newer solutions are more flexible, scalable, and accessible, making them useful across industries such as manufacturing, energy, transportation, healthcare, construction, and services (Labib, 2004).

3.5.2.3 Extended Capabilities and Data Exploitation

Today's CMMS platforms do more than just schedule maintenance. They also help manage spare parts, track costs, analyze failures, and report on performance. For mechanical engineers, this information supports better productivity, lower lifecycle costs, and ongoing improvements. As a result, CMMS has become a key tool for RCM and asset management.

3.5.3 Main Reasons for Adopting a CMMS

The main reasons for adopting a CMMS are presented by the **Fig. 3.5**.

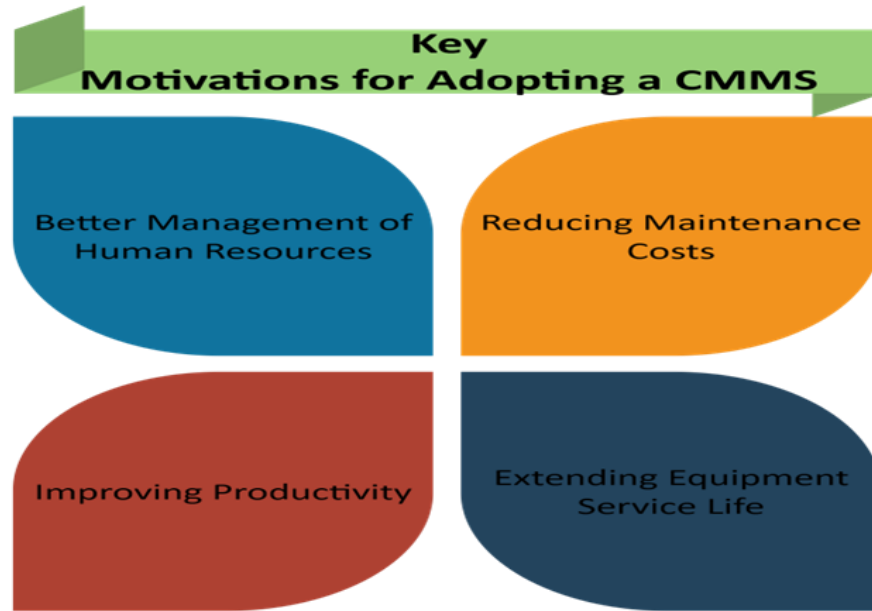


Figure 3-5 Main reasons for adopting a CMMS

3.5.3.1 Reducing Maintenance Costs

Engineering organizations use a CMMS mainly to keep maintenance costs under control. A CMMS helps track technical failures and makes it easier to analyze recurring problems. It also provides a clear overview of maintenance work and resource use (Mobley, 2002; Wireman, 1994)

A CMMS tracks items such as spare parts inventory, labor hours, and the frequency of maintenance. This helps planners predict maintenance needs and make better purchasing decisions. As a result, companies can avoid expensive unplanned repairs, combine their buying activities, and keep stock levels reasonable. Studies show that when a CMMS is used well, it can lower maintenance costs and improve cost control (Eti, Ogaji, & Probert, 2006).

3.5.3.2 Extending Equipment Service Life

A well-planned maintenance strategy helps equipment run smoothly and last longer. With a CMMS, you can schedule maintenance based on real conditions and past failures. This method reduces the risk of surprise breakdowns and reduces machine wear (Dhillon, 2006; Joglar, 2016)

Mechanical engineers gain from this organized method because it matches maintenance tasks with how equipment actually wears down. Industry evidence shows that optimizing maintenance in this way can help assets last longer by avoiding over-stress and ensuring parts are replaced on time (Mobley, 2002).

3.5.3.3 *Improving Productivity*

Another benefit of CMMS is increased productivity. Structured maintenance activities reduce unplanned disruptions and machine downtime. Real-time dashboards and performance indicators give engineers and managers up-to-date asset status (Labib, 2004).

This transparency enables proactive planning, better workflow coordination, and fewer interruptions to production. Studies in manufacturing environments show that CMMS use is associated with higher equipment availability and process throughput, thereby directly supporting productivity gains (Wienker et al., 2016).

3.5.3.4 *Better Management of Human Resources*

The CMMS helps manage maintenance teams more effectively. This software assigns tasks based on each person's skills, availability, and required authorization level. Instead of assigning work randomly, a CMMS ensures the right people with the right qualifications handle the appropriate jobs. This process results in faster responses and guarantees that qualified staff take on specific tasks (Sakib & Wuest, 2018).

For mechanical engineers, this means clearer communication and better use of technical skills. There are also fewer scheduling conflicts. Improved documentation and work history support stronger safety practices. These also help meet regulatory requirements, especially in fields like energy and aerospace, where traceability is essential.

3.5.4 **Main Functions of a CMMS and Their Link to RMA Concepts**

Modern CMMS are essential in maintenance engineering, as they organize information, facilitate technical decision-making, and enhance system performance across the entire life cycle. From an engineering perspective, CMMS functionalities directly support RMA objectives, as outlined in international standards and reliability engineering literature ((Dhillon, 2006; IEC-60050-192, 2016).

3.5.4.1 *Asset and Equipment Management (Link to Reliability)*

Asset management is a key part of any CMMS. It means creating an organized list of equipment, usually arranged by systems, subsystems, and components. The CMMS stores details for each asset, including technical features, operating conditions, location, maintenance history, and related documents.

This organized information is important for reliability analysis. It helps engineers spot repeated failures, understand how equipment wears out, and connect failures to how assets are used. Reliable asset data is needed for tasks such as reliability modeling, failure rate estimation, and the use of methods such as FMEA and RCM(14224, 2016; Bouabid et al., 2024; Joglar, 2016).

3.5.4.2 *Maintenance Intervention Management (Link to Maintainability)*

Maintenance intervention management is a central function of a CMMS. The system allows engineers to plan, schedule, execute, and document maintenance actions, whether preventive, corrective, or condition-based.

By recording task duration, tools used, spare parts consumed, and labor effort, the CMMS provides key data for assessing maintainability. Indicators such as Mean Time to Repair (MTTR) help measure this. These metrics allow engineers to evaluate how quickly and efficiently equipment can be restored after failure. The data also supports ongoing improvement of maintenance procedures (Dhillon, 2006; IEC-60050-192, 2016).

3.5.4.3 *Spare Parts and Inventory Management (Link to Availability)*

Effective spare parts management is crucial for maximizing system availability. A CMMS tracks stock levels, consumption rates, reorder points, and supplier information, while generating alerts to prevent shortages.

Missing critical spare parts often drives extended downtime. By ensuring teams receive components promptly, the CMMS reduces logistical delays and enables faster repairs, thereby improving operational availability. This function becomes especially important in systems that face high downtime costs or strict safety constraints (Blanchard & Fabrycky, 2011; Hodkiewicz, 2014).

3.5.4.4 *Workforce and Scheduling Management (Link to Maintainability and Availability)*

Effective maintenance performance depends on human resource capabilities. A CMMS shows team availability, skills, certifications, and intervention history. Tasks are assigned by technical competence and authorization, with coordination for external contractors.

This structured allocation ensures that qualified personnel perform maintenance tasks correctly and efficiently. At the same time, better scheduling directly reduces response time to failures and increases system availability (Dhillon, 2006; IEC., 1999).

3.5.4.5 *Data Analysis and Performance Reporting (Link to Reliability, Maintainability, and Availability)*

A CMMS takes raw maintenance data and turns it into useful information. It creates key performance indicators like failure rates, MTBF, MTTR, downtime, and maintenance costs.

These indicators help engineers track trends and see how well maintenance is working. They guide decisions to improve reliability and enhance maintenance. For RMA, CMMS reports provide the data needed for ongoing improvement and for managing equipment throughout its life (Dhillon, 2006; Labib, 2004).

3.5.4.6 Maintenance Planning and Work Organization (Integrated RMA Perspective)

When these functions are combined, a CMMS helps create maintenance work plans that align with the organization's goals and system constraints. With better asset knowledge, organized actions, and data analysis, engineers can design maintenance strategies that balance reliability, maintainability, and availability.

In this context, the CMMS shifts from being merely an operational tool to a key driver of RMA-focused maintenance engineering. This helps improve long-term performance, safety, and sustainability.

3.5.5 CMMS Project Management and Conditions for Success in an RMA Context

Implementing a CMMS is a structured project that requires a careful and organized approach, especially when the goal is to improve system reliability.

3.5.5.1 Preparation of Specifications

The specification phase is important and should set clear maintenance goals for reliability, maintainability, and availability. This phase includes listing equipment, defining key performance indicators like MTBF, MTTR, and availability, and considering software complexity, user roles, budget, and schedule. A team-based needs analysis helps align technical needs with organizational limits, reducing the chance of inefficiencies.

3.5.5.2 Software Selection

The chosen CMMS should meet your needs and support RMA analysis, such as tracking failure data, maintenance times, and key statistics. It is also important to review vendor references and make sure the software can grow with your future strategies.

3.5.5.3 System Implementation

Following completion of the system design, managers oversee hardware and software installation and ensure validation tests are conducted. Proper execution at this stage is essential for collecting reliable data, which, in turn, supports effective RMA assessment.

3.5.5.4 Staff Training

Good training is essential for a successful CMMS rollout. Maintenance staff need to know how to use the software and how their data entry supports reliability analysis and improved availability. When users see how CMMS use affects system performance, they are more likely. When the system is running, enter all data—such as equipment inventory, work requests, maintenance reports, and failure descriptions—fully and consistently. This data is used to

calculate RMA indicators and evaluate maintenance. The RMA indicators are used to evaluate maintenance.

3.5.5.5 Operation and Use

Comprehensive and consistent data entry is essential during operation. This includes equipment inventory, work requests, work orders, maintenance reports, and failure descriptions. Such data provide the foundation for calculating reliability, maintainability, and availability (RMA) indicators and for evaluating maintenance effectiveness.

3.5.5.6 Conditions for Success

A successful CMMS project requires strong management support, user involvement, high data quality, and alignment between the organization and the software. The CMMS should support maintenance processes rather than create problems. Despite meeting these conditions, challenges may persist post-implementation.

Although a CMMS significantly improves maintenance time management and RMA monitoring, it does not automatically resolve issues such as staff reluctance or incomplete data entry. Its deployment is often progressive and requires discipline and consistency in daily use. Only through rigorous data management can the CMMS fully contribute to improving reliability, maintainability, and availability.

3.5.6 Purpose and Benefits of a CMMS in Relation to RMA Indicators

Using a CMMS is important in today's maintenance engineering. Besides streamlining operations, a CMMS helps improve key RMA indicators that measure how well industrial systems perform (Mohd Noor et al., 2021; Wienker et al., 2016).

3.5.6.1 Cost Control and Economic Performance

In maintenance engineering, controlling costs depends on system availability and the efficiency of maintenance. A CMMS helps lower energy use, cut down on overtime, and reduce production losses from unexpected breakdowns. By managing spare parts and scheduling maintenance more effectively, a CMMS also reduces downtime costs while keeping systems running as needed.

3.5.6.2 Improvement of Reliability and Availability

A CMMS helps make systems more reliable by collecting and analyzing data on failures, maintenance history, and operational feedback. This information is used to estimate failure rates, spot common problems, and improve maintenance strategies.

Planning preventive maintenance more effectively helps prevent breakdowns. This increases system availability. It also helps equipment last longer.

3.5.6.3 *Enhancement of Maintainability*

How quickly and effectively maintenance is done affects maintainability. A CMMS makes this easier by reducing paperwork, providing quick access to technical documents, and maintaining a clear record of past work. These features help reduce MTTR and enable maintenance teams to respond faster, keeping systems available.

3.5.6.4 *Decision Support for Maintenance Management*

A CMMS provides maintenance managers with clear indicators and dashboards related to RMA, such as how often failures occur, how long equipment is down, the ratio of planned to unplanned maintenance, and how many spare parts are used. These tools help managers make better decisions about maintenance policies, resource use, and improving system reliability.

3.5.7 **Conduct of a CMMS Project and Conditions for Success**

Implementing a CMMS is a structured project that requires a rigorous approach (Mohd Noor et al., 2021; Wienker et al., 2016).

- 1) Implementation of the specifications: It is essential to clearly define the need and objectives (what to do, for whom, and the expected result). This includes the hardware inventory, software sophistication level, required statistics, users, budget, and allocated time. A needs analysis conducted by a multidisciplinary group must be subject to consensus to avoid costly, unrecoverable errors after purchase.
- 2) Choice of software involves deciding between a specific development and the purchase of a software package, and ensuring the software is relevant to the functional specifications. It is recommended to check the supplier's references and ensure the product's durability and its ability to evolve.
- 3) Implementation: Installation of the hardware (hard) and software (soft), followed by tests.
- 4) Staff training: general and software-specific. It is crucial that staff quickly exploit their new knowledge and perceive the benefits of the tool to ensure success.
- 5) Use/Operation: Complete entry of the inventory, requests, work orders, reports, and production of statistics.
- 6) Conditions of Success: Success depends on management and staff involvement, the quality of the specifications, and verification of the organization's suitability for the software (and not vice versa).

Although the use of a CMMS facilitates maintenance time management, it does not automatically resolve difficulties related to obtaining past time, such as staff distrust or incomplete data entry. Moreover, implementing a CMMS can be lengthy and gradual, requiring rigorous daily data entry to overcome the initial drawbacks.

3.6 Conclusion

The study of maintenance organizations highlights the importance of a clear structure for the functions, methods, and tools required to control industrial equipment. An adapted organization enables improved intervention planning, optimized resource use, and reduced impact of failures on production.

The integration of a CMMS is part of this approach by facilitating the management of technical information, the monitoring of interventions, and the analysis of performance. When implemented in accordance with the principles defined by EN 13306 and ISO 55000, CMMS directly contributes to improving reliability, maintainability, and availability indicators.

This chapter provides essential foundations for understanding maintenance's role in industrial systems and prepares students to analyze and implement maintenance solutions suited to professional requirements.

Chapter 4: Equipment Tracking and Logistics function

4 Chapter 4: Equipment Tracking and Logistics function

4.1 Introduction

In industrial systems, equipment represents a major technical and financial asset. Efficient equipment tracking and a well-organized logistics function are essential to ensure the availability, reliability, and optimal use of machines, tools, and spare parts.

This chapter introduces students to the knowledge, identification, handling, and logistical management of equipment, with a focus on maintenance, production continuity, and cost control.

4.2 Knowledge and Handling of Equipment

4.2.1 Definition of Equipment

In an industrial context, equipment refers to all physical assets used in production and maintenance, such as:

- Machines and production units
- Mechanical systems (pumps, compressors, conveyors)
- Tools and instruments
- Spare parts and accessories

Each piece of equipment has a technical role, a lifecycle, and specific operating conditions.

4.2.2 Equipment Identification and Classification

To manage equipment efficiently, it must be clearly identified and classified using the presentation of the **Table 4.1**.

Table 4-1 Identification and classification of the equipment

Equipment identification	Equipment classification
Each equipment item should have: - A unique identification code or tag - A name and technical description - Manufacturer and model - Installation date and location Common identification methods: - Nameplates - Barcodes - QR codes - RFID tags	Equipment can be classified according to: - Function (production, safety, auxiliary) - Criticality (critical, semi-critical, non-critical) - Type (mechanical, electrical, hydraulic, pneumatic) This classification helps prioritize maintenance and logistics decisions.

4.2.3 Equipment Life cycle

4.2.3.1 *Definition of Equipment Life cycle*

The complete life cycle of a physical asset is the equipment lifecycle, which includes planning, purchase, and disposal or retirement. Planning, buying, using, maintaining, and disposing of the asset are all parts of it. Effective asset management ensures organizations gain maximum value from their equipment (Khalyasmaa, Stepanova, Eroshenko, & Matrenin, 2023).

Following this process helps organizations use their equipment effectively and efficiently.

Understanding the equipment lifecycle helps organizations keep their assets functioning well over time. This understanding is key to good asset management.

4.2.3.2 *Definition of Asset Life Cycle Management*

Asset Life Cycle Management (ALCM) is the systematic management of physical assets throughout their lifecycles, from initial concept to final disposal. The main objective of ALCM is to ensure that assets deliver the required performance at the lowest possible cost while maintaining safety, reliability, and availability.(ISO, 2014).

In mechanical and industrial systems, assets such as machines, tools, and equipment represent significant investments. Managing these assets efficiently allows organizations to extend their useful life, reduce failures, and improve productivity. A life-cycle approach helps engineers make better technical and economic decisions by considering not only acquisition costs but also operational, maintenance, and end-of-life costs (Gransberg & O'Connor, 2015).

A key part of ALCM is collecting data during operation and maintenance. Information such as failures, operating conditions, and maintenance actions helps guide decisions. These choices include repair versus replacement and selecting the right maintenance strategy (Lee & Scott, 2009).

4.2.3.3 *Asset Life Cycle Stages*

Although different models exist, the asset life cycle is generally divided into four main stages(Blanchard & Fabrycky, 2011; Gransberg & O'Connor, 2015):

a) Planning

The planning stage starts when the current equipment no longer meets operational needs. Engineers then analyze current performance, define technical specifications, and estimate future requirements. They base their decisions on reliability data, operating conditions, safety requirements, and economic limits.

As a result, good planning reduces the risk of poor asset selection and helps ensure compatibility with the production system and maintenance capabilities.

b) Acquisition and Installation

The acquisition stage includes selecting and purchasing the asset. Technical performance, cost, supplier reliability, and maintenance requirements are key decision criteria. After delivery, the asset is installed, tested, and commissioned to verify proper operation.

During this phase, the asset is also registered in maintenance management systems such as CMMS or EAM. Technical documentation, bill of materials (BOM), spare parts catalog, and preventive maintenance strategy are prepared. Training for operators and maintenance personnel is often conducted at this stage to ensure proper operation and early reliability (Mobley, 2002).

c) Operation and Maintenance

Operation and maintenance make up the longest phase of an asset's life. During this time, the asset performs its main tasks and is maintained to avoid failures and preserve performance.

Maintenance needs change over time. New equipment usually requires limited maintenance, while aging assets are more prone to wear, fatigue, and corrosion. Common maintenance strategies include corrective, preventive, condition-based, and predictive maintenance (Sullivan, Pugh, Melendez, & Hunt, 2010)

Choosing the right maintenance strategy depends on the asset's criticality, failure mode, operating conditions, and cost. Good maintenance increases availability, reduces downtime, and extends asset lifespans.

d) Decommissioning and Disposal

The final stage begins when the asset no longer provides sufficient value or becomes outdated. Decommissioning decisions consider safety, reliability, maintenance cost, and regulatory rules. Disposal options may include recycling, reuse, resale, or scrapping. This depends on the asset type and its materials (ISO, 2014).

Data collected over the asset's life is reviewed at this final stage. This data helps improve future planning and asset choices, which supports ongoing improvement.

For mechanical engineers, Asset Life Cycle Management gives a complete view of equipment behavior. It links design, operation, maintenance, and logistics. Understanding the asset life cycle helps engineers make choices that improve reliability, reduce costs, and enhance industrial performance.

4.2.3.4 Importance of Equipment Lifecycle Management

Effective equipment lifecycle management is vital to businesses for optimizing operations, reducing costs, and improving productivity (See **Fig. 4.1**). By implementing a well-structured strategy, organizations can extend the lifespan of their equipment, minimize downtime, and ensure regulatory compliance (Eti, Ogaji, & Probert, 2006).

Equipment lifecycle management lets businesses make informed decisions about procurement, maintenance, and disposal. This improves operational efficiency and profitability. The approach also helps forecast equipment needs, plan investments, and maintain readiness.

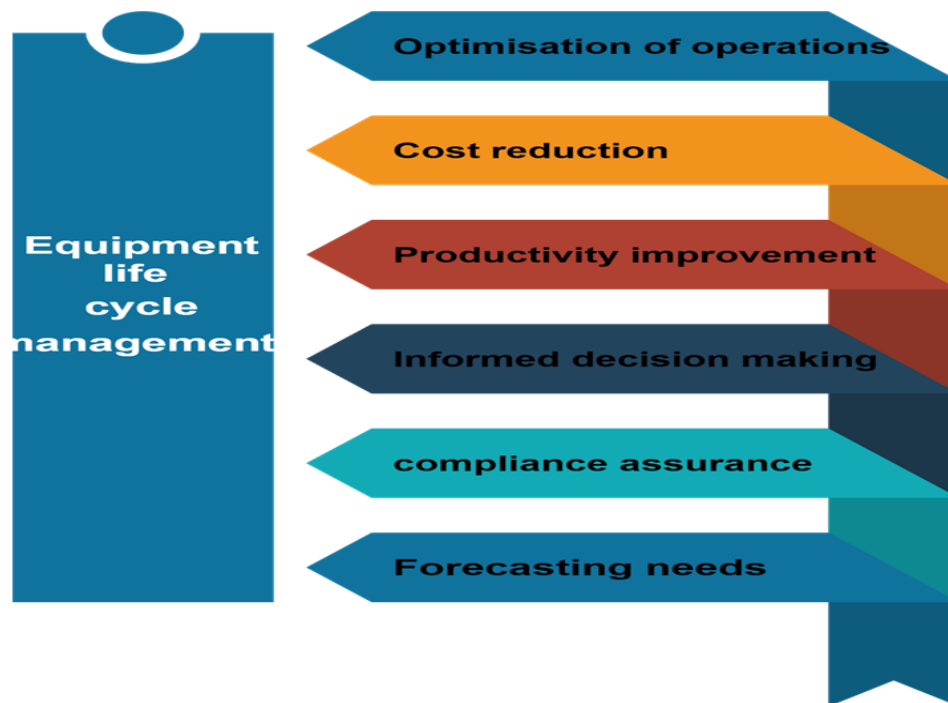


Figure 4-1 Equipment lifecycle management

4.2.4 Equipment behavior during operation

Understanding failure mechanisms and components is a critical aspect of reliability engineering, manufacturing, and maintenance across various industries. Whether you're dealing with machinery, electronic devices, or complex systems, the ability to identify and comprehend how and why failures occur can significantly impact performance, safety, and longevity (Engel, 2014; Otegui, 2011; Tinga, 2013).

This section aims to delve into the intricacies of failure mechanisms and the components most susceptible to them. By gaining a thorough understanding of these elements, professionals can make informed decisions, improve system reliability, and take proactive steps to mitigate risks.

4.2.4.1 Failure mechanisms

a) Mechanical Failures

Mechanical failures often occur due to stress, fatigue, and corrosion. These can be further broken down into: (i) fracture, (ii) fatigue and (iii) wear...etc. (see the section 2.4.3 for more details) (Tinga, 2013).

b) Material Failures

Material failures are often caused due to poor quality, defects, or incompatibility with the environment. For instance, using a material that is not resistant to high temperatures in an environment where it will be exposed to heat or degrade faster than expected is a recipe for failure.

c) Process-Related Failures

These are failures that occur due to issues in the manufacturing or operational process. For example, if a machine is not calibrated correctly, it can lead to the failure of its components.

d) Human-Induced Failures

Sometimes, failures occur due to human error, such as poor maintenance or incorrect operation of machinery.

4.2.4.2 Failure prevention

Understanding failure mechanisms and components is not just about identifying what went wrong but also about taking steps to prevent future failures. Understanding failure mechanisms and components is indeed the first step towards preventing future failures. Here are some preventive measures after understanding the failure mechanisms and components involved (Tinga, 2013): regular maintenance, quality control and proper design (see **Fig. 4.2**).

By combining these preventive measures, you can create a comprehensive strategy for reducing the risk of failure in your systems. This not only improves reliability but also contributes to safety and efficiency, ultimately adding value to your end product or service.

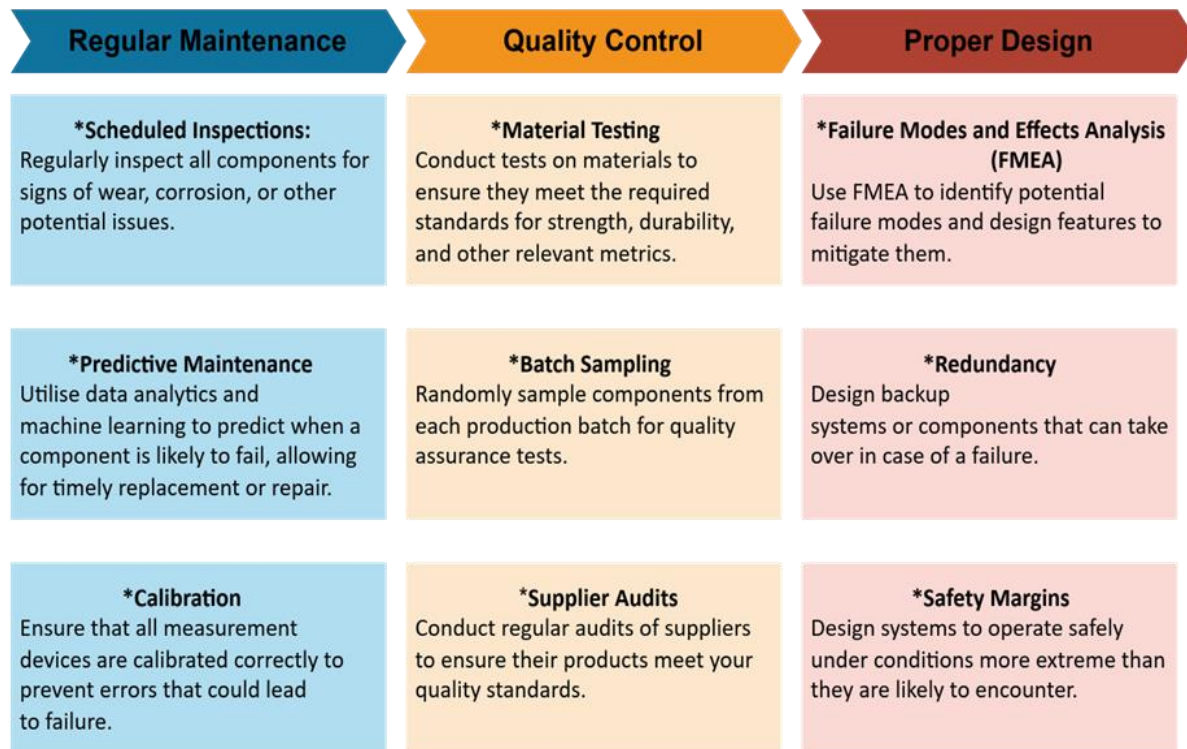


Figure 4-2 Failure prevention

4.2.4.3 Failure analysis

The behavior of equipment in operation is subject to major physical failures: wear, fatigue, and corrosion. These mechanisms, catalyzed by operating conditions, lead to failure modes such as loss of function, degraded operation, or blockage. To address these risks proactively, conducting a Failure Mode and Effects Analysis (FMEA) is crucial. Building on this, the **Fig 4.3** presents a detailed analysis of the three main failure modes(Collins, 1993; Otegui, 2011):

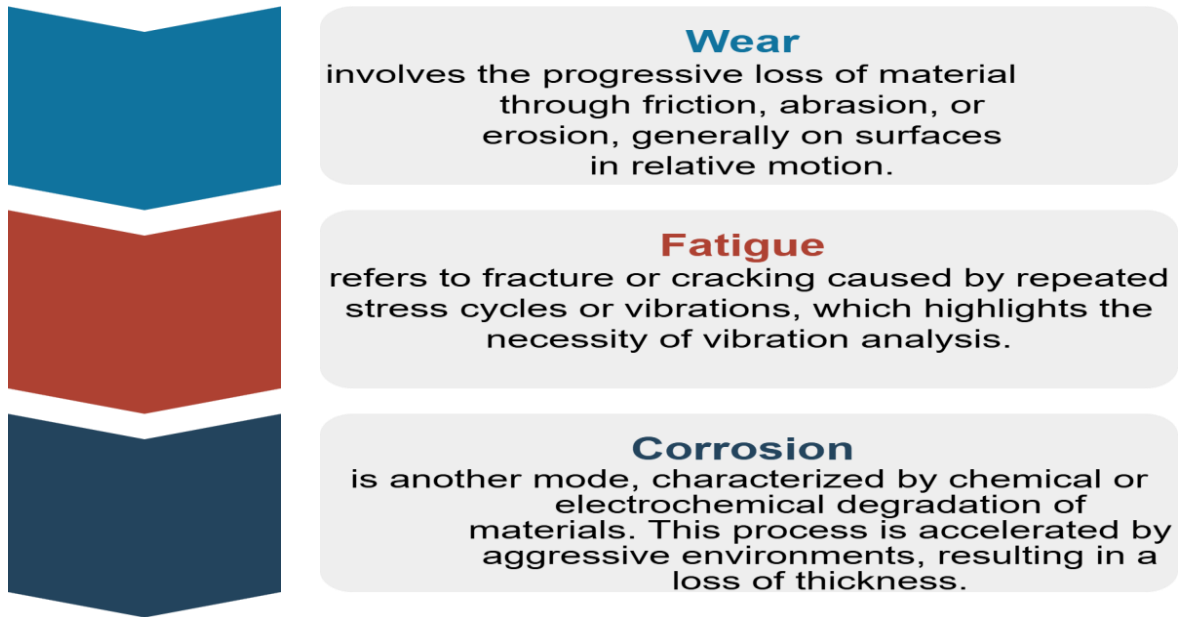


Figure 4-3 Definition of major physical failures (Otegui, 2011)

To mitigate these risks, continuous monitoring (such as vibration and temperature analysis) and condition-based maintenance are key strategies for detecting these mechanisms before failures occur.

a) Wear

Wear is a major reason why machines stop working. Many people think of wear as a single problem, but it actually covers several different types, each with its own causes and effects. Understanding these types helps us examine how materials break down and find better ways to prevent problems (Engel, 2014).

In the study of friction, wear means that material slowly gets worn away where surfaces touch and move against each other (Otegui, 2011).. The amount of wear depends on factors such as the materials, the surface, the weight, how fast parts move, the environment, and whether there is anything to reduce friction (See **Fig.4.4**).

One part may experience multiple forms of wear simultaneously (presented in **Table 4.2**), making it harder to determine why it failed.



Figure 4-4 Presentation of wear types

Table 4-2 Type of wear (TMI, 2026)

Type	Description
Adhesive wear: when surfaces “weld” together	Adhesive wear occurs when two surfaces in contact slide against each other. At the microscopic scale, localized adhesion zones form between surface asperities. During relative motion, these micro-junctions rupture and tear material from one surface to the other. This wear mechanism is commonly associated with: - Similar metallic materials, - Heavily loaded contacts, - Insufficient or ineffective lubrication. It may lead to severe damage such as galling or scuffing.
Abrasive wear: the “sandpaper” effect	Abrasive wear is caused by the presence of hard particles or pronounced surface roughness that scratch or plough the opposing surface. It may occur in two different forms: - Two-body abrasion, when asperities on one surface directly attack the other, - Three-body abrasion, when free particles (dust, debris, wear fragments) become trapped within the contact. This type of wear generally results in visible grooves and a progressive but continuous loss of material.
Fatigue wear : progressive surface degradation	Fatigue wear mainly develops in contacts subjected to cyclic loading, such as rolling bearings or gears. Repeated stresses induce the formation of subsurface cracks, which gradually propagate until fragments of material detach from the surface. This mechanism is responsible for damage phenomena such as: - Pitting, - micropitting, - Surface spalling. Fatigue wear is strongly influenced by contact pressure, lubrication conditions, and the metallurgical state of the materials.
Corrosive wear:	Corrosive wear results from the combined action of mechanical and chemical

the influence of the environment	processes. The surface deteriorates due to chemical reactions (oxidation, corrosion), and the reaction products are then removed by friction, exposing fresh material to further attack. This mechanism is promoted by: - Aggressive environments, - The presence of moisture or chemical agents, - Elevated temperatures. Corrosive wear can significantly accelerate material loss, even under relatively low mechanical loads.
Fretting wear: small movements, severe damage	Fretting is a wear mechanism associated with very small-amplitude relative motions, often smaller than one millimeter. These repeated micro-movements cause localized surface degradation, frequently accompanied by oxidation. Fretting commonly occurs in: - Bolted joints, - Interference fits, - Interfaces subjected to vibrations. Despite the absence of visible macroscopic motion, fretting can lead to rapid deterioration of components.

Each wear mechanism requires specific interventions, including material selection, surface treatments, lubrication modifications, or changes to operating conditions. Failure to correctly identify the dominant wear mechanism can lead to ineffective or counterproductive interventions.

Comprehensive surface analysis and a thorough understanding of wear mechanisms are critical for implementing sustainable interventions.

b) Corrosion

Corrosion is the chemical or electrochemical degradation of materials, particularly metals, caused by environmental exposure. This process reduces material thickness and compromises structural integrity. Corrosion generally arises from redox reactions, which are accelerated by factors such as humidity, oxygen, and aggressive agents, including sulfur dioxide and chlorides. These reactions ultimately convert metals into stable oxides (Revie & Uhlig, 2025). (See **Fig. 4.5**).

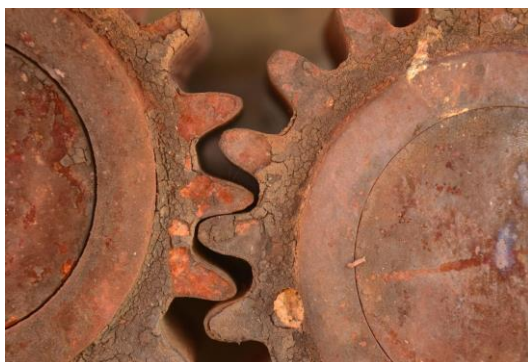


Figure 4-5 Process: *Corrosion is a spontaneous, natural reaction that manifests as rust, tarnish, or pitting*

- Primary types of corrosion

There are three types of corrosion (Landolt, 2003):

- **Electrochemical:** Occurs when water or another liquid is present, creating areas where the metal reacts and areas where it does not.
- **Chemical (dry):** Happens when metals react directly with gases like oxygen or sulfur dioxide at high temperatures.
- **Aggressive environments:** Factors such as moisture, salty sea air, air pollution, and acidic soils accelerate corrosion.
- Consequences

Corrosion leads to material loss, pipe rupture (causing leaks in water supply systems), structural weakening in bridges and buildings, and high economic costs(François, Khan, & Dang, 2013).

- Protection

Main control methods include adding corrosion-inhibiting chemicals, applying protective paint, installing systems to prevent reactions, and choosing materials that do not rust easily, such as stainless steel(François et al., 2013).

c) Fatigue

Mechanical fatigue causes failure in structures and components exposed to repeated loading or vibration. Since it develops at stress levels below the yield strength, failures may occur without warning, potentially resulting in unexpected downtime or safety hazards(Stephens, Fatemi, Stephens, & Fuchs, 2001).

Fatigue is a progressive degradation. It starts with crack initiation, followed by slow crack growth, and ends with sudden fracture, usually without visible plastic deformation. This sudden failure can occur with little warning, posing a significant risk to structural integrity and safety (Handbook, 1996). As example see the **Fig.4.6**.



Figure 4-6 *Presentation of Mechanical fatigue*

- ***Fatigue mechanism***

Fatigue accumulates with repeated, time-varying stresses. Each cycle adds to material damage. The **Table 4.3** presented the three main fatigue mechanism.

Table 4-3 Three main fatigue mechanism.

Fatigue mechanism	Description
Crack initiation	Following the cumulative material damage discussed above, crack initiation corresponds to the formation of microscopic cracks at the microstructural scale. This phase generally occurs in the vicinity of stress concentration zones (notches, holes, welds), at the surface of the component, or in areas affected by metallurgical defects or surface roughness. Expanding on the factors influencing crack initiation, (Suresh, 1998) notes that these factors are strongly influenced by the material microstructure, surface finish, and environmental conditions, such as corrosion and temperature.
Crack propagation	A small crack in a material can gradually expand under cyclic loading, eventually leading to failure. Once initiated, the crack propagates slowly and stably, yet irreversibly. The rate of crack growth is influenced by the stress amplitude, load ratio, and the material's mechanical properties. Linear Elastic Fracture Mechanics (LEFM) describes this propagation phase using the stress intensity factor (K) and the Paris crack growth laws (Paris & Erdogan, 1963).
Final fracture	When the crack attains a critical size, the remaining load-bearing cross-section cannot support the applied load. Consequently, the structure undergoes rapid, catastrophic separation along the crack, resembling brittle failure even in materials that are typically ductile (Dowling, Kampe, & Kral, 2013).

- ***Main causes of fatigue***

Have you ever wondered why seemingly durable materials and equipment sometimes fail unexpectedly? The primary causes of fatigue include repeated cyclic loading, even at low amplitudes; mechanical vibrations (rotating equipment, dynamic systems); load fluctuations due to transient operating conditions (such as start-up and shutdown); and combined effects of cyclic loading and corrosion (corrosion-fatigue).

Among these causes, vibrations are particularly critical because they may induce resonance, a phenomenon in which the excitation frequency matches the system's natural frequency, resulting in a significant increase in alternating stress levels (Inman, 2014). Indeed, according to (Randall, 2021), vibration monitoring enables condition-based maintenance and reduces the risk of catastrophic failure by allowing early detection of hazardous operating states.

- *Types of fatigue*

Two main fatigue regimes are commonly distinguished (see the **Fig. 4.7**): These classifications are widely adopted in standards and scientific literature (Handbook, 1996; Stephens et al., 2001; Suresh, 1998).

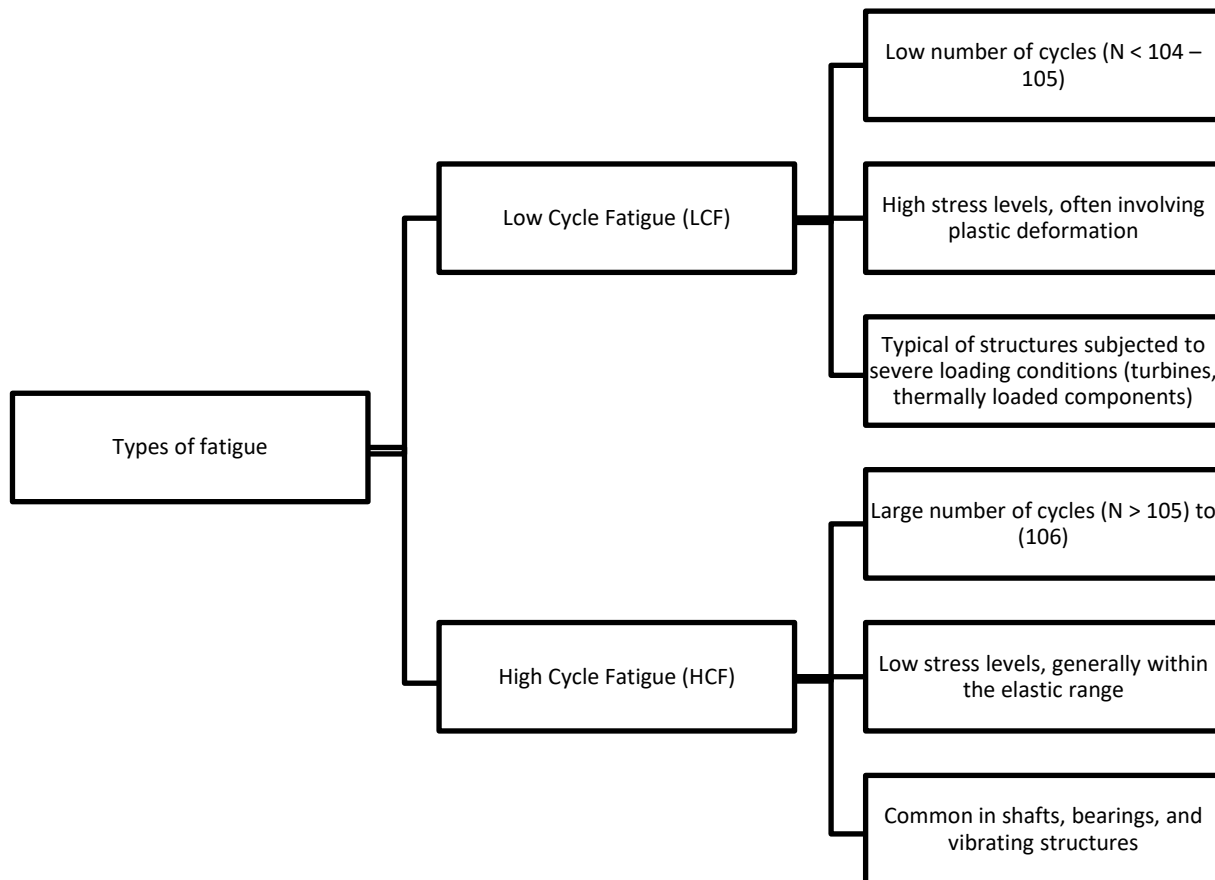


Figure 4-7 Main fatigue regimes

- **Analysis and prevention methods**
 - **Wöhler curves (S–N curves)**

Wöhler curves relate stress amplitude (S) to the number of cycles to failure (N). They represent a fundamental tool for estimating fatigue life during the design phase (Schijve, 2001).

- **Finite Element Analysis (FEA)**

Finite Element Analysis enables the identification of stress concentrations, simulation of cyclic loads, and fatigue life estimation at the design stage. Combined with fatigue criteria, FEA is indispensable in engineering (Bathe, 2006)

Fatigue failure is a progressive and insidious process that occurs in three distinct stages: crack initiation, crack propagation, and final fracture.

Its prevention relies on: sound mechanical design, the use of S–N curves, finite element analysis, and vibration monitoring during operation.

A thorough understanding of fatigue mechanisms is essential to ensure the reliability, safety, and durability of mechanical structures.

4.2.5 Proper Handling of Equipment

Proper handling is essential to ensure safety and equipment longevity. The key principles include:

- Respecting operating limits (load, speed, temperature)
- Using appropriate tools and procedures
- Following safety instructions and standards
- Avoiding misuse and improper storage

Poor handling often leads to premature wear, unexpected breakdowns and, safety incidents.

4.2.6 Documentation and Equipment Records

Each equipment item should have a technical file including:

- Technical datasheet
- Operating manuals
- Maintenance history
- Inspection and repair records

These documents support decision-making in maintenance and logistics planning.

4.3 Monitoring of equipment and information systems

Monitoring of equipment and information systems according to the points mentioned in **Table 4.4**.

Table 4-4 Suivi des équipements et systèmes d'information

Equipment tracking concepts	Equipment tracking tools	Use of tracking data
-Monitoring objectives -Traceability and data collection	-Manual and computerized records -CMMS principles	-Failure analysis -Maintenance decision support -Continuous improvement

4.4 Logistics Function

In industrial systems, logistics is a support function that affects both maintenance and production performance. It keeps operations running smoothly by managing the flow of equipment, spare parts, tools, and information. In fact, if logistics fail, machines can stop working even when the technical system is reliable. This section based on the main reference(Chanter & Swallow, 2008; Gillespie, 2015; Liu, Li, & Yan, 2024; Sakib & Wuest, 2018).

4.4.1 Definition of the Logistics Function

The goal of logistics is to make sure the right equipment or spare part is available at the right time, in the right amount, at the right place, and at the lowest cost (Gillespie, 2015). From an engineering perspective, logistics has a direct impact on how available equipment is, which can be shown as:

$$A = \frac{T_{\text{operating}}}{T_{\text{operating}} + T_{\text{downtime}}} \quad \text{Eq. 4-1}$$

Where: ($T_{\text{operating}}$) is the operating time, and (T_{downtime}) includes breakdown time and logistics delay time.

A poor logistics system increases downtime and reduces availability.

4.4.2 Role of Logistics in Equipment Management

Logistics supports equipment management by ensuring(Chanter & Swallow, 2008; Gillespie, 2015):

- Supply of spare parts and maintenance tools,
- Efficient inventory management,
- Transport and handling of equipment,
- Reduction of downtime caused by waiting for parts.

In maintenance engineering, downtime can be decomposed as:

$$T_{\text{downtime}} = T_{\text{repair}} + T_{\text{logistics}} \quad \text{Eq. 4-2}$$

Where: (T_{repair}) is the technical repair time and, ($T_{\text{logistics}}$) is the waiting time for spare parts, tools, or transport.

Note: Even with a short repair time, large logistics delays can dominate downtime.

4.4.3 Spare Parts Management

Spare parts management is one of the most important logistics activities in maintenance systems.

4.4.3.1 Identification and classification

Spare parts are identified and coded to avoid confusion and errors. They are commonly classified as: Critical parts (safety or production-critical), Fast-moving parts and, Slow-moving parts.

4.4.3.2 Stock level management

To avoid shortages and overstocking, minimum and maximum stock levels are defined. A basic stock balance equation is:

$$S(t + 1) = S(t) + Q_{\text{in}} - Q_{\text{out}} \quad \text{Eq. 4-3}$$

Where: ($S(t)$) is the stock level at time (t), (Q_{in}) is the quantity supplied and, (Q_{out}) is the quantity consumed.

The reorder point can be defined as:

$$R = D \times L \quad \text{Eq. 4-4}$$

Where: (D) is the average demand rate and, (L) is the supply lead time.

Note: When stock reaches (R), a new order must be placed.

4.4.3.3 Impact on maintenance

Good spare parts management helps to:

- Reduce machine downtime,
- Improve maintenance responsiveness,
- Control logistics and maintenance costs.

4.4.4 Storage and Warehousing

Storage conditions directly affect spare part quality and reliability. In addition, the improper storage may cause: Corrosion, Aging, and Loss of functionality.

From a reliability point of view, poor storage increases the failure rate of components:

$$\lambda_{\text{effective}} = \lambda_{\text{nominal}} + \lambda_{\text{storage}} \quad \text{Eq. 4-5}$$

Where: (λ_{nominal}) is the inherent failure rate and, (λ_{storage}) represents degradation due to storage conditions.

Note: Good warehousing practices reduce (λ_{storage}) and preserve component reliability.

4.4.5 Equipment Tracking Systems

Equipment tracking systems provide information on: equipment location, equipment status and, availability of spare parts. In addition, the tracking systems include: Manual records, CMMS, ERP systems, RFID technologies. And the tracking improves planning and reduces losses.

For example, the equipment utilization rate can be expressed as:

$$U = \frac{T_{\text{used}}}{T_{\text{available}}} \quad \text{Eq. 4-6}$$

Where: (T_{used}) is the actual usage time and, ($T_{\text{available}}$) is the total available time.

4.4.6 Logistics Performance Indicators

To evaluate logistics performance, engineers use indicators (KPIs).

4.4.6.1 Equipment availability rate

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad \text{Eq. 4-7}$$

Where: MTBF: Mean Time Between Failures and, MTTR: Mean Time To Repair (including logistics delay).

4.4.6.2 Stock-out frequency

$$F_{\text{stock-out}} = \frac{N_{\text{stock-out events}}}{N_{\text{requests}}} \quad \text{Eq. 4-8}$$

4.4.6.3 Inventory turnover rate

$$\text{Turnover} = \frac{\text{Annual consumption}}{\text{Average inventory}} \quad \text{Eq. 4-9}$$

A high turnover indicates efficient stock management.

Logistics directly affects maintenance performance, equipment availability, and system reliability.

Even simple mathematical indicators help engineers understand and improve logistics decisions.

4.5 Link Between Equipment Tracking, Logistics, and Maintenance

Equipment tracking, logistics, and maintenance are three interconnected functions that work together to ensure the reliability and availability of industrial systems. A weakness in any one of these functions can significantly reduce overall system performance.

4.5.1 Equipment Tracking as the Information Backbone

Equipment tracking provides accurate and up-to-date information about:

- Equipment location,
- Operating condition,
- Usage history,
- Maintenance records are captured during tracking.

Accurate and current information enables effective planning of maintenance activities and organization of logistics support; without reliable tracking data, delays, incorrect actions, or inefficiencies in maintenance may result.

4.5.2 Logistics Support for Preventive Maintenance

Preventive maintenance is planned in advance to reduce the probability of failures. For preventive maintenance to be effective, the required resources must be available when needed, as resource shortages can cause delays or incomplete maintenance work. The logistics ensures:

- Availability of spare parts,
- Availability of tools and consumables,
- Logistics is responsible for properly scheduling deliveries.

If spare parts are missing, preventive maintenance may be postponed, increasing the risk of unexpected failures. Therefore, logistics directly affect the success of preventive maintenance.

4.5.3 Logistics Response in Corrective Maintenance

In this case:

- Equipment tracking helps identify the failed component,
- Logistics ensures fast delivery of the required spare parts,
- When logistics responds quickly, downtime is reduced.

Although the technical repair may be simple, slow logistics still increase repair time. As a result, logistics efficiency strongly influences the performance of corrective maintenance.

4.5.4 Role of Equipment Tracking in Predictive Maintenance

Predictive maintenance relies on condition monitoring data such as:

- Operating hours,
- Vibration levels,
- Temperature,
- Degradation indicators.

To support this, equipment tracking systems (CMMS, sensors, databases) collect and store this data. Accurate and reliable data allows:

- Early detection of degradation,
- Better prediction of remaining useful life,
- Timely ordering of spare parts.

Therefore, without accurate tracking data, predictive maintenance becomes unreliable.

4.5.5 Impact on Maintenance Reliability and System Performance

When equipment tracking, logistics, and maintenance work together efficiently:

- Equipment availability increases,
- Downtime decreases,
- Maintenance costs are optimized,
- System reliability improves.

On the contrary, poor coordination between these functions leads to delays, higher costs, and increased failure risk.

Maintenance cannot be efficient without good logistics, and logistics cannot be efficient without accurate equipment tracking.

4.6 Conclusion

Efficient equipment tracking and logistics management are cornerstones of industrial performance. Throughout this chapter, we have shown that equipment is not simply a technical asset but a strategic resource whose identification, categorization, documentation, and lifecycle control directly impact maintenance efficiency and operational continuity.

A structured equipment-tracking system lays the informational groundwork for informed decision-making. Precise identification, current records, and lifecycle monitoring secure traceability, bolster preventive planning, and enable swift action during failures. Without reliable data, maintenance strategies become fragmented and ineffective.

Likewise, logistics plays a vital role in ensuring spare parts availability, optimizing inventory levels, and maintaining proper storage. Strong spare parts management curbs stock-outs, limits downtime, and controls inventory costs. Logistics performance indicators—such as equipment availability, stock-out rates, and inventory turnover—provide tangible measures to assess system efficiency and direct ongoing improvement.

The connection between equipment tracking, logistics, and maintenance highlights the integrated nature of industrial management. Preventive maintenance hinges on prompt parts availability; corrective maintenance depends on rapid logistical support; and predictive maintenance requires precise historical and operational data. Thus, equipment tracking forms the informational backbone, while logistics delivers the operational support essential for effective maintenance.

For the mechanical engineer, mastering these concepts is crucial to understanding how technical reliability relies on organizational design, information management, and supply chain coordination. Equipment tracking and logistics are core elements of a comprehensive maintenance and asset management strategy focused on reliability, cost control, and sustainable industrial performance.

Chapter 5: Reliability in industrial maintenance

5 Chapter 5: Reliability in industrial maintenance

5.1 Introduction

In today's industrial environment, companies face fierce competition. Equipment grows increasingly complex. Safety and quality demands increase. Maintenance has become a strategic enabler of production performance. While the field was once seen as a support function, maintenance now drives value creation and industrial risk management ((Mobley, 2011 {Ben-Daya, 2016 #69).

Technical failures harm industrial performance in many ways:

- Technical failures drive up substantial direct costs, such as repairs and component replacement, and add indirect costs, including production downtime, contractual penalties, and excess resource consumption.
- Certain failures cause major accidents, putting personnel and the environment at risk.
- Equipment degradation results in defective products.

To address these challenges, reliability is a key measure of effective maintenance ((Villemeur, 1988). Consequently, conducting reliability, maintainability, and availability analysis is essential for industrial systems. One common approach is Failure Modes and Effects Analysis (FMEA), a systematic method for identifying potential equipment failures, assessing their causes and effects, and prioritizing actions to reduce risk.

By building these competencies, students will: understand links between maintenance and performance, calculate basic reliability and maintainability metrics, assess equipment performance and repairability, and apply FMEA to identify risks.

5.2 Maintenance – Reliability Relationship

5.2.1 The Role of Reliability in Maintenance

Reliability drives every maintenance strategy. By allowing us to anticipate equipment behavior and choose the best intervention intervals, reliability guides decisions, resource planning, and strategy selection ((Dhillon, 2006; IEC., 1999).

5.2.2 How Maintenance and Reliability Influence Each Other

System reliability and maintenance are closely linked. In fact, reliable performance relates directly to effective maintenance. Two key concepts illustrate this relationship; Firstly, intrinsic reliability results from the asset design, the materials used, and normal operating conditions. On the other hand, operational reliability is what we see in service. Maintenance, environment, and daily use influence it (Rausand & Hoyland, 2004).

This interplay demonstrates that equipment reliability depends not only on good design but also on well-planned maintenance. Furthermore, according to standards such as ISO 20815 (2018) and IEC 60300-3-1, effective maintenance is essential to maintaining operational performance.

5.2.3 Reliability-Centered Maintenance Policies

Reliability-Centered Maintenance (RCM) is a systematic methodology focused on determining the most effective maintenance strategies to ensure the performance of critical systems. RCM involves in-depth analysis of failure modes and their consequences to systematically prioritize maintenance interventions (Moubray, 2001 {Netherton, 2021 #73}).

This focus on proactive maintenance naturally leads to considering how maintenance strategies affect equipment throughout its lifecycle.

5.2.4 The Impact of Maintenance on Equipment Lifecycle

The bathtub curve shows equipment behavior in three phases ((Nakagawa, 2005):

- **Early Life Phase:** the period during which early failures occur, often related to the manufacturing or commissioning of the asset.
- **Useful Life Phase:** a stable period with a relatively constant failure rate for the asset.
- **Aging Phase:** a progressive increase in failures of the asset due to wear and fatigue.

Preventive and predictive maintenance are applied to prolong assets' useful life and defer the onset of aging, thereby optimizing system reliability and availability. Achieving these goals relies on a comprehensive understanding of reliability, maintainability, and availability (RMA), as outlined by the ISO 2394 and IEC 60300 standards.

5.3 Reliability Functions and Their Indicators

5.3.1 Reliability Functions

5.3.1.1 Probability Density Function $f(t)$

Let $f(t)$ be the probability density function of the variable (t) , representing the likelihood of failure at each moment. This function (presented by Fig. 5.1) is derived from system lifetime data observed from the beginning of operation, providing the foundation for subsequent reliability analysis (Villemeur, 1988).

$$F(t) > 0$$

$$\int_0^{\infty} f(t) * dt = 1 \quad \text{Eq. 5-1}$$

$f(t) * dt$: express the probability that the system will fail between (t) and $(t+dt)$

$$f(t) * dt = \text{Prob}\{t < \text{lifetime} < t + dt\}$$

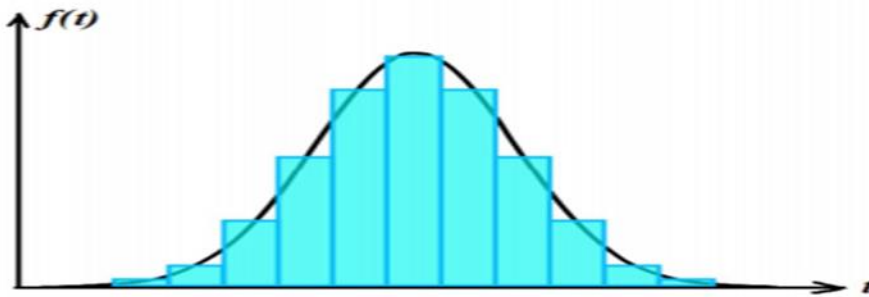


Figure 5-1 Representation of the density function $f(t)$

5.3.1.2 Fault distribution function $F(t)$

Let $F(t)$ be the distribution function associated with the random variable (t) , presented by Fig. 5.2, and expressed by the relationship:

$$F(t) = \int_0^t f(x) * dx \quad \text{Eq. 5-2}$$

$F(t)$: expresses the probability that the system will fail before time t

$$F(t) = \text{Prob}\{0 < \text{lifetime} < t\}$$

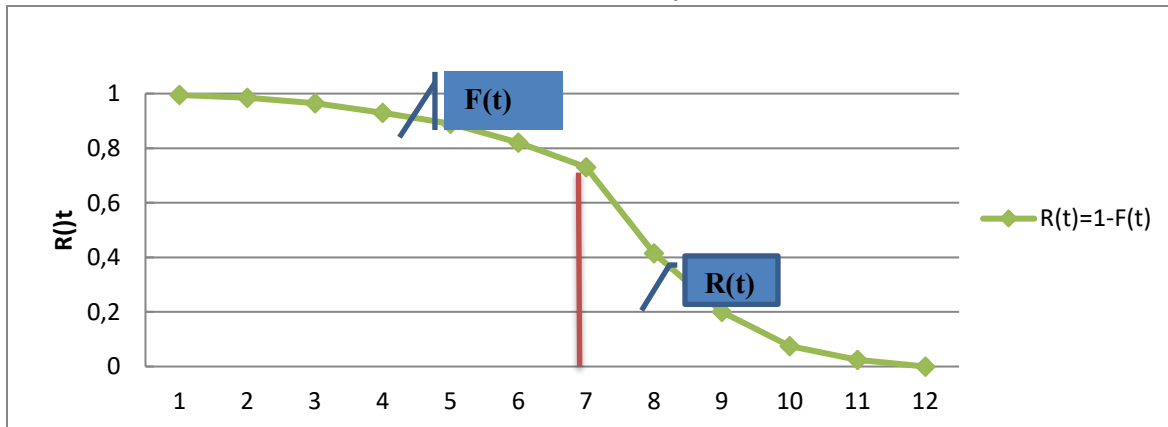


Figure 5-2 Representation of the failure distribution function $F(t)$ and the distribution function $R(t)$

5.3.1.3 Reliability distribution function $R(t)$

Let $R(t)$ denote the system's reliability function, the probability that the system survives to time (t) (see Fig. 5.3). $R(t)$ derives from $f(t)$ (Villemeur, 1988).

$$R(t) = \text{Prob}\{\text{duree de vie} \geq t\}$$

$$R(t) = \int_t^{\infty} f(t) * dx = 1 - F(t) \quad \text{Eq. 5-3}$$

Reliability is measured by the probability of an entity E performing a required function under given conditions, during the time interval $[0, t]$.

$R(t) = P(\text{E not failing over the duration } [0, t], \text{ assuming that it is not failing at time } t = 0).$

This can be expressed as:

$$R(t) = P(T > t) \quad \text{Eq. 5-4}$$

The opposite aptitude is called unreliability, and is defined by:

$$\bar{R}(t) = 1 - R(t) = P(t < T) = F(t) \quad \text{Eq. 5-5}$$

5-5

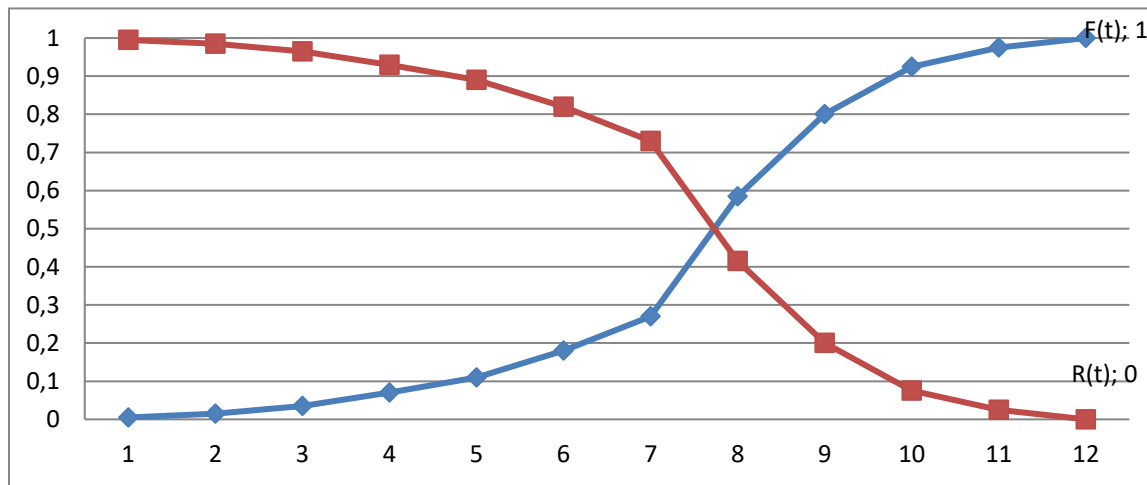


Figure 5-3 Representation of the distribution function $F(t)$ and reliability function $R(t)$

5.3.1.4 Instantaneous failure rate

$\lambda(t) dt$ is the probability of failure in $(t, t + dt)$, given survival up to t . This intensity of failure over time specifies the conditional probability per unit time of failing between t and $t + dt$, based on $f(t)$ and $R(t)$ (Villemeur, 1988).

Applying the theorem of conditional probabilities, we obtain (if dt is small):

$$\lambda(t) dt = \frac{\text{Prob \{défaillant sur } [t, t + dt] \text{ sans défaillance sur } [0, t]\}}{\text{Prob (non défaillant sur } [0, t])}$$

$$\lambda(t) dt = \frac{\text{Prob \{défaillant sur } [0, t + dt]\} - \text{Prob (défaillant sur } [0, t])}{\text{Prob (non défaillant sur } [0, t])}$$

$$\lambda(t) dt = -\frac{1}{R(t)} \frac{dR(t)}{dt} \quad \text{Eq. 5-6}$$

The evolution of a product's failure rate over time is characterized by the bathtub curve (Fig. 5.7). This curve varies depending on the device type (mechanical or electronic).

a) Failure Behavior of Electronic Components

In reliability engineering, the operational lifetime of electronic components is typically broken down into three distinct stages (Procaccia, Ferton, & Procaccia, 2011 {Lyonnet, 2012 #76}):

- **Infant Mortality:** Early high failures from defects, declining as faulty units are removed.
- **Useful Life:** Stable, mostly random failure rates—most reliable period.
- **Wear-Out:** Failures increase with age and wear, ending useful life.

Deciding when to replace or overhaul a component usually involves both technical evaluation and cost considerations, often guided by life cycle cost analysis and reliability modeling (Dhillon, 2006). While preventive maintenance is rarely cost-effective in the early failure phase, it becomes a key strategy during the useful life phase to help minimize the impact of random failures.

The behavior of the failure rate function $\lambda(t)$ over time gives the bathtub curve its distinctive shape (Fig. 5.4).

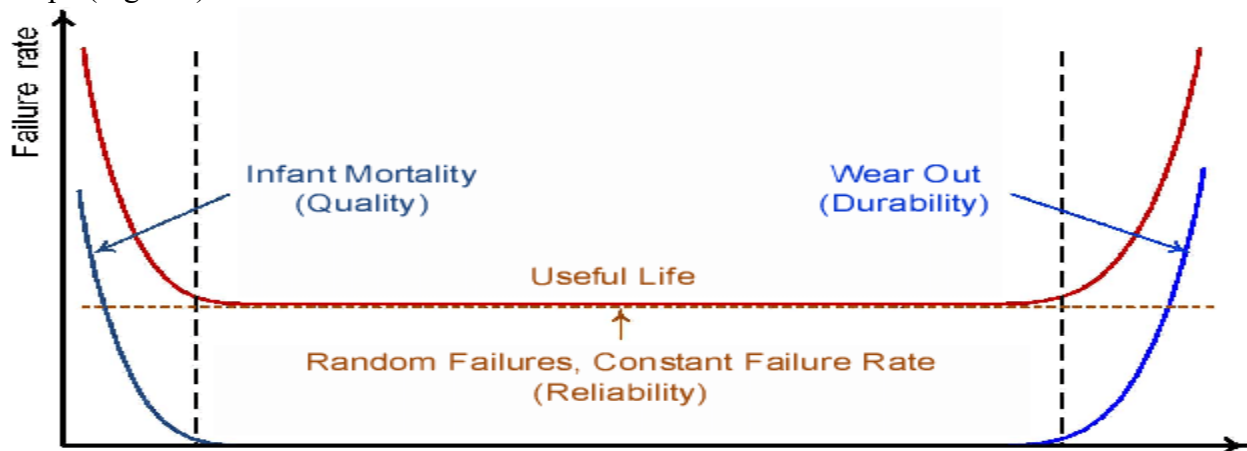


Figure 5-4 Bathtub curve: failure rate $\lambda(t)$

b) Failure Behavior of Mechanical Components

Failure rates in mechanical systems show nonlinear trends across component life stages (Procaccia et al., 2011 {Ouakki, 2011 #77 {Boukeffa, 2020 #78}}) note that the reliability profile often has two main phases:

- **Infant Mortality Phase:** This early stage shows a declining failure rate. Initial defects or surface issues, like wear-in or break-in, cause early failures. Though short, this phase stabilizes performance and removes weak units.
- **Aging Phase:** Over time, the failure rate rises again from gradual aging. Effects may include wear, fatigue, corrosion, deformation, or embrittlement. This phase is longer than the first and aligns with mature operational life, lasting until the component's functional end.

These two phases form a failure rate curve for a mechanical part that first decreases and then slowly increases again. The Fig. 5.5 shows this typical pattern.

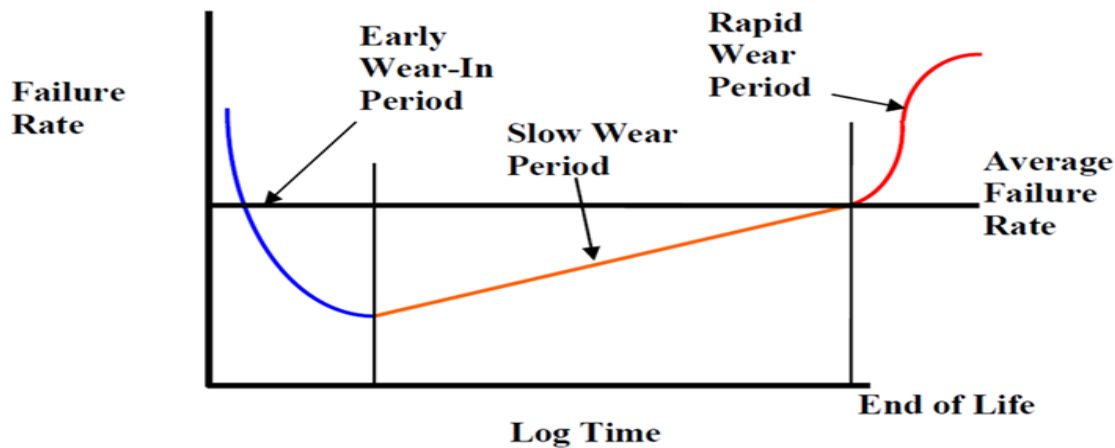


Figure 5-5 The failure rate curve for mechanical components

Before concluding this section, it is important to recall the relationships that link the reliability, failure, and probability density functions.

The failure rate $\lambda(t)$ is an estimator of reliability and is typically expressed in failures per hour. It represents the likelihood of failure at a given time, given that the system has operated without failure up to that point.

$$\lambda = \frac{\text{Number of failures}}{\text{Duration of use}} \quad \text{Eq. 5-7}$$

NB: Relationship between Failure Rate & Reliability Functions

To summarize, the failure rate $\lambda(t)$ is a key indicator of system reliability, commonly expressed as failures per hour. It is intrinsically linked to the following reliability functions (Villemeur, 1988):

$$R(t) = e^{-\int_0^t \lambda(u) du}, F(t) = 1 - R(t), f(t) = \lambda(t)R(t) \quad \text{Eq. 5-8}$$

Where:

- $R(t)$: Reliability function (probability that no failure has occurred by time t),
- $F(t)$: Cumulative distribution function of failures,
- $f(t)$: Probability density function of time to failure,
- $\lambda(t)$: Instantaneous failure rate (hazard rate).

The reliability of a system can be modeled using various probability distributions, selected based on the equipment's behavior. In this teaching resource, we will focus on the two most prevalent models in the industrial sector:

- The **exponential law** applies when the failure rate (λ) is constant. It is well-suited to electronic components or mechanical systems during their maturity phase (useful life), when failures occur randomly.
- The **Weibull law**, with its shape parameter, flexibly models varying failure rates, covering early failures and aging-related wear.

5.3.2 Mathematical modeling of reliability

Within the framework of this course material, we limit ourselves to the two most widely used laws in system reliability: the exponential law and the Weibull law (Hadeif, 2015; Procaccia et al., 2011; Villemeur, 1988).

5.3.2.1 Exponential Law

The exponential distribution is expressed as follows:

$$\text{Reliability: } R(t) = e^{-\lambda t} \quad \text{Eq. 5-9}$$

(e étant la base exponentielle 2.718
 λ , l'intensité)

- Probability density

$$f(t) = \lambda e^{-\lambda t} \quad \text{Eq. 5-10}$$

- The distribution function

$$F(t) = 1 - e^{-\lambda t} = \int_0^t \lambda * e^{-\lambda t} dt \quad \text{Eq. 5-11}$$

- Failure rate

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda = \text{constant} \quad \text{Eq. 5-12}$$

- MTTF

$$\text{MTTF} = \int_0^\infty R(t) dt = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda} \quad \text{Eq. 5-13}$$

$$\text{Variance: } \sigma^2 = \frac{1}{\lambda^2} \quad \text{Eq. 5-14}$$

The following Fig. 5.6 shows the distributions related to this law, illustrating how the failure rate of one or more components, each assumed to have the same λ , is represented by the curves.

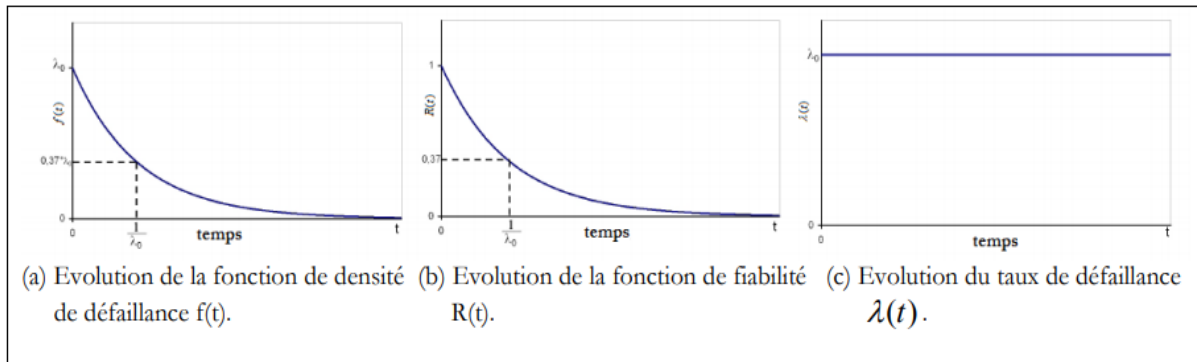


Figure 5-6 Distribution of functions of the exponential law

5.3.2.2 Weibull's Law

This law, represented by the figure, is characterized by three parameters, each associated with a distinct zone of the bathtub curve (Fig. 5.7). This distribution is widely used in reliability engineering for electrical, electronic, and mechanical systems.

- Probability density:

$$f(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta} \right)^\beta} \quad \text{Eq. 5-15}$$

- Failure rate:

$$\lambda(t) = \frac{\beta}{\eta} \left(\frac{t-\gamma}{\eta} \right)^{\beta-1} \quad \text{Eq. 5-16}$$

- Reliability:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta} \right)^{\beta}} \quad \text{Eq. 5-17}$$

- Average MTTF (Mean Time To Failure):

$$MTTF = \gamma + \eta \Gamma\left(\frac{1}{\beta} + 1\right) \quad \text{Eq. 5-18}$$

- Given that Γ is a gamma function defined by:

$$\Gamma(n) = \int_0^{\infty} e^{-x} x^{n-1} dx \quad \text{Eq. 5-19}$$

- η It is a scaling parameter used for time normalization; its unit is homogeneous with that of the stress.
- γ It is a position (or location) parameter and corresponds to the time from which the first failure occurs.
- β This is a shape parameter. From its value, we can determine whether the component or system is in its early stages, its useful life, or its aging phase—reflecting the fineness of the distribution. Therefore:
 - $\beta < 1$, ($\lambda(t)$ Decreases), early stage (break-in, debugging),
 - $\beta = 1$, ($\lambda(t)$ Constant), useful life period (independence from time),
 - $\beta > 1$, ($\lambda(t)$ Growth), period of aging, wear or degradation.

Notes: Special cases:

- The Weibull distribution is defined by two parameters when $\gamma = 0$.
- When: $\beta = 1$ and $\gamma = 0$ we find ourselves in the case of the exponential law with: $\lambda = \frac{1}{\eta}$
- When: $\beta \approx 3, 5$ and $\gamma = 0$, we are in the case of a normal distribution.

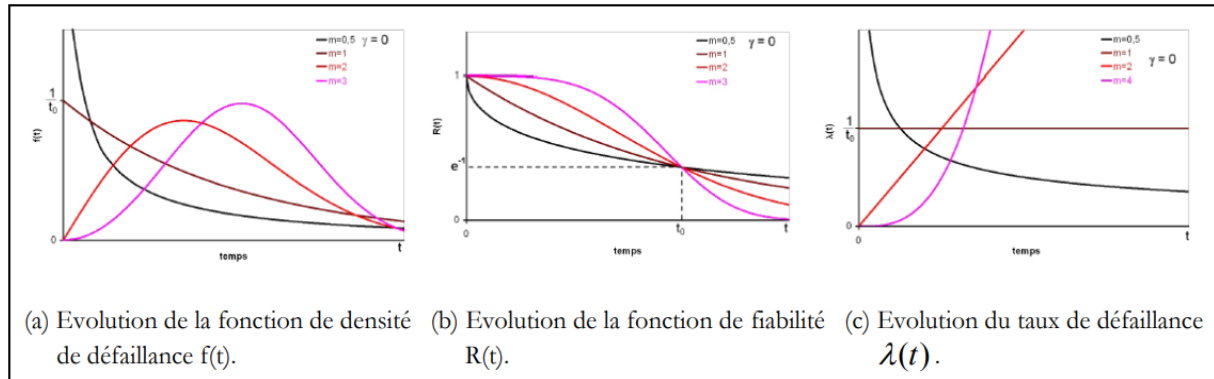


Figure 5-7 Characteristic reliability functions of a component family for a distribution of their failure times following a Weibull distribution

5.3.3 Mean Time Estimators in Reliability and Maintainability Engineering

In reliability analysis, a range of time-based indicators, including reliability, maintainability, and availability, is used to capture how a system performs over time and how easily it can be maintained. Reliability is the probability that a system will perform without failure over a specified period. Maintainability is the ease and speed with which a system can be restored to operational status after a failure. Availability indicates the proportion of time a system is functioning. These indicators, often expressed as mean-time estimators, play a key role in evaluating core dependability attributes. Their foundations lie in statistical and probabilistic modeling, as detailed by {Dhillon, 2006 #42{Ebeling', 2019 '#79{O'connor', 2025 '#80;Lyonnet, 2012 #76}}}. These indicators presented by Fig. 5.8.

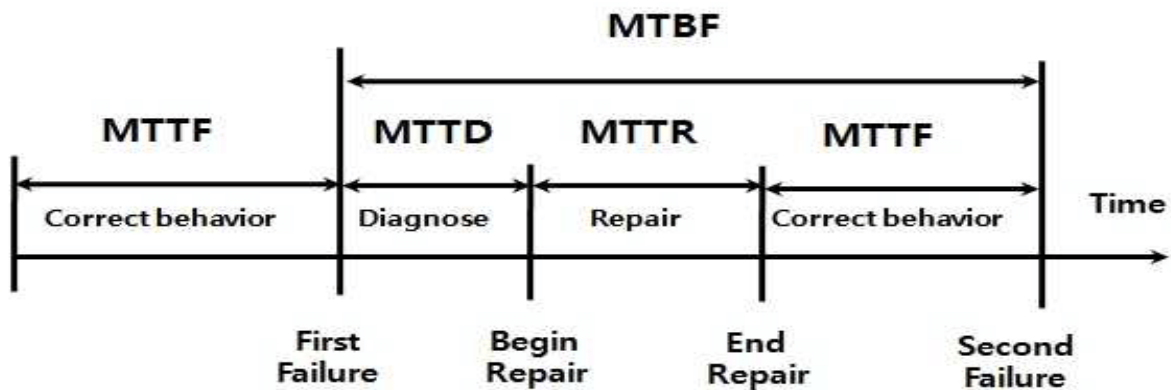


Figure 5-8 Average duration associated with operational safety

5.3.3.1 Failure-Related Estimators

a) Mean Time To Failure (MTTF)

MTTF is the average time a non-repairable system or component operates before its first failure, starting from $t = 0$. It is the integral of the reliability function $R(t)$ over time, as described by (Ebeling, 2019):

$$\text{MTTF} = \int_0^{\infty} R(t) dt \quad \text{Eq. 5-20}$$

b) Mean Time Between Failures (MTBF)

MTBF is the average time between failures in a repairable system. It reflects the typical time interval during which the system remains functional between breakdowns. In practice, one way to estimate it is to run the system for a total time T and record the number of failures, N , that occur during that time (El Hami & Radi, 2011).

$$\text{MTBF} = \frac{T}{N} \quad \text{Eq. 5-21}$$

Special Case: Constant Failure Rate (λ)

If the failure rate λ is assumed constant, the reliability function follows an exponential law (Procaccia et al., 2011; Villemeur, 1988):

$$R(t) = e^{-\lambda t} \quad \text{Eq. 5-22}$$

The MTTF is then given by:

$$\text{MTTF} = \int_0^{\infty} e^{-\lambda t} dt = \frac{1}{\lambda} \quad \text{Eq. 5-23}$$

Consequently, the reliability at $t = \text{MTBF}$ becomes:

$$R(\text{MTBF}) = e^{-\lambda \times \text{MTBF}} = e^{-1} \approx 0.37$$

This means that approximately 63% of the components are expected to fail by the time $t = \text{MTBF}$. In this case, $\text{MTTF} = \text{MTBF} = 1/\lambda$, but their use differs:

- MTTF applies to non-repairable systems,
- MTBF applies to repairable systems.

5.3.3.2 Repair-Related Estimators

a) Mean Up Time (MUT)

The MUT represents the average operating duration or availability period of a system after repair before the next failure, closely related to MTBF, as both metrics describe system uptime between failures. In practice, MUT helps organizations predict system performance and schedule preventive maintenance, serving as a direct measure of system uptime {{Villemeur, 1988 #1} Dhillon, 2006 #13}.

b) Mean Time To Repair (MTTR)

MTTR is the average time required to restore a system to operational status after a failure. It is calculated as the integral of one minus the maintenance function, $M(t)$, over time (Ebeling, 2019{El Hami, 2011 #4}).

$$\text{MTTR} = \int_0^{\infty} [1 - M(t)] dt \quad \text{Eq. 5-24}$$

c) Mean Down Time (MDT)

Mean Time Between Failures (MDT) is the average time a system remains unavailable after a failure. It accounts for both active repair time (including technical actions such as detection, diagnosis, and repair) and passive delays arising from administrative, logistical, or transport-related factors(Sullivan, Pugh, Melendez, & Hunt, 2010{Zhou, 2024 #35; Villemeur, 1988}).

$$\text{MDT} = \text{MTTR} + \text{Delays}_{\text{logistical}} + \text{Delays}_{\text{administrative}} \quad \text{Eq. 5-25}$$

When λ is constant, the following steady-state relationship holds:

$$\text{MTBF} = \text{MUT} + \text{MDT} = \frac{1}{\lambda} \quad \text{Eq. 5-26}$$

Note: Probabilistic and Statistical Aspects of MTBF

Two complementary approaches can be used to estimate MTBF:

- **Probabilistic definition:** MTBF is the expected value of the random variable representing time to failure T , expressed as:

$$\text{MTBF} = E(T) = \int_0^{\infty} t f(t) dt = \frac{1}{\lambda} \quad \text{Eq. 5-27}$$

Where $f(t)$ is the probability density function of time to failure (Ebeling, 2019).

- **Statistical definition:** MTBF is calculated as the mean of observed time intervals between successive failures during operation:

$$MTBF = \frac{\sum_{i=1}^n TBF_i}{n} \quad \text{Eq. 5-28}$$

Let $TBF_1, TBF_2, \dots, TBF_n$ represent the individual times between failures. This value is derived from empirical data such as operational history, lifetime testing, or field reliability statistics (Dhillon, 2006; Lewis, 1996).

Building on these basic failure data, key indicators such as MTTF, MTBF, MTTR, MDT, and MUT are essential to dependability analysis. They provide measurable insights into a system's reliability (λ^{-1}), maintainability (μ^{-1}), and availability. This data helps engineers fine-tune designs, streamline maintenance, and manage life-cycle costs (O'connor & Kleyner, 2025 {Sakib, 2018 #31}).

5.4 Maintainability Modeling for Repairable Systems

Maintainability is a core concept in maintenance engineering and reliability. It measures how quickly a system can be restored after failure.

Formally, maintainability is defined by IEC 60050 (191-02-07) and MIL-STD-721C as: “The probability that a failed system can be restored to its required operational state within a specified time when maintenance is performed under stated conditions and resources.”

5.4.1 Basic Concepts of Repairable Systems

A repairable system is one that, after failure, can be restored to working order through corrective maintenance. We distinguish between: uptime, repair time (downtime), the succession of cycles of operation – failure – repair.(Procaccia et al., 2011; Wang, Deng, Wu, Wang, & Xiong, 2014; Zhou et al., 2024)

Probabilistic modeling of maintainability is based on the random variable:

$$T_r = \text{Reparation time}$$

5.4.2 Maintainability Function

Maintainability measures the probability that the repair time, (T_r), is less than or equal to a given value t . It indicates the likelihood of restoring the system to operation within time t (Villemeur, 1988).

$$M(t) = P(T_r \leq t) \quad \text{Eq. 5-29}$$

Thus, the maintainability function represents the probability that a system will be repaired in time t or less.

By analogy with reliability, we define the non-maintenance function:

$$\bar{M}(t) = 1 - M(t) \quad \text{Eq. 5-30}$$

5.4.3 Maintainability Density Function

If $g(t)$ is the probability density function of the repair time(Villemeur, 1988):

$$M(t) = \int_0^t g(u) du \quad \text{Eq. 5-31}$$

5.4.4 Mean Time To Repair (MTTR)

A key maintainability indicator is MTTR, defined as follows:

$$MTTR = E[T_r] = \int_0^\infty t g(t) dt \quad \text{Eq. 5-32}$$

Physically, MTTR is the average time required to restore the system to working order following failure.

Therefore, a low MTTR reflects good maintainability.

5.4.5 Probabilistic Models of Repair Time (maintainability)

5.4.5.1 Exponential Repair Distribution

If repair times follow an exponential law with repair rate μ (where μ is the average number of repairs per hour)(Ouakki, 2011):

$$M(t) = 1 - e^{-\mu t} \quad \text{Eq. 5-33}$$

μ : Mean repair rate (repairs per hour)

$1/\mu = \text{MTTR}$ Mean Time To Repair

The MTTR is the expected value of repair time, calculated either mathematically or statistically:

The MTTR is the expected repair time, calculated either analytically or empirically:

$$\text{Analytical form: } MTTR = \int_0^\infty [1 - M(t)] dt$$

- Empirical form: $MTTR = \frac{\sum_{i=1}^N TTR_i}{N}$

Maintainability shows how fast a system can be restored.

5.4.5.2 Weibull's Law Applied to Repair Time

a) Density function

When the repair time follows a Weibull distribution, the probability density function is given by (Procaccia et al., 2011):

$$g(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp \left[- \left(\frac{t}{\eta}\right)^{\beta} \right], t \geq 0 \quad \text{Eq. 5-34}$$

Or: ($\beta > 0$) is the shape parameter, and ($\eta > 0$) is the scale parameter (characteristic repair time).

- The shape parameter

$\beta > 0$: governs the temporal dynamics of the repair process. It directly influences the slope of the maintainability function and the behavior of the instantaneous repair rate.

In the probability density function:

$$g(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp \left[- \left(\frac{t}{\eta}\right)^{\beta} \right] \quad \text{Eq. 5-35}$$

The term $\left(\frac{t}{\eta}\right)^{\beta-1}$ determines the variation of density over time.

- **Physical interpretation in maintainability (Hadeif, 2015; Procaccia et al., 2011; Rausand & Hoyland, 2004)**

Physical interpretation of the shape parameter in maintainability is presented by Table 5.1.

Table 5-1 Interpretation of various values of the shape parameter

Value of (β)	Interpretation	
$\beta < 1$	Quick repairs at first, then a gradual slowdown	This reflects a situation in which simple repairs are handled quickly, while more complex repair processes emerge over time (lengthy diagnostics, parts shortages, disorganization).
$\beta = 1$	Constant repair rate (exponential case)	This characterizes a Markovian process: the likelihood of completing a repair remains constant regardless of elapsed repair duration.
$\beta > 1$	Accelerating the repair process	This reflects a learning effect, improved repair team coordination, or enhanced logistics and procedures.

In industrial practice, an increase in β is often associated with increasing maturity of the maintenance organization.

- The scale parameter

$\eta > 0$, also called characteristic repair time, sets the order of magnitude of repair times.

- ***Probabilistic meaning***

Regarding Weibull's law:

$$M(\eta) = 1 - \exp(-1) \approx 63,2\%$$

Thus, η represents the time at which 63.2% of the repairs are completed.

- Operational interpretation
 - A low η indicates:
 - Repairs were generally quick.
 - Good availability of spare parts,
 - Well-defined procedures.
 - A high η translates to:
 - Significant logistical delays,
 - Low standardization,
 - Increased technical complexity of interventions.

Note: Unlike β , the parameter η is directly influenced by material and organizational resources.

b) Maintainability function (distribution function)

The associated maintainability function is (Mobley, 2011; Zhou et al., 2024):

$$\sqrt{M(t) = 1 - \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right]} \quad \text{Eq. 5-36}$$

In reliability engineering, this expression gives the probability that a piece of equipment will be repaired within time t or less.

c) Repair rate function (repair hazard)

By analogy with reliability, we define the instantaneous repair rate:

$$\mu(t) = \frac{g(t)}{1-M(t)} \quad \text{Eq. 5-37}$$

For Weibull's law, we obtain:

$$\mu(t) = \frac{g(t)}{1-M(t)} \quad \text{Eq. 5-38}$$

Physical interpretation:

- ($\beta < 1 \rightarrow \mu(t) \text{ decreasing}$): Repairs start rapidly but then slow down, indicating initial efficiency followed by challenges such as disorganization or difficult diagnosis.
- ($\beta = 1 \rightarrow \mu(t) \text{ constant}$): Repairs proceed at a constant rate, representing the exponential case.
- ($\beta > 1 \rightarrow \mu(t) \text{ increasing}$): Repairs accelerate over time, reflecting a learning effect or improved organization.

d) Mean time to repair (MTTR) under Weibull

The mean time to repair (MTTR) is defined by (Procaccia et al., 2011):

$$MTTR = E[T_r] \quad \text{Eq. 5-39}$$

For a Weibull distribution, we obtain:

$$\sqrt{MTTR} = \eta \Gamma\left(1 + \frac{1}{\beta}\right) \quad \text{Eq. 5-40}$$

Where ($\Gamma(\cdot)$) is Euler's Gamma function.

At (η) constant values, increasing MTTR slows repairs. MTTR depends on the shape parameter (β), which reflects the repair team's organization and experience.

Accordingly, MTTR serves as a key performance indicator, quantifying both the average pace of repair activities and the robustness of maintenance process controls.

Note: Impact on availability

For a repairable system, the steady-state availability is:

$$A = \frac{MTBF}{MTBF + MTTR} \quad \text{Eq. 5-41}$$

Thus, any action that:

- Reduces α (logistics, parts), increases β (training, experience),
- As a result, this change mechanically improves overall availability.

e) Estimation of Weibull parameters for maintainability

These estimates allow for realistic modeling of maintenance performance (Procaccia et al., 2011; Zhou et al., 2024):

- The parameters (β) and (η) can be estimated from the repair data by:
- The maximum likelihood method,
- Weibull paper linear regression,
- graphical methods.

With these estimates, it is possible to create realistic models of maintenance performance

f) Industrial interest of Weibull's law in maintainability

By modeling maintainability using Weibull's law, it becomes possible to:

- To assess the probability of repair within a given time,
- To compare different maintenance organization strategies,
- To optimize human and logistical resources,
- To support decision-making in preventive and predictive maintenance.

5.4.5.3 Lognormal and Gamma Repair Models

In real-world situations, repair times can vary considerably. Therefore, more realistic models are used (Netherton, 2021; Procaccia et al., 2011):

- Lognormal distribution (complex repairs, dependent on human expertise),
- Gamma law (multi-step repairs).

These laws allow for better representation of the durations of diagnosis, supply, and intervention

5.4.5.4 Comparison: Exponential vs Weibull Repair Model

The comparison between the exponential vs Weibull Repair Model is summarized in **Table 5.2**.

Table 5-2 Comparison: Exponential vs Weibull Repair Model

Appearance	Exponential Repair	Weibull Repair
Repair rate	Constant	Time-dependent
Early repairs	Overestimated	More realistic
Learning effect	Not modeled	Modeled if ($\beta > 1$)
Industrial realism	Moderate	High

Engineering Insight:

- The exponential model is convenient but often optimistic.
- The Weibull model:
 - o Captures organizational effects,
 - o reflects real maintenance behavior,

- Improves the credibility of FMD studies.

In industrial practice, Weibull-based maintainability modeling leads to more realistic availability predictions and better maintenance decision-making.

5.5 Relationship between Reliability and Maintainability

5.5.1 Complementary Roles in System Performance

Reliability and maintainability act on different phases of the system life cycle:

- Reliability governs failure frequency (mean time to failure).
- Maintainability governs downtime duration after a failure (mean time to repair).

Thus:

- A highly reliable but poorly maintained system rarely fails but remains unavailable for long periods when it does.
- A maintainable but unreliable system fails often but recovers quickly.
- Optimal system performance requires a balanced trade-off between the two.

5.5.2 Mathematical Relationship through Availability

Their main quantitative link is availability, a key dependability metric.

5.5.2.1 Stationary Availability

For a repairable system operating under steady-state conditions (Ouakki, 2011; Procaccia et al., 2011):

The steady-state availability is:

$$A_{ss} = \frac{\mu}{\lambda + \mu} \quad \text{Eq. 5-42}$$

Or equivalently,

$$A_{ss} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \quad \text{Eq. 5-43}$$

This equation expresses the system's long-term uptime fraction — a critical KPI in asset management (See Fig.5.9).

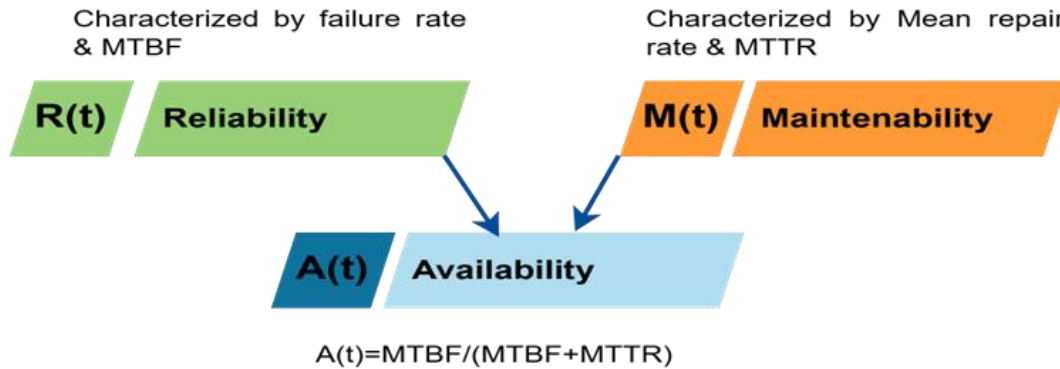


Figure 5-9 Relationship between FMD

Interpretation:

- Increasing MTBF (higher reliability) raises availability.
- Decreasing mean time to repair (MTTR, better maintainability) also improves availability.
- Availability can result from different combinations of reliability and maintainability.

5.5.2.2 Example 1: Maintainability–Availability with exponential Repair Model

An industrial pump has the following data: Failure rate: ($\lambda = 2 \times 10^{-3}$) failures/hour. And Mean time to repair: MTTR = 4 hours.

1) Repair Rate (MTTR):

$$\mu = \frac{1}{\text{MTTR}} = \frac{1}{4} = 0.25 \text{ repairs/hour}$$

2) Maintainability Function calculation: After 2 hours of repair:

$$M(2) = 1 - e^{-\mu t} = 1 - e^{-0.25 \times 2} = 1 - e^{-0.5} = 0.393$$

Interpretation: There is a 39.3% probability that the pump will be repaired within 2 hours.

3) Availability calculation:

$$A = \frac{\mu}{\lambda + \mu} = \frac{0.25}{0.25 + 0.002} = 0.992$$

Interpretation: The pump's steady-state availability is approximately 99.2%.

5.5.2.3 Example 2: Reliability–Maintainability–Availability with Weibull Repair Model

An industrial pump operates under constant operating conditions. Failures are assumed to follow an exponential law, while repair times are modeled using a Weibull distribution, which is more realistic for industrial maintenance processes.

An industrial pump operates under constant conditions. Failures follow an exponential law, and repair times are best represented by a Weibull distribution, which realistically models industrial maintenance processes.

a) Data

Reliability (failure process): Failure rate: $\lambda = 2 \times 10^{-3}$ failures/hour

Failures are assumed memoryless (exponential failure model).

b) Maintainability (repair process – Weibull)

Assume that the time to repair follows a Weibull distribution with: Shape parameter: $\beta = 1.5$ and, the Scale parameter: $\eta = 5$ hours

These values represent:

an improving repair process ($\beta > 1$), learning and organization effect),

Average repair duration of a few hours.

c) Weibull Maintainability Model

- Maintainability Function

The maintainability function is:
$$M(t) = 1 - \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right]$$

This function gives the probability that the repair is completed within time (t) .

- Maintainability after 2 hours

$$M(2) = 1 - \exp \left[- \left(\frac{2}{5} \right)^{1.5} \right]$$

$$\left(\frac{2}{5} \right)^{1.5} \approx 0.253$$

$$M(2) = 1 - \exp(-0.253)$$

$$\sqrt{M(2)} \approx 0.223$$

Interpretation

Based on these assumptions, there is a definitive 22.3% probability that the pump will be repaired within 2 hours.

Compared to the exponential model, in which the probability of repair within 2 hours is higher, the 22.3% probability from the Weibull model is lower. This highlights that the Weibull distribution better accounts for delays due to setup, diagnosis, and coordination, making very fast repairs less likely.

d) Mean Time To Repair (MTTR) under Weibull

For a Weibull distribution, the MTTR is:

$$\sqrt{MTTR = \eta \Gamma\left(1 + \frac{1}{\beta}\right)}$$

With ($\beta = 1.5$):

$$\Gamma\left(1 + \frac{1}{1.5}\right) = \Gamma(1.667) \approx 0.903$$

$$MTTR = 5 \times 0.903 \approx 4.52 \text{ hours}$$

e) Equivalent Mean Repair Rate

For availability calculations, an equivalent average repair rate is defined as:

$$\sqrt{\mu_{eq} = \frac{1}{MTTR}}$$

$$\mu_{eq} = \frac{1}{4.52} \approx 0.221 \text{ repairs/hour}$$

f) Steady-State Availability Calculation

The steady-state availability of a repairable system is:

$$\sqrt{A = \frac{\mu_{eq}}{\lambda + \mu_{eq}}}$$

$$A = \frac{0.221}{0.221 + 0.002}$$

$$\sqrt{A} \approx 0.991$$

- Interpretation of Availability

Furthermore, the pump has a steady-state availability of approximately 99.1%. Despite a slightly longer average repair time than in the exponential case, the availability remains very high because the failure rate is low.

5.5.3 Factors Affecting Maintainability

The main factors influencing maintainability are equipment design (ensuring accessibility and modularity), qualification of maintenance personnel, availability of spare parts, maintenance organization, provision of technical documentation, and establishment of procedures. Understanding these elements forms a foundation for applying advanced methods.

With these foundational factors in mind, advanced approaches build upon them by incorporating the following methods: Reliability-Centered Maintenance (RCM), assigning maintainability to specific system parts, and evaluating the probability of human error.

5.6 Integrated Analysis of Reliability, Maintainability, and Availability (FMD Analysis)

In contemporary industrial systems, operational performance assessment requires evaluating reliability, maintainability, and availability together. Focusing on just one factor is inadequate. Reliability measures how often failures occur. Maintainability shows how long downtime lasts after each failure. Both factors affect operational availability, the main measure of industrial effectiveness. Ignoring the link between reliability and repair time can hurt system performance.

For example, improved reliability means little if repairs are still slow, and high maintainability cannot make up for frequent failures. Standards and references stress that only a combined reliability, maintenance, and development (RMD) approach can optimize system design, maintenance, lifecycle costs, and ensure performance, safety, and continuous operation. Therefore, RMD analysis is essential for industrial decisions, especially for repairable systems where availability drives productivity, safety, and competitiveness. (Bouabid et al., 2026)/

5.7 Case study: Pareto analysis & FMD analysis

5.7.1 Historical Data

The failure history (ATLAS COPCO ZE3 compressor); the processing of raw historical data (Table 5.3) involves the following steps:

- Calculation of downtime hours due to failures (TTR – Time To Repair), obtained from the difference between shutdown and restart dates.
- Calculation of operating time between failures (TBF – Time Between Failures), obtained from the difference between two successive failures.

Table 5-3 Historical Record of the ATLAS COPCO ZE3 Compressor

Ref.	Start Date	Shutdown Date	TTR (h)	Cause	Action
1	12/02/2010	29/04/2010	48	High temperature of front bearing	Oil replacement
2	01/05/2010	14/09/2010	24	High temperature of	Oil replacement

				rear bearing	
3	15/09/2010	03/11/2010	24	Severe vibration at screw 1	Dismantling and balancing of screw 1
4	04/11/2010	09/02/2011	48	Vibration on front and rear bearings	Dismantling and balancing of screws 1 and 2
5	11/02/2011	25/03/2011	10	High temperature of screws 1 and 2	Oil replacement
6	25/03/2011	12/07/2011	20	Severe vibration at screw 2	Dismantling and balancing of screw 2
7	13/07/2011	09/09/2011	48	Abnormal noise from front bearing	Replacement of front bearings
8	11/09/2011	20/01/2012	10	High temperature of front bearing	Oil replacement
9	20/01/2012	30/03/2012	45	Shearing of screw 1	Replacement of screw 1
10	01/04/2012	05/07/2012	22	Severe vibration at rear bearing	Replacement of rear bearings
11	06/07/2012	09/08/2012	8	High temperature of seal	Oil filter replacement
12	09/08/2012	07/11/2012	45	Shearing of screw 2	Replacement of screw 2
13	09/11/2012	15/01/2013	24	High temperature of rear bearing	Oil replacement
14	16/01/2013	07/04/2013	17	High temperature of seal	Oil replacement

1) Pareto analysis

- Using the historical data given in the table, construct a Pareto chart and carry out an ABC curve analysis.

2) Reliability Analysis

- Estimate the Weibull distribution parameters using the time between failures (TBF) data.
- Calculate the reliability function $R(t)$ and the failure density function $f(t)$, the failure distribution function $F(t)$, and the failure rate.
- Please plot the derived functions graphically, identify key features, and interpret the results.
- Determine MTBF graphically and provide the resulting MTBF value, then calculate and specify the optimal time for systematic intervention.

3) Maintainability Analysis

- Assume the time-to-repair (TTR) follows an exponential distribution.
- Estimate the distribution's parameters and calculate the maintainability function $R(t)$.
- Plot the maintainability curve, indicate the axes labels and units, and evaluate the speed of return to service in terms of time to restore or repair.

4) Availability Analysis

- Calculate and report the average system availability value based on the previous results.
- Determine the instantaneous availability as a function of time.
- Interpret the results, specifying the expected outputs, and identify the critical points for system operation.

5.7.2 Results and discussion of Case study

5.7.2.1 Pareto analyzes

To apply the ABC method, begin by ranking breakdowns in descending order of breakdown times. After this, construct a Pareto graph from the ranked data (for more details see the Appendix 2).

Objective: To systematically identify and quantify the primary failure modes that contribute most significantly to total downtime (TTR), adhering to the Pareto principle, which posits that approximately 20% of failure causes account for 80% of downtime.

a) First, list the causes and calculate the total TTR for each.

Next, group the events by cause and sum the TTR (in hours) for each group presented by Table 5.4.

Table 5-4 List the causes and calculate the total TTR for each

	Cause	Total TTR (h)	% of total TTR
1	High temperature of front bearing	68	16.87%
2	High temperature of rear bearing	48	11.91%
3	Severe vibration at screw 1	24	5.96%
4	Severe vibration at screw 2	20	4.96%
5	Vibration on front and rear bearings	48	11.91%
6	Abnormal noise from front bearing	48	11.91%
7	Shearing of screw 1	45	11.16%
8	Shearing of screw 2	45	11.16%
9	High temperature of screws 1 and 2	10	2.48%
10	Severe vibration at rear bearing	22	5.46%
11	High temperature of seal	25	6.20%

b) Sort the causes by descending TTR

Table 5-5 Causes by descending TTR

	Cause	Total TTR (h)	Cumulative %
1	High temperature of front bearing	68	16.87%
2	High temperature of rear bearing	48	28.78%
3	Vibration on front and rear bearings	48	40.69%
4	Abnormal noise from front bearing	48	52.60%
5	Shearing of screw 1	45	63.76%
6	Shearing of screw 2	45	74.92%
7	High temperature of seal	25	81.12%
8	Severe vibration at screw 1	24	87.08%
9	Severe vibration at rear bearing	22	92.54%
10	Severe vibration at screw 2	20	97.50%
11	High temperature of screws 1 and 2	10	100%

The first 7 causes (up to High temperature of seal) account for ~81% of the TTR; therefore, these are the critical causes to be addressed as a priority.

c) ABC Analysis

Objective: To classify the causes according to their contribution to TTR (See Fig.5.10 and Table 5.6):

- Class A: critical causes (~70-80% of TTR)
- Class B: significant causes (~15-20%)
- Class C: minor causes (~5-10%)

Table 5-6 ABC analysis

Cause	Total TTR (h)	Cumulative %	Class ABC
High temperature of front bearing	68	16.87%	HAS
High temperature of rear bearing	48	28.78%	HAS
Vibration on front and rear bearings	48	40.69%	HAS
Abnormal noise from front bearing	48	52.60%	HAS
Shearing of screw 1	45	63.76%	HAS
Shearing of screw 2	45	74.92%	HAS
High temperature of seal	25	81.12%	B
Severe vibration at screw 1	24	87.08%	B
Severe vibration at rear bearing	22	92.54%	B
Severe vibration at screw 2	20	97.50%	C
High temperature of screws 1 and 2	10	100%	C

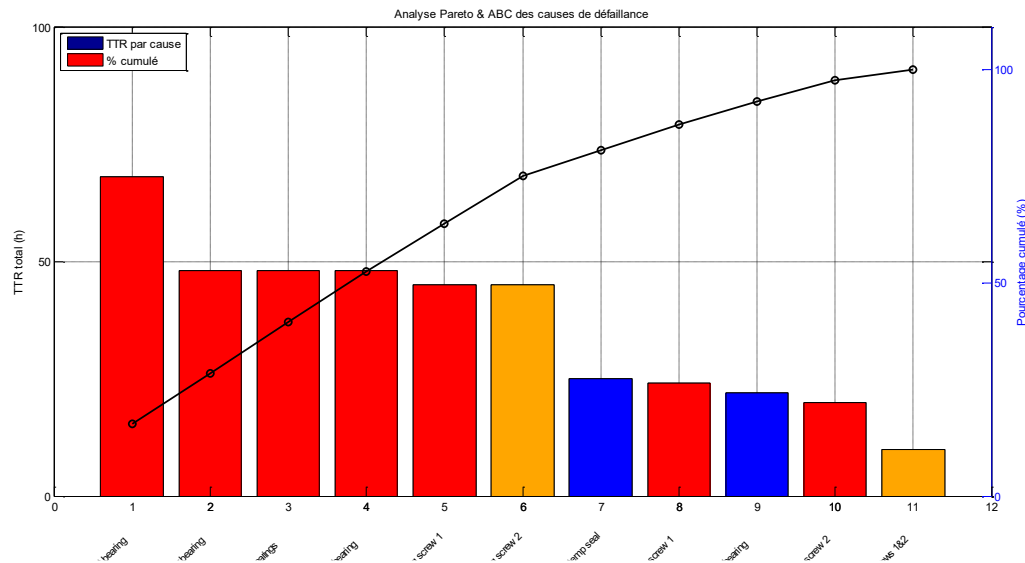


Figure 5-10 Pareto Analysis and ABC Curve

ABC Conclusion:

- A (highest priority for corrective action): 68% of the TTR → 6 main causes
- B (medium priority): 18% of the TTR → 3 causes
- C (low priority): 14% of the TTR → 2 causes

5.7.2.2 Reliability Analysis

a) Calculating Weibull parameters

The following Table 5.7 contains the TBFs ranked in ascending order, and the F(i)s calculated by the median range method (in our case, $N = 14 \leq 20$):

$$F(i) = \frac{\sum n_i - 0.3}{N + 0.4}$$

Table 5-7 Actual distribution function

N	TBF (h)	Neither	$\sum n_i$	F(i)	F(i) (%)
1	312	1	1	0.0486	4.86
2	816	1	2	0.1180	11.80
3	1008	1	3	0.1875	18.75
4	1176	1	4	0.2569	25.69
5	1368	1	5	0.3263	32.63
6	1608	1	6	0.3958	39.58
7	1680	1	7	0.4652	46.52
8	1824	1	8	0.5347	53.47
9	1920	1	9	0.6041	60.41
10	2088	1	10	0.6736	67.36
11	2136	1	11	0.7430	74.30
12	2280	1	12	0.8125	81.25
13	2616	1	13	0.8819	88.19
14	3144	1	14	0.9513	95.13

Weibull curve presented in Fig.5.11

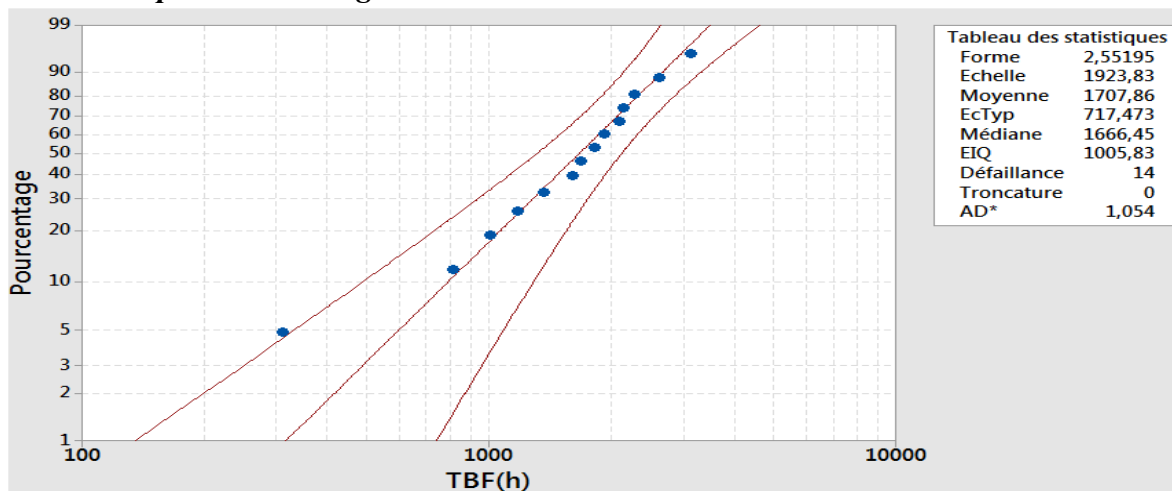


Figure 5-11 Weibull paper in minitab17 software

$Y = 0$, where Y is the failure indicator at time zero, because the breakdowns occur at the origin of time.

b) Test (KOLMOGOROV SMIRNOV)

Before validating all the reliability laws, it is necessary to test the hypothesis to determine whether we should accept or reject the proposed model using the KS test with a confidence level of $\alpha=20\%$. This test consists of calculating the difference between the theoretical function $F(t)$ and the actual function $F(t)$ and taking the maximum absolute value $\Delta n_{\max}$

This value is compared with $D_{n,\alpha}$ the value given by the Kolmogorov-Smirnov table (see Appendix 3). If:

Before validating all the reliability laws, it is necessary to test the hypothesis to determine whether to accept or reject the proposed model using the KS test at a 20% confidence level ($\alpha=20\%$). This test consists of calculating the difference between the theoretical function $F(t)$ and the actual function $F(t)$, then taking the maximum absolute value, $\Delta n_{\max}$.

This value is compared with the value $D_{n,\alpha}$ given by the Kolmogorov-Smirnov table (see Appendix 1). If:

$$\begin{cases} D_{n,\max} > D_{n,\alpha}; & \text{The hypothesis is rejected.} \\ D_{n,\max} < D_{n,\alpha}; & \text{We accept the hypothesis} \end{cases}$$

Given this, we use the Weibull distribution to calculate $F(t)$ (the theoretical failure distribution function) (see Table 5.8).

Table 5-8 KS test (kolmogrov-smirnov)

N	TBF (h)	F(i)	F(t)	Dmax /F(i)-F(t)/
1	312	0.048611111	0.009590422	0.039020689
2	816	0.118055556	0.106011204	0.012044352
3	1008	0.1875	0.174821126	0.012678874
4	1176	0.256944444	0.247814014	0.00913043
5	1368	0.326388889	0.34222709	0.015838201
6	1608	0.395833333	0.468886543	0.07305321
7	1680	0.465277778	0.507183277	0.041905499
8	1824	0.534722222	0.582243716	0.047521494
9	1920	0.604166667	0.630249702	0.026083035
10	2088	0.673611111	0.708412513	0.034801402
11	2136	0.743055556	0.729101383	0.013954172
12	2280	0.8125	0.786175045	0.026324955
13	2616	0.881944444	0.88817766	0.006233216
14	3144	0.951388889	0.96987637	0.018487481

According to the KS table: the condition $D_{n.max} < D_{n.\alpha}$ is verified. Therefore, the Weibull model is accepted.

$D_{n.max} = 0.07308654$ Whereas $D_{n.\alpha} = D_{14.20} = 0.274$ (see Appendix 1)

$0.073008654 < 0.274$, therefore the Weibull model hypothesis is acceptable.

c) Exploiting WEIBULL parameters

- Graphical determination of MTBF

The MTBF table gives $A = 0.8873$ $B = 0.380$ (see appendix 2).

$$MTBF = A\eta + \gamma$$

$$MTBF = 0.8873 * 1923.83 + 0$$

$$MTBF = 1711.45 \text{ h.}$$

- Calculating the desired time for a systematic intervention

$$R(t) = 80\% \text{ à } t = ???$$

$$\text{We have: } R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$$

$$\ln(R(t)) = -\left(\frac{t}{\eta}\right)^\beta = \ln(0.8) \rightarrow -(\ln(R(t)))^{\frac{1}{\beta}} = t \rightarrow t = \eta \left[\ln\left(\frac{1}{R(t)}\right) \right]^{(1/\beta)}$$

$$T = 1923.83 * \left[\ln\left(\frac{1}{0.48}\right) \right]^{\left(\frac{1}{2.55195}\right)}$$

$$t_{sys} = 1704.24 \text{ h}$$

To maintain compressor reliability at 80%, systematic intervention is required at 1704.24 h times.

d) Weibull model study

- The reliability $R(t)$

The reliability function of the distribution function: $R(t) = 1 - F(t)$. After calculating the compressor's reliability at $t = MTBF$, we find it unsatisfactory, so we can say the compressor is not reliable at $t = MTBF$. (see Fig.5.12, Table 5.9).

Table 5-9 Reliability Calculation

N	TBF (h)	R(t)
---	---------	------

1	312	0.990409578
2	816	0.893988796
3	1008	0.825178874
4	1176	0.752185986
5	1368	0.65777291
6	1608	0.531113457
7	1680	0.492816723
8	1824	0.417756284
9	1920	0.369750298
10	2088	0.291587487
11	2136	0.270898617
12	2280	0.213824955
13	2616	0.11182234
14	3144	0.03012363

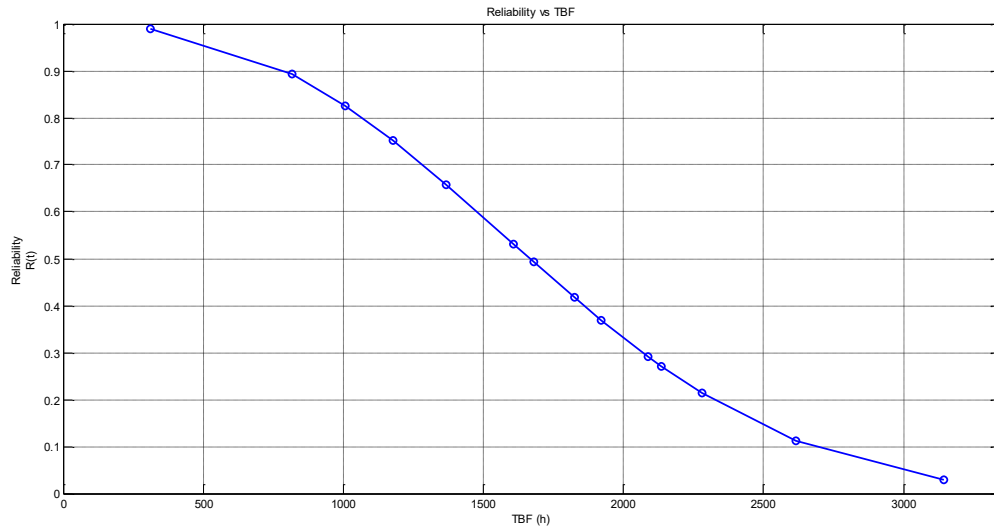


Figure 5-12 Reliability Function Curve

This observation can be linked to the graph, which decreases over time. This decrease reflects degradation phenomena such as wear and tear. For instance, $\beta = 2.5$ (see the course material).

Improving compressor reliability necessarily involves failure analysis with a detailed study of its causes, modes, and consequences.

- Cumulative distribution function $F(t)$

Already calculated and presented by Fig. 5.13 and Table 5.10.

Table 5-10 Distribution function (part of Table 2)

N	TBF (h)	F(t)
1	312	0.009590422
2	816	0.106011204
3	1008	0.174821126
4	1176	0.247814014
5	1368	0.34222709
6	1608	0.468886543
7	1680	0.507183277
8	1824	0.582243716
9	1920	0.630249702
10	2088	0.708412513
11	2136	0.729101383
12	2280	0.786175045
13	2616	0.88817766
14	3144	0.96987637

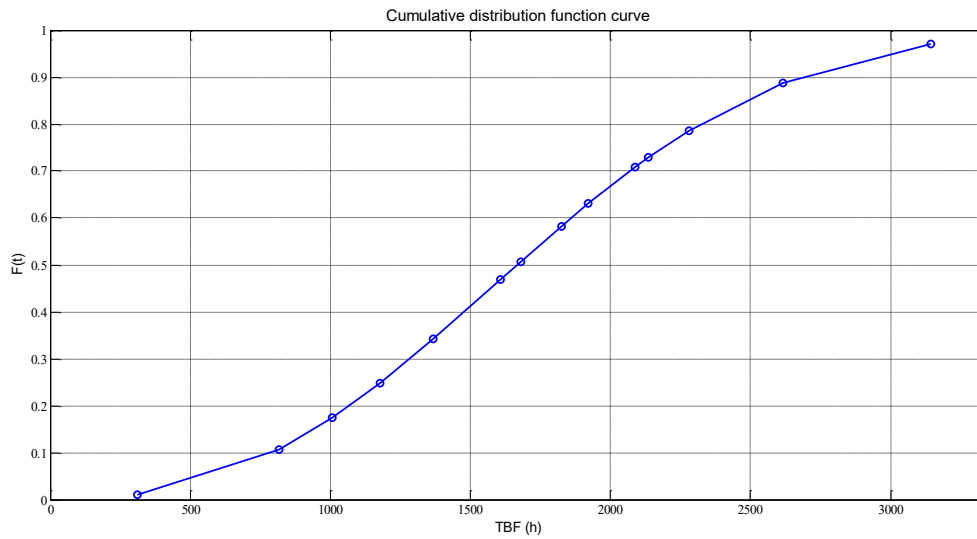


Figure 5-13 Distribution Function Curve

The failure function is increasing with time, and for $t = \text{MTBF}$, $F(\text{MTBF}) = 0.52 = 52\%$.

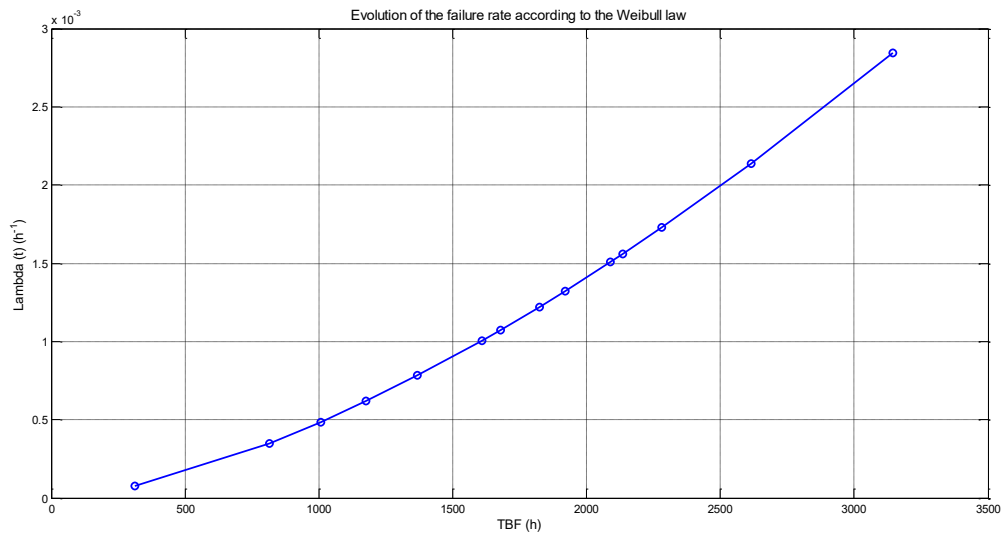
The failure rate $\lambda(t)$

$$\lambda(t) = \frac{\beta}{\eta} \left(\frac{t - \gamma}{\eta} \right)^{\beta-1}$$

The obtained results presented by Table 5.11, and Fig. 5.14.

Table 5-11 Failure Rate

N	TBF (h)	$\lambda(t)$	$\lambda(t)*10(-3)$
1	312	7.88218E-05	0.078821772
2	816	0.000350462	0.350461658
3	1008	0.000486478	0.486478378
4	1176	0.000617962	0.617961776
5	1368	0.000781433	0.781433073
6	1608	0.001004242	1.004242498
7	1680	0.001074884	1.074884274
8	1824	0.00122121	1.221210305
9	1920	0.001322398	1.322398388
10	2088	0.001506256	1.506255723
11	2136	0.001560334	1.560334197
12	2280	0.001726593	1.726592918
13	2616	0.002137203	2.137203415
14	3144	0.002842896	2.842896136

**Figure 5-14** Failure rate curve (matlab software)

The failure rate increases over time.

The probability density function

$$f(t) = \frac{\beta}{\eta} \left(\frac{t - \gamma}{\eta} \right)^{\beta-1} e^{\left(\frac{t-\gamma}{\eta} \right)^{\beta}}$$

$$f(t) = \lambda(t) * R(t)$$

The obtained results summarized by **Table 5.12**, and the **Fig. 5.15**.

Table 5-12 Calculating the probability density function

N	TBF (h)	R(t)	$\lambda(t)$	f(t)	f(t)*10(-5)
1	312	0.990409578	7.88218E-05	7,80658E-05	7.806583749
2	816	0.893988796	0.000350462	0.000313309	31.33087958
3	1008	0.825178874	0.000486478	0.000401432	40.14316801
4	1176	0.752185986	0.000617962	0.000464822	46.48221874
5	1368	0.65777291	0.000781433	0.000514006	51.40055066
6	1608	0.531113457	0.001004242	0.000533367	53.33667045
7	1680	0.492816723	0.001074884	0.000529721	52.97209462
8	1824	0.417756284	0.00122121	0.000510168	51.01682793
9	1920	0.369750298	0.001322398	0.000488957	48.89571982
10	2088	0.291587487	0.001506256	0.000439205	43.92053207
11	2136	0.270898617	0.001560334	0.000422692	42.26923753
12	2280	0.213824955	0.001726593	0.000369189	36.91886538
13	2616	0.11182234	0.002137203	0.000238987	23,8987087
14	3144	0.03012363	0.002842896	8.56384E-05	8.563835126

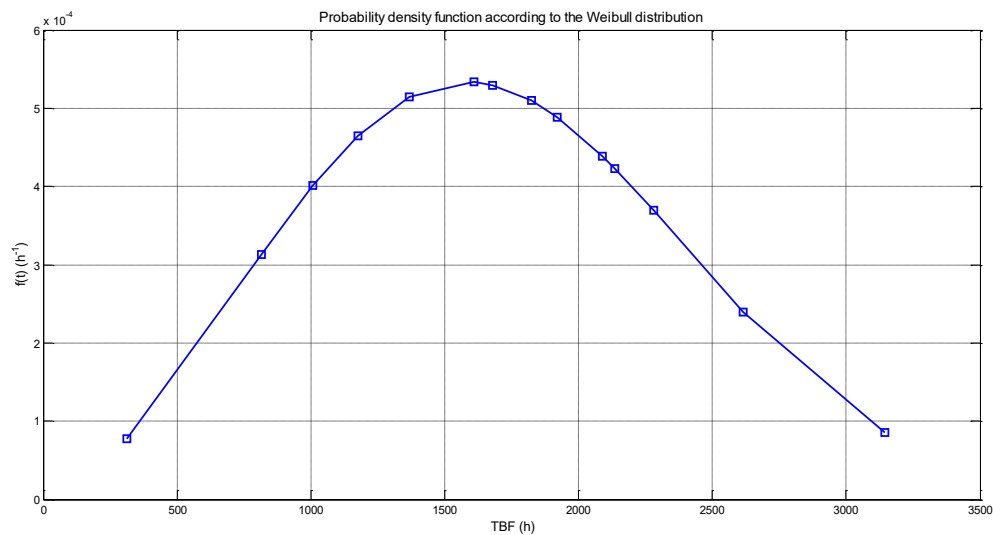


Figure 5-15 Probability Density Curve (matlab software)

5.7.2.3 Maintainability Analysis

According to the compressor's failure history:

$$MTTR = \frac{\sum TTR}{N}$$

TTR: repair time and, N: number of failures.

$$MTTR = 393/14 = 28.07 \text{ h.}$$

$$\text{We have: } M(t) = 1 - e^{-\mu t}$$

$$\text{Including: } \mu = \frac{1}{MTTR} = \frac{1}{28.07} = 0.0356 \text{ Intervention/hour.}$$

The obtained results summarized by Table 5.13, and the Fig. 5.16.

Table 5-13 Compressor maintainability

TTR (h)	$\sum TTR$	M(t)
48	48	0.8191204
24	72	0.92307201
24	96	0.96728257
48	144	0.99408208
10	154	0.99585563
20	174	0.99796747
48	222	0.99963236
10	232	0.99974254
45	277	0.99994818
22	299	0.99997633
8	307	0.9999822
45	352	0.99999642
24	376	0.99999848
17	393	0.99999917

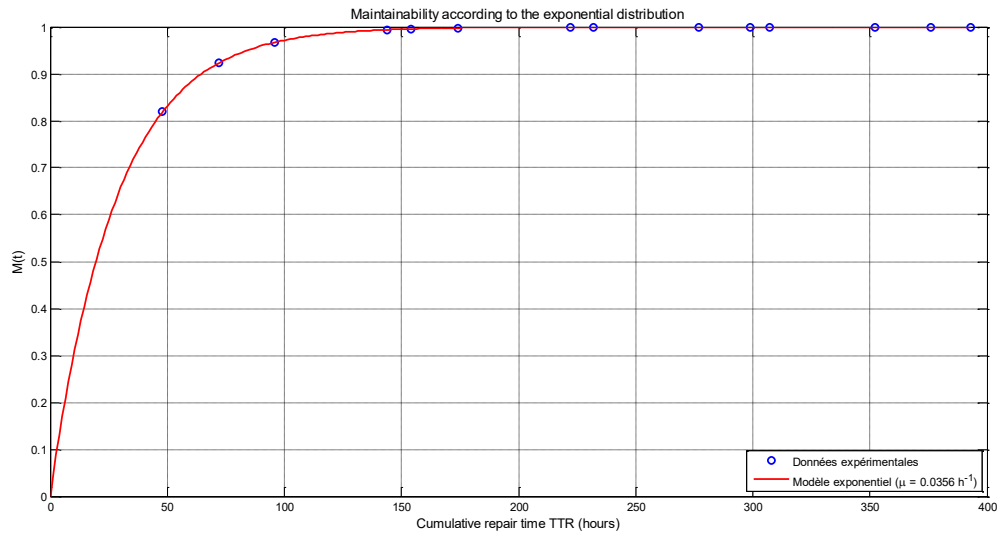


Figure 5-16 Maintainability Curve

Maintainability increases over time; at time $T=260$ hours, maintainability is 99.99%.

5.7.2.4 Availability Analysis

a) Intrinsic (asymptotic) availability

$$D_i = \frac{MTBF}{MTBF + MTTR}$$

- MTBF=1712.571429
- MTTR=28.07142857

$$D_i = 0,983872953 = 98.38\%$$

b) Instant availability

$$D(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} * e^{-(\lambda + \mu)t}$$

The obtained results summarized by Table 5.14, and the Fig. 5.17.

Table 5-14 Calculation of instantaneous availability

ΣTTR	$D(t)$
48	0.986709383
72	0.985062498
96	0.984371825
144	0.983960695

154	0.983934042
174	0.983902565
222	0.983878162
232	0.983876579
277	0.983873664
299	0.983873274
307	0.983873193
352	0.983873
376	0.983872973
393	0.983872964

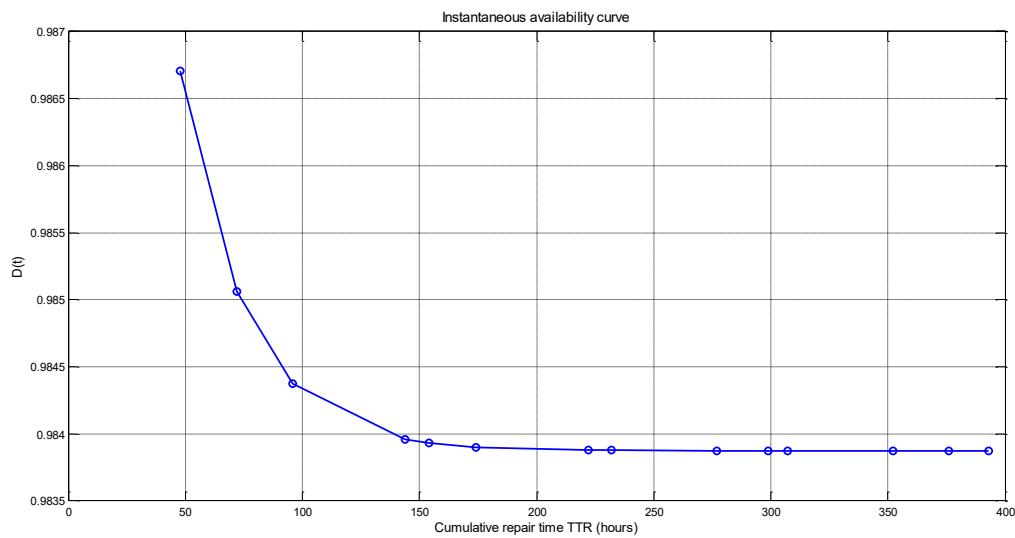


Figure 5-17 *Instantaneous Available Curve*

5.8 Conclusion

This chapter has introduced reliability as a central concept in industrial maintenance and mechanical system performance. In modern industry, maintenance now goes beyond merely repairing failures—it has become a strategic function founded on the analysis and control of failure behavior.

Building on this foundation, the relationship between maintenance and reliability emerges as fundamental. Reliability analysis enables modeling the probability of failure over time using key functions such as the probability density function, cumulative distribution function, reliability function, and failure rate. Mathematical models, particularly the exponential and Weibull laws, provide engineers with practical tools to describe equipment degradation and predict performance.

Maintainability complements this analysis by evaluating repair performance in repairable systems. Indicators such as Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) quantify system performance and directly contribute to availability assessment.

Through these concepts, students acquire the ability to:

- Understand and model failure behavior,
- Calculate essential reliability and maintainability indicators,
- Evaluate system performance using probabilistic tools,
- Support maintenance decision-making using structured approaches, such as Failure Mode and Effects Analysis (FMEA), a systematic method for identifying potential failure modes, their causes, and effects.

In summary, reliability engineering provides a scientific, quantitative foundation for modern maintenance strategies, enabling better risk control, improved equipment availability, and optimized lifecycle management of industrial systems.

Chapter 6: Failure Mode, Effects, and Criticality Analysis (FMECA) Method

6 Chapter 6: Failure Mode, Effects, and Criticality Analysis (FMECA) Method

Il est sugg  r   de mettre une br  ve introduction ici.

6.1 Introduction

Failure Mode, Effects, and Criticality Analysis (FMECA), also known internationally as FMEA, is a systematic, preventive method for identifying potential failures, analyzing their effects, and evaluating their criticality. This helps prioritize corrective actions. The IEC 60812 standard formally describes it. This standard lists the information to record in an FMEA sheet—functions, failure modes, effects, causes, controls, and recommended actions—and explains how to assess and prioritize risks. Assessing risk often uses the risk priority number (RPN). (G  bitz & Klinger, 2023)

In the oil industry, equipment failures may cause production losses, major incidents, and environmental impacts. FMEA (Failure Mode and Effects Analysis) is essential for managing risk. This training document provides a more detailed description of the FMEA method. It draws on main standards and frameworks: IEC 60812, MIL-STD-1629A, API RP 580/581, ISO 31000, ISO 55000, and HSE regulatory requirements.

6.2 Definition of the FMEA method

Failure Mode, Effects, and Criticality Analysis (FMECA) is a structured, proactive method for identifying potential system failures, assessing their impact, and estimating their criticality. It helps prioritize risks to support preventive or mitigating actions (Sharma & Srivastava, 2018).

Basic FMEA is qualitative and explores only hypothetical scenarios. Adding the criticality analysis of FMEA C provides a numerical value that allows you to classify your failure modes. This facilitates task prioritization and, hopefully, problem prevention (See Fig. 6.1).

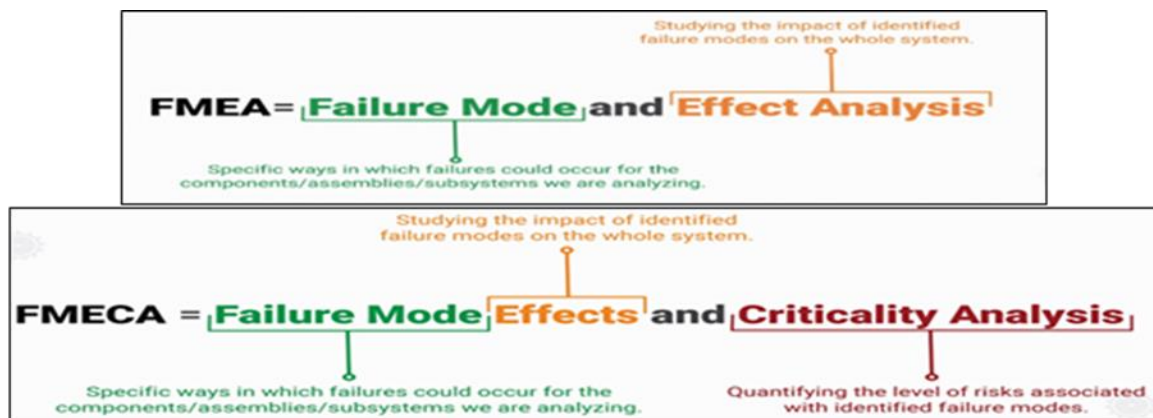


Figure 6-1 FMEA and FMECA presentation

6.2.1 FMEA Objectives

The purpose of conducting an FMEA in the oil & gas sector is to (Wu, Liu, & Nie, 2021):

- Identify potential failure modes of equipment (pumps, compressors, pipelines, drilling rigs) and their subsystems.
- Assess the effects of these failures on safety, the environment, and production.
- Prioritize corrective actions using criticality calculation (RPN or other criteria) to focus resources on the most critical failures.
- Optimize preventive maintenance and asset reliability, reduce downtime, and improve facility safety.
- Complying with HSE standards and regulations: The Health and Safety Executive (UK) require employers to identify risks, assess their likelihood and severity, and eliminate or control them. FMEA addresses this by providing a structured hazard analysis.

6.2.2 History of the FMEA method

The history of the FMEA method is summarized in the Fig. 6.2

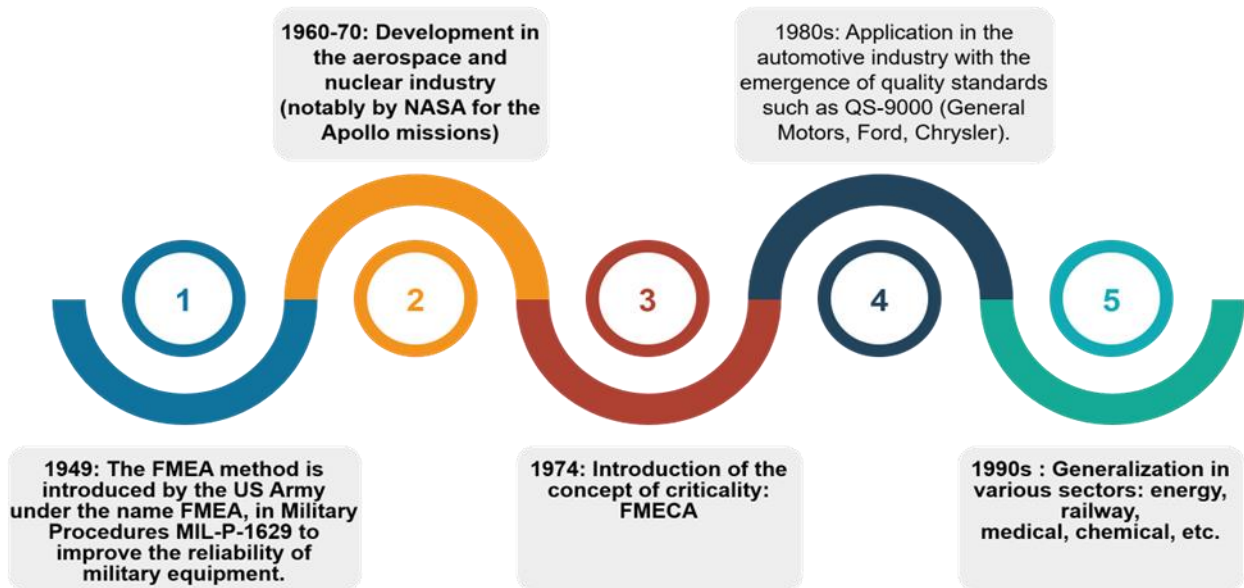


Figure 6-2 History of the FMEA method

6.2.3 Normative frameworks and reference points

The normative frameworks of FMEA method are presented by the Table 6.1 (Baig & Prasanthi, 2013; Bowles, 1998; Gueorguiev, Kokalarov, & Sakakushev, 2020; Ramly & Atan, 2020; Sharma & Srivastava, 2018).

Table 6-1 Summary table of FMEA standards

Standard	Domain	Description	References
MIL-STD-1629A	Military (USA)	First standardization of the FMEA/FMECA.	MIL-STD-1629A: Procedures for Performing a Failure Mode, Effects and Criticality Analysis (Baig & Prasanthi, 2013)
SAE J1739	Automobile	Product and process FMEA guide, widely used at GM/Ford/Chrysler.	
AIAG & VDA FMEA Manual (2019)	Automobile	Methodology harmonized between the USA and Germany.	AIAG & VDA FMEA Handbook, 1st Edition (2019): Automotive Industry Action Group & Verband der Automobilindustrie
ISO 9001 / ISO 31000	Quality / Risks	FMEA as a tool for quality risk management.	ISO 31010: Risk assessment techniques (includes FMEA as a method)
IEC 60812 (2018)	Electrotechnics	International standard for conducting FMEA.	IEC 60812:2018: Failure modes and effects analysis (FMEA and FMECA)
ISO 14971	Medical devices	FMEA is integrated into medical risk management.	ISO 14971: Application of risk management to medical devices
EN 60812 (European equivalent)	Industry	European harmonized standard based on IEC 60812.	
NF X 60-510 (France)	Industry	French guide on the FMEA method.	NF X60-510: Failure Mode, Effects, and Criticality Analysis (FMEA)

6.2.4 FMEA terminology adapted to the Oil & Gas sector according to IEC 60812 (2018) standard

The FMEA terminology according to IEC 60812 (2018) standard is presented by Table 6.2.

Table 6-2 Basic terms according to IEC 60812:2018 (and equivalent standards)

Standardized term	Definition	Oil & Gas Adaptation
Function	A statement of what the system, subsystem, or component must achieve under specific operating conditions.	Example: Maintaining a gas flow rate of 60 bar in a pipe.
Failure Mode	The specific ways in which an entity might stop performing its intended	Examples: Leak, blockage, corrosion, broken seal.

	function.	
Failure Cause	The initial cause or process that leads to the failure mode.	Examples: Thermal fatigue, human error, welding defect, sensor failure.
Failure Effect	The direct or subsequent consequence that results when a failure mode occurs.	Example: Loss of containment, production stoppage, secondary explosion.
Criticality	Risk measurement is determined by assessing severity, likelihood of occurrence, and, at times, detectability.	Example: Pipe rupture under high pressure = high criticality.
Detectability (Detection)	The capacity to detect and recognize a failure mode before it causes any undesirable effects.	Pressure sensor, visual inspection, online control.
Risk Priority (RPN / NPR)	A numerical score to help rank risks, calculated as $RPN = \text{Severity} \times \text{Occurrence} \times \text{Detectability}$.	Helps define maintenance or engineering priorities.
Action recommendation	Proposed measures to reduce the criticality of the risk.	Examples: Redundant valves, additional valves, and more frequent inspections.

Terminology related to FMEA hierarchy levels

Table 6-3 Terminology related to FMEA hierarchy levels

Level	Description	Example: Oil & Gas sector
System	Overall set to be analyzed	Pumping station, compression unit, FPSO
Subsystem	Functional subset	Distribution line, dosing skid, ESD valves
Component	Individual element	Pressure sensor, valve, motor,
Function	Expected action of the component	Open at 50 bar, maintain temperature at 90°C

6.3 The FMEA methodology

IEC 60812 defines a generic FMEA process (see the Fig. 6.3), outlining documentation (functions, failures, effects, causes, existing controls, recommended actions) and risk prioritization, such as Risk Priority Number (RPN). In oil and gas, FMEA identifies and mitigates critical equipment and process failures to avoid production losses, accidents, or environmental issues.

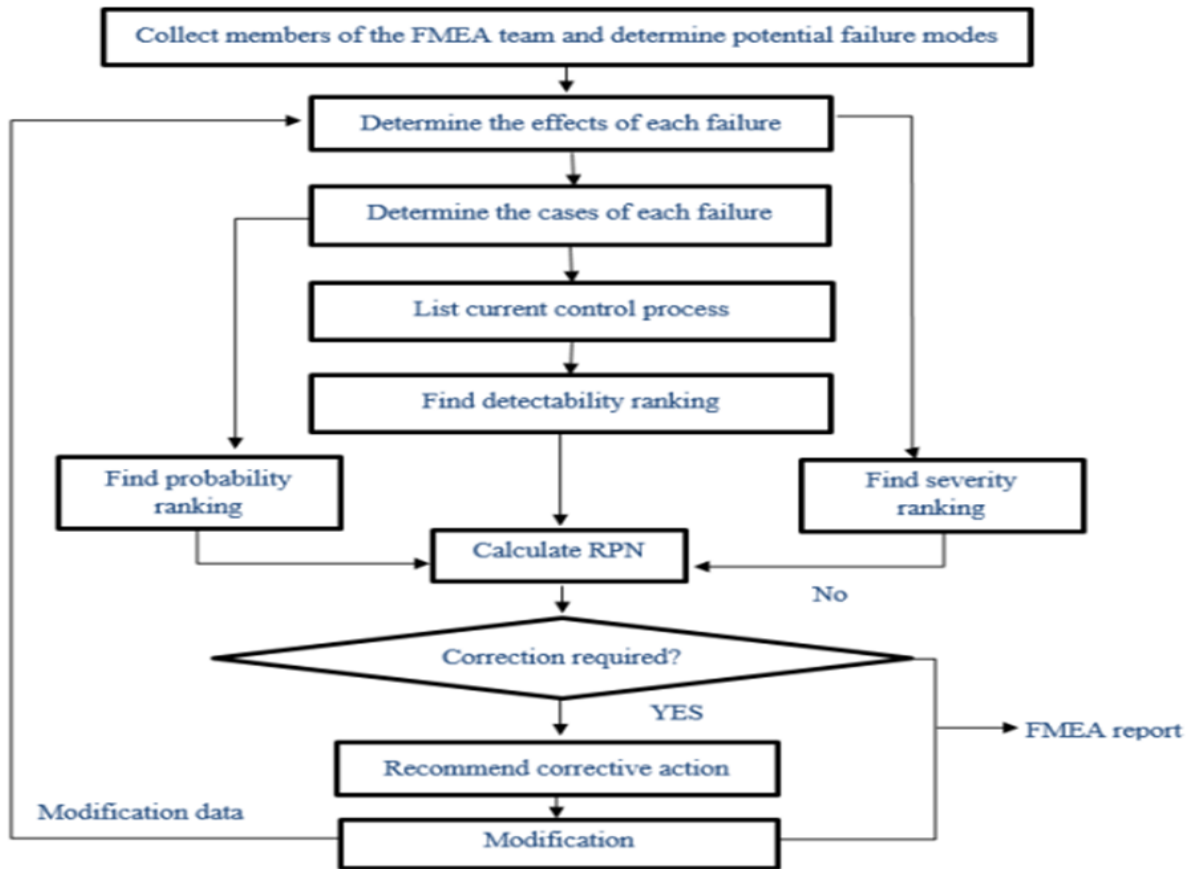


Figure 6-3 FMEA process based on IEC 60812 and MIL-STD-1629A

The general approach is similar across standards, but IEC 60812 focuses on documentation and prioritization, while MIL-STD-1629A emphasizes the systematic identification of failure modes and their effects. The steps below are based on the recommendations of both IEC 60812 and MIL-STD-1629A:

6.3.1 Team planning and assembly:

Define the study object (system, subsystem, or component), set objectives and limits, select a facilitator, and assemble a team (process, maintenance, HSE, operations). Involve operators and HSE specialists to address specific sector risks.

6.3.2 Data collection and functional analysis:

Use plans, diagrams, and failure histories to analyze equipment functions and requirements (SADT or FAST), then define the level of detail (system, subsystem, or component).

6.3.3 Failure mode identification:

For each function or component, list all the possible failure modes that can result in loss or degradation of the function (such as leakage, breakage, corrosion, or human error). The goal is to determine the ways the failure mode could occur, not if it will occur (Gueorguiev et al., 2020).

6.3.4 Determining effects and causes:

Describe the effects of the failure at the local level (component), system level (partial or total shutdown), customer level and HSE level (pollution, fire), then identify the probable causes (wear, design flaw, environment, operation).

6.3.5 Assessment of severity, occurrence, and detectability:

Assign S (severity), O (occurrence), and D (detectability) indices from 1 to 10, or as defined, noting that the IEC 60812 standard also allows alternative ranking methods without RPN. (Bowles, 1998)

6.3.6 Calculating criticality and prioritizing:

Calculate the RPN (severity $\times$ occurrence $\times$ detectability) or the criticality number (probability $\times$ severity) according to MIL-STD-1629A, then rank the failure modes in descending order. However, the standards remind us that the RPN is only an indicator and should not be used in isolation, as it can mask important details (see Fig. 6.4).

critical failure modes. (Baig & Prasanthi, 2013).



Figure 6-4 RPN presentation

6.3.7 Definition of corrective and preventive actions

For the most critical modes, propose actions to reduce severity (design modifications, safety barriers), reduce occurrence (preventive maintenance, process controls), or improve detection (online monitoring, alarms).

6.3.8 Validation, documentation and updates

Record all information in an FMEA sheet and implement the actions. The sheet must be reviewed regularly (to capture lessons learned and process modifications) and serve as the basis for risk-based inspections (RBI) and reliability programs [5].

For more comprehension, the logical relationship between FMECA elements is presented by the Fig. 6.5.



Figure 6-5 Logical relationship between FMECA elements

6.4 FMEA Typology

IEC 60812 (2018 edition – in force), This international standard defines the FMEA/FMECA method and its variants, specifying the steps for identifying, analyzing, and evaluating failure modes, and its possible integration with other methods (HAZOP, LOPA, RBI). Several types of FMEA exist depending on the object being studied (Gueorguiev et al., 2020; Szkoda & Kaczor, 2020).

- Functional FMEA:** Analyzes failure modes of expected functions, without being limited to a specific design. Used in design or during major changes.
- Hardware FMEA:** Analyzes possible failures of hardware components (pump, valve, bearing, electronic board, etc.).

- c) **Process FMEA:** Analyzes failure modes in industrial or operational processes (production, maintenance, operation).
- d) **System FMEA (FMECA):** Analyzes failures at a global level by integrating interactions between subsystems.
- e) **Software FMEA:** Analyzes software errors impacting the system's function (SIS, control).
- f) **Hybrid FMEA (Mixed-Mode FMEA):** Combines several approaches (e.g., functional and hardware) in the same study.

6.4.1 FMEA Maintenance

A variant of FMEA focused on reliability, maintainability and logistics. The aims to identify the failure modes that have the greatest impact on availability, prevention plan, and maintenance costs (Wu et al., 2021). The most used standards are:

- IEC 60300-3-11 (Application guide — Reliability centred maintenance): describes the integration of FMEA into the RCM strategy.
- ISO 14224 (Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data): structure of mode/cause data for maintenance.
- API RP 581 / API RP 580 for linking with RBI (Risk-Based Inspection).

6.4.2 Application in Oil & Gas

Example: FMEA maintenance on an API 617 compressor → prioritize the maintenance of seals, bearings and lubrication systems according to their criticality on the availability of the train.

6.5 Application to the oil industry – synthetic case study

Consider a multi-stage centrifugal pump used for seawater injection. Functional analysis identifies the following sub-functions: power supply (electric motor), fluid intake (pipe and strainer), compression/acceleration (impellers), fluid delivery (discharge), lubrication and cooling (oil system and heat exchanger), and monitoring/control (sensors and PLC). FMEA associates each sub-function with its failure modes (electrical failures, cavitation, impeller corrosion, loss of sealing, lack of lubrication, sensor failure), evaluates their severity, occurrence, and detectability, and proposes priority actions (improved seals, condition monitoring, NPSH control, preventive maintenance). For a complete demonstration of this approach, please refer to the confidential case study file provided separately.

6.6 RPN calculation

6.6.1 Severity (S), occurrence (O) and detection (D) indices

In accordance with IEC 60812 and application guidelines, each mode-effect-cause combination is evaluated according to three indices (Szkoda & Kaczor, 2020):

- **Severity (S):** measures the severity of the effect on safety, the environment, production or the customer.
- **Occurrence (O):** estimates the probable frequency of the cause (e.g., frequency of corrosion, frequency of maneuvers).
- **Detection (D):** assesses the probability of not detecting the failure mode before it has an effect. Continuous monitoring devices or regular inspections reduce the detection score.

6.6.2 RPN calculation

Criticality is generally expressed by the Risk Priority Number (RPN), the product of the three indices:

$$RPN = S * O * D \quad \text{Eq. 6-1}$$

This number is used to prioritize failure modes: failures with a high RPN are dealt with as a priority.

IEC 60812 standard (Wu et al., 2021) does not mandate single numerical scales for FMEA indices, but recommends defining rating scales tailored to the organization to ensure consistent assessment. The tables below illustrate commonly used scales for the three Risk Priority Number (RPN) factors: severity (S), occurrence (O), and detection (D). Each scale ranges from 1 (very low or easily detectable risk) to 10 (very high or undetectable risk).

Table 6-4 Severity scale (S – Consequence)

Note	Description (examples)
10	Catastrophic: danger to human life, explosion, total loss of the system.
9	Very serious: major injury, complete production shutdown, major HSE impact.
8	Serious : regulatory non - non-compliance, significant environmental damage .
7	High: partial process stoppage, major repair, failure to meet a critical customer requirement.
6	Moderate: significant reduction in performance, unplanned maintenance intervention.
5	Low: slight loss of effectiveness, minor retouching, limited impact.
4	Very low: marginal drift in specifications with no noticeable impact.
3	Minor: disruption that is almost imperceptible to the customer or the operation.
2	Very minor: barely noticeable effect, corrected without specific action.
1	Negligible: no detectable effect.

Table 6-5 Occurrence scale (O – Probability of failure)

Note	Approximate probability of failure	Indicative frequency (to be adjusted)
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10	Almost certain: event observed regularly (≥ 1 out of 2).	Several times a year.
9	Very high: 1 failure out of 3.	At least once a year.
8	High : 1 out of 8.	Every 1–2 years.
7	Relatively high : 1 out of 20.	Every 2–5 years.
6	Moderate : 1 out of 80.	Every 5–10 years.
5	Low : 1 in 400.	Every 10–20 years.
4	Very low : 1 in 2,000.	Every 20–50 years.
3	Rare : 1 in 15,000.	Every 50–100 years.
2	Very rare : 1 in 150,000.	Very low probability over the lifetime.
1	Practically impossible : ≤ 1 in 1.5 million.	Never met.

Table 6-6 Detection scale (D- Probability of non - detection)

Note	Description of the detection capability
10	Undetectable: no testing or monitoring procedure; the failure cannot be identified before the effect.
9	Very low: very limited or random detection method; low chance of detecting in time.
8	Low: detection possible but not systematic; results uncertain.
7	Moderately weak: detection is sometimes effective but not reliable.
6	Moderate: periodic monitoring providing partial information; possible delay.
5	Average: existing but non-redundant control devices; failure may be missed.
4	Relatively high: testing and inspection plan established, but not continuous.
3	High: Regular monitoring and well-applied control procedure; probable detection.
2	Very high: high-performance instrumentation and frequent inspections; failure is almost always detected.
1	Almost certain: real - time monitoring or self - diagnosis; the failure is reported immediately.

These grids must be adapted to the specific context of your installation and discussed collectively.

However, the prioritization of failure modes based on the RPN must be complemented by a qualitative analysis (HSE severity, costs, regulatory compliance) to avoid the perverse effects of the product of the scores.

6.6.3 Limitations and precautions for interpretation

- Subjectivity of ratings: The S, O, and D ratings rely on expert opinion. Biases may arise when scales are unclear or when evaluators interpret them differently. Regularly calibrate the team and document rating rules.
- Multiplicative effect: the RPN is a product. A very high factor can mask the importance of other factors or lead to paradoxical rankings (e.g., a mode with high severity but low occurrence may be less of a priority than a less severe but frequent mode). IEC 60812 also indicates that risks can be prioritized without using a single numerical value.
- Criteria not considered: The RPN (Relevant Natural Impact) does not necessarily reflect regulatory compliance, costs, or operational constraints. In the oil and gas industry, a rare but potentially catastrophic event (such as an explosion or major pollution) may require

immediate action even if its RPN is not the highest. HSE standards and requirements must therefore be integrated into the final decision.

- Dynamic FMEA: An FMEA report is a living document. Update it after a process change, incident, or new data. IEC 60812 emphasizes maintaining information consistency and incorporating control actions into risk management.

Much research focuses on improving the FMEA by adding decision support tools, especially for calculating the RPN. For instance, (Tsai et al., 2017) suggests combining fuzzy ordered weighted average and the DEMATEL method to rank default risks. Fuzzy TOPSIS and AHP methods refine the RPN calculation. (Kutlu & Ekmekçioğlu, 2012) proposed a new approach using probative reasoning and the TOPSIS method to aggregate RPN risk factors. This work shows growing interest in better RPN methods.

This brief overview of the scientific and technical literature related to ATEX demonstrates the need to focus ATEX risk assessment on an approach that improves our understanding of these risks. The proposed method, called WP_RPN, aims to simplify the calculation of the RPN while improving performance in the ATEX risk assessment framework. This method is based on adjusting the classic RPN using summation techniques and decision support methods (DSMs) to weight the different risk dimensions, and has been adapted to the ATEX risk assessment framework. The effectiveness of this approach is illustrated through a case study in the ATEX field.(Chati, Hadeif, Djebabra, & Chettouh, 2025)

One initial trend is to compress the RPN dimensions to 5 levels instead of 10 (Table 1). This is because, in many applications, it is difficult to evaluate RPN dimensions across 10 levels, and using 5 levels is the optimal solution. A second trend involves mitigating RPN scores by either using a logarithmic scale (Eq. 2) or summing the dimensions of an RPN (Eq. 3):(Chati et al., 2025)

$$\mathbf{L_RPN = \log (OSD)} \quad \mathbf{Eq. 6-2}$$

$$\mathbf{A_RPN = O + S + D} \quad \mathbf{Eq. 6-3}$$

Thus, L_RPN scores range from 0 to 3 and A_RPN scores from 1 to 30.

$$\mathbf{E_RPN(x) = x W_o. O + x W_s.S + x W_D. D} \quad \mathbf{Eq. 6-4}$$

Where x is a positive integer and W_i (i = O, S or D) are weights of the dimensions "O, S and D".

In summary, the FMEA (Failure Mode and Effects Analysis) sheet is a structured tool for identifying and prioritizing potential failures. Its effective use in the oil and gas industry requires clearly defining functions, distinguishing levels of impact, assessing causes, and understanding the limitations of the RPN, which is calculated by multiplying severity, occurrence, and

detectability, in order to adapt decisions to the severity of HSE (Health, Safety, and Environment) and operational challenges.

6.7 Construction of a criticality matrix in FMEA

The criticality matrix helps visualize and rank failure modes using severity of effects (S), probability of occurrence (O), and detectability (D). IEC 60812 and FMECA guidelines recommend this tool for fast risk comparison and setting action priorities. In the oil and gas industry, similar matrices appear in API RP 580/581. They classify equipment risk for inspection (RBI) based on the probability of failure and its impact on safety, the environment, and production downtime.

6.7.1 Position the failure modes

For each failure mode identified in the FMEA:

- Assess the severity of the effects, the probability of the cause, and the detection capacity using the defined grids.
- Calculate the $RPN = S \times O \times D$ if a numerical indicator. Calculate the $RPN = S \times O \times D$ if you need a numerical indicator.

Otherwise, use the severity and probability categories to position the mode in the matrix, with the vertical axis representing severity levels and the horizontal axis representing probability levels. Each cell can be colored according to the risk level (high, medium, low). Failure modes are placed in the cells corresponding to their ratings.

6.7.2 Example of a criticality matrix for the oil & gas industry

Here is an example of a 5×5 matrix inspired by oil operators' practices. The severity headings take into account the human, material, and environmental impact. The probability categories reflect the facilities' history of failures. The legend indicates the priority levels: VH (Very High risk), H (High), M (Medium), and L (Low). If the detection capability is particularly low for a failure mode, indicate this by color-coding or noting it in the matrix to draw attention to the reduced detectability (Fig. 6.6).

Severity / Probability	Very common	Frequent	Occasional	Rare	Very rare
Catastrophic – death or total loss of the system	VH	VH	H	H	M
Major – serious injury, major pollution, prolonged work stoppage	VH	H	H	M	M
Serious – minor injury, significant damage, a few days off work	H	H	M	M	L
Minor – slight disruption, quick repair	M	M	M	L	L
Negligible – virtually no impact	L	L	L	L	L

Figure 6-6 *Example of a criticality matrix for the oil & gas industry*

6.7.3 Use

A failure mode classified as Catastrophic/Frequent (top-left cell) is critical and requires immediate action, such as design changes, enhanced detection, or improved inspection.

A mode rated as Minor/Rare (bottom right) may be tolerated with minimal monitoring.

If the detection capability is low (high D), escalate the risk level even if probability and severity are unchanged: for example, apply a color code (e.g., dark red) or artificially increase the severity category to reflect the added risk from poor detectability.

Key points

- Choose categories by calibrating scales with the company's reliability database and HSE regulatory requirements.
- To reduce subjectivity, record rules for assigning severity, probability, and detection levels.
- Regularly review the matrix: update categories and thresholds in response to feedback, process changes, or new monitoring technologies.

Integrating severity, probability, and detectability into a matrix provides HSE and maintenance teams with a clear decision-making tool. This method aligns with the Risk-Based Inspection (RBI) approach in API 580/581, supporting effective equipment classification and inspection resource allocation.

6.8 Case study: FMEA applied to a multi-stage centrifugal pump

6.8.1 Context and regulatory framework

FMEA a preventive tool defined in IEC 60812, which specifies what information to record (functions, failures, effects, causes, controls, recommended actions) and how to prioritize risks. In the oil industry, a multi-stage centrifugal pump is critical equipment: its failure can lead to production losses and HSE risks. FMEA is used to identify failure modes, analyze their effects, and determine corrective actions.

6.8.2 Equipment Description and Scope

The pump under study is a multi-stage centrifugal pump that delivers 600 m³/h at 80 bars for water injection or hydrocarbon transfer. It is equipped with an electric motor, a mechanical seal, roller bearings, a lubrication system, and instrumentation (pressure, vibration, temperature). The scope of the FMEA covers the pump and motor; downstream equipment (piping, valves) is

considered only for its effects on the pump (e.g., cavitation due to a blocked strainer). The details show in the Fig. 6.8 and Table 6.7{14224: 2016 #21}.

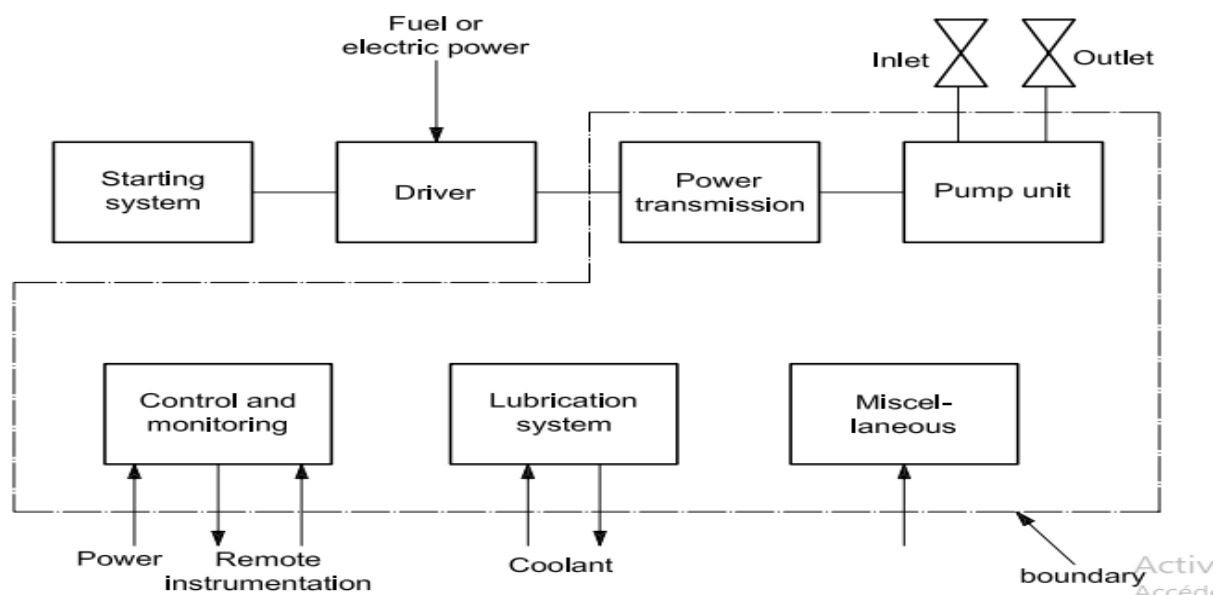


Figure 6-7 Equipment subdivision- Pumps

Table 6-7 Equipment subdivision- Pumps

Equipment unit	Pumps				
Subunit	Power transmission	Pump unit	Control and monitoring	Lubrication system	Miscellaneous
Maintainable items	Gearbox/ variable drive	Support	Actuating device	Reservoir	Purge air
	Bearing	Casing	Control unit	Pump	Cooling/heating system
	Seals	Impeller	Internal power supply	Motor	Cyclone separator
	Coupling to driver	Shaft	Monitoring	Filter	Pulsation damper
	Coupling to driven unit	Radial bearing	Sensors ^a	Cooler	Flange joints
	Belt/sheave	Thrust bearing	Valves	Valves	
		Seals	Wiring	Piping	
		Valves	Piping	Oil	
		Piping	Seals	Seals	
		Cylinder liner			
		Piston			
		Diaphragm			

6.8.3 Functional Analysis (SADT)

A SADT functional analysis precedes the FMEA and decomposes the overall function into sub-functions. Initially, the A-0 diagram describes the overall function: transferring fluid from the reservoir to the pipeline at the required pressure and flow rate.

- Diagram A0 (main decomposition)

Following the main decomposition in Diagram A0, this overall function can be broken down into several sub-functions, each described by an SADT block with its inputs, outputs, constraints, and means. The table below summarizes the main sub-functions (the sentences are condensed to fit the table format). The diagram A0 breaks down this function into six sub-functions presented in Table 6.8.

Table 6-8 Diagram A0 breaks down sub-function

Sub - function (SADT)	Description	Entrances	Outings	Controls	Mechanisms
Supply with energy	Convert electrical energy into mechanical energy to drive the shaft.	Electricity (6 kV)	Mechanical torque	Voltage/current guidelines, HSE requirements	Electric motor, speed controller, protection devices
Aspirate the fluid	Draw the fluid from the reservoir without cavitation.	Raw fluid, mechanical energy	Fluid aspirated	Minimum level/NPSH, suction pressure	Suction tube, strainer, inlet wheel
Compress/accelerate the fluid	Increase the pressure and velocity of the fluid by means of the wheel stages.	Fluid drawn in, mechanical energy	Pressurized fluid	Pressure setpoint, safety valves	Pump body, wheels, guides
Transport the fluid	Convey the pressurized fluid to the process line.	Pressurized fluid	Fluid in the network	Nominal flow rate, maximum pressure losses	Discharge piping, check valves, valves
Lubricate and cool	Lubricate and cool the bearings, the lining and the motor.	Oil and cooling water	heated oil/fluid	Permissible temperature of bearings and seals	Lubrication system, heat exchangers, filters
Monitor and control	Monitor the parameters and control the pump.	Signals (pressure, temperature, vibration)	Alarms, commands, data	Alarm limits, HSE procedures	Sensors, control system, operators

http://ced.forget.free.fr/html/co/exemple%20du%20cours_6.html

These sub-functions serve as a reference structure for FMEA.

6.8.4 FMEA Methodology Applied to Sub-Functions

The FMEA is conducted by a multidisciplinary team (engineering, maintenance, HSE, operations) as recommended by the guidelines [2]. Failure modes are identified through brainstorming and feedback, and their effects, causes, and existing measures are then analyzed. The severity (S), occurrence (O), and detection (D) indices are rated from 1 to 10 according to IEC 60812. The risk priority number (RPN) is calculated ($RPN = S \times O \times D$). The sub-functions of the FMEA correspond to the six sub-functions of the SADT, ensuring consistency between the functional and failure analyses.

Table 6-9 FMECA of Supply with energy

Failure mode	Effects	Probable causes	S	O	D	RPN	Existing controls	Recommended actions
Engine overheating or short circuit	Pump stopped, risk of fire; loss of pressure on the network.	Insulation fault, overcurrent due to overload, insufficient cooling, electrical protection fault.	9	3	4	108	Thermal relays, stator and winding temperature monitoring, current sensors.	Improve the cooling system, monitor the power supply quality, test the insulation regularly, and provide a backup motor.
Power outage	Immediate pump shutdown; loss of production; activation of shutdown alarms.	Network failure, high-voltage circuit breaker tripped, variable frequency drive failure.	8	2	3	48	Emergency power supply (generator), residual current circuit breaker.	Regularly check the power supply circuits, test the generator set, and implement variable frequency drive redundancy.

Table 6-10 FMECA of Aspirate the fluid

Failure mode	Effects	Probable causes	S	O	D	RPN	Existing controls	Recommended actions
Cavitation (bubble formation and erosion)	Noise, vibrations, progressive destruction of the wheels; loss of flow and pressure; risk of leakage.	Suction level too low, strainer obstruction, insufficient NPSH, high temperature.	8	6	4	192	Suction pressure sensor, NPSH control available, level monitoring.	Clean the strainer regularly, check the suction piping, increase the load height, reduce the rotation speed.
Obstruction or blockage during suction	Loss of flow rate, pump under - supply,	Accumulation of abrasive particles in the strainer or	7	5	5	175	Differential pressure switch on strainer,	Install filters or particle separators, schedule frequent inspections and

	cavitation.	tubing, contamination by debris.					periodic inspections.	cleanings, and raise operator awareness of suction pressure monitoring.
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Table 6-11 FMECA of Compress/accelerate the fluid

Failure mode	Effects	Probable causes	S	O	D	RPN	Existing controls	Recommended actions
Corrosion or erosion of the wheels (impeller)	Reduced efficiency, vibrations, impeller breakage; loss of pressure.	Corrosive fluid, abrasive particles, cavitation, inadequate coating.	7	4	6	168	Periodic inspections, anti - corrosion coatings.	Select more resistant materials, install upstream filtration, adjust the speed to avoid cavitation.
Tree imbalance or misalignment	Vibrations, premature wear of bearings and seals, leakage; risk of shutdown.	Poor alignment during assembly, vibration due to impeller wear, weakened foundations.	6	3	5	90	Initial alignment verified by laser, vibration measurement.	Periodic realignment, ensuring the rigidity of the supports, balancing the impeller after repair.
Loss of sealing (mechanical seal)	Fluid leak, pressure drop, risk of explosion and pollution.	Seal wear, excessive vibrations, pressure or temperature increase, lack of lubrication.	9	4	6	216	Pressure and level instrumentation, regular inspections.	Use seals made of resistant material, improve cooling/lubrication, add a leak sensor with alarm.

Table 6-12 FMECA of Transporting the fluid

Failure mode	Effects	Probable causes	S	O	D	RP N	Existing controls	Recommended actions
Leak or rupture of the discharge pipe	Loss of pressurized fluid, reduced flow rate, risk of environmental damage.	Internal or external corrosion, aging, overpressure due to downstream blockage.	8	3	6	144	Safety valves, discharge pressure control, visual inspections.	Strengthen ultrasonic inspections, apply an internal coating, check the proper functioning of the valves, adjust wall thicknesses.
Partial blockage of the	Increased pressure in the pump, motor	Deposits, partially closed valve,	7	4	5	140	Pressure gauge at the discharge,	Schedule periodic cleaning, test the valves, monitor the

discharge pipe	overload, cavitation at the suction.	failure of a non - return valve.					flow control.	position of the valves and train the operators.
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Table 6-13 FMECA of Lubricate and cool

Failure mode	Effects	Probable causes	S	O	D	RPN	Existing controls	Recommended actions
Insufficient or loss of lubrication	Overheating of the bearings and the lining, vibrations, seizing; pump stoppage.	Low oil level, particle contamination, oil pump failure, clogged filters.	8	5	5	200	Periodic oil analysis, monitoring of vibrations and temperature.	Implement condition-based lubrication, install bypass filters and an oil flow sensor, and schedule regular inspections and oil changes.
Cooling system failure	Overheating of the pump and motor, accelerated wear of seals and bearings.	Insufficient water flow, blocked heat exchangers, cooling pump failure.	7	3	4	84	Temperature sensors, over-temperature alarms.	Periodically check the cooling system, clean the heat exchangers, add a redundant cooling pump.

Table 6-14 FMECA of Monitor and control

Failure mode	Effects	Probable causes	S	O	D	RPN	Existing controls	Recommended actions
Sensor failure (pressure, vibration, temperature)	Failure to detect an imminent failure, absence of an alarm or untimely triggering.	Faulty sensor, damaged cables, incorrect configuration, incorrect calibration.	7	4	7	196	Regular functional tests, connection checks.	Doubling the sensors on critical parameters, setting up online diagnostics, training staff to interpret alarms.
Control system failure (PLC, relay)	Unexpected or non - starting of the pump, production losses.	Programming error, PLC power supply failure, relay aging.	8	3	6	144	Periodic testing of the control system, operating procedures.	Strengthen redundancy of controls, test power supplies, maintain a software update and relay replacement program.

6.8.5 Interpretation of results and priority actions

The RPN classification identifies “Lubricate and Cool” (insufficient lubrication: RPN 200), “Draw Fluid” (cavitation: 192), and “Compress/Accelerate” (seal leakage: 216) as the most

critical sub-functions. These could cause sudden pump shutdowns or leakage, posing serious safety and environmental risks. Priority actions include:

- **Improved sealing:** use of double seals made of durable materials, improved lubrication and cooling, and installation of leak sensors.
- Next, **condition monitoring** involves implementing redundant vibration, pressure, and temperature sensors, along with oil analysis to detect early bearing wear.
- **Cavitation prevention:** NPSH control, strainer cleaning, and rotation speed adjustment.
- **Proactive maintenance:** preventive replacement of critical components according to failure history, staff training, and regular updating of the FMEA sheet [3].

By aligning the sub-functions of SADT functional analysis with those of FMEA, this corrected version ensures consistency between the system description and the identification of failure modes. In addition, the approach follows the recommendations of the IEC 60812 standard and reliability guides: the formation of a multidisciplinary team, data collection, functional analysis, identification of failure modes, calculation of the RPN, and definition of actions [1].

The study highlights that lubrication defects, seal leaks, and cavitation (the formation of vapor cavities in a liquid) are the major risks for a multistage centrifugal pump in operation in the oil industry. Adopting technical solutions such as reinforced seals, NPSH (Net Positive Suction Head) controls, and filtration, as well as organizational solutions such as condition monitoring and preventive maintenance, significantly reduces these risks and increases equipment reliability and availability.

6.9 Conclusion

The FMEA method is a proven, versatile risk management tool. By adhering to IEC 60812 and MIL-STD-1629A standards, and integrating risk management (ISO 31000), asset management (ISO 55000), and risk-based inspection practices (API 580/581), oil companies can systematically evaluate equipment failures, prioritize interventions, and enhance reliability and safety. FMEA is therefore integral to effective risk management and HSE regulatory compliance.

Conclusion

This educational course on industrial maintenance concludes with a summary of key knowledge gained and an assessment of the discipline's role in modern mechanical engineering. The six chapters built a complete, coherent understanding of maintenance, from key concepts to advanced tools.

The initial chapter established that maintenance is intrinsically linked to operational safety and that it has four fundamental attributes: reliability, maintainability, availability, and safety. These attributes form the essential theoretical basis for any rigorous maintenance approach.

The examination of different maintenance types showed many available strategies: corrective, systematic preventive, condition-based preventive, and predictive maintenance. Choosing the right maintenance policy helps balance performance and cost.

The course showed that effective maintenance relies on clear organization and modern management tools. Computerized Maintenance Management Systems (CMMS) are now essential in industry.

Managing equipment and logistics demands strict asset management. Maintaining spare parts, tracking interventions, and controlling supply chains directly affect maintenance performance.

Learning the reliability approach introduced mathematical and statistical tools for modeling equipment behavior, estimating lifespan, and optimizing interventions. This quantitative perspective provides maintenance with a solid scientific foundation.

FMEA (Failure Mode and Effects Analysis) uses analysis to identify, assess, and rank system failure modes, focusing maintenance where it is most needed and effective.

These chapters show that industrial maintenance goes beyond technical tasks. It is now a strategic function that supports full organizational performance.

In summary, mastery of maintenance means: preserving industrial assets, ensuring steady production, protecting people and the environment, and optimizing all resources to maximize facility availability.

Recent technological developments, including the Industrial Internet of Things (IIoT), artificial intelligence, predictive maintenance based on big data analytics, and digital twins, are creating significant opportunities for the future of maintenance. These technologies enable more accurate failure prediction, reduce unplanned downtime, and enable dynamic, real-time optimization of maintenance strategies.

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Appendix 1: Detailed Course Programme

According to the National Programme Framework 2021–2022

Semester	5
Teaching Unit	UED 3.1
Subject	Maintenance
Total Weekly Hours (VHS)	22h30 (Lectures : 01h30)
Credits	1
Coefficient	1

1 Learning Objectives

Through this course, students will acquire a comprehensive understanding of the role of maintenance within industrial enterprises, including its organizational structure and functional dimensions. Students will furthermore develop the analytical capabilities required to perform reliability calculations relevant to maintenance engineering.

2 Recommended Prior Knowledge

Foundational knowledge in mechanical systems, industrial engineering, and basic probability and statistics is recommended prior to undertaking this course.

3 Course Content

- **Chapter 1: General Principles of Maintenance (2 Weeks)**
 - *The role and importance of maintenance within the industrial enterprise*
 - *Objectives of maintenance in an enterprise context*
 - *Maintenance strategies and policies*
- **Chapter 2: Forms and Types of Maintenance (4 Weeks)**
 - *Forms of maintenance action*
 - *Maintenance operations and procedures*
 - *Maintenance levels*
 - *Related and ancillary maintenance activities*
- **Chapter 3: Maintenance Organisation (4 Weeks)**
 - *Preparation of maintenance work orders*
 - *Planning and scheduling of maintenance tasks*

- *Human resource management in maintenance*
- *Methods and engineering office (Bureau d'études et méthodes)*
- **Chapter 4: Equipment Monitoring and Logistics (2 Weeks)**
 - *Equipment knowledge and behavioural analysis*
 - *The logistics function in maintenance*
- **Chapter 5: Maintenance Reliability (3 Weeks)**
 - *Maintenance and reliability interrelationship*
 - *Key reliability indicator parameters*
 - *Reliability calculation methods*
 - *Failure Mode, Effects and Criticality Analysis (FMECA)*

4 Assessment Method

Final Written Examination: 100%

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Appendix 2: Pareto Chart and ABC Analysis in Industrial Maintenance

These two graphs help determine priorities or the relevance of a proposed action. They are, therefore, decision-making tools that the management assistant must master.

1 The Pareto Principle (80/20 Rule)

Vilfredo Pareto, an Italian economist and sociologist born in Paris in 1848, showed that 80% of Italy's wealth was held by just 20% of the population. This observation led to the 80/20 rule—sometimes 85/15—a principle frequently seen across many fields.

The main idea is that 80% of results come from just 20% of causes. You can see this pattern in many places. For example, in factories, 80% of breakdowns come from 20% of the machines. In warehouses, 80% of inventory costs are caused by 20% of the items. In quality control, 80% of defects come from 20% of the main problems.

There are two main tools that use this principle: the Pareto chart, which clearly shows the imbalance, and the ABC analysis, which helps organize this information into categories. These tools help teams focus on what matters most rather than trying to solve every problem at once.

In maintenance, this principle is especially useful. Often, about 20% of equipment failures account for most downtime and extra work. By identifying and focusing on this critical 20%, maintenance teams can set better priorities, reduce unexpected stoppages, and make smarter choices about where to spend their time and resources. Instead of trying to fix every problem, this approach helps you focus on the changes that will make the biggest difference.

2 The Pareto Chart in Maintenance

In industrial maintenance, the Pareto chart is used to identify the equipment or failure modes that concentrate the majority of downtime, costs, or interventions. It is based on the principle that 20% of causes generate 80% of consequences, translated here as: 20% of equipment causes 80% of production stoppages (Moubray, 1997; Wireman, 2004).

2.1 Construction stages

1) Step 1: Data collection

List the categories of events and their absolute frequency or value (e.g., cost, time, loss).

2) Step 2: Sort descending

Sort the categories by size from largest to smallest.

3) *Step 3: Statistical calculations*

For each category:

- Relative frequency (%):

$$p_i = \frac{f_i}{\sum_{i=1}^n f_i} \times 100$$

- Cumulative percentage (%):

$$P_i = \sum_{j=1}^i p_j$$

4) *Step 4 : Plotting the Chart*

- Abscissa axis (x): categories classified in descending order.
- Left axis (y₁): frequency or cost f_i (bars).
- Right axis (y₂): cumulative percentage of P_i (curve).

The Pareto chart is a histogram with a cumulative curve: this curve helps visually identify the 20% of elements responsible for approximately 80% of the effects.

2.2 Interpretation

- The first bars show the dominant causes (class A).
- The 80% portion of the curve represents the priority elements to address first.

Applied example: a refinery records unplanned stoppages of its rotating equipment over 12 months.

Unplanned stoppages over 12 months — rotating equipment (refinery): Bearings (38 h) Seals (27 h) Centrifugal pumps (18 h) Compressors (9 h) Valves (5 h) Other (3 h)

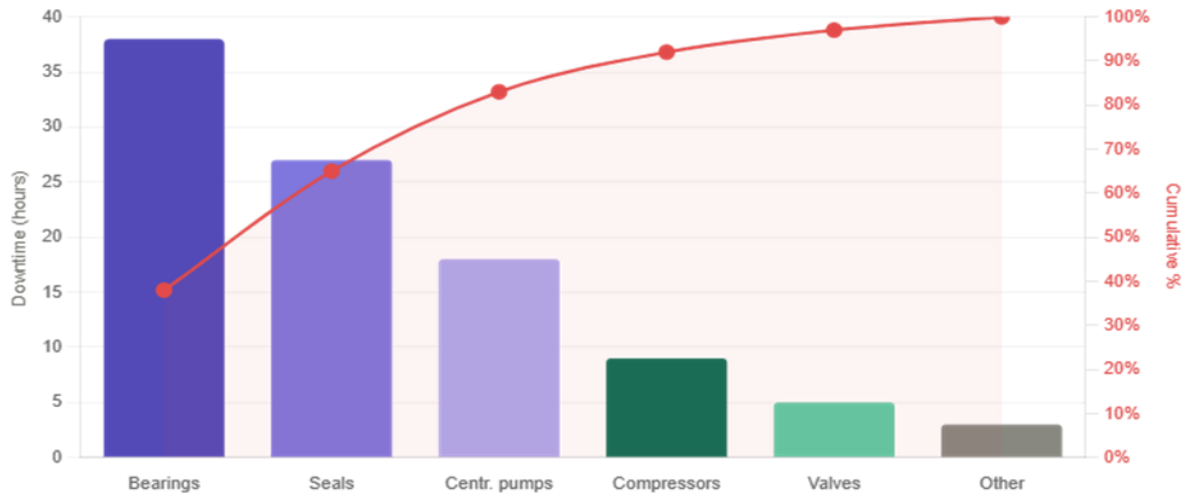


Fig. Pareto curve

Reading: bearings + seals account for 65% of downtime. Addressing these 2 causes resolves two-thirds of the problem.

- **Maintenance decision:** concentrate resources on bearings (lubrication plan, preventive replacement) and seals (periodic inspection, reference standardization). This logic is central to the RCM (Reliability-Centered Maintenance) methodology described by Moubray (1997).

3 ABC Analysis in Maintenance

ABC analysis is applied in maintenance to classify equipment, spare parts, or suppliers according to their criticality or consumption value. It complements the Pareto chart: where Pareto identifies the causes, ABC organizes the resources accordingly (Sherbrooke, 2004; EN 13306:2017).

Class	Share of items	Maintenance impact	Associated policy
A	~20%	~70–80% of costs/stoppages	Systematic preventive maintenance, CMMS, safety stock
B	~30%	~15–25%	Condition-based preventive maintenance
C	~50%	~5–10%	Corrective maintenance acceptable

Applied example: classification of spare parts in the maintenance store of a cement plant, based on annual consumption value.

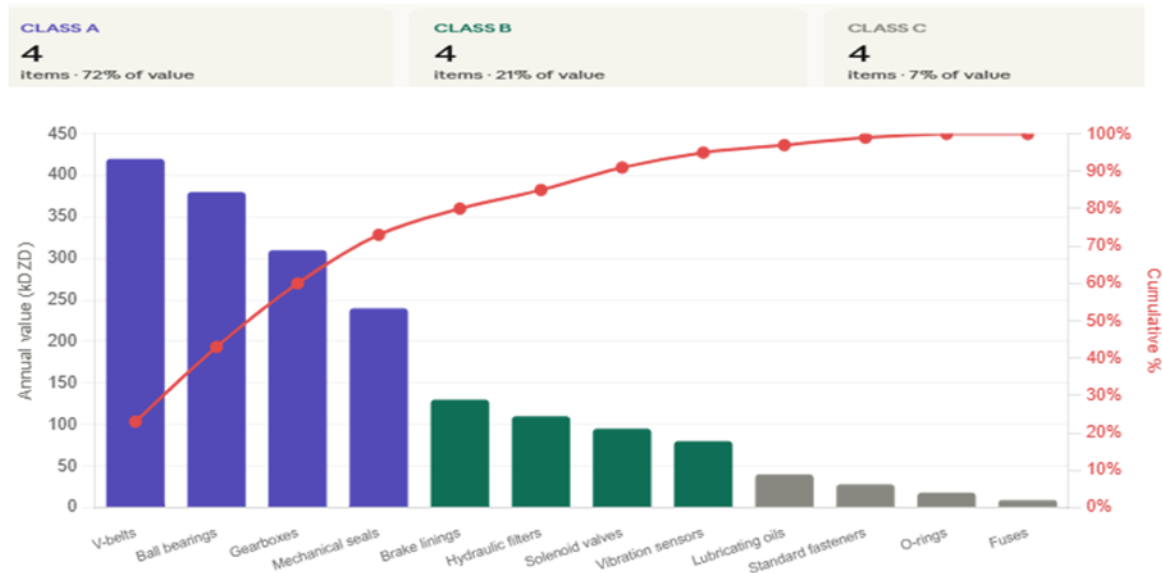


Table:

Item	Value (kDZD)	% value	Class	Policy
V-belts	420	23%	A	Systematic preventive + safety stock
Ball bearings	380	20%	A	Systematic preventive + safety stock
Gearboxes	310	17%	A	Systematic preventive + safety stock
Mechanical seals	240	13%	A	Systematic preventive + safety stock
Brake linings	130	7%	B	Condition-based preventive
Hydraulic filters	110	6%	B	Condition-based preventive
Solenoid valves	95	5%	B	Condition-based preventive
Vibration sensors	80	4%	B	Condition-based preventive
Lubricating oils	40	2%	C	Deferred corrective
Standard fasteners	28	2%	C	Deferred corrective
O-rings	18	1%	C	Deferred corrective
Fuses	9	0%	C	Deferred corrective

4 Combining Both Tools in Maintenance

The two methods work together within a reliability-based maintenance approach. The Pareto chart identifies which problems should be addressed first, guiding corrective and preventive action plans. In addition to the Pareto chart, the ABC analysis addresses the question: "How should resources (parts, budget, personnel) be managed?" → It guides stock policy and service levels.

By combining both methods, they form the foundation of predictive maintenance management, integrated into any CMMS (Computerized Maintenance Management System) and aligned with the requirements of EN 13306:2017, the standard on maintenance terminology.

5 Example application

Table 4: Machine Downtime

Equipment	Downtime (min)
Mould	675
Motor	405
Low oven	180
Water circuit	160
Blow valve	155
Pneum. circuit	120
Air circuit	110
Chute	90
Punch jack	80
Ejector	60
Temp. regulator	40
Blower	10

5.1 Pareto chart

Equipment	Downtime (min)	% downtime	Cumulative %
Mould	675	32.37%	32.37%
Motor	405	19.42%	51.79%
Low oven	180	8.63%	60.42%
Water circuit	160	7.67%	68.09%
Blow valve	155	7.43%	75.52%
Pneum. circuit	120	5.76%	81.28%
Air circuit	110	5.28%	86.56%
Chute	90	4.32%	90.88%
Punch jack	80	3.84%	94.72%
Ejector	60	2.88%	97.60%
Temp. regulator	40	1.92%	99.52%
Blower	10	0.48%	100.00%

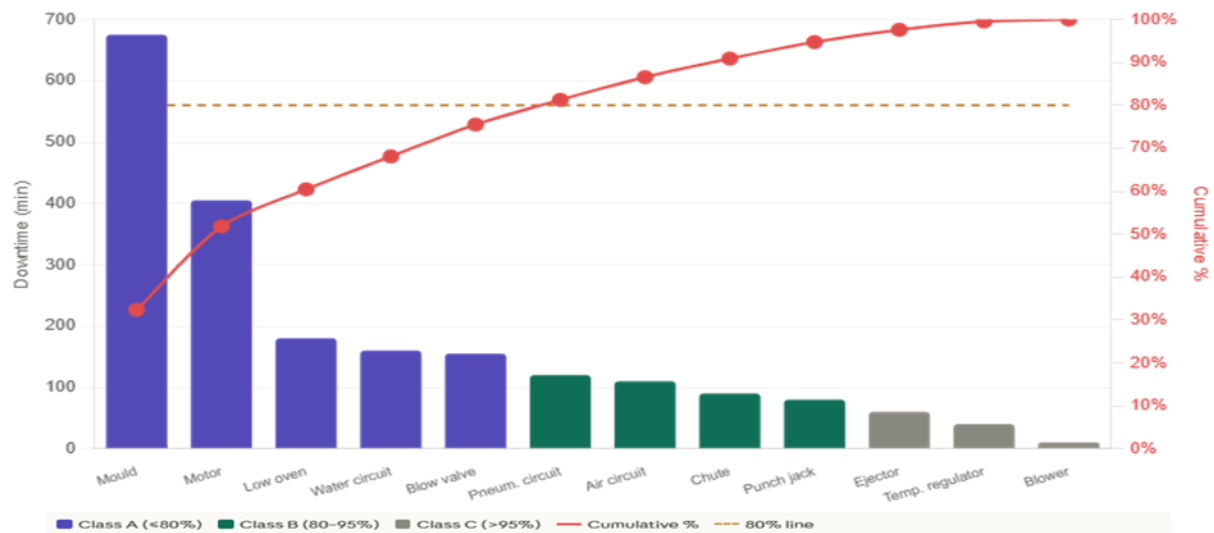


Fig. Pareto chart: equipment downtime (min)

Bars = individual downtime · Red line = cumulative % · Dashed line = 80% threshold

5.2 ABC analysis

Table: classification table: Boundaries: A $\leq$ 80% · B 80–95% · C > 95%

Equipment	Downtime (min)	% downtime	Cumulative %	Class	Maintenance policy
Mould	675	32.37%	32.37%	A	Systematic preventive maintenance — top priority
Motor	405	19.42%	51.79%	A	Systematic preventive maintenance — top priority
Low oven	180	8.63%	60.42%	A	Systematic preventive maintenance — top priority
Water circuit	160	7.67%	68.09%	A	Systematic preventive maintenance — top priority
Blow valve	155	7.43%	75.52%	A	Systematic preventive maintenance — top priority
Pneum. Circuit	120	5.76%	81.28%	B	Condition-based preventive maintenance
Air circuit	110	5.28%	86.56%	B	Condition-based preventive maintenance
Chute	90	4.32%	90.88%	B	Condition-based preventive maintenance
Punch jack	80	3.84%	94.72%	B	Condition-based preventive maintenance
Ejector	60	2.88%	97.60%	C	Corrective maintenance — low priority
Temp. regulator	40	1.92%	99.52%	C	Corrective maintenance — low priority
Blower	10	0.48%	100.00%	C	Corrective maintenance — low priority

Key insight: Mould + Motor alone account for 51.8% of all downtime. The first 6 equipment items (class A+B) drive 81.3% — prioritising these is the highest-leverage maintenance action.

Here is how your data looks when sorted using the ABC classification:

- **Class A (1575 min: 5 items · 76% of downtime):** includes the Mould, Motor, Low oven, Water circuit, and Blow valve (together making up to 80% of downtime). These five cause most of the downtime, so they should have regular preventive maintenance, dedicated spare parts, and close CMMS tracking.
- **Class B (400 min: 4 items · 19% of downtime):** covers the Pneumatic circuit and the Air circuit (together accounting for 80% to 95% of downtime). These have a moderate impact and are best managed with condition-based maintenance and regular inspections.
- **Class C (110 min: 3 items · 5% of downtime):** includes the Chute, Punch jack, Ejector, Temperature regulator, and Blower (together making up more than 95% of downtime). Each has a small effect on its own, so fixing them only when they fail is fine and does not risk overall availability.

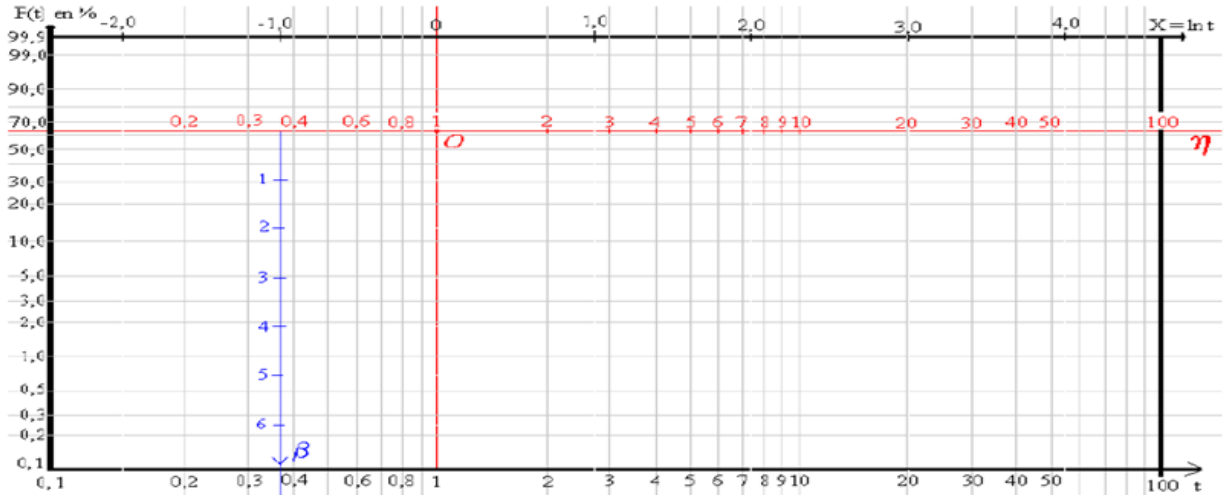
The most important takeaway is that the Mould alone accounts for 32.4% of all downtime, almost a third of the total. Focusing on this one item would make a bigger difference than fixing the bottom seven items together.

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Appendix 3: Weibull paper and table of Test of kolmogorov Smirnov

1 Weibull paper



2 Test of kolmogorov Smirnov

N	Niveau significatif				
	0,2	0,15	0,1	0,05	0,01
1	0,900	0,925	0,950	0,975	0,995
2	0,684	0,726	0,776	0,842	0,929
3	0,565	0,597	0,642	0,708	0,828
4	0,494	0,525	0,564	0,624	0,733
5	0,446	0,474	0,510	0,565	0,669
6	0,410	0,436	0,470	0,521	0,618
7	0,381	0,405	0,438	0,486	0,577
8	0,358	0,381	0,411	0,457	0,543
9	0,339	0,360	0,388	0,432	0,514
10	0,322	0,342	0,368	0,410	0,490
11	0,307	0,326	0,352	0,391	0,468
12	0,295	0,313	0,338	0,375	0,450
13	0,284	0,302	0,325	0,361	0,433
14	0,274	0,292	0,314	0,349	0,418
15	0,266	0,283	0,304	0,338	0,404
16	0,252	0,274	0,295	0,328	0,392
17	0,250	0,266	0,286	0,318	0,381
18	0,244	0,259	0,278	0,309	0,371
19	0,237	0,252	0,272	0,301	0,363
20	0,231	0,246	0,264	0,294	0,356
25	0,210	0,220	0,240	0,270	0,320
30	0,190	0,200	0,220	0,240	0,290
35	0,180	0,190	0,210	0,230	0,270
>35	$\frac{1,07}{\sqrt{N}}$	$\frac{1,22}{\sqrt{N}}$	$\frac{0,188}{\sqrt{N}}$	$\frac{1,36}{\sqrt{N}}$	$\frac{1,63}{\sqrt{N}}$

β	A	B	β	A	B	β	A	B
0,2	120	1 901	1,5	0,9027	0,613	4	0,9064	0,254
0,25	24	199	1,55	0,8994	0,593	4,1	0,9077	0,249
0,3	92,625	50,08	1,6	0,8966	0,574	4,2	0,9086	0,244
0,35	5,291	19,98	1,65	0,8942	0,556	4,3	0,9102	0,239
0,4	33,234	10,44	1,7	0,8922	0,54	4,4	0,9146	0,235
0,45	24,686	6,46	1,75	0,8906	0,525	4,5	0,9125	0,23
0,5	2	4,47	1,8	0,8893	0,511	4,6	0,9137	0,226
0,55	17,024	3,35	1,85	0,8882	0,498	4,7	0,9149	0,222
0,6	1,546	2,65	1,9	0,8874	0,486	4,8	0,916	0,218
0,65	13,663	2,18	1,95	0,8867	0,474	4,9	0,9171	0,214
0,7	12,638	1,85	2	0,8862	0,463	5	0,9162	0,21
0,75	11,906	1,61	2,1	0,8857	0,443	5,1	0,9192	0,207
0,8	1,133	1,43	2,2	0,8856	0,425	5,2	0,9202	0,203
0,85	1,088	1,29	2,3	0,8859	0,409	5,3	0,9213	0,2
0,9	10,522	1,17	2,4	0,8865	0,393	5,4	0,9222	0,197
0,95	1,0234	1,08	2,5	0,8873	0,38	5,5	0,9232	0,194
1	1	1	2,6	0,8882	0,367	5,6	0,9241	0,191
1,05	0,9803	0,934	2,7	0,8893	0,355	5,7	0,9251	0,186
1,1	0,9649	0,878	2,8	0,8905	0,344	5,8	0,926	0,165
1,15	0,9517	0,83	2,9	0,8919	0,334	5,9	0,9269	0,183
1,2	0,9407	0,787	3	0,893	0,316	6	0,9277	0,18
1,25	0,99314	0,75	3,1	0,8943	0,325	6,1	0,9266	0,177
1,3	0,9236	0,716	3,2	0,8957	0,307	6,2	0,9294	0,175
1,35	0,917	0,667	3,3	0,897	0,299	6,3	0,9302	0,172
1,4	0,9114	0,66	3,4	0,8984	0,292	6,4	0,931	0,17
1,45	0,9067	0,635	3,5	0,8997	0,285	6,5	0,9316	0,168
1,5	0,9027	0,613	3,6	0,9011	0,278	6,6	0,9325	0,166
1,55	0,8994	0,593	3,7	0,9025	0,272	6,7	0,9335	0,163
1,6	0,8966	0,574	3,8	0,9083	0,266	6,8	0,934	0,161
1,65	0,8942	0,556	3,9	0,9051	0,26	6,9	0,9347	0,15