الجمهورية الجزائرية الديمقراطية الشعبية
People's Democratic Republic of Algeria
وزارة التعليم العالي والبحث العلمي
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THESIS
Submitted for the degree of **DOCTOR IN LMD**
In: Electromechanics
Specialization: Industrial Maintenance

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Contribution to the Improvement of Preventive Maintenance for Dynamic Machines

Defended publicly on: 09/07/2025, before the jury:

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DEDICATION

*I dedicate this modest work to **my dear parents** who have patiently awaited this moment*

ACKNOWLEDGEMENTS

I thank Almighty God for granting me the strength, courage, and determination to successfully complete this thesis.
First of all, I would like to express my sincere gratitude to Professor LOUAFI MESSAOUD, my thesis supervisor, for giving me the opportunity to carry out this research within a high-level academic framework and for guiding this work. I would also like to extend my heartfelt thanks to Dr. TALEB MOUNIA, co-supervisor of the thesis, who stood by my side throughout the process, both scientifically and morally.My special and respectful thanks also go to Dr. AOULMI ZOUBIR, Director of the Institute of Mines, who played a major role in the realization of this thesis through his guidance and scientific advice.

I would like to express my deep gratitude to all those who supported me in completing this thesis, especially my professor, Dr. KAREK RABIE, who made a significant contribution to this work.I would also like to express my heartfelt appreciation to my family, particularly my parents who encouraged me immensely, my sisters, my brother, my professors, and my mentors.I am also thankful to the professors who contributed to my education, my friends, and all the individuals from various organizations who were contacted during my research.

RESUME

Au fil des années, le monde de l'industrie a souffert du spectre des pannes des machines industrielles à un taux de 70%, ce qui fait du progrès dans ce domaine un défi majeur qui peut se transformer en conflit et en course entre les pays pour avancer plus loin dans ce domaine.

Malgré le développement technologique auquel le monde est témoin dans divers domaines en général et dans le domaine de la maintenance en particulier, des dysfonctionnements entourent encore terriblement ces machines, ce qui nécessite chaque fois plus de travail pour améliorer et développer le domaine de la maintenance, notamment préventive.

Les transports publics modernes et avancés sont considérés comme faisant partie du département des machines industrielles en raison des installations et du soutien qu'ils offrent pour le mouvement rapide des individus et contribuent ainsi proportionnellement au taux de production élevé et à la reprise de l'indice économique.

Ces machines sont exposées à des processus de détérioration qui entraînent leurs pannes et des conséquences potentielles sur le bon fonctionnement des installations entières. Il existe différents types de processus de dégradation : usure, fatigue, vieillissement, etc..., dont la vitesse d'évolution varie en fonction de divers facteurs, tels que les conditions d'environnement et de fonctionnement.

Cette thèse vise à développer des méthodes de maintenance préventive de ces véhicules et ainsi augmenter le taux de fiabilité et développer un plan de maintenance préventive prédictive efficace, en réduisant les pannes résultant de la technologie AMDEC, considérée comme la technologie la plus utilisée dans le plan de maintenance préventive, qui fait diminuer le taux de panne par rapport au taux de fiabilité.

Mots clés : maintenance préventive, fiabilité, MBF, défaillance, véhicules tramway, système de climatisation AMDEC, MCDM, FUZZY-AHP, TOPSIS VIKOR.

ABSTRACT

Over the years, the industrial world has suffered from the specter of industrial machine breakdowns at a rate of 70%, making progress in this area a major challenge that can turn into conflict and race between countries. To advance further in this area.

Despite the technological development that the world is witnessing in various fields in general and in the field of maintenance in particular, malfunctions still terribly surround these machines, which requires every time more work to improve and develop the field of maintenance, particularly preventive.

Modern and advanced public transportation is considered to be part of the industrial machinery department due to the facilities and support it offers for the rapid movement of individuals and thus contributes proportionately to the high rate of production and

These machines are exposed to deterioration processes which lead to their breakdowns and potential consequences on the proper functioning of entire installations. There are different types of degradation processes: wear, fatigue, aging, etc., whose speed of evolution varies depending on various factors, such as environmental and operating conditions. Recovery of the index economic.

This thesis aims to develop preventive maintenance methods for these vehicles and thus increase the reliability rate and develop an effective predictive preventive maintenance plan, by reducing breakdowns resulting from FMEA technology, considered the most used technology in the plan. Preventive maintenance, which reduces the breakdown rate in relation to the reliability rate.

Keywords: preventive maintenance, reliability, MBF, Failures, tram vehicles, FMEA, air conditioning system, MCDM, FUZZY-AHP, TOPSIS,VIKOR.

ملخص

ان عالم الصناعة على مر السنين يعاني من شبح الأعطال المحيطة بالآلات الصناعية بنسبة 70% مما يجعل التقدم في هذا المجال يستوجب تحديا كبير قد تتحول الى صراع وتسابق بين الدول للتقدم أكثر في هذا المجال

رغم التطور التكنلوجي الذي يشهده العالم في شتى المجالات عامة وفي مجال الصيانة بشكل خاص الا انه لا تزال الأعطال محيطة بهذه الآلات بشكل رهيب، مما يستوجب في كل مرة العمل أكثر على تحسين وتطوير مجال الصيانة خاصة الصيانة الوقائية

تعتبر وسائل النقل العمومي الحديثة والمتطورة ضمن دائرة الآلات الصناعية نظرا لما تقدمه من تسهيلات ودعم لتنقل الإفراد بشكل سريع وبالتالي تساهم بشكل تناسبي في ارتفاع معدل الإنتاج وانتعاش مؤشر الاقتصاد.

تتعرض هذه الآلات لعمليات التدهور التي تؤدي إلى تعطلها والعواقب المحتملة على حسن سير العمل في المنشآت بأكملها. هناك أنواع مختلفة من عمليات التحلل: التآكل، والتعب، والشيخوخة، وما إلى ذلك، والتي تختلف سرعة تطورها تبعًا لعوامل مختلفة، مثل الظروف البيئية والتشغيلية.

تهدف هذه الاطروحة الى تطوير طرق وأساليب الصيانة الوقائية لهذه المركبات وبالتالي زيادة نسبة الموثوقية وتطوير مخطط فعال للصيانة الوقائية النبوئية، وذلك من خلال تقليل الأعطال الناتجة عن تقنية AMDEC والتي تعتبر التقنية الأكثر استعمالا في مخطط الصيانة الوقائية، مما يجعل نسبة الأعطال تتناقص مقارنتا بنسبة الموثوقية

<u>الكلمات المفتاحية:</u> الصيانة الوقائية، الموثوقية ,الأعطال,عربات الطرامواي, نظام التكييف ,AMDEC, MCDM, VIKOR ,
,FUZZY-AHP

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List of Abbreviations, Acronyms, and Initializes

F(t)	Cumulative Distribution Function
f(t)	Probability Density Function
h(t) = λ(t)	Hazard Function or Failure Rate
μ	Repair Rate
A(t)	Availability
R(t)	Reliability
M(t)	Maintainability
TBF	Time Between Failures
CTBF	Cumulative Time Between Failures (Cumulative TBF)
MTBF	Mean Time Between Failures
TTR	Time To Repair
MTTR	Mean Time To Repair
RCM	Reliability-Centered Maintenance
CBM	Conditiona-Based Preventive Maintenance
FTA	Failure Tree Analysis Approach
FEMA	Failure Effects, Modes and Criticality Analysis (FMECA or FMEA)
AHP	Analytic Hierarchy Process
DRE	Water Resources Department
MAUT	Multi-Attribute Utility Theory (MAUT)
MAVT	Multi-Attribute Value Theory (MAVT)
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
SMART	Simple Multi-Attribute Rating Technique (SMART)
MCA	Multi-Criteria Analysis
MCDM	Multiple Criteria Decision Making (MCDM)
PROMETHE	Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE)
OSM	Open Street Map

Wi	Weight of Each Criterion
□□	Eigenvalue of the Matrix
□□	Fuzzy Utility of the Alternative or Criterion
Aj min.	Minimum Value of the Criterion
aj max	Maximum Value of the Criterion
Aij.	Simulation Value
Xij	Normalized Value
AC	Air Conditioning
HP	High Pressure
CITAL	Compagnie Industrielle des Transports Algériens *(Industrial Transport Company of Algeria)*
DT	Detectability
EDAS	Evaluation Based on Distance from Average Solution
LP	Low Pressure
MBF	Reliability-Centered Maintenance
OT	Occurrence
RCM	Reliability-Centered Maintenance
RPI	Risk Priority Index
RPN	Risk Priority Number
St	Severity
VIKOR	Multi-Criteria Optimization and Compromise Solution *(original in Serbian)*

General Introduction

Economic stagnation has become a reality with which all countries, large and small, are now living especially as it is seen as the only option for recovery and progress. It helps countries establish efficient infrastructure capable of keeping pace with the modern world, particularly as competition among nations today has become economic, intellectual, and industrial.

This category (of competition) has led to the dramatic technological development the world is witnessing. As the industrial sector expands through modern technologies, which have become the core of industrial machinery, it becomes increasingly difficult to keep pace with their diversity especially in the field of maintenance. It is therefore essential to continuously develop maintenance solutions that keep up with the evolution and variation of failures and risks surrounding these machines.

The evolution of these machines leads each time to more complex industrial behavior, which also means more complex maintenance behavior and strategies. Furthermore, the random nature of deterioration and failure makes it difficult to determine a clear maintenance strategy or make proper maintenance decisions.

Despite their advancement, these machines are subject to various deterioration mechanisms over time such as corrosion, fatigue, and aging that cause breakdowns and can impact the operation of entire systems.

Preventive maintenance is considered a protective shield for these machines, and therefore an effective element in supporting economic recovery, thanks to the various methods and techniques it offers. These are well-suited to the diverse and complex nature of industrial machinery. Preventive maintenance schedules are systematically established, often based on the manufacturer's recommendations, and implemented at predetermined times.

However, after decades of use, certain machine components may operate under conditions harsher than those specified, leading them to deteriorate faster than expected. This results in breakdowns occurring before the scheduled maintenance, disrupting operational and maintenance processes, and causing major production losses, financial damage, wasted time, and even a decrease in company competitiveness.

Transport is considered one of the most important economic activities worldwide, having a direct and effective impact on the global economy. The British economist Alfred Marshall explained this in his book *Economics of Industry*, where he stated that the dominant economic reality of our time is not industrial development, but rather the conveniences provided by transportation [1]. The expansion and improvement of transport enterprises are directly linked to the growth and optimization of national economies, depending on the infrastructure they offer. This justifies the implementation of preventive actions.

Transport vehicles are considered among the most sensitive due to their tremendous technological advancement, which makes them more vulnerable and prone to breakdowns particularly in desert areas leading to a deterioration of their condition.

Preventive maintenance methods aim to find solutions that preserve these vehicles and protect them from failures that could threaten their overall reliability. Traditional maintenance methods have repeatedly proven effective, but due to the increasing complexity and transformation of these vehicles, it has become difficult to assume a limited number of failures at any given time. Therefore, it is necessary to develop solutions and decision-support methods that can help decision-makers organize and collect information without error.

Various multi-criteria methods have been proposed to overcome the limitations of traditional techniques. The initial approach was known as "Multi-Criteria Decision Making" (MCDM), developed by the American school. More recently, a new approach has been proposed by the European school for such problems, also known as "Multi-Criteria Decision Aid" (MCDA). Although fully axiomatized, MCDA aims to address the complexity of decision problems by removing the constraints of strict mathematical formalism and offering a more flexible modeling of real-world problems [3]. Moreover, many real-life applications have successfully demonstrated the viability of this method. For these reasons, MCDA now holds a leading role in the field of operational research.

From a technical point of view, FMEA (Failure Modes and Effects Analysis) addresses different classes of decision-making problems (selection, classification, ranking), explicitly taking into account multiple perspectives (multiple attributes or criteria). However, these categories have become increasingly affected by error margins, especially in modern and advanced machines and vehicles, which continually threatens the system’s reliability the system being considered the beating heart of these machines.

This has necessitated the search for solutions that connect traditional maintenance methods with technological advancements. FMEA technology has become linked to artificial intelligence methods such as MCDM (Multi-Criteria Decision Making), an approach that would significantly reduce errors and thus maintain the reliability and efficiency of preventive maintenance methods.

This thesis aims to study and analyze the failures of tramway vehicles in the southern region. The work focuses on failures in the air conditioning system, which is considered a core unit of these vehicles and is essential for passenger comfort, particularly during the summer. The work includes the development of traditional preventive maintenance methods through the direct application of Reliability-Centered Maintenance (RCM) in the first stage. In a second stage, artificial intelligence methods will be integrated with the FMEA approach to eliminate error rates. These steps will proceed as follows:

The first chapter presents a summary of studies on maintenance methods, a detailed explanation of the essential concepts of maintenance and safety, as well as the various maintenance strategies and policies adopted by companies. In particular, we present key principles such as reliability-centered maintenance methods, along with the challenges associated with using these techniques in industrial environments.

The introduction to industrial maintenance aims to define the objectives of maintenance operations, i.e., whether they meet the maintenance requirements established during the system design phase. To achieve the objectives of maintaining technological processes, increasingly sophisticated methods are being employed. This added sophistication aims to enhance the performance, reliability, availability, and operational safety of industrial processes.

Through this literature review, it becomes possible to understand the various maintenance methods applied to industrial processes and confirm that those based on reliability represent a fascinating research area.

The next chapter deals with Reliability-Centered Maintenance (RCM) techniques, including additional tools used to determine the root causes of anomalies or malfunctions when identifying critical components requiring an optimal maintenance plan. The goal is to target maintenance actions that ensure maximum cost-effectiveness. In applying the method to turbo machinery, it becomes possible to identify key elements that allow for the definition of an action plan aimed at reducing maintenance costs. The various tools used in the RCM method are derived from well-established approaches such as the criticality matrix, failure modes, effects and criticality analysis (FMECA), and decision guides.

The third chapter will cover artificial intelligence techniques such as MCDM (Multi-Criteria Decision Making), which will be integrated into the preventive maintenance technology of FMEA. These will be defined in detail, along with their methods of application and implementation, as well as the types of components involved in these technologies — such as FUZZY-AHP, VIKOR, TOPSIS, and other techniques. Each of these will be broken down step-by-step, along with the rules and principles that will be used and applied within the FMEA method.

The final chapter explains the results of applying preventive maintenance methods to the air conditioning system of southern tramways. The outcomes of the first stage are presented following the application of Reliability-Centered Maintenance (RCM), and these results are then validated through the integration of MCDM (Multi-Criteria Decision Making) technology with the FMEA method, in order to eliminate the error rate.

CHAPTER I

General Concepts and Basic Notions of Maintenance

1. **Introduction**
2. **History and Evolution of Maintenance**
3. **Maintenance Strategy**
4. **Differences Between Types of Maintenance**
5. **Maintenance Policy**
6. **Maintenance Tools and Technologies**
7. **Objectives of Maintenance**
8. **Reliability-Centered Maintenance (RCM)**
9. **Conclusion**

1. Introduction

In today's competitive economic environment, it has become crucial to reduce production costs in order to support the development and sustainability of a company. In addition to maintaining operational and well-conditioned production equipment, reduced maintenance costs and increased equipment availability rates play an essential role in productivity and even in competitiveness. This represents a major challenge for any company.

Breakdowns and incidents in production systems are among the main problems in the industry. Machine downtime significantly reduces production capacity, leading to an increase in production costs. Indeed, industrial machinery is a complex component that can help prevent many failures or disruptions. These issues are among the key concerns in the industrial sector. An unexpected machine stoppage can have significant financial repercussions. The following machine is no longer able to process output, or even deliver the final product.

It is often very difficult to anticipate a breakdown. Some mechanisms can be overly complex, making them highly vulnerable. It should also be noted that existing machines rarely suffer from faults that require their replacement with newer equipment, and the issue of accessibility to machine components can also accelerate the repair process for certain failures. Moreover, the impact of a hidden function failure on the equipment is not always noticeable during the operators' routine inspections. Furthermore, although preventive maintenance and regular, systematic interventions are costly, they do not guarantee the absence of breakdowns.

Since the beginning of the industrial era, the maintenance function has continued to evolve and become more structured. From a simple reactive approach, where action was only taken after a breakdown, maintenance has transformed into a key factor in ensuring quality, safety, meeting deadlines, productivity, and even the competitiveness of a growing company [4–6]. It is also worth noting that maintenance has undergone significant development throughout this evolution, with the aim of making it both more efficient and more effective. In this context, one can cite: systematic preventive maintenance, condition-based preventive maintenance, predictive maintenance, design-integrated maintenance, total life cycle cost, total productive maintenance (TPM), reliability-centered maintenance (RCM), computer-aided maintenance, expert diagnostic support systems, maintenance auditing, and more.
For a long time, maintenance was mainly curative, with the sole objective of minimizing machine downtime. This short-term, preventive approach did not address issues related to inevitable degradation [7, 8].

2. History and Evolution of Maintenance

Industrial maintenance has a rich history that dates back to the Industrial Revolution in the 18th century.

The evolution of industrial maintenance is characterized by a gradual shift from a reactive approach to proactive and predictive strategies. Technological advancements such as automation, computing, the Internet of Things (IoT), and Artificial Intelligence (AI) have transformed the way maintenance is planned, executed, and optimized to support productivity and the competitiveness of industrial companies.

Over time, the development of industrial maintenance has been marked by significant progress in the methods, technologies, and strategies employed mainly in response to technological innovations, industry demands, and new management approaches aimed at ensuring the reliability and availability of industrial equipment.

Below is an overview of the evolution of maintenance:

- **Reactive Maintenance:**

During the early stages of industrialization, maintenance was primarily reactive. Equipment was operated until it broke down, at which point repairs were carried out to restore it to service. This approach was often costly due to unplanned downtime and the need for urgent interventions to address failures. [9]

- **Industrial Revolution and Early 20th Century:**

At the beginning of the Industrial Revolution, maintenance was largely reactive. Equipment was used until it failed, resulting in unplanned downtime and disruptions in production. With the advancement of engineering and the rise of mass production industries in the early 20th century, preventive maintenance began to emerge. Companies started planning and performing regular inspections and preventive repairs to avoid costly breakdowns and prolonged production stoppages. [9]

Throughout the 20th century, preventive maintenance became increasingly widespread. This approach involved the scheduling and execution of regular maintenance activities such as inspections, lubrication, and parts replacement in order to prevent equipment failures and optimize asset lifespan. As a result, unplanned downtime was reduced, and equipment reliability improved.

- **World War II and the Post-War Period:**

During World War II, maintenance experienced significant advancements due to the critical need to keep military equipment in proper working condition. More sophisticated preventive maintenance methods were developed, including the use of Gantt charts for planning maintenance activities.

- **1960s–1980s:**

During this period, automation and computerization revolutionized industrial maintenance. The first Computerized Maintenance Management Systems (CMMS) were developed to efficiently manage maintenance activities.Predictive maintenance also began to emerge, driven by the use of advanced monitoring technologies such as vibration analysis and thermographic analysis.

- **1990s–2000s:**

The advent of the Internet of Things (IoT) opened up new possibilities for predictive maintenance. Connected sensors enabled the real-time collection of data on equipment performance, making it easier to detect potential failures at an early stage. [10]

There was a strong emphasis on proactive asset management and on maximizing equipment lifespan through optimized maintenance programs.

- **2010s and Beyond:**

Predictive maintenance continues to evolve with the increasing integration of Artificial Intelligence (AI) and Machine Learning (ML). These technologies enable the analysis of large volumes of data to predict failures with greater accuracy.

Reliability-Centered Maintenance (RCM) and Condition-Based Maintenance (CBM) have become more common approaches, aiming to maximize equipment availability while minimizing costs.

The evolution of industrial maintenance is marked by a gradual shift from reactive strategies to proactive and predictive ones. Technological advances including automation, computing, IoT, and AI have transformed the way maintenance is planned, executed, and optimized to support the productivity and competitiveness of industrial enterprises. [11]

3. Maintenance Strategy

3.1. Definition of Maintenance

According to the French standard **NF EN 13306 X 60-319**, maintenance is defined as:*"All the technical, administrative, and managerial actions during the life cycle of an asset intended to maintain it in, or restore it to, a state in which it can perform the required function."* [9,12]

Maintenance encompasses both **planned and unplanned activities** aimed at ensuring the proper functioning, reliability, and availability of equipment, facilities, and systems across various sectors such as industry, services, transportation, and mo

It icludes a wide range of tasks and strategies, from regular inspections to the repair and replacement of parts, as well as continuous monitoring of equipment condition. The main objective of maintenance is to ensure that an organization's physical assets operate optimally minimizing unplanned downtime, extending their useful life, and reducing maintenance costs.

Maintenance can be classified into various categories such as corrective maintenance, preventive maintenance, predictive maintenance, and condition-based maintenance depending on the nature of the activities and the timing of interventions. It plays a crucial role in asset management and in maximizing the productivity and profitability of organizations.

Industrial maintenance is a critical field within the manufacturing and industrial sectors. It encompasses all activities aimed at ensuring the availability, reliability, and durability of equipment, machinery, and facilities used in production processes. [11]

In summary, maintenance is a vital function across all industrial and commercial sectors, aimed at ensuring the availability, reliability, and longevity of equipment and installations to support operations efficiently and cost-effectively.

3.2. Maintenance Function

The primary objective of the maintenance function is to support the company's operations by ensuring the continuous availability, reliability, and optimal performance of equipment, while also safeguarding personnel and controlling maintenance-related costs, in accordance with AFNOR standards [13].

In other words, the core responsibility of maintenance is to optimally manage production equipment in alignment with the company's specific objectives [14].

The following figure illustrates the main functions of maintenance. The key processes of the maintenance function can be summarized as follows:

- **Planning :**
  - Developing a preventive maintenance schedule based on manufacturer recommendations and operational experience.
  - Preparing the necessary resources (labor, spare parts, and tools).
- **Execution :**
  - Carrying out the planned maintenance activities.
  - Inspections, cleaning, replacement of faulty parts, adjustments.

- **Monitoring and Analysis:**
  - Recording completed maintenance activities.
  - Monitoring equipment performance after maintenance.
  - Analyzing data to optimize maintenance practices.

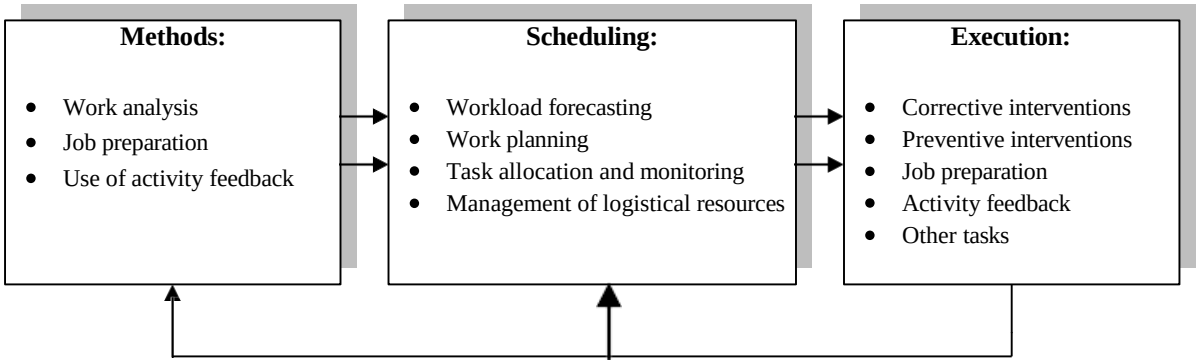


Figure I.1: Operational Functions of Maintenance [31]

3.3. Types of maintenance

There are several types of maintenance used in organizations to ensure the reliability and availability of equipment [15]. Each type of maintenance addresses specific needs depending on the characteristics of the equipment, operational requirements, and the organization's objectives. The diagram (Figure I.2) illustrates the main types of maintenance.

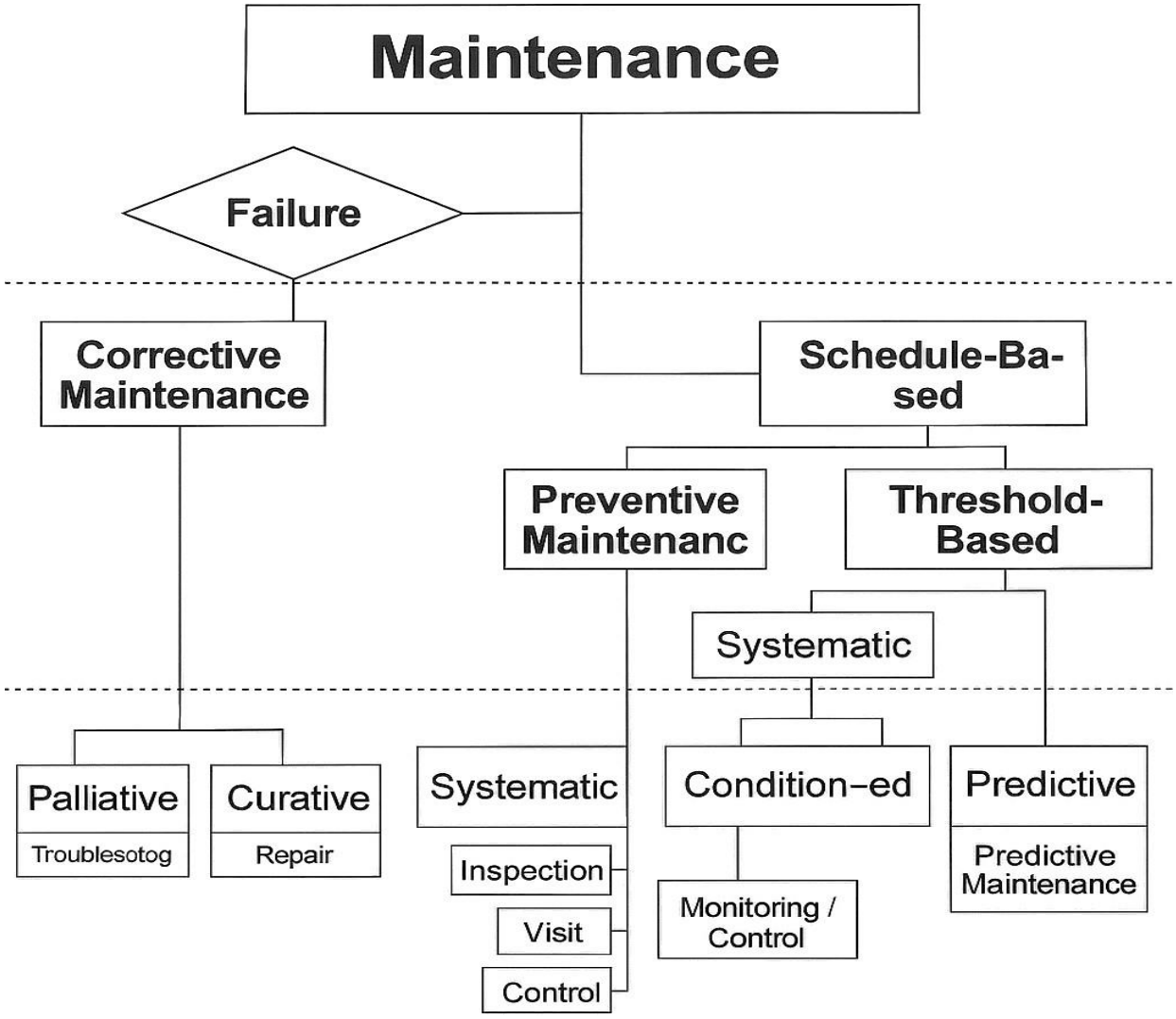


Figure I.2: Classification of Maintenance Types [31]

3.3.1. Corrective maintenance

According to the NF EN 13306 standard, corrective maintenance is a maintenance strategy that involves intervening on equipment or a system after a failure or malfunction has been detected.Unlike preventive maintenance, which aims to prevent breakdowns through planned actions, corrective maintenance is reactive in nature and focuses on repairing or restoring equipment that is no longer functioning properly.

Although corrective maintenance is often seen as a reactive and costly approach, it remains essential for ensuring equipment availability and minimizing production losses in the event of unexpected failures.However, it can be optimized by implementing preventive measures to reduce the number of failures and by improving diagnosis and repair processes to shorten downtime.According to Figure I.3, corrective maintenance activities are carried out as a direct result of the occurrence of a failure.

Here are some key points to know about corrective maintenance:

- **Reactivity:**

Corrective maintenance is often reactive, meaning it is triggered in response to a failure or a problem that affects the normal operation of equipment. Its goal is to restore equipment functionality as quickly as possible in order to minimize production downtime.

- **Diagnosis and Repair:**

When a breakdown occurs, maintenance technicians must diagnose the root cause of the issue and take the necessary steps to resolve it. This may involve repairing or replacing faulty components, adjusting parameters, or performing other appropriate corrective actions.

- **Downtime Management:**

Downtime associated with corrective maintenance can have a significant impact on production and profitability. Therefore, it is crucial to minimize these downtimes by planning and executing interventions effectively and efficiently.

- **Root Cause Analysis:**

While corrective maintenance aims to restore functionality, it is also important to conduct root cause analysis to understand why the failure occurred and how it can be prevented in the future. This helps in implementing preventive measures to reduce the risk of recurrence.

- **Costs:**

Corrective maintenance can be costly, especially when it leads to extended downtime or involves complex repairs. Therefore, it is often preferable to adopt a proactive approach by combining corrective maintenance with preventive and predictive strategies to minimize costs and optimize equipment availability.

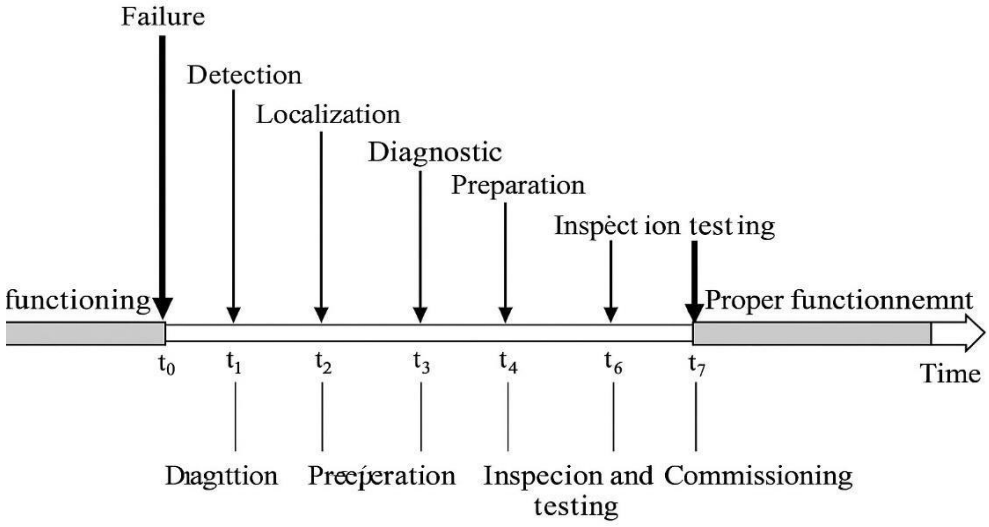


Figure I.3: Corrective Maintenance Application Process [31]

3.3.1.1. Curative maintenance

Curative maintenance, also known as breakdown maintenance**,** is a type of maintenance performed after the detection of a failure or malfunction. Its main objective is to restore the normal operation of equipment, machinery, or a system by repairing or replacing the defective components. Corrective maintenance is therefore **reactive**, as it is carried out in response to a failure**.** [16]

3.3.1.2. Palliative maintenance

Palliative maintenance is short-term and temporary. It mainly consists of interventions that must later be followed by troubleshooting or full repair operations. Troubleshooting involves temporary maintenance work aimed at restoring the system's functionality so that it can perform at least part of its required functions**.** These interventions are often brief but can occur frequently, and due to their recurrence, they can also be very costly. [16, 17]

3.3.1.3. Steps for Developing a Corrective Maintenance Plan

A corrective maintenance plan is a structured set of procedures and guidelines used to effectively manage maintenance interventions in response to failures or malfunctions occurring on industrial equipment. The purpose of this plan is to minimize downtime, quickly restore proper equipment functionality, and ensure operational safety.

Here are the typical steps for developing a corrective maintenance plan:

- **Identification of Critical Equipment:** Determine which equipment is critical to production and requires the highest responsiveness in the event of a failure.

- **Definition of Intervention Procedures:** Establish detailed procedures for reporting failures, prioritizing interventions, and mobilizing the necessary resources (technicians, spare parts, tools).
- **Creation of Intervention Sheets:** Develop standardized intervention forms for each common type of failure, outlining the steps to diagnose and resolve the issue.
- **Staff Training:** Ensure that maintenance technicians are trained on the specific procedures to follow during corrective interventions, including safety instructions.
- **Intervention Request Management:** Implement a system to manage maintenance requests, allowing for the tracking and prioritization of tasks based on urgency and production impact.
- **Resource Planning:** Plan the resources required for executing corrective interventions, including work schedules, technician availability, and spare parts supply.
- **Monitoring and Reporting:** Set up a tracking system to record the details of each corrective intervention, including downtime, parts used associated costs, and actions taken to prevent similar future failures.
- **Root Cause Analysis:** After each corrective intervention, conduct a thorough root cause analysis to understand why the failure occurred and implement preventive corrective measures if necessary.
- **Continuous Improvement:** Use the collected data to continuously improve corrective maintenance procedures and reduce overall downtime.

3.3.1.4. Example of Corrective Maintenance Plan Content :

- Procedures for failure notification and intervention request.
- Intervention prioritization matrix based on production impact.
- List of resources required for each type of corrective intervention.
- Control checklists for maintenance technicians.
- Intervention form templates for different types of failures.
- Root cause analysis methods.
- Performance metrics and key indicators to evaluate the effectiveness of corrective maintenance.

3.3.1.5. Advantages and Disadvantages

Although corrective maintenance is often considered reactive (i.e., performed after a failure or breakdown has occurred), it still presents certain advantages in specific situations:

- **Quick Response:** One of the main advantages of corrective maintenance is its ability to quickly respond to an immediate issue. When a failure occurs unexpectedly, prompt action can restore normal equipment operation without the need for prior scheduling.

- **Lower Initial Costs:** In some cases, corrective maintenance may be less expensive in the short term, as it does not require advance planning resources or efforts. Costs are generally limited to replacement parts and labor needed for the repair.
- **Simplified Management:** Since corrective maintenance does not involve long-term planning, it can be easier to manage in situations where the equipment is not critical or where the risks associated with failure are acceptable.
- **Maximum Equipment Utilization:** In certain cases, a corrective maintenance **approach** may be appropriate for equipment whose failure does not significantly impact overall operations, or where downtime costs are not prohibitive.

- However, it is important to note that corrective maintenance also comes with significant disadvantages:

  - R**isk of Prolonged Downtime:** In the case of major failures, corrective maintenance can result in extended downtime, which may negatively impact production or operations.
  - **High Indirect Costs:** In addition to the direct repair costs, there are often indirect costs associated with corrective maintenance, such as production losses, delivery delays, and potentially further damage to equipment or processes.
  - **Increased Risk of Recurring Failures:** Corrective maintenance often only addresses the immediate symptom of the failure without tackling the root cause. This can lead to repeated failures, requiring multiple repairs and affecting the overall reliability of the equipment.

3.3.2. Preventive maintenance

Preventive maintenance is a planned maintenance strategy that involves performing regular and proactive actions on equipment, machinery, or industrial installations to reduce the risk of failures and ensure their proper functioning.
The main objective of preventive maintenance is to prevent potential breakdowns by carrying out interventions before critical issues occur.

Preventive maintenance can be classified into several types based on the nature of the planned activities and the methods used to keep equipment in good working condition. Here are the main aspects of preventive maintenance:

- **Scheduling:** Preventive maintenance is scheduled in advance based on a predefined calendar, manufacturer recommendations, or industry standards. Interventions are programmed at regular intervals (weekly, monthly, annually, etc.) depending on the specific needs of each piece of equipment.

- **Preventive Actions:** Specific tasks are carried out during preventive interventions, such as visual inspections, replacement of worn parts, lubrication, cleaning, parameter adjustments, performance **tests**, and more.

- **Risk Reduction:** By identifying and correcting potential issues before they cause major failures, preventive maintenance helps reduce the risk of unplanned downtime, production disruptions, and high repair costs.
- **Extended Equipment Lifespan:** By keeping equipment in good working condition and avoiding major breakdowns, preventive maintenance contributes to extending the operational life of assets and optimizing their performance.
- **Improved Safety:** Regular inspections carried out as part of preventive maintenance activities also help identify and address safety hazards, thereby improving working conditions and reducing the risk of accidents.

3.3.2.1. Systematic Preventive Maintenance

Systematic preventive maintenance consists of planned and regular actions carried out according to a pre-established schedule. These actions include periodic inspections, lubrication, replacement of parts at fixed intervals, performance tests, etc.

3.3.2.2. Time-Based Preventive Maintenance

In this type of preventive maintenance, activities are scheduled based on the time elapsed since the last intervention or since the equipment was first put into operation. For example, an annual inspection or part replacement every 10,000 operating hours.

3.3.2.3. Usage-Based Preventive Maintenance

Usage-based preventive maintenance considers the actual operating hours of the equipment to schedule interventions. Maintenance activities are triggered based on the number of production hours or equipment usage cycles.

3.3.2.4. Condition-Based Preventive Maintenance

This type of preventive maintenance uses equipment condition indicators to determine the optimal time for interventions.Sensors, data analysis, and monitoring techniques are used to detect signs of degradation or impending failure

3.3.2.5. Opportunistic Preventive Maintenance

This type of preventive maintenance involves taking advantage of scheduled production downtimes or low-load periods to carry out preventive maintenance tasks. It helps minimize the impact

3.3.3. Condition-Based Maintenance (CBM)

Condition-based maintenance, also known as preventive condition-based maintenance, is defined by the AFNOR standard X 60-010 as a proactive and effective maintenance strategy that involves continuous monitoring of the condition and performance of equipment using specialized monitoring and analysis techniques. On production while ensuring equipment availability.

This method allows the detection of early signs of failure or potential issues, enabling maintenance interventions to be scheduled at the most appropriate time, before a major failure occurs.

3.3.3.1. Tools Used in Condition-Based Maintenance

It is essential to use condition-based maintenance tools to monitor the condition of machines and industrial equipment and anticipate failures before they occur.The most commonly used tools in condition-based maintenance are illustrated in FigureI.4.

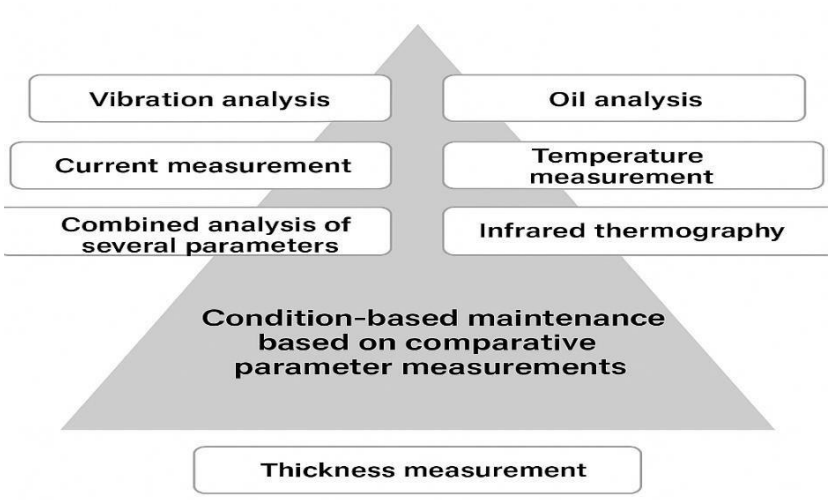


Figure I.4: Tools for Conditional Maintenance [20]

- **Vibration Analysis**: Monitoring vibrations to detect anomalies in bearings, gears, and mechanical components.
- **Infrared Thermography**: Detecting temperature variations to identify hotspots indicating overheating issues or poor insulation.
- **Oil Analysis**: Evaluating the condition of lubricants to detect the presence of contaminants or metallic particles indicating abnormal wear.
- **Electrical Current Analysis**: Monitoring electrical parameters to detect imbalances, overloads, or electrical faults.
- **Non-Destructive Testing (NDT)**: Using techniques such as radiography, ultrasound, or magnetic particle inspection to examine components without damaging them.

3.3.3.2. Characteristics of Condition-Based Maintenance

- **Continuous Monitoring**: Equipment is continuously monitored using sensors, measuring instruments, and monitoring systems to collect data on critical operating parameters such as vibrations, temperature, pressure, etc.
- **Data Analysis**: The collected data is analyzed to detect trends, patterns, or anomalies that may indicate potential issues. Advanced analysis techniques such as machine learning or signal processing algorithms can be used to interpret the data.
- **Early Failure Detection**: Condition-based maintenance allows for the early detection of failure indicators or anomalies as soon as they appear, enabling intervention before the failure occurs or becomes critical.
- **Maintenance Planning**: Maintenance interventions are scheduled based on monitoring results and recommendations from diagnostic systems, allowing for efficient use of maintenance resources and reducing unplanned downtime.
- **Types of Techniques**: Condition-based maintenance includes various monitoring techniques such as vibration analysis, infrared thermography, oil analysis, acoustic signal analysis, etc., adapted to the specific characteristics of the monitored equipment.
- **Resource Optimization**: By specifically targeting equipment that requires immediate attention, condition-based maintenance enables optimal use of maintenance resources and reduces costs associated with preventive or corrective interventions.

3.3.3.3. Principle of Condition-Based Preventive Maintenance

The main objective of condition-based preventive maintenance is to detect early signs of failure or potential issues in industrial equipment by continuously monitoring critical operating parameters.

Condition-based preventive maintenance is defined as maintenance that is carried out only when the condition of the asset requires it. For this reason, it is essential to control and schedule various condition monitoring methods (both technical and economic reliability) in order to provide an accurate assessment of the equipment's state.To perform this task, it is necessary to first select a set of monitoring indicators, derived from a more or less precise parameter or variable, which is often accessible during operation. The purpose of an indicator is to characterize the condition or performance of a device. Its progression over time should be significant due to the appearance or worsening of a defect or a set of defects (see Figure I.5). [18,19].

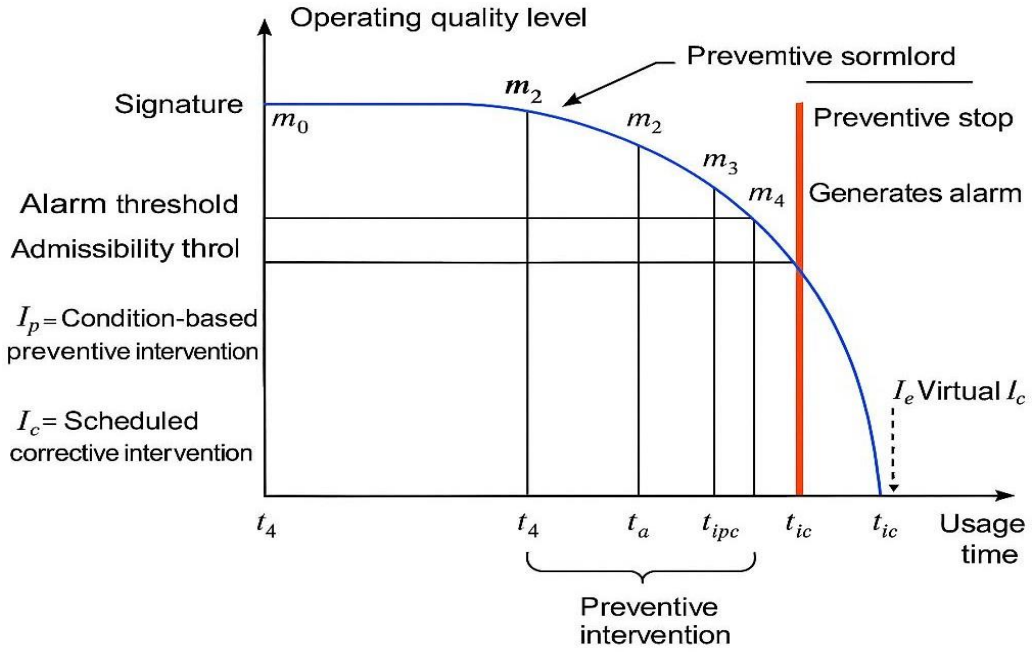


Figure I.5: Principle of Conditional Preventive Maintenance [20]

3.3.3.4. Advantages of Condition-Based Maintenance

- **Reduction of Downtime**: By detecting issues before they lead to major failures, condition-based maintenance allows for proactive scheduling of interventions, thereby reducing unplanned downtime.
- **Resource Optimization**: Maintenance activities are focused on equipment that requires immediate attention, optimizing the use of maintenance resources.
- **Extension of Equipment Lifespan**: By identifying and correcting problems as soon as they appear, condition-based maintenance helps extend the operational life of equipment.
- **Improved Safety**: By reducing the risk of major failures, condition-based maintenance contributes to maintaining a safe working environment.

3.3.3.5. Steps to Develop a Preventive Maintenance Plan

A preventive maintenance plan is essential for effectively implementing regular and scheduled maintenance activities aimed at preventing failures and keeping equipment in good working condition. Here are the steps to develop a preventive maintenance plan:

- **Inventory of Equipment**: Create a complete list of equipment that requires preventive maintenance, including machines, tools, production systems, etc.
- **Risk and Criticality Analysis**: Assess the importance of each piece of equipment in terms of production, safety, and operational impact. Determine the consequences of a failure for each item.
- **Identification of Maintenance Tasks**: Define the preventive maintenance tasks required for each piece of equipment, based on manufacturer recommendations, industry best practices, and past experiences.
- **Definition of Frequencies and Interventions**: Establish how often each preventive maintenance task should be carried out (daily, weekly, monthly, annually, etc.) based on the manufacturer's specifications and operational requirements.
- **Development of Procedures**: Create detailed procedures for each preventive maintenance task, describing the steps to follow, required tools, part replacement intervals, etc.
- **Assignment of Responsibilities**: Clearly assign responsibility for carrying out each preventive maintenance task, identifying the team members in charge of each piece of equipment or area.
- **Resource Planning**: Plan the resources needed to implement the preventive maintenance plan, including skilled technicians, spare parts, safety equipment, etc.
- **Implementation of a Monitoring System**: Set up a monitoring system to record completed preventive maintenance activities, observations, and results. Use Computerized Maintenance Management System (CMMS) tools if needed.
- **Evaluation and Revision**: Regularly evaluate the effectiveness of the preventive maintenance plan by analyzing equipment performance and collecting feedback from operators. Revise the plan as needed to optimize it.

3.3.3.6. Example of the Content of a Preventive Maintenance Plan

A well-designed preventive maintenance plan helps ensure the availability, reliability, and durability of industrial equipment by minimizing the risk of failure and optimizing operational performance. It is important to tailor the plan to the specific needs of your organization and the characteristics of your equipment. (Figure I.6)

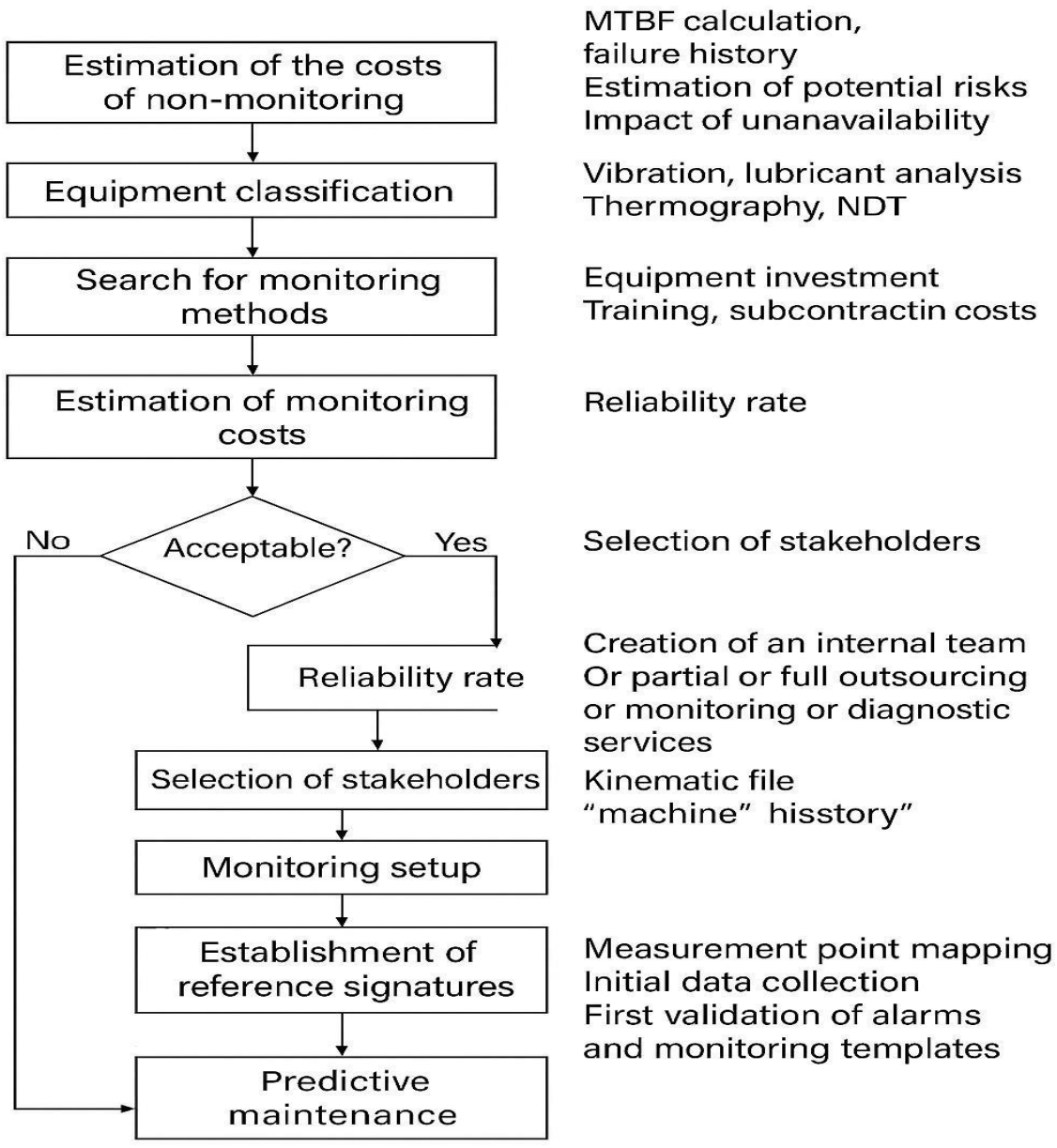


Figure I.6: Logical Diagram of a Preventive Maintenance Plan [11]

3.3.4. Predictive Maintenance

Predictive maintenance is a maintenance strategy based on real-time monitoring of the health status of equipment and systems. It uses sensors, measuring instruments, and advanced technologies to collect data on equipment operating conditions, in order to anticipate failures and identify maintenance needs before they become critical. (Standard NF EN 13306)

The technologies used in predictive maintenance include IoT (Internet of Things) sensors, remote monitoring systems, advanced data analysis software, and artificial intelligence algorithms. These tools enable organizations to adopt a proactive and efficient maintenance approach, thereby improving the availability, reliability, and overall performance of their industrial assets [21, 22]. Below are the main aspects of predictive maintenance:

- **Monitoring of Operating Parameters**: Predictive maintenance uses sensors and monitoring systems to collect real-time data on operating parameters such as vibrations, temperature, pressure, electric current, etc.
- **Data Analysis**: The collected data is analyzed using advanced techniques such as variance analysis, machine learning algorithms, or other statistical analysis methods to detect trends, patterns, or anomalies that indicate potential problems.
- **Early Failure Detection**: By proactively monitoring equipment, predictive maintenance enables the detection of early signs of failure (e.g., abnormal increases in vibration) before the failure actually occurs.
- **Maintenance Scheduling**: When anomalies or deviations are detected, alerts are triggered to schedule maintenance interventions at the most appropriate time, such as during a planned production shutdown or a low-activity period.
- **Resource Optimization**: Predictive maintenance optimizes resource usage by specifically targeting equipment that requires immediate attention, thereby reducing maintenance costs and unplanned downtime.
- **Cost Reduction**: By anticipating failures and performing targeted interventions, predictive maintenance helps reduce overall maintenance costs by avoiding emergency repairs and extending equipment lifespan.

3.3.4.1. Tools of Predictive Maintenance

Predictive maintenance relies on several methods and techniques to monitor and analyze industrial equipment data, detect early signs of failure, and proactively schedule maintenance interventions. Below are some of the main types of techniques used in predictive maintenance:

- ✓ **Vibration Analysis**: This technique involves monitoring equipment vibrations using vibration sensors. Abnormal variations in vibration levels may indicate issues such as imbalance, misalignment, bearing wear, or other defects.
- ✓ **Acoustic Signal Analysis**: This method detects sounds emitted by equipment using acoustic sensors. Variations in sound signatures can indicate problems such as excessive friction, leaks, or mechanical failures.
- ✓ **Infrared Thermography**: Infrared thermography uses thermal cameras to measure the surface temperatures of equipment. Abnormal temperature variations can indicate hot spots, overheating, insulation defects, or electrical issues.
- ✓ **Oil Analysis**: This method involves periodically analyzing the condition of equipment lubricating oil to detect the presence of metal particles, moisture, acids, or other contaminants that could indicate lubrication or contamination problems.
- ✓ **Electric Current Analysis**: This technique monitors the electrical parameters of equipment such as voltage, current, and power. Abnormal variations may indicate problems like overload, short circuit, or poor connections.
- ✓ **Process Data Analysis**: This method uses process data such as pressure, flow, temperature, or other variables to detect abnormal trends or variations that may indicate performance or operational issues with the equipment.
- ✓ **Artificial Intelligence and Data Analysis**: AI techniques, including machine learning and signal processing algorithms, are used to analyze large volumes of data and detect patterns or anomalies that may signal potential problems.

These techniques are often combined and integrated into advanced monitoring systems to provide a comprehensive assessment of equipment condition and enable informed decision-making in predictive maintenance. By using these methods, organizations can optimize the reliability, availability, and performance of their industrial assets while reducing maintenance costs and avoiding unplanned downtime.

Implementing a predictive maintenance plan requires a specific approach to continuously monitor equipment and analyze data in order to detect early signs of failure.

3.3.4.2. Advantages of Predictive Maintenance

The advantages of predictive maintenance include a reduction in unplanned downtime, an extension of equipment lifespan, optimization of maintenance costs, better planning of resources, and improved operational safety.

By integrating predictive maintenance into a broader asset management strategy, organizations can enhance the reliability, availability, and performance of their equipment while reducing maintenance costs and optimizing operational efficiency.

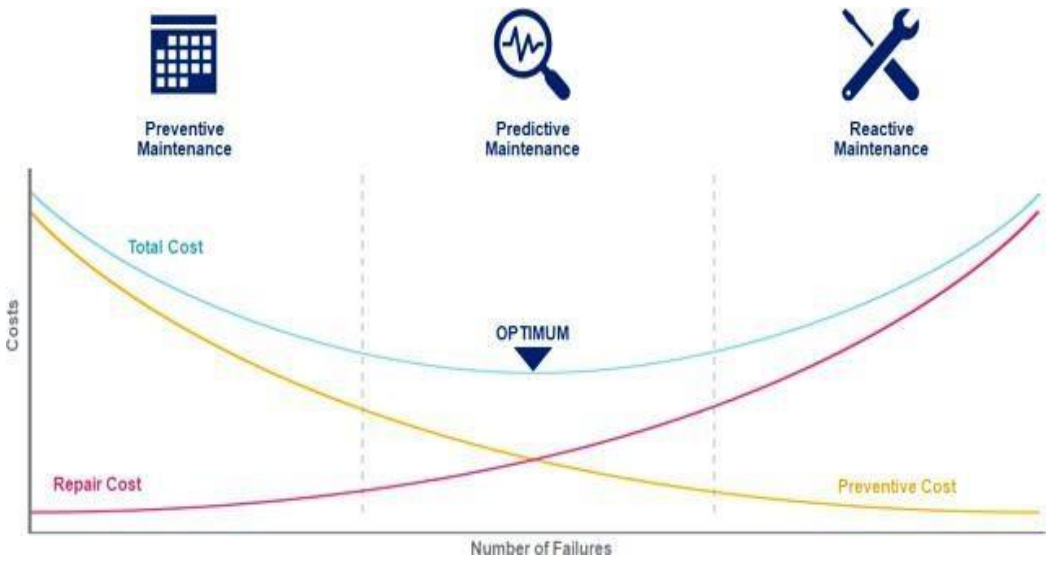


Figure I.7: Curve Showing the Effect of Predictive Maintenance [32]

3.3.4.3. Steps to Develop a Predictive Maintenance Plan

- **Identification of Critical Equipment**: Identify the most critical equipment for business operations those whose failure could have a major impact on production, safety, or quality.
- **Selection of Monitoring Parameters**: Determine the key operating parameters to monitor for each piece of equipment (vibrations, temperature, pressure, electric current, etc.), based on potential failure modes.
- **Installation of Sensors and Monitoring Systems**: Install the necessary sensors and monitoring systems to continuously collect data on the equipment's operating parameters.
- **Configuration of Alerts and Alarm Thresholds**: Set up alerts and alarm thresholds for each monitored parameter to trigger notifications when predefined limits are exceeded.
- **Real-Time Data Analysis**: Use real-time data analysis tools to monitor and analyze trends, patterns, and anomalies in the collected data.
- **Development of Predictive Models**: Develop predictive models based on data analysis to anticipate failures or potential issues and predict the optimal timing for maintenance interventions.
- **Scheduling of Maintenance Interventions**: Schedule maintenance tasks according to the forecasts provided by predictive models, taking into account operational priorities and available resources.

- **Implementation of a Data Management System**: Set up a data management system to store, organize, and analyze monitoring data, and to generate reports on equipment performance and trends.
- **Training of Personnel**: Train maintenance staff in the use of monitoring equipment, data analysis tools, interpretation of results, and maintenance scheduling.
- **Evaluation and Adjustment**: Regularly assess the effectiveness of the predictive maintenance plan by analyzing equipment performance and comparing actual outcomes with model predictions. Adjust the plan as needed to optimize it.

3.3.4.4. Content of a Predictive Maintenance Plan

- List of critical equipment and monitoring parameters
- Description of the sensors and monitoring systems to be used
- Configuration of alerts and alarm thresholds
- Predictive models developed for each piece of equipment
- Predictive maintenance schedule based on model forecasts
- Data management system for storing and analyzing monitoring data
- Training program for maintenance personnel

By implementing an effective predictive maintenance plan, organizations can reduce unplanned downtime, minimize maintenance costs, and improve the reliability and availability of their industrial equipment.

3.3.5. Proactive Maintenance

Proactive maintenance is a strategic approach that aims to identify and eliminate the root causes of potential failures before they occur. Unlike corrective maintenance, which is carried out after a failure has happened, proactive maintenance involves preventive actions designed to avoid failures before they disrupt operations.

3.3.5.1. Characteristics and Key Principles of Proactive Maintenance

- **Failure Modes and Effects Analysis (FMEA):**
  - Identification of potential equipment failure modes.
  - Evaluation of the consequences of these failures on operations and safety.
- **Preventive Planning :**
  - Implementation of preventive maintenance programs based on risk analysis.
  - Scheduling maintenance activities to eliminate root causes of failures.

- **Continuous Monitoring :**
  - Use of sensors and monitoring systems to detect early signs of failure.
  - Real-time data collection on equipment performance to anticipate potential issues.
- **Staff Training :**
  - Raising staff awareness of the importance of proactive maintenance.
  - Training on detecting early signs of failure and on actions to take to prevent breakdowns.
- **Process Improvement**
  - Analysis of root causes of failures to identify opportunities for process improvement.
  - Implementation of changes to eliminate recurring issues and enhance equipment reliability.

3.3.5.2. The Advantages of Proactive Maintenance Include

- Reduction of Downtime: By preventing failures before they occur, proactive maintenance reduces unexpected downtime and ensures operational continuity.
- Performance Optimization: By keeping equipment in optimal condition, proactive maintenance helps maximize operational efficiency and productivity.
- Cost Savings: By avoiding emergency repairs and major breakdowns, proactive maintenance reduces overall maintenance costs and optimizes resource use.

3.3.6. Renovation or Rehabilitation Maintenance

This approach aims to refurbish aging, obsolete, or damaged equipment to extend its operational life, improve performance, or adapt it to new requirements. Unlike corrective maintenance, which restores equipment functionality after a failure, renovation or rehabilitation often involves more extensive actions to modernize or upgrade the equipment.

3.3.6.1. Objectives of Renovation or Rehabilitation Maintenance

- **Extension of Equipment Lifespan:** By refurbishing worn or defective components, the operational life of equipment can be extended.
- **Performance Improvement:** Renovation can enhance equipment performance by modernizing certain parts or adapting them to new requirements.
- **Compliance with Standards or Regulations:** Rehabilitation is sometimes necessary to ensure equipment complies with evolving safety, environmental, or industrial standards.

3.3.6.2. Process of Renovation or Rehabilitation Maintenance

- **Inspection and Evaluation:** Equipment is inspected to assess its current condition and determine necessary renovation actions.
- **Planning:** A renovation plan is developed, outlining the work to be done, required resources, and schedule.
- **Execution:** Renovation work is carried out, often including replacement of worn components, modernization of obsolete technologies, and system upgrades.
- **Testing and Validation:** Renovated equipment is tested to ensure it functions according to the required specifications.

3.3.6.3. Advantages

- **Financial Savings:** Renovation can be more cost-effective than complete equipment replacement, especially for large or expensive assets.
- **Waste Reduction:** Rehabilitation extends the life of equipment, thereby reducing the amount of waste generated from replacements.
- **Maintaining Competitiveness:** By modernizing existing equipment, companies can remain competitive by improving operational efficiency and production capacity.

4. Difference Between Types of Maintenance

The difference between corrective, preventive, and predictive maintenance lies in the timing of the maintenance activities and their objectives.

- Corrective maintenance responds to failures that have already occurred.
- Preventive maintenance aims to prevent failures by performing regular, scheduled actions.
- Predictive maintenance anticipates failures by monitoring equipment performance in real time.

Each of these approaches has its own advantages and is applied according to the specific needs of the organization and its asset management goals. The main points of difference can be summarized as shown in Table I.1.

Table I.1: Comparison Between Maintenance Types

Type of Maintenance	Approach	Planning	Objective	Advantages
Corrective Maintenance	Takes place after a failure or malfunction has been detected on a piece of equipment. It aims to restore proper functioning after a problem has occurred.	Corrective interventions are reactive and not planned in advance. They are triggered in response to a failure or malfunction.	To repair or replace faulty components to restore normal operation and minimize unplanned downtime.	Quick equipment repair, reduction of downtime, suitable for emergency situations.
Preventive Maintenance	Involves performing regular planned actions on equipment, regardless of any signs of failure, to prevent breakdowns.	Preventive maintenance interventions are scheduled in advance based on time, usage, or performance criteria.	To prevent failures by performing inspections, lubrication, adjustments, and part replacements at regular intervals.	Reduces risk of failure, extends equipment lifespan, minimizes planned downtime, and helps prevent breakdowns.
Predictive Maintenance	Uses continuous monitoring of equipment operating parameters.	Predictive maintenance interventions are based on real-time monitoring and data analysis.	To detect early signs of failure or potential problems before they lead to breakdowns.	Early fault detection, optimized maintenance schedules, reduced maintenance costs, increased equipment reliability.

The three maintenance approaches (corrective, preventive, and predictive) are complementary and can be used together to optimize equipment reliability and availability while minimizing maintenance costs. A balanced combination of these strategies enables an organization to improve its operational performance and maximize the return on its industrial assets.

5. Maintenance Policy

An organization's maintenance policy defines the principles, objectives, and strategies that guide the management of maintenance activities. It serves as a guiding framework for making decisions related to the maintenance of equipment and facilities, aligning maintenance practices with the overall goals of the organization. The different types of maintenance policies can be summarized in Figure I.8 [21].

A well-defined maintenance policy helps align the efforts of the maintenance team with the organization's strategic objectives, optimize investments in physical assets, and ensure sustainable operations. It is a critical strategic framework for managing resources effectively and maximizing the value of industrial equipment.

The maintenance policy also referred to as the maintenance strategy defines the guiding principles and overall direction for decisions and actions related to maintenance management within an organization. This policy aims to optimize the availability, reliability, and sustainability of equipment, while controlling costs and ensuring safe operations [23]. Below are the key elements generally included in a maintenance policy:

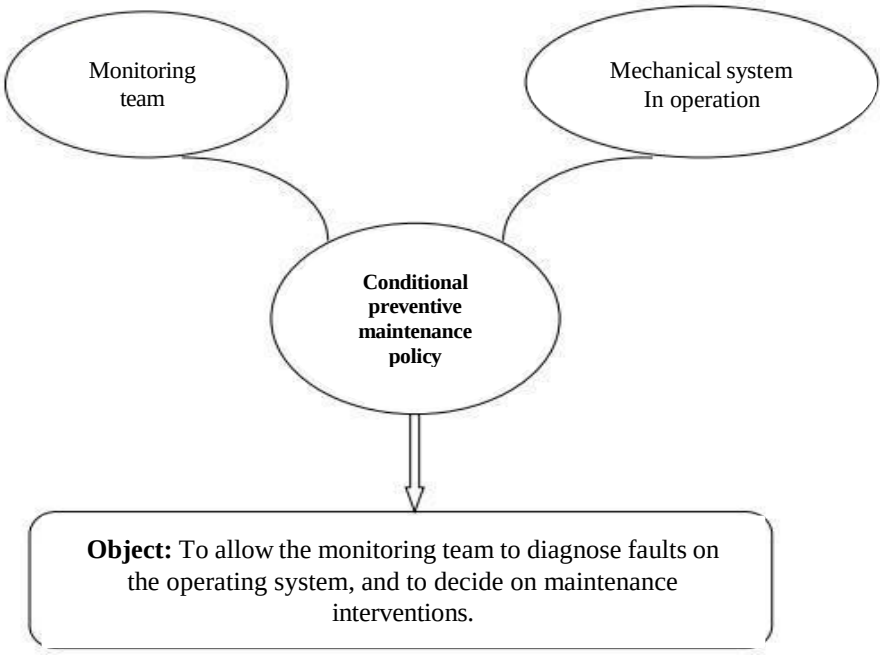


Figure I.8 : Different Maintenance Policies [24]

- Key Aspects of a Maintenance Policy:

- **Performance Objectives:** The maintenance policy defines the performance targets to be achieved in terms of equipment availability, reliability, safety, sustainability, and operational efficiency. These objectives may vary depending on the specific needs of the organization and its industry sector.

- **Maintenance Strategies:** It outlines the approaches and maintenance strategies to be adopted to meet the defined objectives. This may include methods such as preventive maintenance, corrective maintenance, predictive maintenance, condition-based maintenance, as well as specific programs to manage critical assets.

- **Planning and Resource Allocation:** The maintenance policy establishes the processes and criteria for effectively planning and allocating the necessary resources for maintenance, including human, material, financial, and technological resources.

- **Documentation and Monitoring:** It defines the requirements for documenting maintenance activities, including procedures, intervention reports, maintenance history, and key performance indicators (KPIs). It also specifies methods for monitoring and evaluating maintenance performance in relation to the defined objectives.
- **Safety and Compliance:** The maintenance policy incorporates safety measures and regulatory compliance to ensure that maintenance activities are conducted safely and in accordance with applicable standards and regulations.
- **Continuous Improvement:** It promotes the continuous improvement of maintenance practices by identifying opportunities to optimize processes, technologies, and workforce skills. This may include implementing best practices, adopting new technologies, and investing in staff training.

5.1. Choiosing a Maintenance Policy

Each component of a system is subject to deterioration processes caused by operating conditions and/or the environment, such as wear, fatigue, aging, and various physico-chemical degradations. But what does the term "maintenance policy of a system" actually mean?

All stakeholders involved in maintenance must understand the economic importance of such a definition in order to properly grasp the different steps involved in selecting an appropriate maintenance policy for equipment. The goal is to achieve the lowest possible total maintenance cost for the equipment. [18,23]

Defining the maintenance policy of a system involves making deliberate decisions on the following:

Which maintenance method should be implemented? Preventive or corrective? What level of preventive maintenance? What type of preventive maintenance? And at what frequency should interventions be carried out?

What are the most cost-effective methods to minimize failure-related costs in corrective maintenance?

How can an effective maintenance policy be introduced?

Since maintenance requires a rational combination of resources and is an ongoing process, it is essential to establish a preliminary policy.

Maintenance studies aim to implement a condition-based preventive maintenance policy, which is built on the use of tools tailored to a complex mechanical system.

Thanks to this maintenance policy, the monitoring team can identify problems occurring in the system during operation and take corrective action [23], as illustrated in Figure I.9.

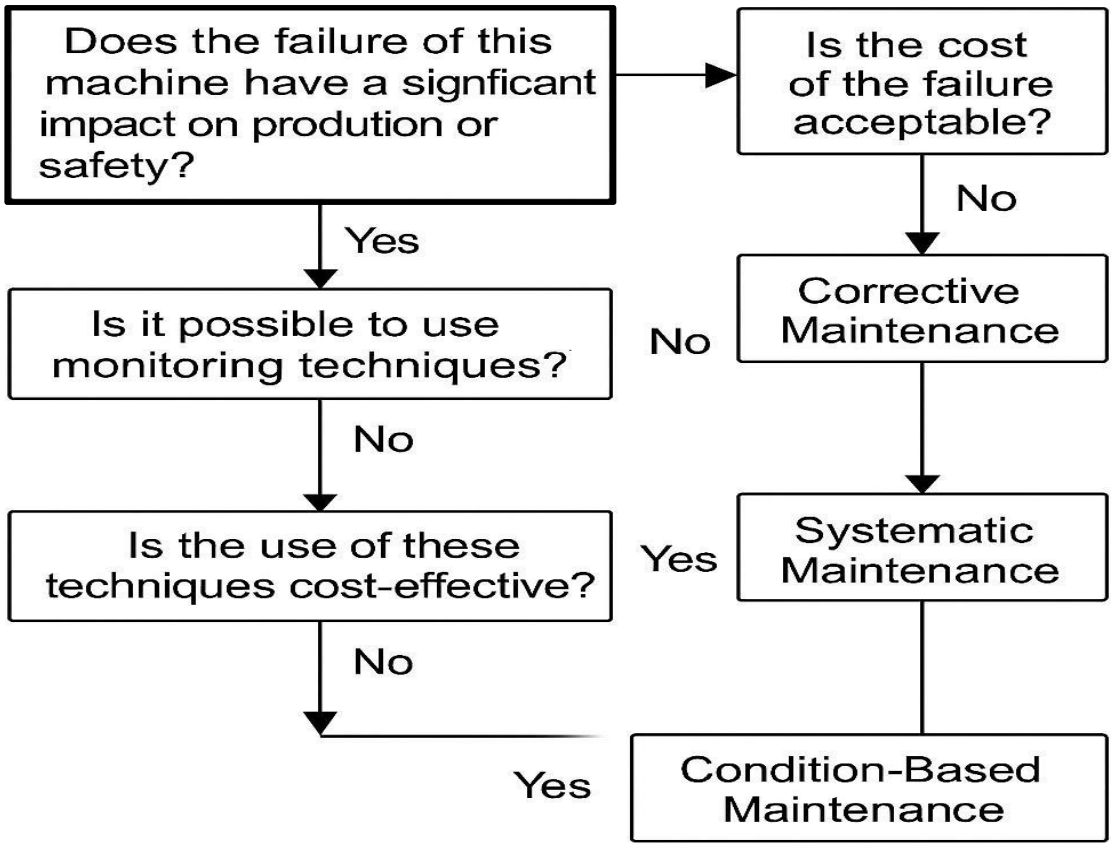


Figure I.9: Selection of Preventive Maintenance Policy. [24]

In summary, a well-developed maintenance policy is a key element of asset management and the operational performance of an organization. It provides a strategic framework to optimize the availability, reliability, and sustainability of equipment, while ensuring efficient resource utilization and compliance with safety and quality standards

6. Maintenance Tools and Technologies

Industrial maintenance is a strategic process aimed at optimizing equipment operational availability, reducing maintenance costs, and improving the overall productivity of industrial facilities. Its continuous evolution, driven by technological advancements, enables the adoption of smarter and more preventive approaches to ensure efficient and reliable industrial operations.

Maintenance tools and technologies have significantly advanced with technological progress. Here are some of the main tools and technologies used in the maintenance field:

- **Computerized Maintenance Management System (CMMS):** CMMS software helps plan, organize, and track maintenance activities. It enables the management of work orders, asset tracking, intervention planning, spare parts inventory monitoring, and more.

- **Real-Time Monitoring Systems (SCADA):** These systems enable remote monitoring and control of equipment and industrial processes. They collect real-time data on equipment performance, allowing for the detection of anomalies and potential failures.
- **Predictive and Condition-Based Maintenance:** These approaches use sensors and monitoring technologies to collect data on equipment condition. By analyzing this data, it becomes possible to predict imminent failures and schedule maintenance before problems occur.
- **Internet of Things (IoT) Technologies:** IoT sensors can be used to monitor various parameters such as temperature, pressure, vibrations, etc., enabling real-time monitoring of equipment and processes.
- **Data Analytics and Artificial Intelligence (AI):** Data analytics and AI techniques can be used to analyze large datasets from sensors and other sources to identify trends, patterns, and anomalies that may indicate maintenance issues.
- **Augmented Reality (AR) Technologies:** AR headsets or devices can provide real-time maintenance instructions to technicians in the field, improving the efficiency and accuracy of interventions.
- **Asset Management Technologies:** Specialized software tools allow for the tracking and management of asset inventory, including equipment, spare parts, and supplies, thereby facilitating the planning and execution of maintenance activities.

7. Objectives of Maintenance

The primary objective of maintenance is to ensure the reliability, availability, and safety of equipment and facilities, while optimizing operational efficiency and reducing long-term costs.

The goal of maintenance is to ensure the proper functioning and continuous availability of equipment, machines, or systems. This includes preventing failures, correcting issues as soon as they arise, and carrying out planned actions to extend the useful life of equipment. In essence, it's a combination of foresight and intervention to avoid costly interruptions and maintain productivity.

This generally involves several key aspects:

- **Failure Prevention:** Maintenance aims to identify and address potential issues before they lead to major failures. This can include regular inspections, performance testing, and preventive replacement of worn components.
- **Performance Optimization:** By ensuring regular servicing, maintenance helps to maintain optimal equipment performance. This may involve adjustments, cleaning,

lubrication of components, as well as software updates or parameter tuning.

- **Lifespan Extension:** Proper maintenance can extend the useful life of equipment by preventing premature wear and maintaining efficient operation over time.
- **Safety:** Maintenance helps ensure that equipment and facilities are safe to use, by identifying and correcting potential risks to the health and safety of personnel.
- **Cost Reduction:** By avoiding major breakdowns and optimizing performance, maintenance helps to reduce repair and replacement costs, as well as minimize unplanned downtime.
- **Regulatory Compliance:** In many industries, maintenance is necessary to comply with safety, environmental, or other industry-specific regulations.
- **Reliability:** Ensuring proper functioning of equipment to prevent production interruptions.
- **Availability:** Maximizing equipment uptime to support production.
- **Cost-effectiveness:** Optimizing maintenance costs through efficient planning of interventions.

8. Reliability-Centered Maintenance (RCM)

Reliability-Centered Maintenance (RCM) is an essential tool for designing preventive maintenance, balancing the dual objectives of availability and total cost of ownership of facilities. Failure Modes, Effects, and Criticality Analysis (FMECA) is among the tools or methods RCM uses. Implementing this method provides a deep understanding of how a system functions and interacts, through the systematic analysis of cause-effect relationships [25].

RCM plays a crucial role in improving the maintenance function. Nowadays, maintenance is increasingly valued not just for corrective measures but for its economic contribution through the anticipation of potential faults and mastery of the production process. RCM aims to guide industrial practices toward growth in organizational, technical, and informational resources [26].

The objectives of RCM are to:

- Define and justify scheduled maintenance actions during the design phase;
- Redefine scheduled maintenance actions during the operational phase;
- Ensure and improve performance of production tools in terms of reliability and safety;
- Formulate recommendations concerning techno-economic issues (investment, refurbishment, procedures, justification).

Reliability-Centered Maintenance (RCM) is a strategic approach aimed at optimizing the availability, reliability, and performance of equipment by focusing on the proactive management of failure risks.

Rather than following a fixed maintenance schedule, RCM relies on reliability data and analyses to determine the optimal time to perform maintenance.

The reliability of equipment is essential to ensure the smooth operation of industrial processes and customer satisfaction. Unexpected breakdowns can lead to costly production stoppages, delivery delays, and reduced product quality. RCM therefore aims to anticipate and prevent failures by using continuous monitoring data and advanced analytical techniques.

In addition to maximizing operational availability, RCM also seeks to optimize equipment performance. This involves maintaining assets in optimal condition, avoiding major failures that could compromise productivity or product quality. By proactively planning maintenance activities, organizations can minimize risks associated with operating equipment at suboptimal performance levels.

The main goal of RCM is to optimize asset availability, reduce total maintenance costs, and extend the useful life of assets. By adopting this approach, companies can improve operational efficiency and extend equipment life while reducing the risks of unexpected failures.

Another key objective of RCM is to ensure operational availability of equipment by anticipating and preventing potential failures before they occur. Instead of following a standard preventive maintenance schedule, RCM uses reliability data, predictive analytics, and advanced monitoring technologies to make informed decisions about maintenance planning.

This enables optimized resource utilization, reduction of unplanned downtime, and increased asset lifespan.

By adopting a reliability-centered maintenance approach, organizations can achieve several objectives:

- Maximize equipment availability by minimizing unplanned downtime.
- Optimize asset performance to ensure smooth and efficient operations.
- Extend the lifespan of equipment by preventing premature wear.
- Reduce maintenance costs by planning interventions proactively and efficiently.
- Improve operational safety by preventing critical failures.
- Use human and material resources effectively to maximize their productivity.

In conclusion, Reliability-Centered Maintenance is a proactive and strategic approach to optimizing the performance of industrial equipment while minimizing costs and risks associated with maintenance. By focusing on failure prevention and resource optimization, RCM offers organizations an effective way to maintain competitiveness in a demanding and constantly evolving business environment.

9. Conclusion

Maintenance plays a crucial role in asset management and the sustainability of equipment and infrastructure. By ensuring proper operation and extending the lifespan of machines and systems, maintenance makes a significant contribution to the operational performance and overall safety of businesses. Maintenance is an indispensable component of asset management in any organization.

By adopting effective maintenance practices and leveraging technological advancements, companies can improve operational performance, ensure safety, reduce costs, and extend the service life of their equipment.

A well-planned and well-executed maintenance strategy is an investment with long-term benefits, ensuring the sustainability and competitiveness of organizations in an increasingly demanding environment.

CHAPTER II

Reliability-Centered Maintenance Modeling

1. **Introduction**
2. **RCM Approach (Reliability-Centered Maintenance)**
3. **Methodology and Reliability Analysis**
4. **Maintainability**
5. **Availability**
6. **6. Conclusion**

1. Introduction

Reliability-Centered Maintenance (RCM) is a structured approach used to identify the maintenance needs of a physical asset based on its reliability and performance. This methodology was originally developed in the aerospace industry and has since become widely adopted across various industrial sectors to improve equipment performance and safety while optimizing maintenance costs.

Reliability-Based Maintenance (RBM) is a maintenance management strategy aimed at ensuring that systems and equipment continue to operate reliably and safely throughout their lifecycle. This approach relies on a thorough analysis of potential failure modes, their causes, and consequences, in order to develop effective and tailored maintenance plans for each specific asset.

RCM seeks to optimize the use of maintenance resources by ensuring that interventions are performed efficiently and economically. This includes maintenance planning, spare parts management, and the allocation of appropriate technical skills.

RCM makes use of FMECA (Failure Modes, Effects, and Criticality Analysis) to systematically evaluate potential failure modes, their causes, effects, and criticality. This analysis helps prioritize maintenance efforts based on the impact of failures on safety, production, and costs.

2. RCM Approach (Reliability-Centered Maintenance)

The various steps of the proposed methodology are presented in Figure II.1.

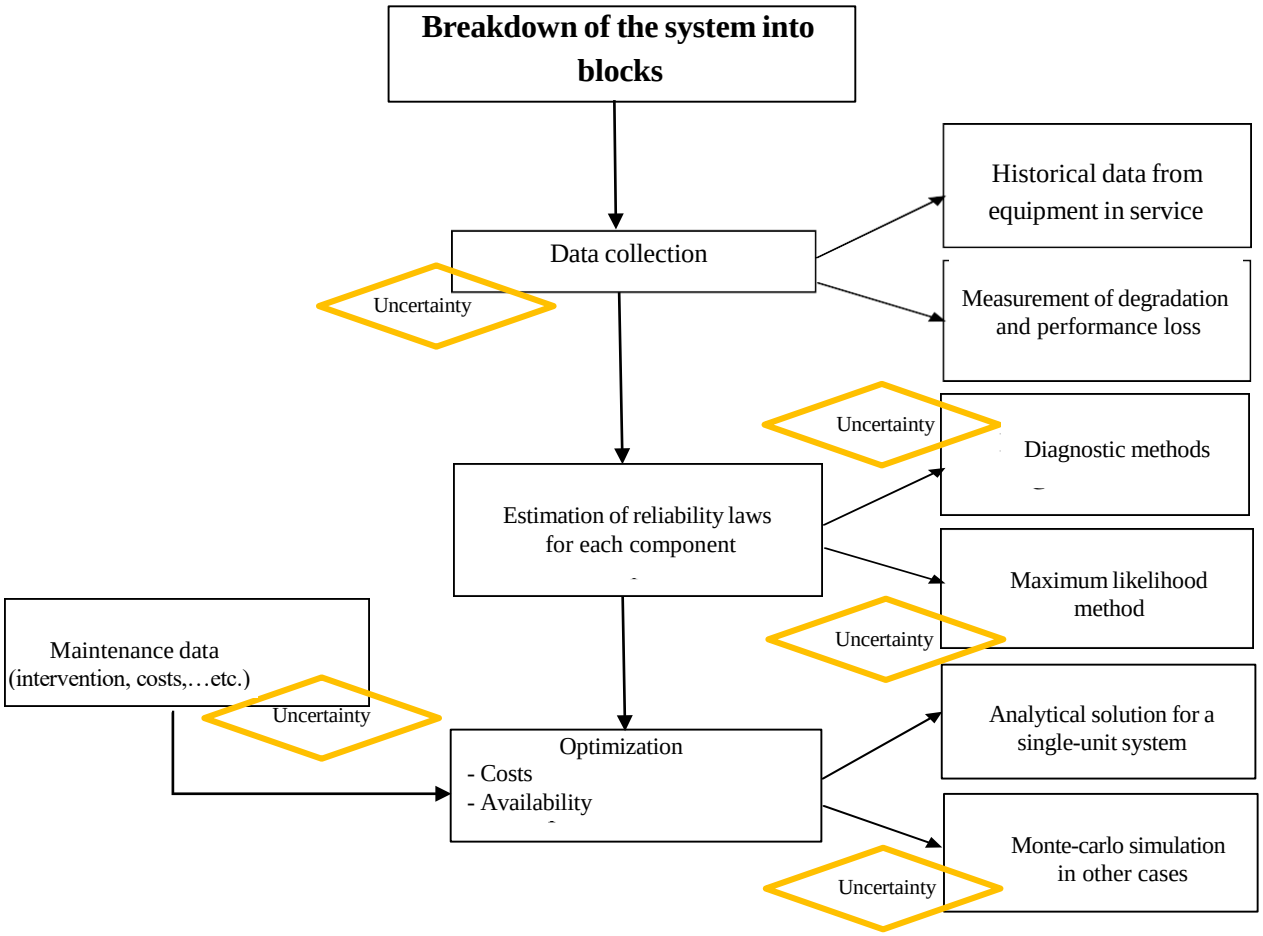


Figure II.1: RCM (Reliability-Centered Maintenance) Approach [20].

2.1. System Representation Using Block Diagrams

In most cases, a system can be viewed as a set of elements whose proper functioning determines the overall system's performance. To that end, an analysis of various failures is carried out, resulting in a topological model of the system where each element is represented by a block [27].

- In series configuration, elements are connected such that the failure of a single component causes the failure of the entire system.
- In parallel configuration, the entire group fails only if all the components fail.

Other configurations may also be studied, such as modeling redundancy or backup elements.

2.2. Data Collection

The next step consists of collecting data for each machine in the system. These data can originate from either a timeline of events or from degradation measurements [18].

In the first case, information about the machine's status is recorded from the time of its initial commissioning (startup, first failure, maintenance, restart, inspection shutdown, restart, second failure, etc.).Sometimes, the history is incomplete (i.e., there are no records between two events), so the methods used must be able to handle censored data [28].

In the second case, degradation measurements can be obtained either through manual spot inspections or via continuous recordings, as highlighted by V.A. Koupnov in [29]. There are also situations where degradation can be assessed directly, and others where it must be assessed indirectly using explicit degradation variables (covariates).

2.3. Estimating the Reliability Law of Each Component

All available information is considered (see Figure II.2). According to Fleurquin et al. [30], this data may be related to failure periods derived from a breakdown history (statistical models based on historical event data), to physical degradation measurements recorded over time in order to assess the degradation law (physical failure models), or to the evolution of explicit degradation variables (i.e., monitoring of a degradation indicator) [15].

This information can be used to estimate reliability laws by applying regression techniques or maximum likelihood methods. In the first case, it is necessary to fit the desired parametric reliability law in a linear form and to determine its parameters using linear regression.
In the second case, the objective is to estimate the parameters of the reliability law that maximize the likelihood and to reconstruct the observed failure periods [20]. The reliability method also enables the calculation of the Mean Residual Life (MRL) of the equipment, which is the mathematical expectation of its remaining useful life. Having this information is crucial for implementing an appropriate maintenance policy.

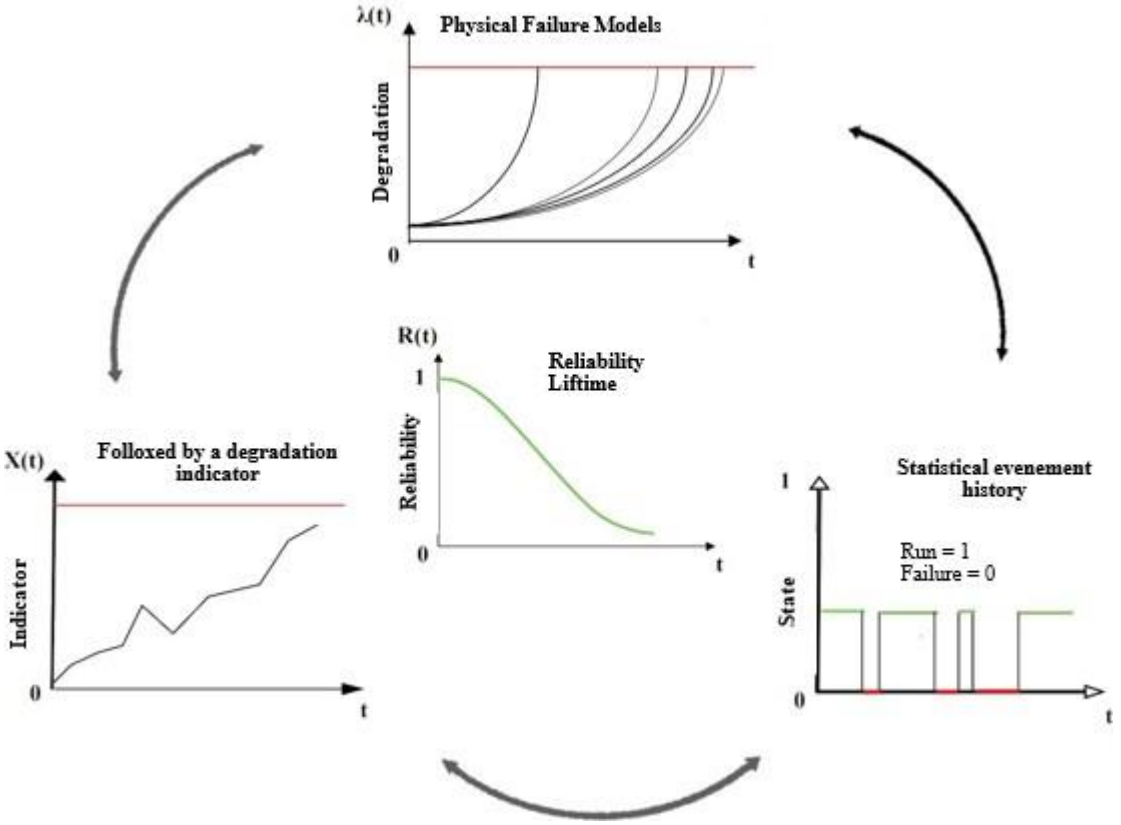


Figure II.2: The Three Approaches to Reliability and Lifetime Estimation. [20]

2.4. Maintenance Optimization

After determining the reliability of each component, the next step is to establish the optimal frequency for preventive maintenance [30]. It is essential to have maintenance-related information for this purpose. This data includes:

- The feasibility of performing corrective or only preventive actions.
- The fixed costs associated with preventive and corrective actions.
- The variable costs associated with preventive and corrective actions, i.e., indirect expenses related to production losses.
- The duration of preventive and corrective maintenance.
- The inspection frequency of each component.

3. Methodology and Reliability Analysis

Reliability is the probability that a system, equipment, or component will function properly over a specified period of time under defined operating conditions.

In other words, it is the ability of a system to perform its intended function without failure for a given duration under normal operating conditions.

Reliability is a key characteristic for many products and systems, especially in critical sectors such as aviation, manufacturing, electronics, automotive, healthcare systems, and more.

High reliability often implies increased safety, consistent performance, reduced maintenance costs, and higher customer satisfaction.

3.1. Mathematical Reliability Index

The reliability function R(t) represents the probability of operating over a specific time period [0; t], that is, the probability that the equipment will function without failure during that time.

$$R(t) = P(T > t) = 1 - F(t)\ pour\ t \geq 0$$
$$= \int_t^{+\infty} f(u)du = F(t) \quad \text{(II.1)}$$

The continuous random variable T takes positive values and has a probability density function (PDF) denoted by *f*.
R(t) represents the probability of proper functioning at time *t*. The relationship is defined as:

$$f(t) = -\frac{dR(t)}{dt} \quad \text{(II. 2)}$$

Where *F* is the **survival function**

$$\begin{cases} F(0) = 1 \\ \lim_{t\to\infty} F(t) = 0 \end{cases} \quad \text{(II.3)}$$

3.2. Failure Function

The failure probability refers to the likelihood that a randomly selected device from the considered population fails before time *t* [04, 92, 106]. The failure function, denoted by F(t), is defined as the probability that the component fails before time *t*. Mathematically:

$$F(t) = P(T \leq t) = \int_0^t f(u)du \quad \text{(II . 4)}$$

Where F (t) is a cumulative distribution function (CDF) and is a monotonically increasing function.

$$\begin{cases} F(0) = 0 \\ \lim_{t\to\infty} F(t) = 1 \end{cases} \quad \text{(II.5)}$$

The failure density function is defined as the rate of change of the failure function F (t).

$$F(t) = \lim_{\Delta t\to 0} \frac{F(t+\Delta t)}{\Delta t} = \frac{dF(t)}{dt} \quad \text{(II.6)}$$

Two **non-parametric estimation methods** of the cumulative distribution function **F(t)** are commonly noted:

- **Median rank method** $t_i = \frac{n_i - 0.3}{N+0.4}$ for **small sample sizes** N≤30.
- **Mean rank method** $t_i = \frac{n_i}{N+1}$ for **sample sizes** N>30

The reliability function and the failure function are complementary and satisfy the following identity: *R(t)+F(t)=1 since R(t)=1−F(t)* At the time point *ti*, if $R(t_i)=F(t_i)$

Then the system has reached the stage where the reliability function equals the failure function.

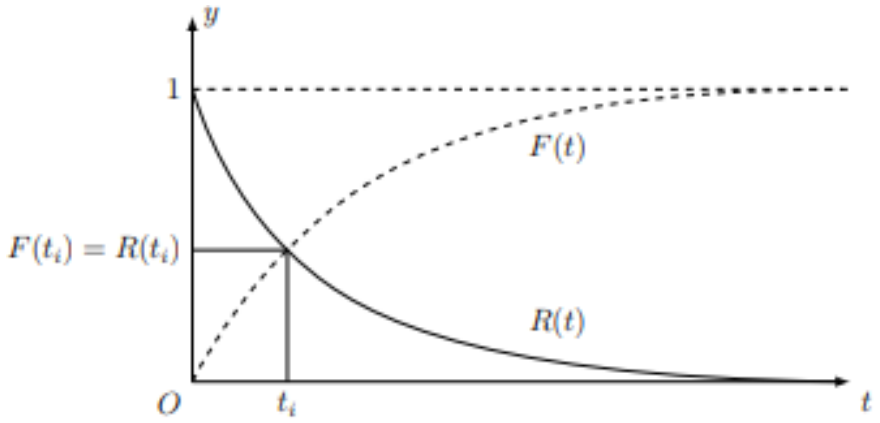


Figure II.3: Reliability Curve as a Function of Failures. [31]

3.3. Failure Rate

The failure rate is the *infinitesimal probability* of failure at time t, given that the component has survived up to time ttt, and that the failure occurs within the interval (t+Δt). It is defined as:

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{R(t+\Delta t) - R(t)}{\Delta t} = \frac{f(t)}{R(t)} \quad \text{(II.7)}$$

Proof:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P(t<T<t+\Delta t)}{\Delta t.P(T<t)} \tag{II.8}$$

$$= \lim_{\Delta t \to 0} \frac{1}{\Delta t} \frac{(P(t < T < t + \Delta t)}{1 - F(t)}$$

$$= \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t(R(t))} \qquad we\ have\ \ F(t) = 1 - R(t)$$

$$= \frac{1}{R(t)} \lim_{\Delta t \to 0} \frac{F(t + \Delta t) - F(t)}{\Delta t} \qquad avec\ f\ (t) = -R'(t)$$

$$\lambda(t) = \frac{1}{R(t)} \lim_{\Delta t \to 0} \frac{1 - R(t + \Delta t) + R(t) - 1}{\Delta t} = \lim_{dt \to 0} \frac{R(t) - R(t + dt)}{dt(R(t))}$$

$$= \lim_{dt \to 0} \frac{R(t) - R(t + dt)}{dt(R(t))}$$

$$\lambda(t) = -\lim_{dt \to 0} \frac{R(t + dt) - R(t)}{dt(R(t))}$$

$$\lambda(t) = \frac{F'(t)}{R(t)} = \frac{f(t)}{R(t)} \tag{II.9}$$

So:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{-dlogR(t)}{dt} = \frac{-dR(t)}{dt.R(t)} \tag{II.10}$$

Where F (t) represents the survival function. By integrating both sides from 0 to t, knowing that R(t)=1.

$$F = R(t) = \exp(-\int_0^t \lambda(u)du) \tag{II.11}$$

F : The survival function can be expressed in terms of the failure rate.

The discrete-time failure rate λ(t) is expressed in terms of reliability as follows:

$$\lambda(t) = \begin{cases} 1 - \frac{R(t)}{R(t-1)} & si\ R(t-1) \neq 0 \\ 0 & si\ non \end{cases} \quad \text{(II.12)}$$

- In general, the time-dependent behavior of the failure rate is represented by the 'bathtub curve' (Figure II.4).

The bathtub curve is a graphical representation of the failure rate of a product or system over time, named for its shape, which resembles a bathtub, and typically consists of three phases.

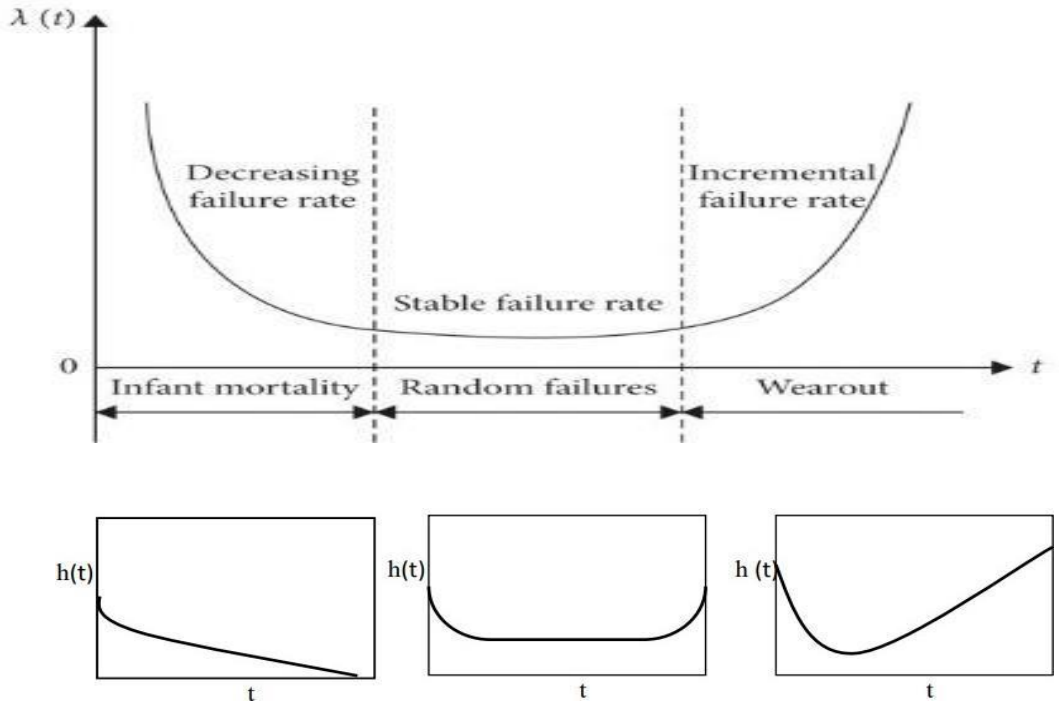


Figure II.4: Bathtub Curve of Failure Rate Evolution. [32]

- **Infant Mortality Period (Early Failure Phase):** At the beginning of a product's life, the failure rate is generally high. Failures during this phase are often caused by manufacturing defects, assembly errors, or other initial problems that were not detected during quality testing. The failure rate quickly decreases as these issues are identified and corrected.
- **Useful Life Period (Random Failure Phase):** After the initial period, the product enters a phase where the failure rate is relatively low and stable. Failures occurring during this phase are usually random and not due to inherent product defects. This is the phase during which the product is considered the most reliable.

- **Wear-Out Period (Aging Failure Phase):** Toward the end of the product's life, the failure rate begins to rise again. This increase is due to natural wear and tear, material fatigue, and other age-related deterioration. Components start reaching the end of their expected life span and often need to be replaced.

This curve is widely used for preventive maintenance planning and decision-making related to product design, equipment replacement, and warranties. It helps engineers and maintenance managers understand and predict failure behaviors, thereby optimizing reliability and maintenance costs.

- **MTBF (Mean Time Between Failures):** The mathematical expectation of the random variable T defined initially is the average time between failures, or the average operating time between breakdowns.

$$MTBF = \frac{Temps\ total\ de\ Bon\ Fonctionnement\ entre\ les\ N\ des\ defaillances\ (TBF)}{Nombre\ total\ de\ défaillances} \quad \text{(II.13)}$$

We have

$$MTBF = \int_{-\infty}^{+\infty}{}^{+\infty} tf(t)dt) = \int_{-\infty}^{+\infty}{}^{+\infty} R(t)dt)$$

$$MTBF = \frac{1}{\lambda} \quad \text{(II.14)}$$

By definition, MTBF is the average lifespan of the system.

- **Exemple 01 :** Un compresseur industriel a fonctionné en continu pendant 9000 heures, avec 6 pannes, dont les durées (temps de réparation) sont : 9 ; 21 ; 7,5 ; 3,5 ; 6 ; 9 heures

$$MTBF = \frac{9000 - (9 + 21 + 7.5 + 3.5 + 6 + 9)}{6} \approx 1491\ Hours$$

And if λ is assumed to be constant

$$\lambda = \frac{1}{MTBF} = \frac{1}{1491} = 6.70.10^{-4}\ \ Failures/hours$$

- **Exemple 02 :** A generator is analyzed after being decommissioned following 16,500 hours of operation. During this period, the generator experienced a total of 218 shutdowns. The information is summarized in the following table II.1. The objective is to understand how the generator's reliability and wear-out phase evolved based on the shutdown intervals.

Tableau II.1 Historique de panne d'une machine.

hours	MTBF	Failure Rate
1000	66.7	0.015
2000	100	0.01
3000	250	0.004
4000	500	0.002
5000	400	0.0025
6000	555.6	0.0018
7000	416.7	0.0024
8000	526.32	0.0019
9000	500	0.002
10000	476.2	0.0021
11000	555.6	0.0018
12000	512	0,0019
13000	200	0.005
14000	111.1	0.009
15000	100	0.01

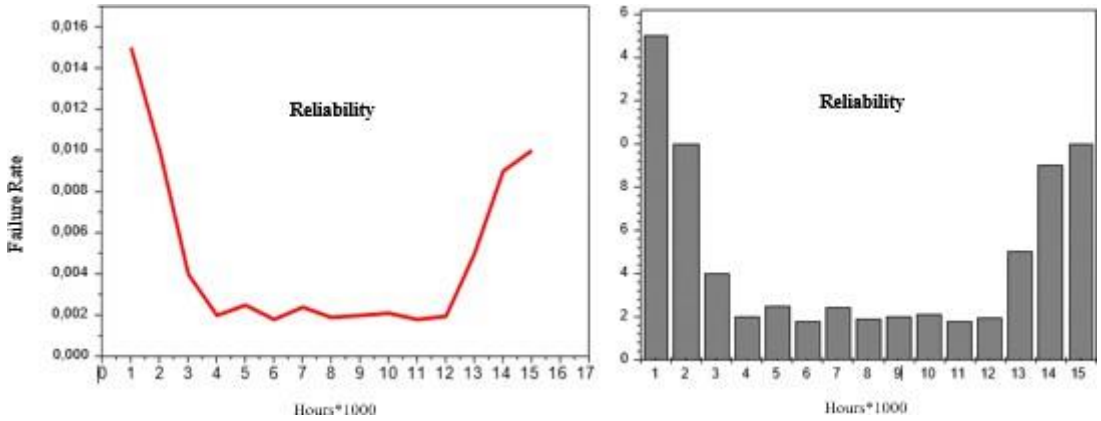


Figure II.5: Failure Rate Curve.

It is observed that the generator begins to deteriorate after 12,000 hours of operation. The bathtub failure rate reflects a more or less normal operatio

3.4. Probability Distributions Used in Reliability

In reliability engineering, various probability distributions are used to model the lifespan of components or systems, and to predict the frequency of failures. Here are some of the main distributions used:

3.4.1. Exponential Distribution

- **Use**: Commonly used to describe the time between failures in a system where the failure probability is constant, meaning the system does not age.
- **Characteristic**: Memoryless property, which implies that the probability of failure in the future is independent of the time already elapsed.

3.4.2. Weibull Distribution

- **Use**: Very versatile, suitable for modeling various types of failure behaviors depending on shape and scale parameters.
- **Characteristic**: Can represent scenarios where the failure rate increases or decreases over time, useful for studying aging or improving components.

3.4.3. Normal (Gaussian) Distribution

- **Use**: Often used for manufacturing tolerances or measurement errors, where extreme values are rare but possible.
- **Characteristic**: Symmetric around the mean, used to model variations around an expected average value.

3.4.4. Log-Normal Distribution

- **Use**: Suitable for modeling time to failure when data follow a skewed distribution, typically with a long right tail.
- **Characteristic**: Useful when values cannot be negative and are multiplicative, typical in growth processes.

3.4.5. Gamma Distribution

- **Use**: Can be used to model time to failure in systems that must go through several stages/phases before failing.
- **Characteristic**: Flexible, with shape and scale parameters, suitable for processes involving successive phases.

3.4.6. Binomial Distribution

- **Use**: Used to model the number of successes in a fixed number of trials, useful for reliability testing in limited quantities.
- **Characteristic**: Models probabilities of discrete outcomes (success/failure).

3.4.7. Chi-Square Distribution

Often used to highlight the importance of minimalist and efficient design, encouraging designers to avoid unnecessary overloads and focus on essentials to enhance overall system or product reliability. It is characterized by a positive parameter α called degrees of freedom and is defined only for positive values [33].

3.4.8. Birnbaum-Saunders Distribution

Also called the fatigue distribution, it is primarily used to model the lifespan of materials subjected to fatigue stress. This distribution was developed by Z.W.

These distributions are essential for reliability engineers to predict product lifespan, optimize maintenance, and conduct risk analyses. Each distribution has specific features that make it more or less suited to certain situations or data types.

3.5. Maintenance Cost

Maintenance cost refers to the expenses related to each corrective or preventive maintenance operation, whether time-based or condition-based. The cost of anticipated corrective maintenance corresponds to the total amount of maintenance resources required to repair or troubleshoot damaged elements [33]. Similarly, the cost of anticipated preventive maintenance is the total amount of maintenance resources required to inspect and/or assess a component before failure occurs and sometimes to replace a part of that component.

The total amount of corrective, preventive, and replacement maintenance costs thus represents the global maintenance cost over the life cycle of system components. Overhead includes all costs other than those related to direct material, labor, and system equipment. Therefore, the total cost of maintenance tasks can be calculated using the following expression:

$$coût\ total = C_{UM} + C_{PM} + C_{RM} \qquad \text{(II .15)}$$

With $C;\ C_{PM};\ C_{RM}$, they respectively represent the total cost of corrective maintenance, the total cost of preventive maintenance, and the cost of rational replacement or refurbishment of system components.

The calculation of the total life cycle cost (LCC), based on well-defined constraints, begins with the long-term step of determining the optimal service life of a machine by calculating the sum of the following expenditures:

The following equation (II.16) represents the overall cost: the purchase cost A, the operating cost f, the total maintenance cost M, and the estimated resale value VR.

$$coût\ global = A + f + M - VR \qquad \text{(II.16)}$$

Due to the increase in total maintenance cost with the age of the machine and the decrease in resale value, it is relevant to determine the point in time at which a minimum is reached [27].
The point of tangency of the line drawn from the origin to the curve, as shown in Figure II.6, corresponds to the abscissa of the optimal service life.

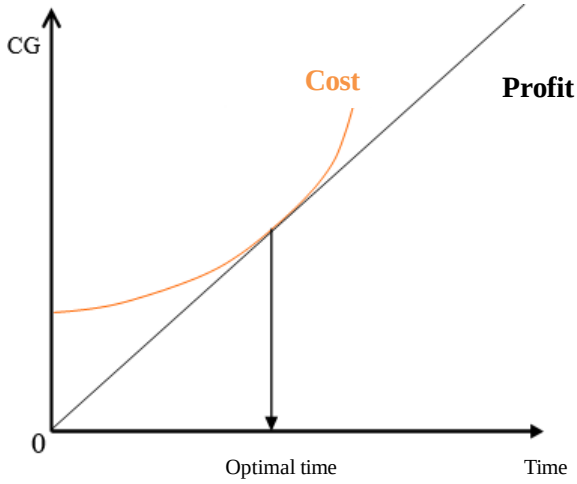


Figure II.6: Evaluation of Maintenance Cost Contact [33]

Lack of reliability leads to increased post-sale expenses (warranty claims, legal fees). Designing for higher reliability results in increased design and production costs. The total cost takes both of these constraints into account.

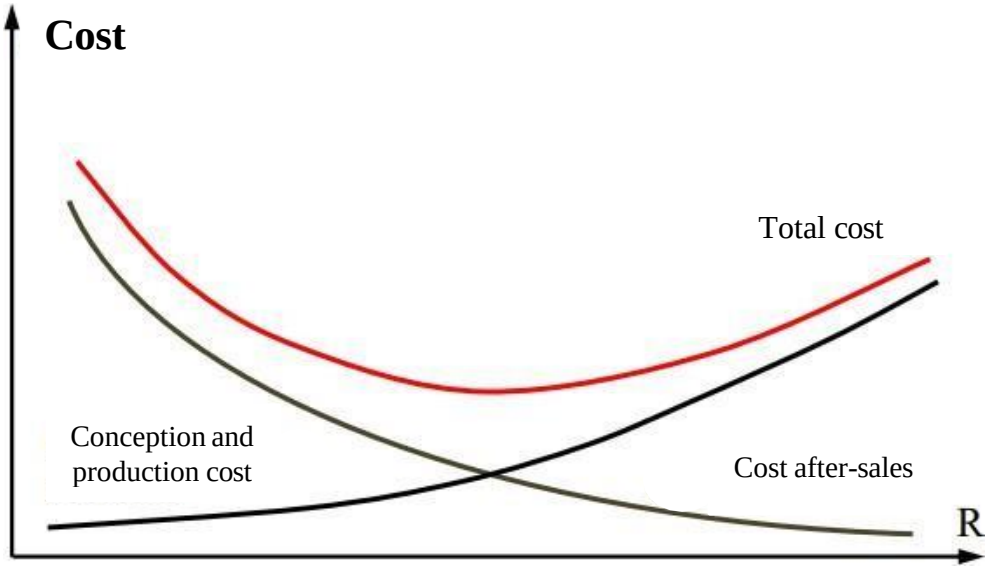


Figure II.7: Maintenance Cost Evaluation in Relation to Reliability. [33]

3.6. Reliability Block Diagram Approach

3.6.1. Series Model

The reliability of a series system refers to the probability that the entire system will operate correctly over a given period of time, despite the potential failure of individual components [33]. In other words, in a series system, each component is connected in sequence with the others, so that if one component fails, the entire system fails.

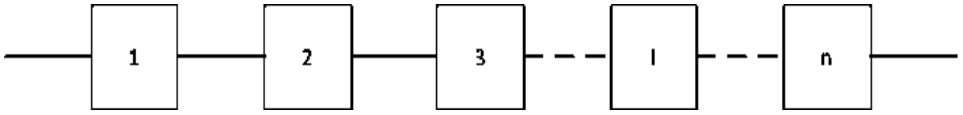


Figure II.8: Example of a Series System. [33]

To calculate the reliability of a series system, the following formula is generally used:

$$R_{serie} = R_1 x R_2 x \dots \dots x R_n \quad \text{(II.17)}$$

With :

- R_{serie} is the reliability of the series system.
- $R_1, R_2,$ are the respective reliabilities of each component in the system.

Since the exponential distribution is often used, multiplying several cumulative probability terms can be quite lengthy to write, so we prefer to use the cumulative reliability probability R.
In this way, the reliability (probability of operation) of a series system can be evaluated using:

$$R_{serie} = 1 - F_s = \prod_{i=1}^{n} R_i \quad \text{(II.18)}$$

3.6.2. Parallel Model

In this configuration, the system continues to operate as long as at least one component is functioning.

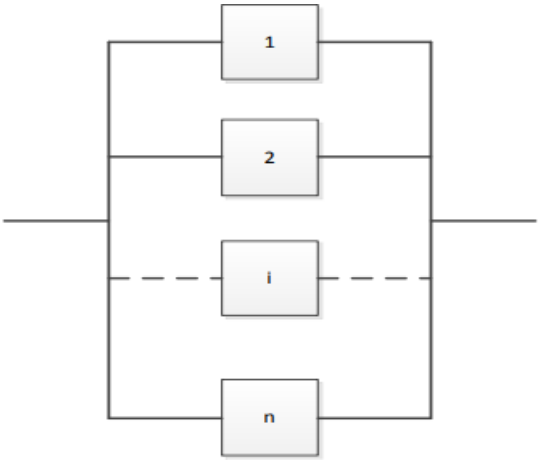


Figure II.9: Example of a Parallel System [32]

In other words, the probability that this system operates is calculated using the following equation.

$$R_p = 1 - \prod_{i=1}^{n} F_i = 1 - \prod_{i=1}^{n} (1 - R_i) \qquad \text{(II.19)}$$

3.6.3. Complex System

In reality, it is not truly a matter of complex systems, but rather systems that require a certain mastery of probability axioms. The specific illustration that we will focus on is as follows:

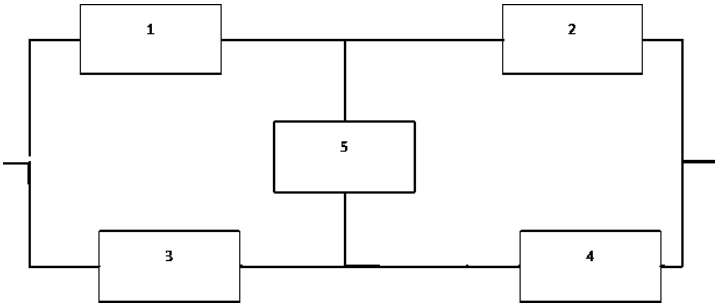


Figure II.10: Example of a Complex System 1. [33]

Component 5 is what makes the system complex. It is therefore possible to consider an initial approach that involves breaking down the problem. If component 5 fails, the system will be in one of the following states:

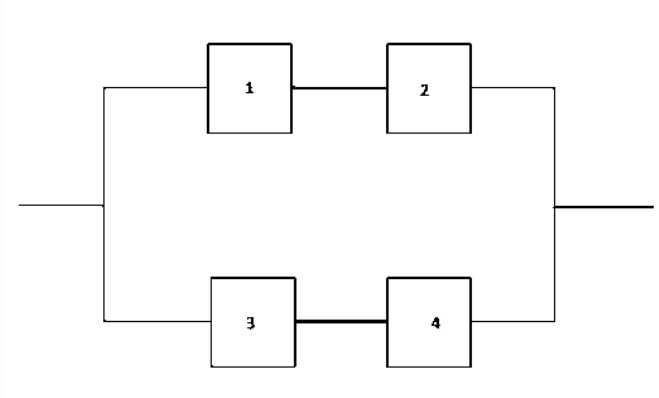


Figure II.11: Example of a Complex System 2. [31]

If it is faulty with a probability density function and has a reliability of:

$$R_{s1} = 1 - \prod_{j=1}^{2}(1 - \prod_{i=1}^{2} R_{ij}) \qquad \text{(II.20)}$$
$$= 1 - (1 - R_1.R_2)(1 - R_3.R_3)$$

According to the relationship of the complex series/parallel system, it will be in the following state if it is functional, with a probability density function:

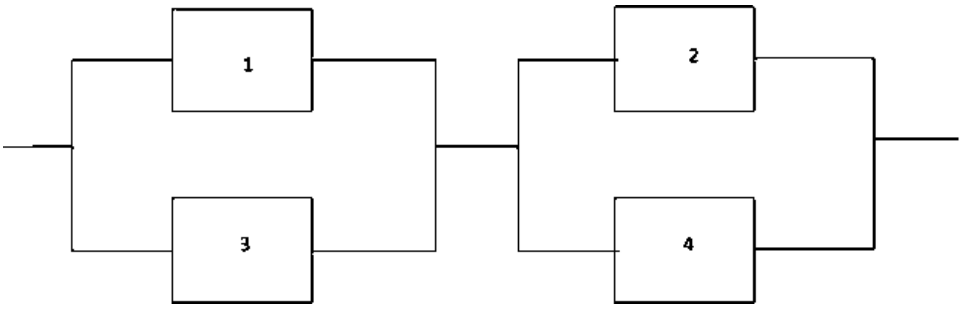


Figure II.12: Example of a Complex System 3. [32]

So :

$$R_{s2} = \prod_{i=1}^{2}(1 - \prod_{j=1}^{2}(1 - R_{ij})) \qquad \text{(II.21)}$$
$$= (1 - (1 - R_1)(1 - R_3))(1 - (1 - R_2)(1 - R_4))$$

3.6.4. K/n System

If k out of n components each following the same reliability law R are operational, then the system is considered active or functional. This concept is often applied in computing systems, such as RAID disk arrays, where multiple disks must remain operational for the system to function properly. The required number of functioning disks depends on the volume of stored data and the redundancy level of the system [32].

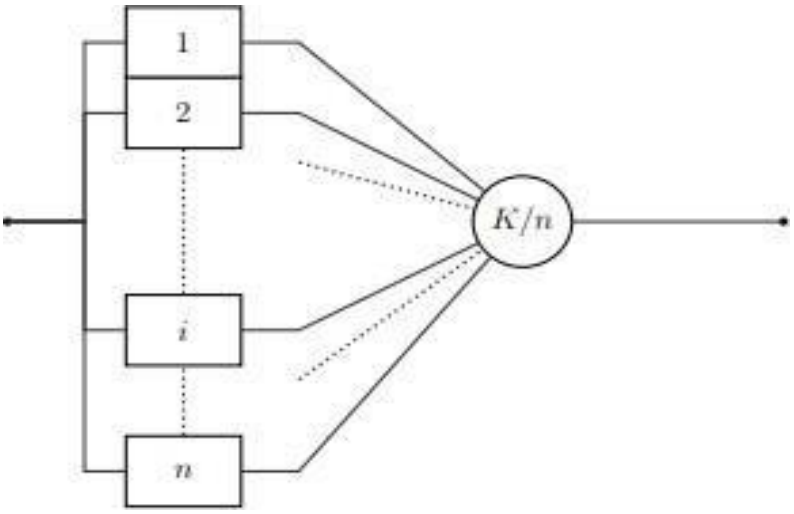


Figure II.13: Example of a k/n System. [32]

L'exploration de la loi de probabilité cumulée de fiabilité consiste donc à se demander la probabilité cumulée d'avoir k éléments fonctionnant parmi n qui ne peuvent pas être distingués [34]. The exploration of the cumulative reliability probability law thus involves determining the cumulative probability of having k functioning elements out of n indistinguishable ones [34].
According to the binomial distribution, the total probability is calculated using:

$$R_s(k,n,R) = \sum_{i=k}^{n} \binom{n}{i} (1-R)^{(n-i)} R^i \qquad \text{(II.22)}$$

3.7. Fault Tree Analysis (FTA) Approach

A fault tree is a graphical method used in reliability engineering to analyze potential causes of system failure and to assess the likelihood of these failures. It is a structured analysis tool that graphically represents the events and conditions that could lead to a system failure [35].

The fault tree starts with a top-level event, often referred to as the "top event" or "system event," which represents the overall system failure. From this top-level event, the analyst identifies the various sequences of events and conditions that could lead to this failure. These sequences are represented as branches in the fault tree [35–37].

Each branch of the fault tree represents a specific combination of events and conditions that could occur and lead to system failure. These branches are broken down into potential causes, often represented by logic gates such as "AND" (logical AND) or "OR" (logical OR), to depict different combinations of conditions required for the failure to occur.

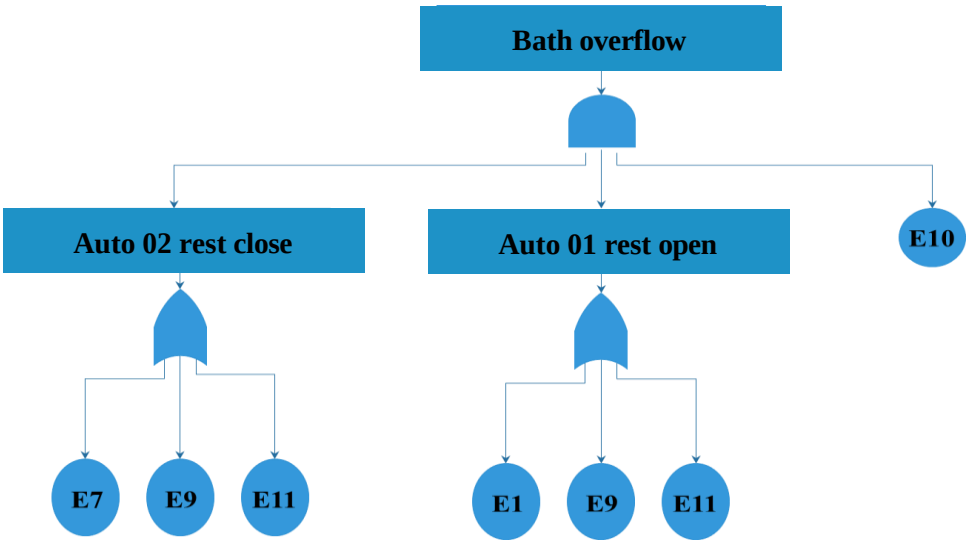
Fault trees enable engineers and analysts to visually understand the underlying mechanisms of potential system failures and to identify critical risk factors. They are used to assess the reliability and safety of systems across many fields, including engineering, aviation, nuclear industry, healthcare, and other sectors where system reliability is crucial.

Using information derived from the fault tree analysis, decision-makers can take preventive actions to minimize failure risks and improve the overall reliability of the system.
Here is how a **fault tree typically works**:

- **Top-Level Event**: The fault tree starts with a top-level event, often called the "end event" or "system event." This event represents the overall system failure that needs to be analyzed.
- **Intermediate Events**: Beneath the top-level event, the analyst identifies various intermediate events that could contribute to the system failure. These intermediate events represent potential failures of subsystems or specific components.
- **Cause Decomposition**: Each intermediate event is further broken down into potential causes that could lead to it. These causes may include component failures, human errors, adverse environmental conditions, etc.
- **Logical Connections**: The events and causes are linked through logic gates such as **AND** and **OR**. For example, an intermediate event may result from several causes occurring simultaneously (AND gate) or from any one of several causes (OR gate).
- **Probability Assessment**: For each event and cause, the analyst can assign a probability of occurrence. These probabilities can be based on historical data, testing, mathematical models, etc.
- **Failure Path Analysis**: Using the fault tree, analysts can identify different paths by which a system failure may occur. This helps prioritize risk prevention and mitigation actions.

➢ **Example :** Using the probability table below, calculate the probability of the feared event "Bathtub Overflow" occurring, knowing that a short circuit is not possible.

To calculate the probability of this event, it is necessary to build the fault tree.



With: **E1**: Valve 01 stuck open, **E7**: Valve 02 stuck closed, **E9**: Faulty switch, **E10**: Faulty float, and **E11**: Faulty battery.

Figure II.14: Structure of a Fault Tree.

Step 02: Probability Calculation:

According to the pre-established fault tree, we can deduce that the top event **S** (bath overflow) is expressed by the following Boolean equation:

$$S = E10 * (E7 + E9 + E11) * (E1 * E9 * E11)$$

After simplification, we can find that

$$S = (E10 * E7 * E1) + (E10 * E9) + (E10 * E11)$$

So

$$(S) = ((E10 * E7 * E1) + (10 * E9) + (E10 * E11))$$

3.8. FMEA Approach

The FMEA method (Failure Modes, Effects and Criticality Analysis) is a quality management and risk analysis tool primarily used in engineering and manufacturing fields to identify potential failures in a system or product, analyze the effects of these failures, and assess their criticality in order to take preventive measures. [38]

$$Criticality = S \times O \times D \qquad \text{(II.23)}$$

Steps for Developing the FMEA:

- **Preparation**
  - **Define the scope**: Clearly define the system or subsystem to be analyzed.
  - **Form the team**: Assemble a multidisciplinary team including experts in engineering, quality assurance, production, and other relevant fields.
- **System Breakdown**
  - **Identify functions**: List each function the system or component is supposed to perform.
  - **Component analysis**: Break the system down into components or subsystems and understand how these elements interact.
- **Identification of Failure Modes**
  - **List failure modes**: For each component or subsystem, identify all possible ways it could fail, considering the various mechanisms and conditions that may cause each type of failure.
- **Effects Analysis**
  - **Assess immediate effects**: Determine the immediate consequences of each failure mode on the component or system.
  - **Assess system-level effects**: Analyze how the failure impacts overall system performance, safety, and regulatory compliance.
- **Severity Evaluation (S)**
  - **Evaluate consequence severity**: Assess the severity of the consequences for each failure. Typically rated on a scale from 1 (least severe) to 10 (most severe). Severity considers impacts on safety, system function, regulatory compliance, and environmental or economic damage.
- **Occurrence Evaluation (O)**
  - **Determine likelihood:** Estimate the probability of each failure mode occurring, also usually on a 1 to 10 scale.
- **Detection Evaluation (D)**
  - **Assess detection methods**: Evaluate the likelihood of detecting the failure mode before it leads to a system-level failure.
- **Risk Priority Number (RPN)**
  - **Calculate the RPN**: Multiply the severity (S), occurrence (O), and detection (D) scores to obtain a Risk Priority Number. This helps prioritize failure modes that require urgent attention based on their risk level.

- **Action Plan**
  - **actions**: Based on the RPN, propose actions to reduce, mitigate, or eliminate high-risk failure modes.
  - **Implement changes**: Develop and apply solutions, such as design modifications, improved materials, additional testing, or enhanced monitoring.
- **Documentation and Follow-up**
  - **Document the analysis**: Record all findings and recommended actions.
  - **Review and update**: Regularly review and update the FMEA as the system evolves or new information becomes available.

FMEA is an iterative and comprehensive approach that requires in-depth knowledge of the analyzed system and a proactive risk management mindset. This method helps improve product reliability, enhance safety, and ensure compliance with industry standards.

- **Example :** Developing an FMEA table (Table II.3) for a drilling machine used in mining operations.

Table II.2: Example of Rating Severity, Detectability, and Occurrence Probability [39].

Rating	Occurrence (O)	Severity (S)	Detection (D)
1	Max 1 failure per year	No production stoppage	Easily visible to the operator
2	Max 1 failure every 3 months	Stop = 1 hour	Easily detected by a maintenance agent
3	Max 1 failure per month	1 hour < Stop < 1 day	Difficult to detect
4	Max 1 failure per week	Stop > 1 day	Undetectable

Tableau II.3: FMEA Worksheet [39]

	FMEA machine - Analysis of failure modestheir effects and criticality					Operating phase				Corrective Action
	SYSTEM "drill machine"									
Elements	**Function**	**failure modes**	**Cause of failure**	**Effect of failure**	**Detection mode**	**criticality**				
						O	S	N	RNP	
O- ring	Separator	deformation	wear	Oil loss	visual inspection	3	2	2	12	changing
Oil filter (compressor)	Filtration	function loss	Dust and oil quality	Deterioration of compressor bearings	visual inspection	3	3	2	18	Filter cleaning
hoses	oil transmission	breaking cracking bursting	High load High tempera-ture high pressure	Oil loss Affects the hydraulic system	Visual Manometer	3	3	2	18	Replacing hose
drilling motor	Drives the compress or	Do not start	Battery dis-charged Faulty fuel injectors Clogged air filter	Starting impos-sible after arrest breakdown Stopped Produc-tion	Visual Indicator	2	2	2	8	Corrective maintenance
		Overheat	Problem in the cooling circuit		Visual Indicator	3	3	2	18	Conditional preventive maintenance
		Low pressure	Low compres-sion due to the valves		Visual Indicator	2	2	2	8	Corrective maintenance
Oil Filter (hydraulic jack)	Oil filtration	clogged filter or dirty	Dust and oïl quality	Restriction valve opens, and motor stopped	Indicator	3	3	2	18	changing filters
Pump	Debit the lubricant under pressure Alimentation ofinjectors	No flow	rupture of mating	The pump does not debit	Visual Manometer	2	2	2	8	Changing
		flow insuffi-cient		weak compres-sion		3	3	2	18	
		Excess black smoke	faulty injector Too high injection rate	bad combustion		2	3	2	12	Changing injectors Tuning
Compressor	Ensures the air for pneumatic hammer	short duration operation and stop	High discharge temperature	No pressure	Visual	3	3	2	18	Conditional preventive maintenance
Compressor		works, but does not produce air	The stuck valve	No pressure	Visual	1	3	3	9	Change
Compressor		Excessive oil consumption	Passage of oïl in the discharge flexible	No pressure	Visual	3	3	2	18	Change

3.9. Relationship Between Reliability and Maintenance

The relationship between reliability and maintenance is fundamental in the field of asset management and industrial operations. Reliability refers to the ability of a system or component to operate without failure over a specified period under defined

conditions. Maintenance, on the other hand, encompasses all necessary actions to preserve or restore equipment, machinery, or systems so that they can fulfill their required function [40].

Reliability and maintenance studies are carried out simultaneously at various stages—project design, production, acceptance, transportation, operation, and renovation—and are approached from a holistic perspective. Maintenance operations are directly linked to the reliability characteristics of the component, such as the reliability function, MTBF (Mean Time Between Failures), and failure rate toward the end of the life cycle, time *t*, etc.

Corrective maintenance reduces the risk of failures and enhances reliability. The curve (Figure I.14) illustrates the connection between maintenance and reliability. As the system enters operation, systematic and condition-based maintenance strategies are implemented.

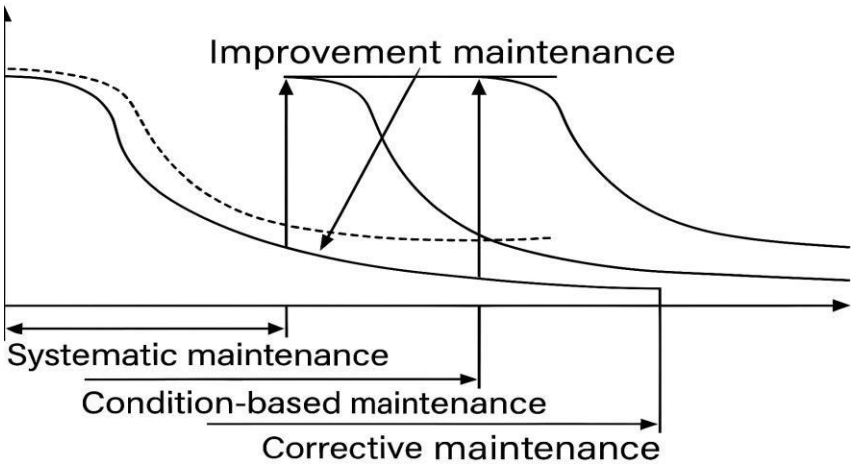


Figure II.15: Link Between Maintenance and Reliability [32]

4. Maintainability

The maintainability of a system is a key characteristic that determines how easily the system can be maintained to ensure its continuous and efficient operation. It encompasses the ability to diagnose, repair, replace, or carry out preventive maintenance on system components within a specified time frame and with defined resources. Below are the main aspects of maintainability and how it is generally addressed in system design and operation [32]:

- **Ease of Maintenance**: Maintainability refers to how easily maintenance activities can be performed on a system or product. This includes the speed and ease of access to necessary components, the execution of repairs or replacements, and the completion of preventive maintenance tasks.
- **Maintenance Speed**: This refers to the time required to perform maintenance tasks, including diagnosing issues, repairing or replacing components, and returning the system to service. A high level of maintainability helps to minimize downtime.
- **Maintenance Cost**: Maintainability also assesses whether maintenance tasks can be performed at a reasonable cost, including spare parts, required tools, and skilled labor.
- **Maintenance Predictability**: A system well-designed for maintainability enables easy prediction of when maintenance will be required, either through regular inspections or integrated monitoring systems that alert users before a failure occurs.

4.1. Operational Maintainability Analysis

Operational maintainability analysis focuses on assessing and improving a system's ability to be maintained under operational conditions with minimal effort, cost, and downtime. This analysis is crucial in industries where availability and reliability are critical, such as aerospace, defense, industrial manufacturing, and critical infrastructure. The typical steps and components of this analysis include:

- **Defining Maintainability Objectives**

Clearly define maintainability targets, such as the Mean Time to Repair (MTTR), component accessibility, or preventive maintenance frequency. These objectives should align with overall system requirements and user expectations.

- **Data Collection**

Gather historical data on system performance and maintenance, including repair times, failure frequencies, intervention costs, and spare part availability. These data are essential to assess the current state of maintainability.

- **Current Configuration Evaluation**

Analyze the system's current design to identify factors affecting maintainability, such as component accessibility, design modularity, and standardization of parts.

- **Identification of Improvements**

Identify improvement opportunities by comparing current maintainability performance with defined objectives. This may involve redesigning component layouts for better

access, standardizing parts to reduce inventory complexity, or integrating advanced diagnostic tools for quicker fault detection.

- **Impact Analysis**

Evaluate how proposed changes might affect other system aspects like performance, safety, or costs. A cost-benefit analysis is crucial for each suggested change.

- **Implementation of Modifications**

Plan and carry out the necessary design or maintenance procedure changes. This may also include training maintenance personnel in new practices and technologies.

- **Continuous Monitoring and Evaluation**

After implementation, it's critical to track the impact of changes on operational maintainability. Use Key Performance Indicators (KPIs) to evaluate whether the objectives are being met and to identify further adjustments if needed.

- **Feedback Integration**

Incorporate feedback into the design of future systems or updates to existing ones. Continuous learning from past experiences is essential for long-term maintainability improvement.

This analysis, focused on improving the ease and efficiency of maintenance, aims to lower maintenance costs, minimize downtimes, and extend system reliability and service life. High operational maintainability is a key driver of long-term success and user satisfaction.

4.2. Mathematical Approach to Maintainability M(t)

Maintainability is often evaluated using metrics such as Mean Time to Repair (MTTR), and it is influenced by system design, maintenance techniques, and the skill level of maintenance personnel. Good maintainability is crucial for ensuring system durability, efficiency, and reliability ultimately reducing operational costs and increasing user satisfaction.

The repair duration for a repairable system is treated as a random variable with a probability density function h(t). The probability that a failed system becomes operational between time t and t + dt is h(t)·dt **[41,42].** Other quantities representing maintainability can be derived from this density function, such as: The cumulative probability H(t) that a repair is completed within time t. The mean time to repair (MTTR).The repair time distribution function, t.

$$MTTR = \frac{\sum Temps\ d'interventionpour\ n\ pannes}{Nombre\ total\ de\ défaillances} \quad \text{(II.24)}$$

The cumulative distribution function is denoted **M (t)**. It represents the probability that a repair intervention has a duration **(TTR < t)**, or that a system which failed at **t = 0** is restored by time **t**

$$M(t) = g(t).\, dt = Prob(TTR < t).$$
$$(t) = 1 - e{-}\mu t \qquad \text{(II.25)}$$

With g(t) as the probability density function:
– Similar to the failure rate, a repair rate μ(t) is defined as follows:

$$E(t) = MTTR = \tau = \frac{1}{\mu}$$

$$\mu(t) = \frac{g(t)}{1-M(t)} \qquad \text{(II.26)}$$

The exponential assumption is used for maintainability forecasting calculations, which implies that the repair rate is assumed to be constant. Therefore, the repair times (TTR) are exponentially distributed.

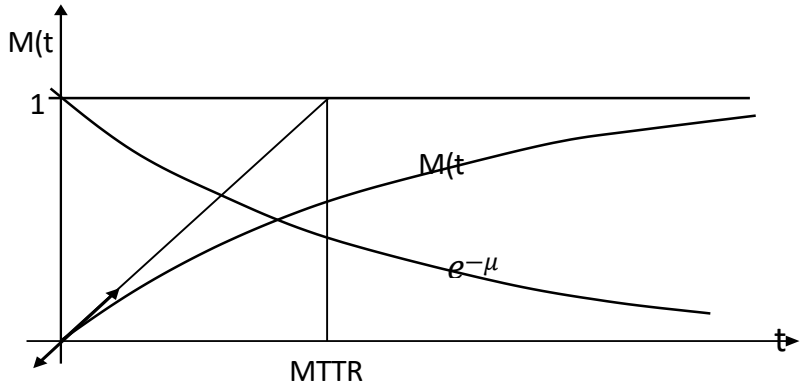


Figure II.16: MTTR Curve Based on Exponential Law. [41]

The figure below illustrates the successive states that a repairable system can take.

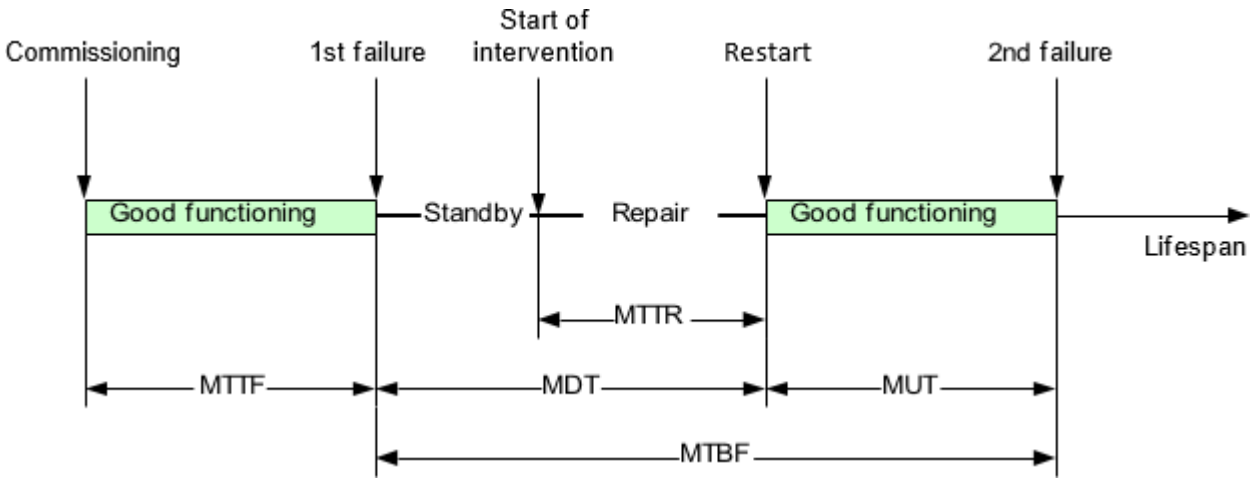


Figure II.17: Successive States of a Repairable System. [31]

With:

- **MUT – Mean Up Time**: Average operating time after repair
- **MDT – Mean Down Time**: Average downtime (failure detection time + repair time + system recovery time)

4.3. Maintainability and Maintenance

The relationship between maintainability and maintenance is fundamental and intrinsic to the management and operation of systems, whether mechanical, electronic, or software-based. Maintainability directly influences the effectiveness and efficiency of maintenance [43-45].

4.3.1. Influence of Maintainability on Maintenance

- **Reduction in Repair Times**: Good maintainability involves a design that allows easy and quick access to necessary components. This reduces the Mean Time To Repair (MTTR), meaning the system can be restored to service more quickly after a failure.
- **Reduction in Maintenance Costs**: A design that facilitates maintenance lowers labor costs and service downtime. Standardizing components can also reduce inventory and storage costs.
- **Improved Reliability**: Effective maintenance supported by high maintainability can enhance the overall reliability of the system. Systems that are easy to maintain are generally inspected and repaired more effectively, reducing the likelihood of unexpected failures.
- **Better Planning and Predictability**: Good maintainability enables better planning of maintenance activities, as personnel can more accurately estimate the duration and complexity of tasks. This helps minimize unplanned downtime and optimize resources.

In summary, excellent maintainability is essential for efficient maintenance. It not only reduces the cost and time associated with maintenance but also improves the overall reliability and availability of systems. Designers and engineers should therefore consider maintainability as a core element of system design to optimize maintenance throughout the system's life cycle.

4.4. Reliability and Maintainability Analyses

The table below shows the various relationships between reliability and maintainability.

Table II.4: Difference Between Reliability and Maintainability [44].

RELIABILITY	MAINTAINABILITY
Probability of "uptime duration**"**	**Probability of** "repair duration"
$R(t) = P(Tp > t)$	$M(t) = P(TR < t)$
Random variable: uptime (operating time)	**Random variable:** repair time
Probability density of time to failure: f(t)	**Probability density of repair time:** g(t)
Reliability:	**Maintainability:**
(□) = $\int_t^{+\infty}$ f(t) dt = e^($-\int_0^t$ λ(u) du)	$(t) = \int_0^t$ g(t) dt = 1 − e^($-\int_0^t$ μ(u) du)
Failure rate λ(t):	**Repair rate μ(t):**
λ(t) = f(t) / R(t) = f(t) / (1 − F(t))	μ(t) = g(t) / (1 − M(t))
MTBF (Mean Time Between Failures):	**MTTR (Mean Time To Repair):**
MTBF = $\int_0^{+\infty}$ t·f(t) dt = $\int_0^{+\infty}$ R(t) dt	MTTR = $\int_0^{+\infty}$ t·g(t) dt
Fundamental relation:	**Fundamental relation:**
f(t) = λ(t) · exp($-\int_0^t$ λ(u) du)	g(t) = μ(t) · exp($-\int_0^t$ μ(u) du)
Common laws:	**Common laws:**
If λ = constant → Exponential law:	If μ = constant → Exponential law:
R(t) = e^(−λt)	M(t) = 1 − e^(−μt)
Application: repairable & non-repairable systems	**Application:** repairable systems

5. Availability

Availability is a key performance indicator in many fields, particularly in engineering, maintenance, and systems management. It measures the extent to which a system or equipment is operational and ready for use at any given moment. Availability is critical for systems where continuous operation is essential, such as in manufacturing industries, IT services, and critical infrastructure [46,47].
Availability can be defined as the probability that a system is functioning properly when it is required. It is generally expressed as a percentage and is calculated using the following formula:

$$D = \left(\frac{Temps\ de\ fonctionnement\ total - Temps\ d'arrêt}{Temps\ de\ fonctionnement\ total}\right) \text{x } 100 \qquad \text{(II.27)}$$

Where the total uptime includes both the operational time and the periods of maintenance or repair.

A company's maintenance policy is fundamentally based on the availability of the equipment involved in the production system.

5.1. Factors Affecting Availability

The availability of equipment depends on several factors:

- **Reliability (MTBF)**: The more reliable a system is, the less likely it is to fail, which increases its availability.
- **Maintainability (MTTR)**: Better maintainability reduces the time required to repair a system, thereby decreasing downtime and improving availability.
- **Logistical Support**: The speed and efficiency with which logistical support (spare parts, tools, personnel) is provided also affect availability.
- **Maintenance Policy**: Preventive and predictive maintenance strategies can significantly reduce unexpected downtime.

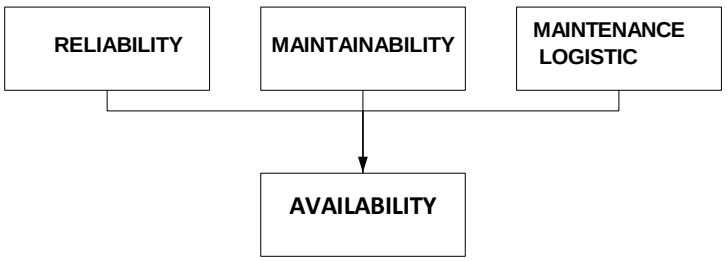


Figure II.18: Factors Affecting Availability [46]

5.2. Availability Laws

5.2.1. Average Availability

The **average availability** of a system is a key performance indicator that measures the probability that a system is operational and ready to be used at any given time. It incorporates the concepts of **reliability**, **maintainability**, and **logistical support** to provide a comprehensive assessment of a system's ability to perform its required functions over an extended period. [48]

Average availability is usually calculated using the following formula

$$D = \frac{Temps\ moyen\ disponibilité}{Temps\ moyen\ de\ disponibilité - Temps\ moyen\ d'indisponibilité}$$

$$D = \frac{TMD}{TMD-TMI} \quad \text{(II.28)}$$

Where: **TMD = MUT** (Mean Up Time)**TMI = MDT** (Mean Down Time).

5.2.2. Intrinsic Availability □□

Intrinsic availability is defined as the probability that a system is operational at a given moment, under the assumption that when it fails, it is not repaired or replaced. It focuses solely on the Mean Time Between Failures (MTBF), which is a measure of reliability [49,50].

The standard formula for calculating intrinsic availability **(D□)** is:

$$D_i = \frac{MTBF}{MTBF+MTTR} \quad \text{(II.29)}$$

In the context of intrinsic availability, MTTR is often considered to be infinitely large (since no repair is performed), thereby simplifying the formula to:

$$D_i = \frac{MTBF}{\infty} = 0$$

However, this extreme simplification is not always useful in practice. Therefore, to be more realistic without considering maintenance interventions, MTTR is generally interpreted as the time until complete replacement or irreversible failure, assuming the system continues to operate until that point without intervention.

5.2.3. Operational Availability (D*o*)

Operational availability (Do) is the measure of a system's ability to perform its required functions at specified performance levels in a given operational environment, at any given time.It reflects the actual performance and efficiency of a system under normal operating conditions.

The general formula for calculating operational availability is:

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

This formula accounts for the probability that a system is operational at a given time, based on the frequency of failures as well as the speed and efficiency with which those failures can be rectified.

5.2.3.1. Importance of Operational Availability

- **Operational Planning**: It helps in planning operations by providing a realistic estimate of system availability. This is crucial for organizations that rely on continuous operations, such as emergency services, military facilities, or industrial production processes.
- **Performance Evaluation**: Operational availability allows managers to measure and assess the real performance of systems compared to goals and expectations.
- **System Improvement**: By identifying areas where operational availability is low, engineers and managers can target specific improvements in design, maintenance, and logistical support to enhance reliability and maintainability.

5.2.3.2. Application of Operational Availability

For a complex system such as a fighter jet, operational availability would include not only the aircraft's ability to fly without technical failures but also how quickly it can be returned to flight status after a mission. This includes refueling, routine maintenance, and repair of weapons systems.

5.3. Relationship Between Reliability, Maintainability, and Availability

The relationship between reliability, maintainability, and availability is critical in the design, operation, and maintenance of technical and organizational systems. These three attributes largely determine the performance and operational efficiency of systems. Figure II.18 illustrates the relationship between the three concepts [46].

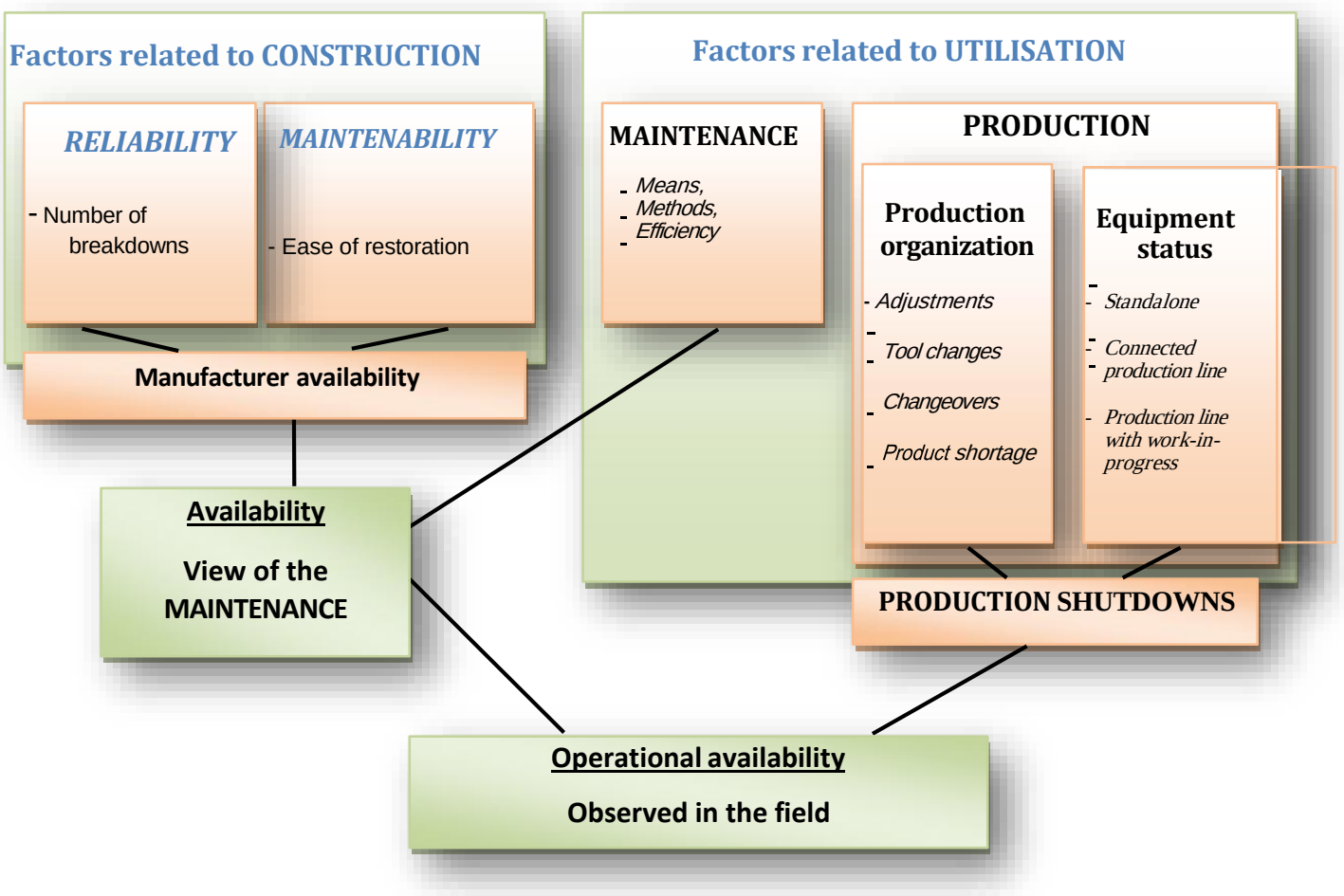


Figure II.19: Relationship Between Reliability, Maintainability, and Availability [37].

- **Relationship Between Reliability and Availability**
  - Reliability directly impacts availability. A system with a high MTBF (high reliability) will experience fewer failures over a given period, thus reducing downtime and increasing availability.
  - A reliable system requires fewer repairs and can operate longer without intervention, which increases its uptime and therefore its overall availability.
- **Relationship Between Maintainability and Availability**
  - Maintainability also affects availability, but through a different mechanism. A system that is easy to maintain (low MTTR) can be quickly restored to operation after a failure. This reduces total downtime, thereby improving the system's availability.
  - Good maintainability allows for more efficient and less invasive maintenance interventions, contributing to a quicker return to normal operation after a failure.

- **Three-Way Interaction:**
    - Reliability and Maintainability: These two aspects are often considered together during system design. For example, equipment may be designed to be reliable (with fewer failure-prone components), while also being easy to repair or maintain (e.g., through the use of modular components).
    - Availability is the result of the optimal combination of reliability and maintainability. A system may be very reliable but still have low availability if it is difficult to repair. Conversely, a less reliable system that is very easy to repair may still achieve high availability.

6. Conclusion

Reliability-Centered Maintenance (RCM) is a strategic methodology designed to optimize system and equipment performance while minimizing costs and risks. By integrating in-depth failure mode analyses and developing targeted maintenance strategies, RCM helps organizations maximize operational efficiency, ensure safety, and maintain asset sustainability.

This approach represents a significant advancement in maintenance management by aligning maintenance activities with an organization’s overall performance and reliability goals.

The main objective of RCM is to identify the essential functions of each system and equipment, along with the failure modes that could compromise these functions. This requires a deep understanding of the operational requirements and the expected performance of the equipment.

CHAPTER III

Optimization of FMEA using the MCDM Method (FUZZY-AHP, VIKOR, RPI-RPN)

1. **Introduction**
2. **Historical Background**
3. **Definition**
4. **General Principle of Multi-Criteria Analysis**
5. **Classification of Multi-Criteria Methods**
6. **Multi-Criteria Decision-Making (MCDM) Methods**
7. **Conclusion**

1. Introduction

Managers in the mining and mineral processing industries often face complex challenges; solving these problems frequently requires multidisciplinary knowledge, including technical, economic, environmental, and social aspects, as well as political and regulatory considerations. The difficulty lies in the fact that the manager must take into account the various objectives and criteria of different stakeholders.

It is also important for the decision-maker to consider the various risks related to geological data, mining techniques, emerging technologies, land acquisition, resource nationalism, commodity prices, and market conditions—areas where information is often difficult to obtain or not always accurate. Moreover, the uncertain nature of this information can lead to uncertain decision-making. Operations research includes multi-criteria decision-making (MCDM), which supports decision-makers in solving problems involving multiple, often conflicting, criteria that need to be assessed [51].

Constructive and analytical methods—both quantitative and qualitative—help reduce risks and improve capabilities. FMEA and other approaches highlight potential failures; quantitative methods, on the other hand, provide reliability measures and are often focused on the product's or its components' limit state [52].

FMEA, also known as Failure Modes and Effects Analysis, is a systematic method aimed at identifying the various ways a process, product, or service can fail, along with the resulting consequences, causes, and associated risks. This approach facilitates the identification and prioritization of areas requiring improvement by regularly assessing risks. FMEA adopts a multidisciplinary approach, highlights high-risk zones, and develops preventive measures. Moreover, it plays an essential role in the production process by identifying potential problems and devising strategies to reduce or eliminate hazards.Failure modes are ranked in classical FMEA systems according to their severity, occurrence, and detectability (Equation 1) [52–54]:

$$RPNt = St \times Ot \times Dt \quad \text{(III.1)}$$

Failure modes with the highest RPNt scores often considered critical indicate areas requiring further attention or intervention. The FMEA process steps include assessment, action planning, management recommendations, and design adjustments. While the changes made by engineers are reliable, the method has limitations despite its widespread adoption. Most of these constraints stem from the non-injective and non-surjective nature of the RPNt function, as shown in Equation 1. The RPN scale exhibits non-surjective behavior, which can cause ambiguity in prioritization, since different failure modes may receive the same score despite having different proportions.

Research studies highlight the relative importance of risk variables, as their significance may vary depending on risk scenarios and application sectors, making the original RPN technique ineffective [55–58]. In this chapter, we will present a definition of the various decision support methods, along with their main categories. Then, the main steps and the process of developing each method will be presented in detail.

2. Historical Background

The history of Multi-Criteria Decision-Making (MCDM) dates back to the 1950s and 1960s, when researchers in social sciences and economics began exploring approaches to account for multiple criteria in the decision-making process. Below are some key milestones in the development of MCDM:

- **1950s–1960s: Early Beginnings and Initial Development** the first research on multi-criteria decision-making was influenced by work in fields such as game theory, decision theory, and operations research. Researchers like Howard Raiffa, Robert Schlaifer, and Harold Linstone were among the pioneers in exploring these concepts.
- **1970s: Development of Formal Methods** during the 1970s, formal methods for multi-criteria decision-making began to emerge. Among them was the Analytic Hierarchy Process (AHP) developed by Thomas Saaty, which became one of the most widely used methods in this field. [59]
- **1980s: Expansion of Applications** in the 1980s, the use of MCDM methods expanded to a wide range of fields, including engineering, management, environmental studies, healthcare, and other disciplines. Researchers such as Bernard Roy helped popularize approaches like the ELECTRE method. [60–62]
- **1990s–2000s: Methodological Evolution and Application Growth** during this period, new methods and approaches were developed to address specific needs across different areas of application. Advances were also made in computer modeling and visualization of MCDM results. [63]
- **2000s to Present: Widespread Use and Continued Development** MCDM has become an established discipline, widely used in many academic and industrial sectors. Advances in information technology have enabled the development of specialized software for multi-criteria analysis, facilitating its application in various contexts.

Today, MCDM continues to evolve with the emergence of new methods, including the use of artificial intelligence and machine learning for multi-criteria decision support. It remains a dynamic and continuously evolving field, playing a key role in decision-making within complex and uncertain environments.

3. Definition

Multi-Criteria Decision-Making (MCDM) is an analytical approach used for making decisions when multiple criteria must be considered simultaneously. Instead of focusing on a single decision criterion, MCDM allows for weighting and evaluating various factors that may be conflicting or carry different levels of importance. The main objective of MCDM is to provide a structured and systematic framework to assist decision-makers in assessing and comparing different alternatives based on multiple criteria. These criteria can be qualitative or quantitative in nature, and may include factors such as cost, quality, sustainability, technical feasibility, stakeholder preferences, and more.

MCDM methods offer tools and techniques such as FUZZY-AHP, BWM, DEMATEL, TOPSIS, and SAW [62,64] to help clarify decision-makers' preferences, prioritize criteria according to their relative importance, evaluate alternatives on each criterion, and aggregate these evaluations to generate rankings or recommendations.

Some of the most commonly used MCDM methods include the Analytic Hierarchy Process (AHP), the ELECTRE method, and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [65–67], among other multi-criteria analysis techniques.

In summary, MCDM provides a robust and methodological framework to help decision-makers make informed and transparent choices in situations where multiple criteria must be taken into account. It is widely used in fields such as management, engineering, environmental science, healthcare, finance, and other domains that involve complex decision-making [66].

4. General Principle of Multi-Criteria Analysis

The general principle of Multi-Criteria Decision Analysis (MCDM) is to provide a structured and systematic framework to support decision-makers in evaluating and comparing various alternatives based on multiple criteria [62].

In general, when a multi-criteria problem arises, it is essential to identify the most appropriate solution or alternative based on the set of criteria F. This solution can take different forms, such as selection, assignment, or ranking. The process typically involves four steps:

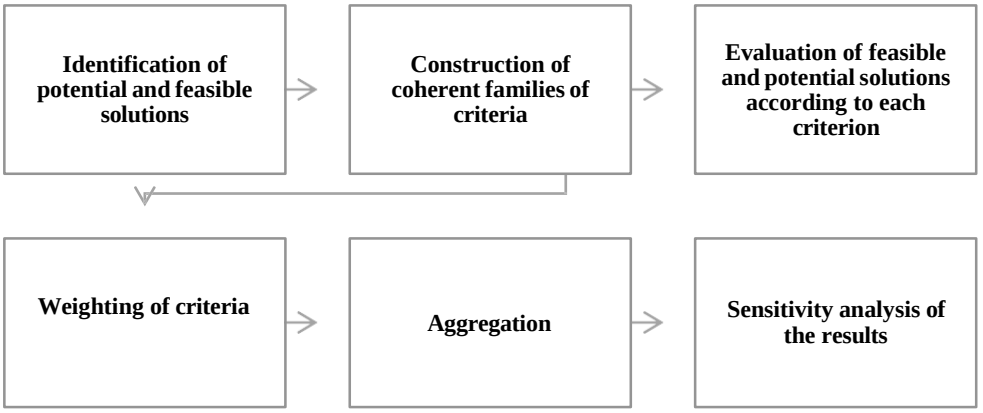


Figure III.1: General Steps of Multi-Criteria Analysis[69].

- **Identification of Criteria**: First, the relevant criteria for the decision must be identified. These criteria can be qualitative or quantitative in nature and may include aspects such as cost, quality, technical feasibility, stakeholder preferences, etc.
- **Definition of Alternatives**: Next, all possible alternatives must be identified. These may consist of different options, strategies, or actions that can be considered to solve the problem or address the question at hand.

- **Evaluation of Criteria**: Each alternative is evaluated against each of the identified criteria. These evaluations can be based on quantitative data (e.g., numerical measurements) or qualitative data (e.g., expert judgments).
- **Weighting of Criteria**: Some criteria may be more important than others in the decision-making process. Decision-makers assign weights to each criterion to reflect their relative importance. These weights may be determined subjectively or using analytical techniques such as the Analytic Hierarchy Process (AHP) or proportional weighting methods.
- **Aggregation of Evaluations**: The evaluations of alternatives on each criterion are aggregated while taking their respective weights into account. Various aggregation methods may be used, such as weighted sum, utility-based methods, or more complex techniques like PROMETHEE or ELECTRE.
- **Sensitivity Analysis**: It is often important to analyze the sensitivity of the results to changes in the criterion weights or in the evaluations of alternatives. This helps identify areas where adjustments may be needed or assess the robustness of the recommendations.
- **Decision-Making**: Finally, the aggregated results are used to make an informed decision. Decision-makers should consider both the quantitative results from the multi-criteria analysis and the qualitative and contextual factors.

Multi-criteria decision analysis (MCDA) thus offers a methodological framework to structure the decision-making process, allowing decision-makers to make informed and transparent choices, even in complex situations where multiple criteria must be considered. [68]

5. Classification of Multi-Criteria Decision-Making Methods

The classification of multi-criteria decision-making (MCDM) methods can vary based on several factors such as complexity, application domain, ability to handle uncertainty, and decision-maker preference. Experts in MCDM generally agree on three main categories [69].

5.1. Approaches Based on Utility Theory-: Single-Synthetic-Criterion Analysis

These approaches involve combining various perspectives into a single function, which is then optimized. Research in this category focuses on the mathematical conditions for aggregation, the specific forms of the aggregating function, and the methods used to construct these functions. This family includes methods such as: **MAUT** (Multi-Attribute Utility Theory), **SMART** (Simple Multi-Attribute Rating Technique), **UTA** (UTilités Additives), **TOPSIS** (Technique for Order of Preference by Similarity to Ideal Solution), **AHP** (Analytic Hierarchy Process), **G.P.** (Goal Programming).

Despite their mathematical rigor, these methods are often considered complex, or they may exclude certain optimal solutions due to their compensatory nature i.e., allowing trade-offs between criteria that may not always reflect real-world decision preferences.

5.2. Outranking Techniques: Outranking Synthesis Approach

These approaches first aim to establish a preference relation known as the outranking relation, which reflects the decision-maker's well-defined preferences based on the available data [70]. This category defines indifference and preference thresholds for each criterion before constructing the outranking relation.

This relation is typically neither exhaustive nor transitive. In the second stage, the outranking relation is used to support the decision-maker in resolving the problem.

These methods are known for their flexibility, particularly in complex decision-making contexts. They introduce many innovative concepts, particularly in the area of preference modeling. The most widely known methods in this family are: **ELECTRE** (Elimination and Choice Expressing Reality), **PROMETHEE** (Preference Ranking Organization Method for Enrichment Evaluation

5.3. Interactive Approaches

A Local Interactive Judgment Approach: Although these are now generally classified within the second family, these methods have been programmed with varying quality and adaptability in different academic and research labs, depending on specific needs. Interactive approaches alternate between computation steps and dialogue steps. They are typically developed within a multi-objective mathematical programming framework.

6. Multi-Criteria Decision-Making (MCDM) Methods

6.1. AHP Method (Analytic Hierarchy Process)

In the 1970s, Thomas L. Saaty developed the AHP (Analytic Hierarchy Process), also known as Hierarchical Process Analysis, which is a multi-criteria analysis technique. It is used to facilitate decision-making in situations where it is necessary to consider multiple criteria simultaneously. [71] The method is based on the combination of two simultaneous approaches: systemic thinking and causal thinking.

The first approach occurs when the problem is simplified and its elements are organized hierarchically [72].

The second approach, based on the perspectives and judgments of the decision-makers, contributes through pairwise comparisons evaluating the impact of one variable on another.

In short, this approach involves representing a decision problem through a hierarchical structure that illustrates the interactions between the various elements of the problem, then performing pairwise comparisons of the elements in the hierarchy, and finally determining the priorities of the actions.

The procedure for applying the AHP method is as follows:

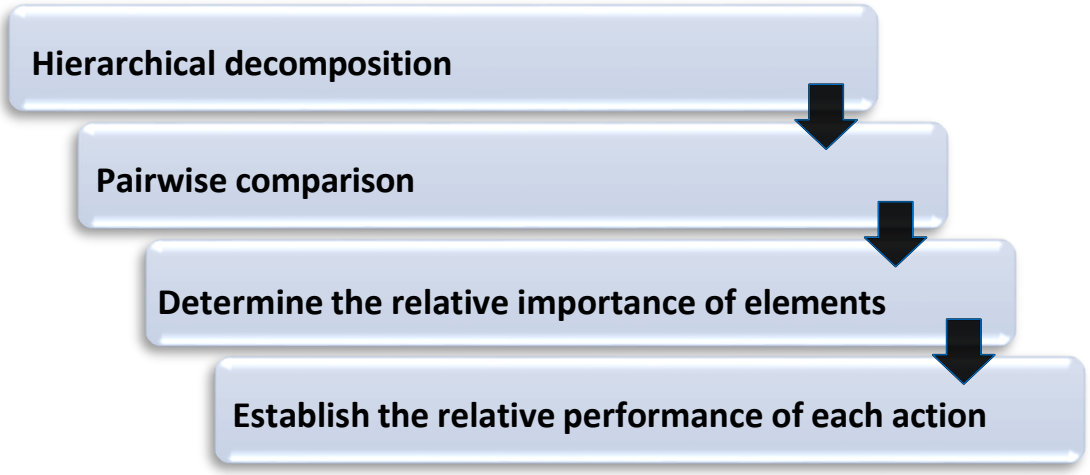


Figure III.2: Procedure for Using the AHP Method [77].

Step 1: Hierarchical Decomposition : The AHP method begins by decomposing the decision problem into a series of hierarchical levels. At the top of the hierarchy is the overall goal of the decision, followed by more specific criteria, and finally the available alternatives [73] .

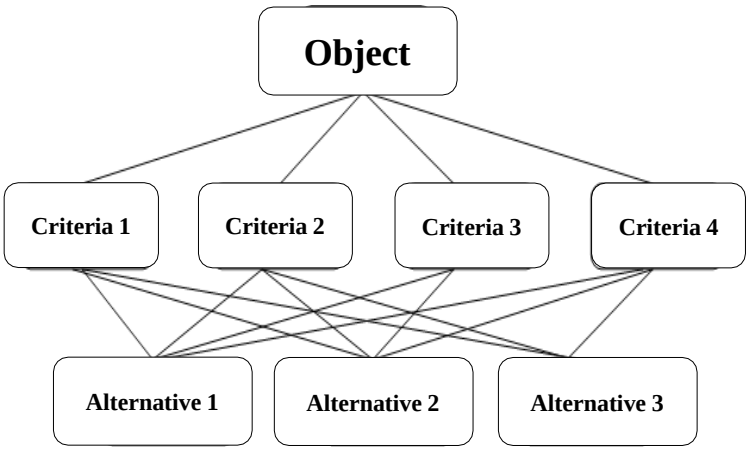


Figure III.3: Decomposition of Criterion Values. [77]

Step 2: Pairwise Comparison: Decision-makers compare the elements at each level of the hierarchy in pairs, in terms of their relative importance. This step typically involves the use of rating scales to quantify the decision-maker's preferences. Comparisons are carried out both between criteria and between alternatives [74].

Table III.1: Fundamental AHP Scale. [74]

Degree of Importance	Definition: The fundamental scale for pairwise comparisons in AHP
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
Intermediate values **(2, 4, 6, 8)** can be used to express **compromise or intermediate judgments**. Values such as **1.1, 1.2, 1.3**, etc., can be used when **alternatives are very close in importance**.	

Step 3: Determine the relative importance of elements: This step involves calculating the eigenvectors corresponding to the maximum eigenvalues of the pairwise comparison matrices. These eigenvectors represent the relative weights or priorities of the elements.

Step 4: Check the consistency of the pairwise comparison matrix: To verify the consistency of the pairwise comparison matrices from Step 3, the Consistency Index (CI) must be calculated. The number of independent rows in the matrix is defined by the matrix's eigenvalue and n (the order of the matrix) [75]. In the case of a fully consistent matrix, known as Sila's matrix, the following holds:

$$IC = \frac{\lambda_{max} - n}{n - 1} \tag{III.2}$$

Where: λmax is the maximum eigenvalue corresponding to the pairwise comparison matrix, and n is the number of elements being compared.

The Consistency Ratio (CR) is then calculated and defined as:

$$RC = 100\frac{IC}{ACI} \tag{III.3}$$

Table III.2: Consistency Random ACI. [75]

Matrix	1	2	3	4	5	6	7	8	9	10
Consistency Random ACI	0.00	0 .00	0.58	0 .90	1 .12	1.24	1.32	1.41	1.45	1.49

In general, a Consistency Ratio (CR) of less than 10% is considered acceptable. If the value exceeds this threshold, it is necessary to revise the pairwise comparisons to minimize inconsistencies.

Step 5: Establish the relative performance of each alternative.

$$P_k(e_i^k) = \sum_{i=1}^{n_{k-1}} P_{k-1}(e_i^{k-1}) P_k\left(\frac{e_i^k}{e_i^{k-1}}\right), \text{ avec } \sum_{i=1}^{n_k} P_k(e_i^k) = 1 \quad \text{(III.4)}$$

Where ***nk-1*** is the number of elements at the hierarchical level ***k–1***, and ***Pk (eik)*** is the priority assigned to element ***ei*** at level ***k*** of the hierarchy.

The AHP method offers several advantages, such as modeling the decision problem using a hierarchical structure and utilizing a semantic scale to express the decision-maker's preferences. However, despite its widespread popularity, AHP has been subject to various criticisms.

6.2. FUZZY-AHP Method (Fuzzy Analytic Hierarchy Process)

The FUZZY-AHP method is an extension of the classical AHP that integrates fuzzy logic concepts to handle uncertainty and subjectivity in decision-makers' judgments. This method is particularly useful when preferences are difficult to quantify precisely or when available data is imprecise or subjective [76].

In the FUZZY-AHP method, pairwise comparisons between elements in the hierarchy are not based on precise numerical values as in traditional AHP, but rather on fuzzy membership degrees. These fuzzy values reflect the uncertainty in the decision-maker's assessments and allow for more flexible and nuanced preference representation.

Step 1: Problem Structuring: First, the decision problem is broken down into a hierarchical structure of criteria and alternatives. This structuring helps clarify the objectives of the decision and the relationships between elements.

Step 2: Assignment of Fuzzy Membership Functions: Unlike traditional AHP, where pairwise comparisons are based on exact numerical values, FUZZY-AHP uses fuzzy membership functions to represent the decision-maker's preferences. These functions help capture the uncertainty and subjectivity inherent in human judgments [77].

Step 3: Construction of Fuzzy Comparison Matrices: The pairwise comparisons between elements of the hierarchy result in fuzzy comparison matrices, where each element is associated with a membership degree at each level of the hierarchy. These matrices reflect the decision-maker's fuzzy preferences [77].

Once the network is established, fuzzy comparison matrices are evaluated for all criteria in the system, as shown in Table III.3.

Table III.3: Evaluation of Criterion Values [77]

Linguistic Variables	Numerical Values	Fuzzy Interval Scales (Trapezoidal)
Absolutely Important	9	(9, 9, 9)
Strongly Important	7	(6, 7, 8)
Moderately Important	5	(4, 5, 6)
Slightly Important	3	(2, 3, 4)
Equally Important	1	(1, 1, 1)

Step 4: Calculation of Fuzzy Weights: The weights of the elements at each level of the hierarchy are calculated by aggregating the corresponding fuzzy membership degrees. These fuzzy weights capture the uncertainty in the decision-maker's preferences and allow for a more nuanced evaluation of the alternatives. Typically, the geometric mean of each row is used.

Step 5: Aggregation of Fuzzy Weights: The fuzzy weights obtained at each level of the hierarchy are aggregated to produce a global weight for each alternative. This aggregation accounts for the uncertainty in preferences and enables the generation of more flexible and robust rankings of the alternatives.

Step 6: Analysis and Decision-Making: The aggregated weights are used to evaluate and rank the alternatives according to their contribution to the decision-maker's objectives. Decision-makers can then use these results to make an informed decision, despite the uncertainty and subjectivity in preferences.

The FUZZY-AHP method allows for the integration of fuzzy logic concepts into the hierarchical analysis process to handle uncertainty and subjectivity in multi-criteria decision-making. It offers a flexible and robust approach to support decisions in complex and uncertain environments. [78]

6.3. SMART Method: Simple Multi-Attribute Rating Technique

According to Edwards, due to the complexity of accurately representing preferences especially because of measurement errors it would be worthwhile to simplify the process by proposing a simple method to capture the decision-maker's true preferences, which are inevitably individual. This is what led to the development of the SMART procedure.

He observed that several experiments and simulations involving decision-makers confirmed that the approximations obtained using an additive function are just as effective as those produced by more complex nonlinear models. The method is as follows [79]:

Step 1: Rank the attributes in decreasing order of importance: This step is crucial and should encourage dialogue between the decision-maker and their collaborators in the decision-making process.

Step 2: Assign weights to each attribute: The decision process may involve differing opinions on the values of the attribute weights. These evaluations are conducted interactively by experts, using a scale from 0 to 100.

Step 3: Sum the importance coefficients and multiply each weight by this total: This step normalizes the relative importance coefficients, so that final weights range between 0 and 1.

$$U(a_i) = \sum_{j=1}^{n} \pi_j \cdot u_j(a_i) \quad \text{(III.5)}$$

Step 4: Evaluate where each alternative stands on each attribute

Step 5: Calculate the alternatives using the following weighted sum

$$Ui = \sum_{i=1}^{n} W_i, r_{ij} \quad \text{(III.6)}$$

Step 6: Use the utility function U(ai) to rank or select the best alternative

$$U(a_i) = \sum_{j=1}^{n} \pi_j \cdot u_j(a_i) \quad \text{(III.7)}$$

6.4. TOPSIS Method

The TOPSIS method was developed by Hwang and Yoon to solve Multi-Criteria Decision-Making (MCDM) problems. They proposed using the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) based on the shortest Euclidean distance, where each criterion is either maximized or minimized.

According to the authors, the TOPSIS method enables ranking of alternatives based on their closeness to the ideal solution, with the first-ranked alternative being the best, and the lowest-ranked alternatives being the worst. Each option is positioned between the two extremes of best and worst responses. A consistent set of selection criteria allows for a meaningful evaluation of relative performance, which is critical when identifying options that require special attention.

TOPSIS considers a geometric system where m points in an n-dimensional space are viewed as an MCDM problem with m alternatives. The chosen option should have the shortest geometric distance from the PIS, and the farthest from the NIS. It is typically assumed that criteria are monotonically increasing or decreasing, which facilitates the identification of PIS and NIS [81–83].

The TOPSIS process involves generating a decision matrix A=(aij)m×n followed by a normalized matrix R=(rij)m×n, and then a weighted matrix T=(tij)m×n. The ideal solutions S+ and S− are then identified from the weighted normalized matrix. Next, the Euclidean distance between each alternative and both S+ and S− is calculated to determine each alternative's relative closeness to the ideal solution. Alternatives are then ranked based on this relative closeness [84].

Step 1: Criteria Normalization: The values of the criteria for each alternative are normalized in order to make them comparable. This normalization can be performed using various methods, such as min-max normalization or the z-score method.

Step 2: Construction of the Decision Matrix : A decision matrix is built in which each row represents an alternative, and each column represents a criterion. The entries in the matrix are the normalized values of the criteria for each alternative. [85]

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdot & \cdot & a_{1m} \\ a_{21} & a_{22} & \cdot & \cdot & a_{2m} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ a_{q1} & a_{q2} & \cdot & \cdot & a_{qm} \end{bmatrix} \quad \text{(III.8)}$$

Step 3: Generation of the Decision Matrix: The decision matrix is represented as A=(Xij)m×n , where there are m alternatives denoted by d1, d2,...,dm, and n criteria denoted by C1, C2,...,Cn. The performance of each alternative on a specific criterion is represented by Xij.

Step 4: Normalization of the Decision Matrix: The normalized decision matrix (NDM) is calculated to express the relative performance of the different alternatives. The normalization is typically done using:

$$X^{\cdot} = L_{ij} = \frac{Xij}{\sqrt{\Sigma X^2}} \mathbf{i = 1, 2 \ldots, m,\ j = 1, 2, \ldots, n} \quad \text{(III.9)}$$

Step 5: Construction of the Weighted Normalized Decision Matrix (WNDM): Each element of the NDM is multiplied by the corresponding weight of the criterion to produce the Weighted Normalized Decision Matrix (V):

$$\mathbf{V} = \boldsymbol{Vij} = \boldsymbol{Wi} * \boldsymbol{Lij} \quad \text{(III.10)}$$

Where $\boldsymbol{Wi}$ is the weight of criterion $\boldsymbol{j}$.

Step 6: Identification of the PIS and NIS

The Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) are determined from the WNDM:

$$NIS = I^{-} = \{V^{-}_{1}, V^{-}_{2}, \ldots . V^{-}_{m}\}; \text{ou}$$

$$V^{-}_{i} = \{(\min (V^{-}_{ij}) \ if \ m \in J; (maxi \ V^{-}_{ij} \ \text{if m} \in \text{J'})\} \quad \text{(III.11)}$$

With J beneficial (to be maximized) criteria and J' non-beneficial (to be minimized) criteria.

Step 7: Ideal and Anti-Ideal Solutions:For each criterion, determine: The **best value** (ideal solution), and The **worst value** (anti-ideal solution).

These values are used to calculate the **distance of each alternative** from both the ideal and anti-ideal solutions.

$$Si+ = \left[\sum_{i=1}^{m}(V_i^+ - V_{ij})^2\right]^{0.5} \quad ,i=1,2,\ldots,m$$
$$Si- = \left[\sum_{i=1}^{m}(V_i^- - V_{ij})^2\right]^{0.5} \quad ,i=1,2,\ldots,m \qquad \text{(III.12)}$$

Step 8: Distance Calculation: For each alternative, the Euclidean distance is calculated between its normalized values and the values of the ideal and anti-ideal solutions.

Step 9: Ranking the Alternatives: Alternatives are ranked based on their closeness score. The closer the score is to 1, the better the alternative. Thus, alternatives with the highest closeness scores are considered the most favorable solutions.

TOPSIS is widely used across various fields to support decision-making in situations involving multiple criteria. It is relatively simple to implement and provides intuitive and easy-to-interpret results.

6.5. VIKOR Method

The VIKOR approach (VlseKriterijumska Optimizacija I Kompromisno Resenje) is a multi-criteria decision-making (MCDM) method frequently used to evaluate and rank different options based on multiple criteria. It is especially useful in situations where decision-making requires trade-offs between conflicting criteria. [86]

VIKOR focuses on the ranking and selection of a set of alternatives in the presence of conflicting criteria. It introduces the concept of a compromise solution, which represents an acceptable choice for the decision-maker and is the closest to the theoretical ideal. The method applies normalization and weighting to evaluate and compare alternatives, then determines the compromise solution by minimizing the distance from the ideal. [87–89]

Step 1: Identification of Criteria and Alternatives:

- Identify the criteria $C_1, C_2, \ldots\ldots, C_n$ according to which the alternatives will be evaluated.
- Identify the alternatives $A_1, A_2, \ldots\ldots, A_n$ to be assessed.

Step 2: Construction of the Decision Matrix:

- Construire une matrice X où chaque élément x_{ij} représente la performance de l'alternative A_i selon le critère C_j.
- Construct a matrix X, where each element x_{ij} represents the performance of alternative A_i with respect to criterion C_j.

Step 3: Determine Best and Worst Values for Each Criterion

- For each criterion, determine the best value f_j^* and the worst value f_j^-, across all alternatives.

Step 4: Compute the Deviation Measures S_i and :

- S_i represents the distance to the ideal solution and is calculated as follows:

$$P_i = \frac{S_i^-}{(S_i^+ + S_i^-)}, \quad 0 \le P_i \le 1 \tag{III.13}$$

- R_i represents the regret criterion and is calculated as follows:

$$R_i = \max_j \left(w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \right) \tag{III.14}$$

- w_j is the weight of criterion j.

Step 5: Calculation of the Compromise Measure Q_i:

- The compromise measure Q_i is calculated as follows:

$$Q_i = v \left(\frac{S_i - S^*}{S^- - S^*} \right) + (1 - v) \left(\frac{R_i - R^*}{R^- - R^*} \right) \tag{III.15}$$

- S^* and S^- are the best and worst values of Si, respectively.
- R^* and R^- are the best and worst values of R_i, respectively.
- υ is the weight of the strategy emphasizing the maximum group utility versus individual regret (commonly υ =0.5).

Step 6 : Ranking the Alternatives:

- Rank the alternatives based on their Q_i values. The alternative with the lowest Q_i value is considered the best.

6.6. RPN and RPI Approaches

The RPN (Reference Point Normative) approach is a multi-criteria decision-making method similar to the RPI approach but focuses on the use of normative reference points to evaluate and compare alternatives. Unlike the RPI approach, which is interactive and adjustable, the RPN approach emphasizes predefined standards or ideal values for each criterion. [90,91]

The RPN approach is a multi-criteria decision-making technique that uses normative reference points to guide the evaluation of alternatives. These reference points are standard or ideal values set in advance for each criterion. This method allows the performance of alternatives to be measured against these standards and ranks them based on their conformity to the norms.

The RPI (Reference Point Interactive) approach is a multi-criteria decision-making technique that uses reference points to guide the evaluation process. These reference points are desired or ideal values for each criterion, defined by the decision-maker. This method evaluates how closely each alternative approaches or deviates from these reference points, thus facilitating the selection of the alternative most aligned with the decision-maker's preferences. [92–94]

Step 1: Identification of Criteria and Alternatives:

Identify the evaluation criteria $C_1, C_2, \ldots, C_n$ and the alternatives $A_1, A_2, \ldots, A_n$

Step 2: Definition of Reference Points:

The decision-maker specifies the reference points r_j for each criterion Cj. These reference points represent the desired or ideal values that the alternatives should reach.

Step 3: Construction of the Decision Matrix:

Build a matrix where each element x_{ij} represents the performance of alternative A_i with respect to criterion.

Step 4: Evaluation of Distances to Reference Points :

Calculate the distance d_{ij} between the performance of each alternative and the reference point for each criterion. This can be done using various distance measures, such as Euclidean distance, Manhattan distance, or any other appropriate metric.

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \qquad \text{(III.16)}$$

Step 5: Calculation of Overall Scores:

Integrate the calculated distances using an aggregation function to obtain an overall score for each alternative. This function can be a weighted sum of the distances, where the weights w_j reflect the relative importance of each criterion.

Step 6 : Interaction and Adjustment:

The RPI approach is interactive, meaning the decision-maker can adjust the reference points and the criterion weights based on the results obtained and any new information or preferences. This interactive process continues until the decision-maker is satisfied with the resulting solution.

Step 7: Ranking and Selection of Alternatives:

Rank the alternatives based on the overall scores calculated. The alternative with the **lowest score** (i.e., the one **closest to the reference points**) is considered the best.

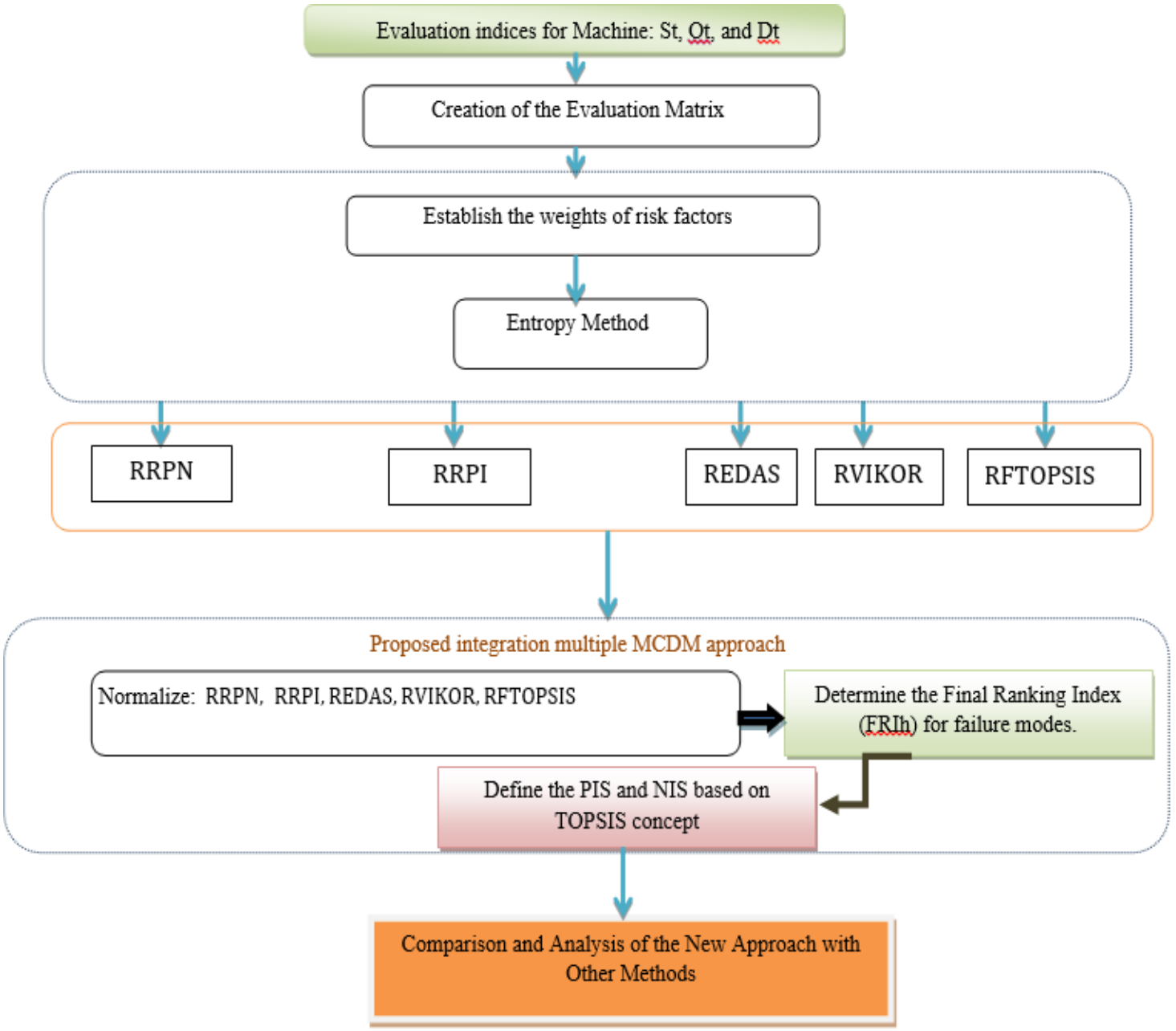


Figure III.4: Relationship Between MCDM Decision-Making Methods [93]

7. Conclusion

Following this theoretical analysis, we continue this chapter by addressing the concepts of MCDM, FUZZY-AHP, VIKOR, MAUT, RPN-RPI, and queuing theory.

In order to reduce the error rate in calculating the RPN during the implementation of the FMEA plan, we will use methods that help limit and eliminate failures. Each approach is clearly presented, and the key steps are thoroughly explained.

The two Fuzzy-AHP techniques that we will use in our case study are also detailed.

CHAPTER IV

Results Analysis and Interpretation

1. **Introduction**
2. **Company Description**
3. **Zone Study and Analysis**
4. **System Description**
5. **Case 01: Application of MBF**
6. **Case 02: Application of the FMEA Method Using MCDM**
7. **Conclusion and Future Research**

1. Introduction

Transportation is perceived as one of the major economic activities on a global scale, having a direct and effective impact on the global economy. This was explained by British economist Alfred Marshall in his book *Economics of Industry*, which asserts that the dominant economic reality of our era is not industrial development, but rather the conveniences offered by transportation [95,96]. The growth and improvement of transport companies directly lead to an increase and optimization of the national economy, depending on the infrastructure they provide. This justifies the need for prevention.

These vehicles require air conditioning systems, particularly in southern regions where temperatures rise significantly during the summer. Trams are generally considered more environmentally friendly than other modes of transportation, as they are usually powered by electricity and generate fewer emissions. Therefore, maintaining the reliability of these air conditioners is essential to ensure a suitable environment for passengers [97].

Preventive maintenance is a proactive maintenance method aimed at avoiding equipment failures and ensuring the proper functioning and efficiency of machines, vehicles, or other assets. Its main goal is to guarantee vehicle reliability, which is the indicator that combines vehicle quality and economic growth.

In this chapter, we will examine the air conditioning system of trams operating in southern Algeria, focusing on the company CITAL in the Ouargla region. This area is experiencing a significant degradation and a failure rate of up to 97%, leading to the breakdown of these air conditioners completely halting their operation. This has resulted in a sharp decline in passenger numbers, especially during the summer, as the tramway management company experiences a substantial drop. Passengers refrain from using the service due to the high temperature inside the vehicles caused by air conditioning issues.

Despite the implementation of a Periodic Preventive Maintenance (PPM) program, the parent company FAIVELEY has not resolved the problem, even though the maintenance manual provided with the tram was adopted. Moreover, the air conditioning system is still under warranty from FAIVELEY.

The objective of this study is to analyze the air conditioning system through two situations. First, we aim to determine the level of reliability based on the accumulation of faults, then develop a maintenance plan covering all components of the air conditioning system. Next, we will identify all defects and address the problem, which has lasted for years and caused significant financial losses for the company.

Ultimately, the stability rate will be calculated after resolving the issue and compared to the stability rate over the past two years.

In the second case, the study focuses on the maintenance analysis of the tram air conditioning system to improve overall reliability and extend the system’s lifespan. To enhance the performance in design and maintenance, the FMEA method was used for the first time. However, limitations such as non-injection of data and lack of objectivity affected the FMEA results.

This research introduces an integrated risk assessment model that combines various methodologies to comprehensively assess failure modes. The entropy method is used to determine the weights of risk variables, followed by the integration of failure mode rankings using RPI, EDAS, VIKOR, and FUZZY TOPSIS through integrated MCDM techniques. The TOPSIS method, based on preference ranking through similarity to the ideal solution, is applied. The effectiveness of the proposed methodologies and a 22.72% increase in system reliability were verified using statistical data and expert analysis for trams in southern Algeria.

2. Company Description

CITAL was established in 2011 to provide Algeria with modern industrial infrastructure for the assembly and maintenance of trams. Its objective is to meet the tramway demands of both current and future projects in Algeria. Since December 2010, CITAL has been maintaining six tram lines: Algiers, Oran, Constantine, Sidi Bel Abbès, Ouargla (since March 2018), and Sétif (since May 2018). Maintenance for the Mostaganem tramway and CORADIA ALGERIA long-distance trains will also be handled by CITAL in the near future. [98]



Figure IV.1: Photo of CITAL Company. [98]

CITAL is ISO 9001:2015 certified. [99].

- Construction of 145 CITADIS tram sets.
- Establishment of a railway industrial and economic network in Annaba around the factory, and across Algeria around CITAL's maintenance centers.
- Recruitment of over 500 local managers and employees, trained in Europe and Algeria, to become highly skilled and proficient in cutting-edge technologies.
- Three major partners: EMA, FERROVIAL, and ALSTOM.
- Globally recognized quality with ISO 9001 certification.
- Commitment to environmental preservation with ISO 14001 certification.
- Employee health and safety certified under ISO 14001.

2.1. Production

CITAL assembles CITADIS tram sets in Annaba over an area of 5.2 hectares. The plant is capable of delivering 5 tram sets per month with a steady production workload, similar to other ALSTOM plants.

The production facility is equipped with all necessary assembly, testing, and inspection tools to perform both type and series dynamic testing.The center's state-of-the-art power system includes a 1000-meter test circuit. [99]

2.2. General Information about the Site

- Total area: 52,000 m²
- Developed area: 11,871 m²
- Productivity: 5 tram sets per month

2.3. Workload Plan

- **Phase 1:** Construction of 213 CITADIS tram sets in two stages
- **Phase 2:** Deployment of 50% of the CITADIS tram sets to meet Algeria's future transportation needs
- At the same time, CITAL will manage the maintenance of all tram sets operating across Algeria

2.4. Maintenance

Maintenance is one of CITAL's core activities. Each city equipped with a tram system will have a dedicated maintenance center where all maintenance operations will be carried out.



Figure IV.2: Photo of CITAL Maintenance Chain. [98]

It is essential to provide these services both to ensure the availability of the tram sets and to promote a positive image of the tramway systems

- Systems maintained by CITAL:
    - **Algiers (since December 2010):** 41 tram sets + Tramway System and Infrastructure.
    - **Oran (since April 2013):** 30 tram sets + Tramway System and Infrastructure.
    - **Constantine (since June 2013):** 27 tram sets + Tramway System and Infrastructure.
    - **Sidi-Bel-Abbès (since July 2017):** 30 tram sets + Tramway System and Infrastructure.
    - **Ouargla (since March 2018):** 23 tram sets + Tramway System and Infrastructure.
    - **Setif (since May 2018):** 26 tram sets + Tramway System and Infrastructure.

It is important to note that all these activities are carried out by local teams, which means CITAL directly contributes to the regional development across Algeria. [98]

3. Zone Study and Analysis

The city of Ouargla is located in the northern part of the Algerian Sahara. It lies at 31.56° latitude and 5.19° longitude. The ecosystem of this region is characterized by a hot desert climate, consistently high temperatures throughout the year, and low biodiversity. [100]

Below are some key weather statistics for 2021 [101]:

- The hottest average temperature is in July, reaching 49.94°C.
- The coldest average temperature is in January, at 11.95°C.
- The air is extremely dry, with relative humidity levels varying by season but often reaching very low thresholds.
- Maximum annual wind speeds reach up to 69.7 m/s, peaking in summer, as illustrated in the following charts.

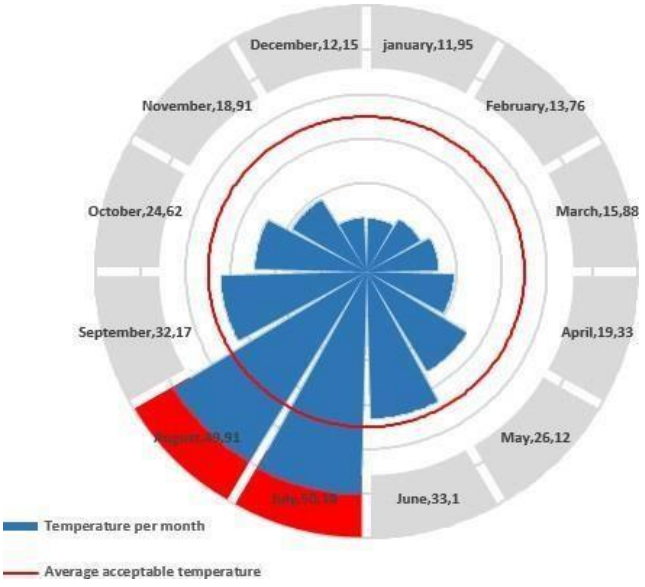


Figure IV.3: Graph Showing Monthly Temperature Changes.

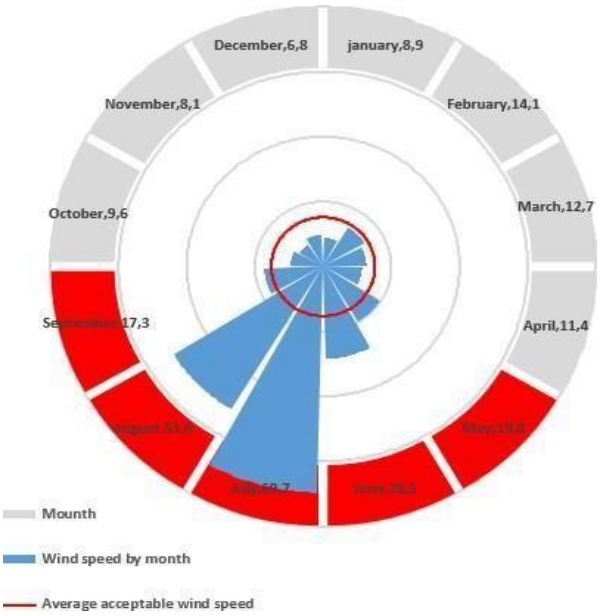


Figure IV.4: Graph Showing Monthly Wind Speed Changes

According to the data, it appears that the region's climate is hot and dry, with strong monsoon winds, especially during the summer when the maximum temperature reaches 49.94°C and wind speeds reach 69.7 m/s. This climate requires the continuous use of air conditioning systems throughout the year, with increased strain during the summer, which exposes the AC units to numerous malfunctions due to fatigue.

Moreover, the nature of this climate exposes the mechanical, electrical, and electronic components to a variety of failures, which can lead to tramway breakdowns and numerous operational issues.

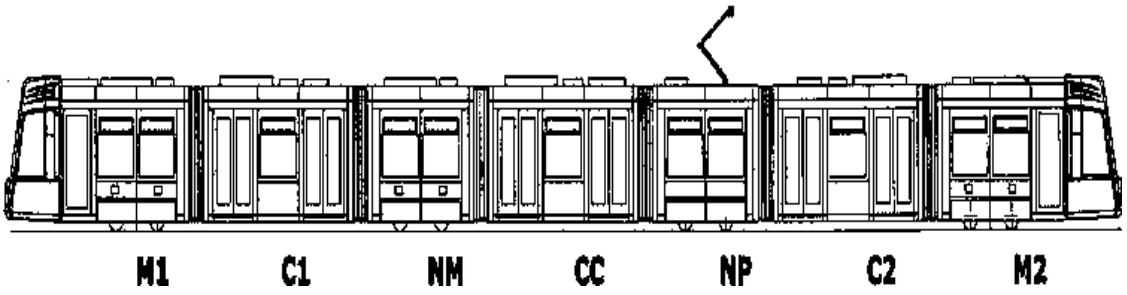
4. System Description

Tramways are considered one of the many modes of transport, and their technical configuration varies depending on the location and climate in which they are used. Examples include:

- **Citadis™ 202** (Melbourne), length: **20 m**
- **Citadis™ 301** (Orléans, Dublin), length: **27 m**
- **Citadis™ 302** (Adelaide, Lyon, Paris T2, Valenciennes, Rotterdam, Buenos Aires, Madrid, Melbourne, Murcia, Barcelona), length: **33 m**
- **Citadis™ 304**, length: **33 m**
- **Citadis™ 401** (Montpellier, Dublin), length: **39 m**
- **Citadis™ 402** (Bordeaux, Grenoble, Paris T3, Tours), length: **44 m**
- **Citadis™ 404**, length: **43 m**

4.1 . Citadis™ 402 Tramway Type

The tramway model used in southern Algeria, particularly in the Ouargla region, is the CITADIS 402, operating over a line 9.2 km long. It is powered by overhead contact lines (LAC) and is specifically manufactured to suit the characteristics and climate of desert regions. These are bi-directional vehicles, equipped with: 6 double-entry doors and 2 single-entry doors on each side, Large windows, Air conditioning in the driver's cabin, And both heating and air conditioning in the passenger cabin.



C1: Suspended car body **NM**: Motorized bogie **CC**: Suspended bogie
NP: Carrier bogie **C2**: Suspended car body **M2**: Motorized unit

Figure IV.5: Diagram of Citadis™402 Tram Type [102]

4.2. Tramway Air Conditioning System

Heating system of CLU45-type tram. The upper part (roof) of the vehicles is equipped with the air conditioning system, as shown in (Figure IV.6). Two separate cooling circuits, a heating system, and an air handling unit are integrated into the CLU45 air conditioner. The HVAC system consists of a single unit, with components mainly made from aluminum sheets. There are three distinct zones in the vehicle's air conditioning system: the electrical zone, the air treatment zone, and the cooling circuit zone (Figure IV.7). Each tram car is equipped with 03 HVAC kits to facilitate access to all components. The use of this type of air conditioner enables heating, cooling, and ventilation of the passenger areas to ensure excellent thermal quality and optimal comfort throughout the journey. [102].

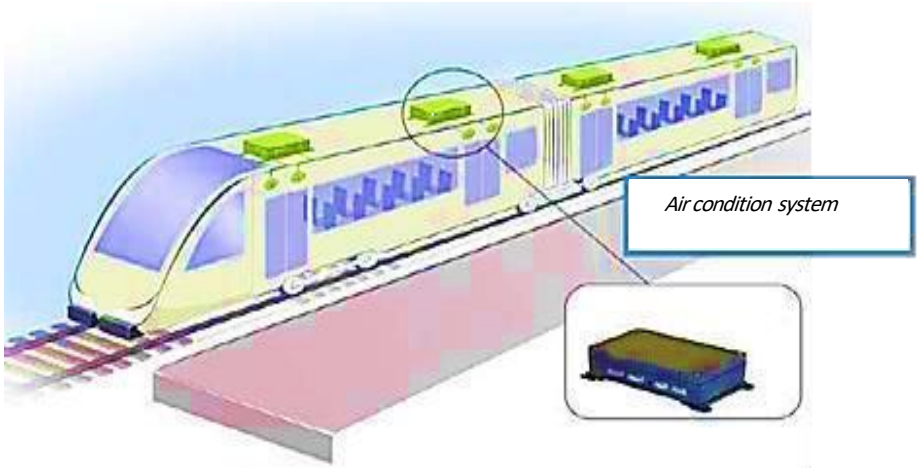
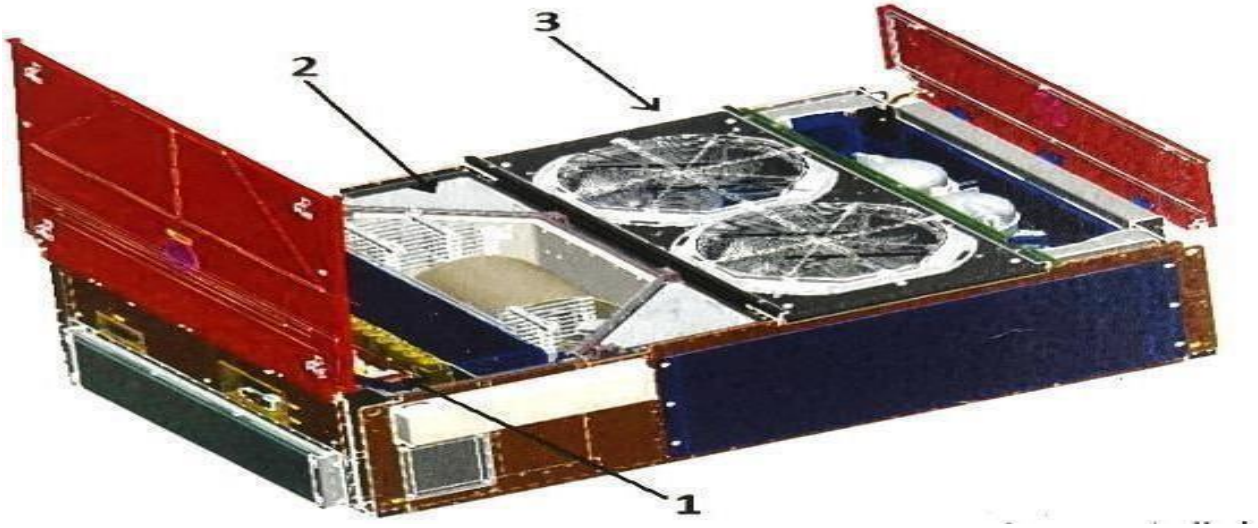
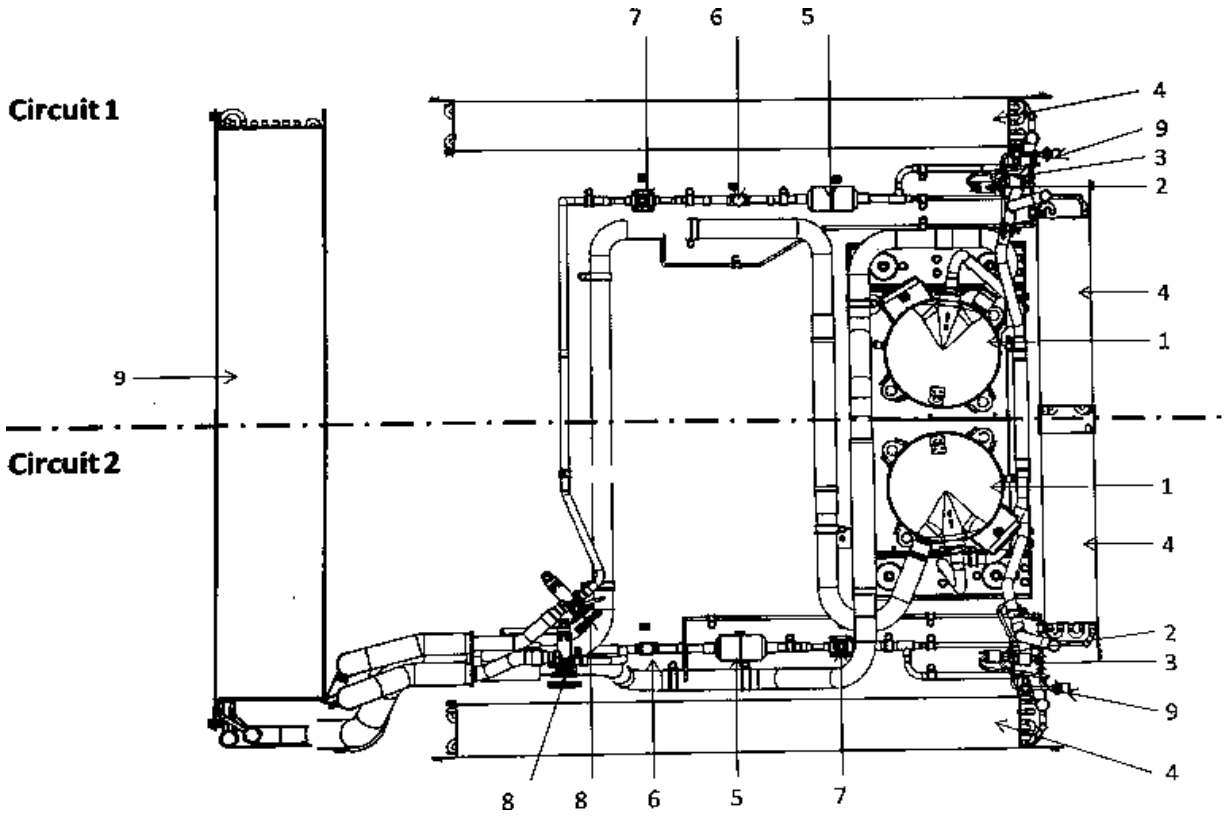


Figure IV.6: Location of the Air Conditioning System on the Tram [102].



1. Electrical panel **2.**Air treatment zone **3.**Cooling circuit zone

Figure IV.7: Image of Air Conditioning System Zones [102].



1.Compressor **2.**High pressure switch HP **3.**Low pressure switch LP **4.**Condenser **5.**Drier filter

6.Sight glass **7.**Solenoid valve **8.** Expansion valve **9.**Evaporator

Figure IV.8: Diagram of Tram Air Conditioning System Components. [102]

4.3. Drier filter

The drier filter is an essential element for the reliability of the system as well as its lifespan. The Danfoss filter drier range covers both hermetic and exchangeable core types. The core allows the filter drier to absorb water and acids more efficiently to prevent corrosion of the compressor's metal surfaces and ensure that oil and refrigerant do not decompose [7].

The filter drier must absorb any residual humidity from the refrigeration circuit. It has an extractable cartridge retaining all kinds of impurities such as particles, sludge and oil decomposition products coming from the refrigeration circuit. [6].

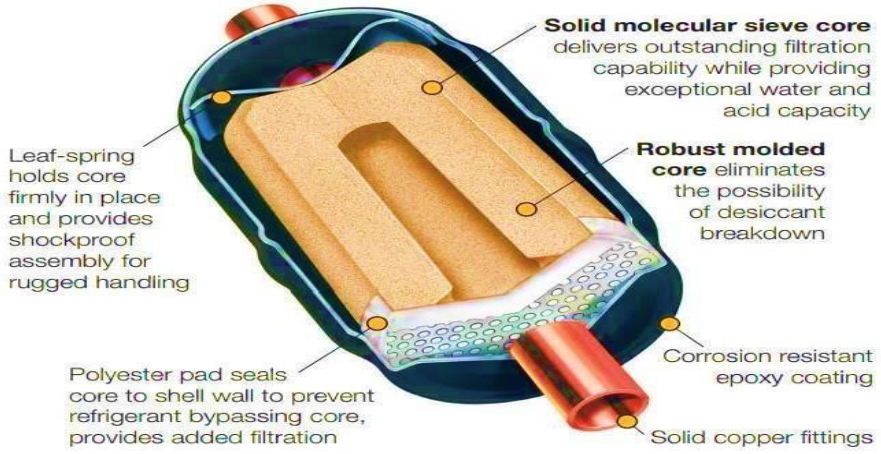


Figure IV.9: Diagram of the Drier Filter Components. [7]

5. Case 01 :

5.1. Methodology

- Calculate the system's reliability during the year in which failures occurred and prepare a comprehensive preventive maintenance plan (PM Plan and FMEA).
- Analyze and study the results.
- Calculate the system's reliability after eliminating the failure.

5.1.1. System Reliability Calculation (PM Plan and FMEA)

The first step is to use calculation software and plot curves to determine the reliability and the failure rate of the tramway system during the year 2021, as the failure rate is alarmingly high, with the air conditioning system failing at a rate of 97%. The results are presented in Table 1.

Table IV.1: Reliability and Failure Rates – Year 2021.

Month	*Numberfail ures*	*TBF(h)*	*TTR(h)*	*MTBF*	*λ(t)*	*R(t)%2021*	*F(t)% 2021*
January	11	5596,23	22	5594,23	0,00017	87,53	12,47
February	15	5483,75	30	5481,75	0,00018	88,48	11,52
March	12	5913,21	24	5911,21	0,00016	88,18	11,82
April	21	4063,59	52,5	4061,09	0,00024	83,76	16,24
May	33	1321,24	82,5	1318,74	0,00075	56,89	43,11
June	57	2080,83	199,5	2077,33	0,00048	70,72	29,28
July	80	532,21	280	528,71	0,00189	24,49	75,51
August	71	720,03	248,5	716,53	0,00139	36,6	63,4
September	69	597,521	310,5	593,02	0,00168	31,6	68,4
October	59	1013,324	206,5	1009,82	0,00099	49,02	50,98
November	29	1075,14	101,5	1071,64	0,00093	49,94	50,06
Décember	73	815,61	328,5	811,11	0,00123	40,95	59,05

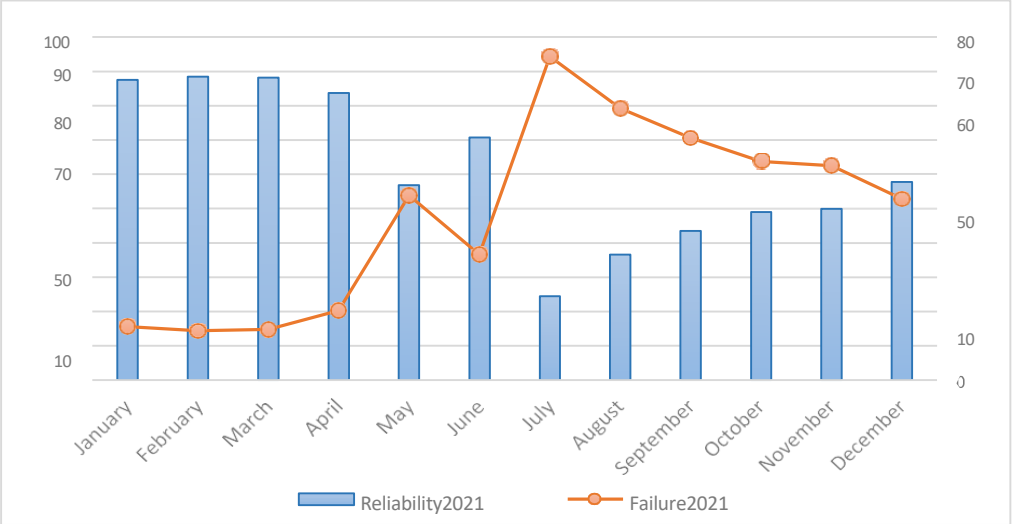


Figure IV.10: Reliability Rate Diagram vs. Failures in 2021

Through the reliability diagram, it can be observed that the reliability rate of the vehicles was good at the beginning of the year, particularly during the winter season, compared to the summer season in June, when failures began to increase significantly and reached a peak rate of 75.51%.

- The second step involves developing an FMEA sheet to identify which components are the most failure-prone and have a high criticality rate (Table 2).

5.1.2. Analysis and Study of the Results

Tram 101 was selected, and the air conditioning system was set to maximum until the IOS 04 error was reported on the control panel. According to the parent company's manual, the IOS04 error indicates a failure in both heating and cooling modes. Next, the train components were connected to a specific program (FAIVELEYLOG13NSF0015), which is equipped with artificial intelligence technology to accurately analyze faults and imperfections.

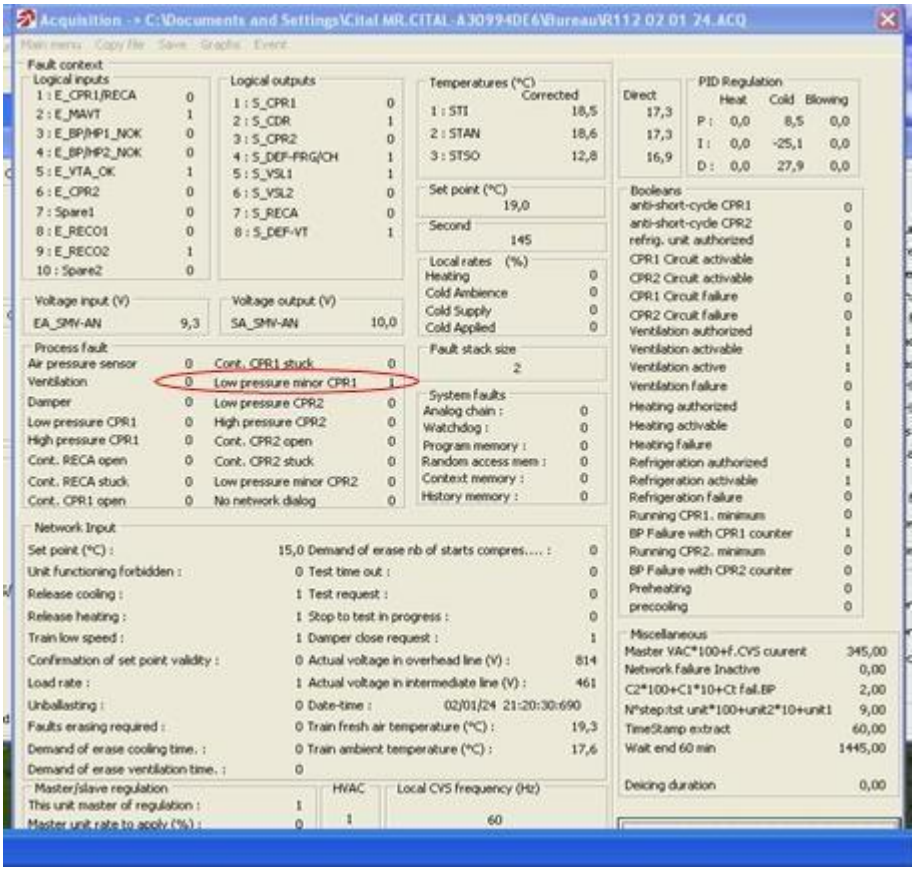


Figure IV.11 diagnostique des panne par logicielle FAIVELEY A001.

The FAIVELEY LOG13NSF0015 program detects a BP failure (low-pressure valve failure), according to the actuator manual provided by FAIVELEY, which identifies a malfunction in the tramway's air conditioning system. The LP failure indicates the following:

- Evaporation pressure is below 0.5 bar.
- Lack of refrigerant in the circuit.
- Malfunctioning solenoid valve.
- Malfunctioning capacity regulator.

The third step is to diagnose the faults and send a report to the parent company, as it is responsible for operational and maintenance decisions in accordance with the agreed tramway warranty program. After reviewing the results, a team of technicians from Alstom was dispatched to Algeria to perform the maintenance.

➢ **Decisions made by the parent company's technicians:**

- Change the air conditioning system version on tram 103 (from version 1 to version 2 or 3).
- Change the solenoid valve on tram 104.
- Change the capacity regulator on tram 105.

The low-pressure valve (BP) failure rate is high on tram 108, so tram 108 will serve as a benchmark for comparing the results obtained from the other trams. The results are shown in the following graphs:

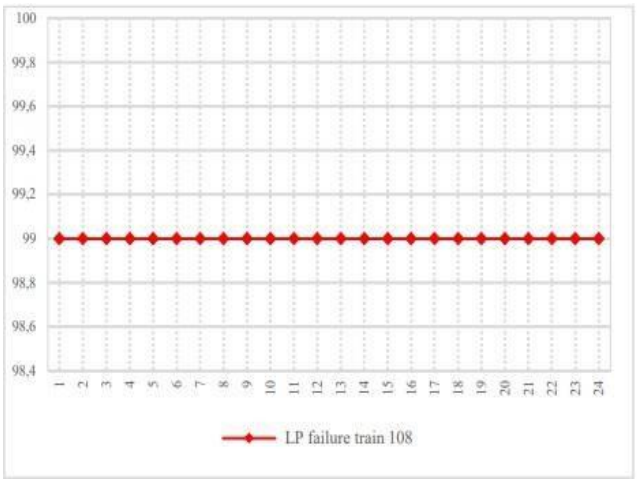


Figure IV.12: Graph Showing LP Failure Percentage in Tram 108.

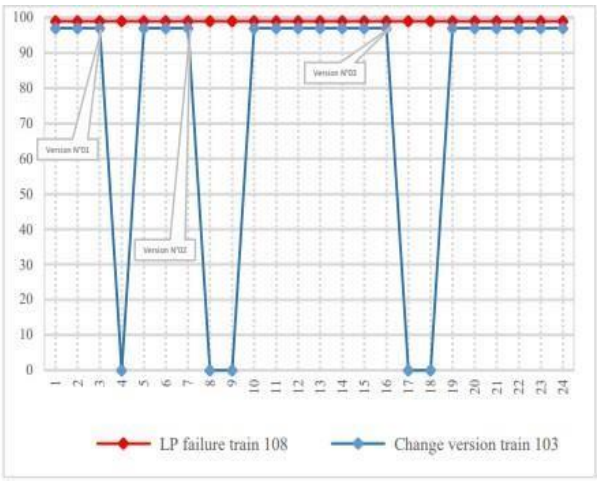


Figure IV.13: Graph Showing the LP Failure Rate in Tram 103 After Version Change.

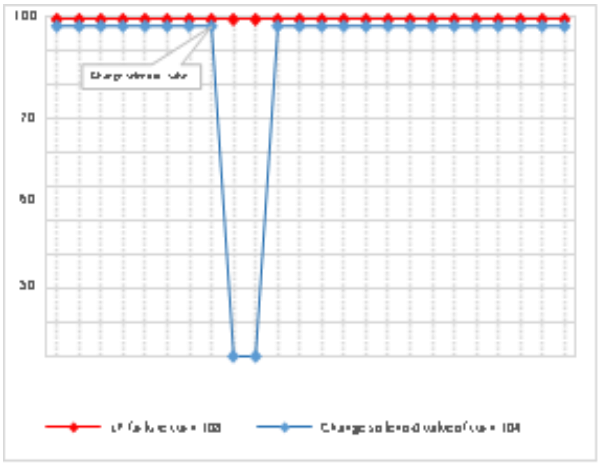


Figure IV.14: Graph Showing the BP Failure Rate in Tram 104 After Solenoid Valve Replacement.

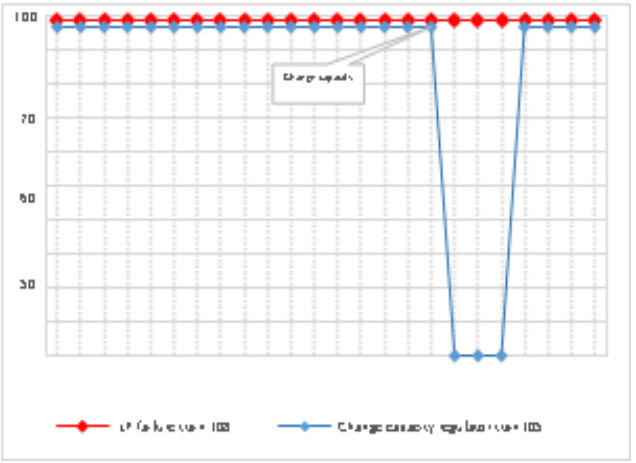


Figure IV.15: Graph Showing the LP Failure Rate in Tram 105 After Capacity Regulator Replacement.

By comparing the results of the three trams with tram 108, we observed that the BP failure disappears for only a few minutes after changing the three versions on tram 103, then reappears as soon as the air conditioners are turned back on. In contrast, for trams 104 and 105, we noted that the fault disappears for more than an hour after replacing the solenoid valve and the capacity regulator. However, the fault eventually returns, meaning that all the interventions are considered unsuccessful, as the BP failure did not permanently disappear.

Fourth step: A subsequent step after the parent company's technicians failed to resolve the problem was that the situation worsened—especially due to rising ambient temperatures. We sent a detailed report on the high failure rate of the vehicle air conditioning systems, which led to:

- A significant increase in temperature inside the tram cars
- A severe drop in passenger numbers
- Resulting in major financial and time losses for the transport company

A request was submitted to the parent company to approve our intervention to help solve the issue. After approval, a **preventive maintenance plan** was developed, which included the inspection of all cooling system components of vehicle 101 (HVAC). Thanks to the initial diagnostics, we obtained the following results:

- The refrigerant level was too high in circuit 2 between the compressor and the dryer filter, and too low afterwards.

- **Final diagnosis**: A possible blockage in the dryer filter (circuit 2).

➢ **Decisions of parent company:**

- A complete blockage of the filter is considered unacceptable, as the filter has a lifespan of over 10 years and there is no valid reason for it to be blocked especially since both compressors appear to be in good condition according to diagnostics.
- The most likely solution is to install a new version of the air conditioning units.

➢ **Decisions of CITAL technician:**

Two operations were carried out on two different vehicles to validate the findings:

- Change the version of the air conditioning unit on tram 104.
- Replace the dryer filter on tram 101.

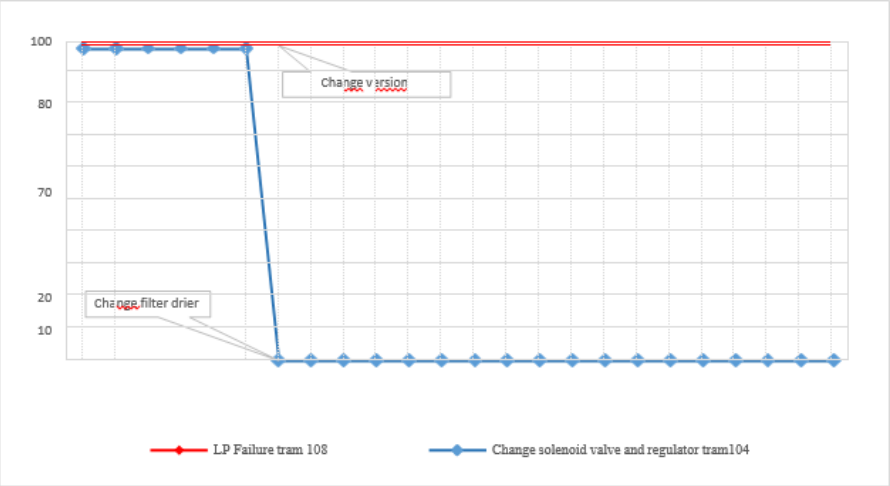


Figure IV.16: Graph Showing the LP Failure Rate in Tram 104 After change the Drier Filter.

Complete disappearance of BP pressure failures on tram 101 after replacing the dryer filter in circuit 2, while the failures persisted on tram 104.

Following our diagnostics and the impressive results obtained—namely, the complete disappearance of BP failures on tram 101 after replacing the dryer filter and restarting the air conditioning units—the parent company decided to validate our findings by conducting three different experiments on three vehicles as follows:

- **Tram 108**: Replace the solenoid valve along with the dryer filter.
- **Tram 109**: Replace the dryer filter together with the capacity regulator.
- **Tram 110**: Replace only the dryer filter.

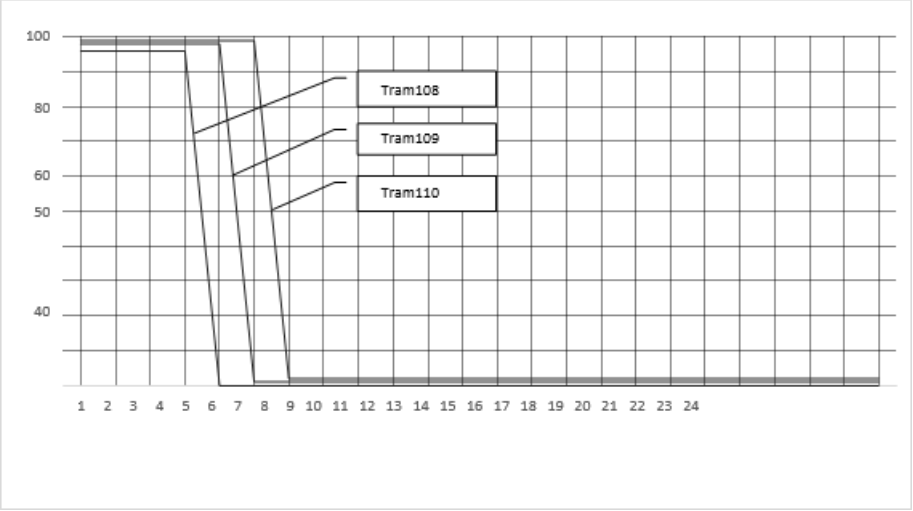


Figure IV.17: Graph Showing LP Distribution After Three Different Operations on Three Different Trams.

The low-pressure valve (BP) failure completely disappeared on all three vehicles, even after running the air conditioning systems at full capacity throughout the entire day.

- **The final conclusion** is that the dryer filter was blocked in all the vehicles.final est que le filtre déshydrateur est bloqué dans tous les véhicules.

➢ **Diagnosis of Drier Filter Failure**

In this step, we aim to identify the root cause of the dryer filter failure by opening one of the damaged filters that was replaced in circuit 2 of the air conditioning system and comparing it with the internal section of a new filter. (Figures 18 and 19) show the difference between a good filter and a damaged one.



Figure IV.18: Photo of an Internal Section of the New Drier Filter.



Figure IV.19: Photo of a Damaged Internal Part of the Drier Filter.

The photos show that the inner cotton of the good filter is white and in good condition, whereas in the damaged filter, the inner cotton appears black and completely burnt, forming a solid insulating layer that blocks the flow of liquid—this being the cause of the blockage.

Having understood that the blockage is due to the melting of the cotton layer at the bottom of the dryer filter, it can be concluded that the primary cause of the melting is an error that occurred during the installation process of the filter in circuit 2 of the air conditioning system. This is supported by the fact that the tram is still within its first two years of of operation, and there is no other logical reason for the blockage.

- To confirm this, we welded two different filters: the first was welded while following the recommendations provided with the dryer filter (Figure 20), and the second was welded without following the recommendations (Figure 21). The results are shown in the photos.



Figure IV.20: Photo of the Dehydrator Filter: (A) Correct Welding Method, (B) Internal Part of the Filter After Welding

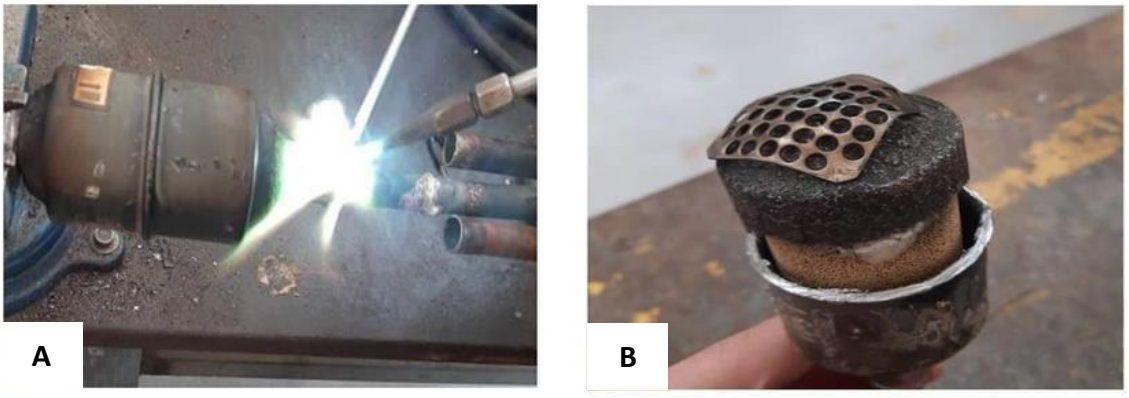


Figure IV.21: Photo of the Dehydrator Filter: (A) Incorrect Welding Method, (B) Internal Part of the Filter After Welding.

It can be observed that the dryer filter, which was welded according to the recommended procedure, remained intact. In contrast, the second filter, which was welded without following the guidelines, was completely destroyed. The main reason for the clogging of the dryer filter is the melting of the inner cotton layer due to an incorrect welding method.

5.1.3. System Reliability after Reliability Improvement contribution

After identifying the main issue and its root cause, the filters in all vehicles were replaced using the correct welding method. The results are presented as reliability rates after the filter replacements, as shown in the following Table IV.3.

Table IV.2: Reliability and Failure Rates – Year 2022.

Month	*Number failures*	*TBF(h)*	*TTR(h)*	*MTBF*	*λ(t)*	*R(t)% 2021*	*F(t)% 2021*
January	11	5596,23	22	5594,23	0,00017	87,53	12,47
February	15	5483,75	30	5481,75	0,00018	88,48	11,52
March	12	5913,21	24	5911,21	0,00016	88,18	11,82
April	21	4063,59	52,5	4061,09	0,00024	83,76	16,24
May	33	1321,24	82,5	1318,74	0,00075	56,89	43,11
June	57	2080,83	199,5	2077,33	0,00048	70,72	29,28
July	80	532,21	280	528,71	0,00189	24,49	75,51
August	71	720,03	248,5	716,53	0,00139	36,6	63,4
September	69	597,521	310,5	593,02	0,00168	31,6	68,4
October	59	1013,324	206,5	1009,82	0,00099	49,02	50,98
November	29	1075,14	101,5	1071,64	0,00093	49,94	50,06
December	73	815,61	328,5	811,11	0,00123	40,95	59,05

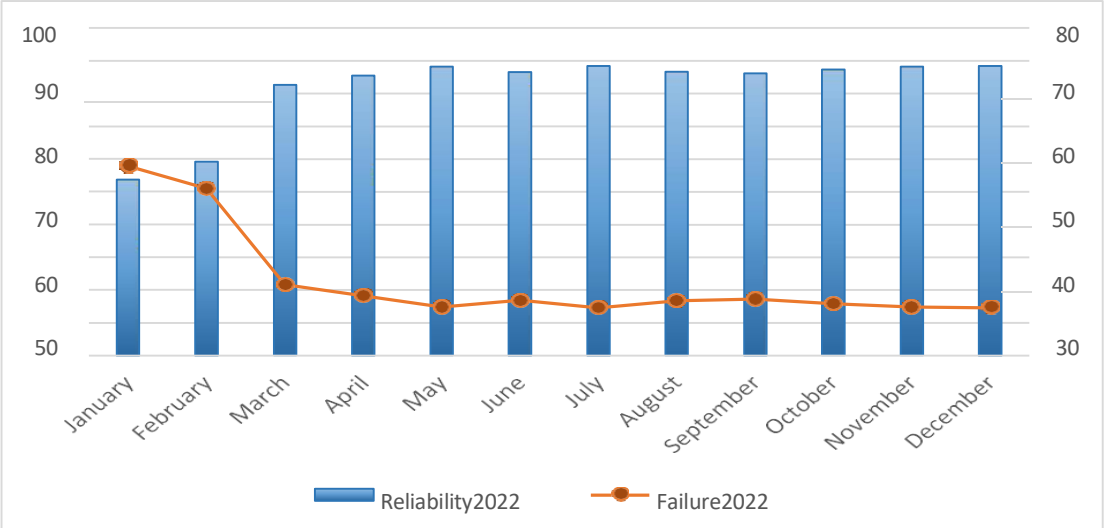


Figure IV.22: Reliability Rate Diagram versus Failures in 2021

According to the results, we observe that reliability increases to 88.33% in summer, with a significant decrease in the failure rate compared to the year 2021, during which the LP failure occurred. As a result, the vehicles returned to normal operation, leading to a notable increase in the company's revenue in 2022

6. Case 02 :

6.1. Methodology

Figure 1 illustrates the structural arrangement of the tram risk assessment model. The implementation of the proposed model comprises three phases. Initially, the identification of risk variables and failure modes takes place. Subsequently, risk factors are formulated as criteria within the Failure Mode and Effects Analysis (FMEA), among which St, Ot, and Dt are included. These parameters pertain to various faults and are subject to evaluation in the matrix. The weights assigned to the risk factors are determined utilizing the entropy method. In the second phase, classification via different methods is established, and the hybrid method is employed for the final classification. Lastly, a comparison and analysis are conducted in the concluding phase.

6.1.1 Phase 1: Weight Identification and Their Impact

The criterion weights are employed to ascertain their relative significance within the assessment framework [21-22]. In this study, the Entropy Method is utilized for this purpose.

6.1.1.2. Entropy Method

The entropy method determines the relative weights of each factor in the cases examined based on a predetermined decision matrix of a quantity of offered data. [23].

For the jth criterion, the application of the information entropy value Ej is as follows:

$$E_j = -\frac{[\sum_{i=1}^{m} P_{ij} ln(P_{ij})]}{\ln(m)}; \quad (2)$$

j=1,2,…,n and i=1,2,…,m

The Pij is provided by the normalized decision matrix, as :

$$P_{ij} = \frac{r_{ij}}{\sum_{i}^{m} r_{ij}}; \quad (3)$$

where r_{ij} is an element of the decision matrix

The criteria weights wj can be obtained using the following expression:

$$\mathrm{W_j} = \frac{1-E_j}{\sum(1-E_j)}; j = 1,2,\dots,n \quad (4)$$

Where (1-Ej) is the measure of the diversity of information found in the results of the criterion's results.

6.1.2. Phase 2. Application of Different Methods for Ranking Failure Modes

6.1.2.1 Using the RPI method

The Risk Priority Index (RPI) and Risk Isosurface (RI) functions make up the Risk Priority Index (RPI) model. RI concerns scenarios in which the priority of risk variables is sufficient for prioritization of failure modes, while RPI incorporates variable weights for nuanced prioritization. RI is easy to use and understand, and is typically adequate to classify failure modes. However, RPI becomes crucial when it is necessary to adjust for variations in risk variables.

The different steps of the RPI model are presented as follows:

a) Calculate the Risk Isosurface (RI), prioritizing A > B > C in terms of significance, using the following equation:

$$\mathrm{RI(A,\ B,\ C)}_{A>B>C} = (1 - A).\propto^{2} + B \propto + C - \propto \quad (5)$$

Where A, B, C, α ∈ N.

For instance, in a risk scenario where the risk elements are arranged as D > O > S, the risk index (RI) is calculated using the following equation:

$$\mathrm{RI(D, O, S)}_{D>O>S} = (1 - D).10^{2} + O.10 + S - 10 \quad (6)$$

b) Assign weights to risk elements

$$RPI = w_A\delta_A + w_B\delta_B + w_C\delta_C \quad (7)$$

Where the delta risk variables are designated by δA, δB, and δC. For example, δS, δO, and δD are associated with risk factors like severity, occurrence, and detectability.

$$\delta A = \frac{\mathrm{RI(A,B,C)}_{A>B>C_{Rank}} + \mathrm{RI(A,B,C)}_{A>C>B_{Rank}}}{2} \quad (8)$$

$$\delta B = \frac{\mathrm{RI(A,B,C)}_{B>A>C_{Rank}} + \mathrm{RI(A,B,C)}_{B>C>A_{Rank}}}{2} \quad (9)$$

$$\delta C = \frac{\mathrm{RI(A,B,C)}_{C>A>B_{Rank}} + \mathrm{RI(A,B,C)}_{C>B>A_{Rank}}}{2} \quad (10)$$

Applying the significance order $w_S > w_O > w_D$ to the equation below, the Failure Mode Risk Priority Index (RPI) is obtained:

$$RPI = w_S\delta_S + w_O\delta_O + w_D\delta_D \quad (11)$$

c) Verification of $w_A - w_B$ by flowing inequality:

$$w_S - w_O > \frac{1}{S^2} - \frac{1}{S^3} \quad (12)$$

Equation (12) maintains the user's original importance rating by requiring a difference of over 0.009 percentage points between the highest and intermediate weights.

d) Equation 13 presents the final form of the RPI:

$$RPI = \left(\frac{w_A s^3+1}{s^3}\right)\delta_A + \left(\frac{w_B s^2+1}{s^2}\right)\delta_B + w_C\delta_C \quad (13)$$

6.2. MCDM approaches': VIKOR, EDAS and FUZZY-TOPSIS

6.2.1. VIKOR

The following steps provide an explanation of the VIKOR algorithm's mathematical calculations:

a) **Determine the normalized value:** To perform the normalization practice, assume that each criterion i has a numerical alternative, j.

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}, j = 1,2,.....,m, i = 1,2,...,n \quad (14)$$

b) Find out the best f_i^* and the worst f_i^- values of each criteria function, $i = 1,2,...,n$

$$f_i^* = \left\{\begin{matrix}\max\limits_i f_{ij} & \text{for benefit criterion}\\ \min\limits_i f_{ij} & \text{for cost criterion}\end{matrix}\right\}, j = 1,2,...,m \quad (15)$$

$$f_i^- = \left\{\begin{matrix}\min\limits_i f_{ij} & \text{for benefit criterion}\\ \max\limits_i f_{ij} & \text{for cost criterion}\end{matrix}\right\}, j = 1,2,...,m \quad (16)$$

Where J is the number of alternative, n is the number of criteria and f_{ij} is the rating of i^{th} criterion function for alternative a_j.

c) Determine the S_j and R_j measures utilizing the provided values for material alternatives. $j = 1,2,...,m$;

$$S_j = \sum_{i=1}^{n}\left[\frac{w_i(f_i^* - f_{ij})}{(f_i^* - f_i^-)}\right] \quad (17)$$

$$R_j = \max_i \left[\frac{w_i (f_i^* - f_{ij})}{(f_i^* - f_i^-)} \right] \tag{18}$$

In the ranking measure formulation, w_i represents the weight of the ith criterion, while S_j and R_j are utilized.

d) Determine the values of Q_j using the following formula

$$Q_j = \frac{v(S_j - S^*)}{(S^- - S^*)} + \frac{(1-v)(R_j - R^*)}{(R^- - R^*)} \tag{19}$$

$$S^* = \min_j S_j \quad , \quad S^- = \max_j S_j \quad , \quad R^* = \min_j R_j \quad , \quad R^- = \max_j R_j$$

The value of v falls within the range of [0, 1]. Typically, v is assumed to be 0.5.

e) Evaluation based on Distance from Average Solution (EDAS)

The EDAS method [24-25], is used to rank the best alternative, focusing on its application to the classification problem for inventory management. The phases of this approach are described as follows:

- **Phase 1:** Selection of important criteria and alternatives.

- **Phase 2:** Create the Decision Matrix (D)

$$D = [x_{ij}]_{nxm} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ x_{31} & x_{32} & \dots & x_{3m} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{nm} \end{bmatrix} \tag{19}$$

Where x_{ij} represents the i_{th} alternative's on j_{th} criteria.

- **Phase 3:** Calculate the mean solution for all criteria.

$$AV = [AV_j]_{1xm} \tag{20}$$

With,

$$AV_j = \frac{\sum_{i=1}^{n} D_{ij}}{n} \tag{21}$$

- **Phase 4:** Determine the positive and negative distances from the mean solution (PDA and NDA), respectively, based on the criteria's beneficial and non-beneficial nature.

$$PDA = [PDA_{ij}]_{nxm} \tag{22}$$

$$NDA = [NDA_{ij}]_{nxm} \tag{23}$$

If j_{th} beneficial criteria

$$PDA_{ij} = \frac{\max(0,(D_{ij}-AV_j))}{AV_j} \quad (24)$$

$$NDA_{ij} = \frac{\max(0,(AV_j-D_{ij}))}{AV_j} \quad (25)$$

If j_{th} non-beneficial criteria

$$PDA_{ij} = \frac{\max(0,(AV_j-D_{ij}))}{AV_j} \quad (26)$$

$$NDA_{ij} = \frac{\max(0,(D_{ij}-AV_j))}{AV_j} \quad (27)$$

- **Phase 5:** Calculate weighted summation of PDA and NDA

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij} \quad (28)$$

$$SN_i = \sum_{j=1}^{m} w_j NDA_{ij} \quad (29)$$

w_j is the weight of j_{th} criteria

- **Phase 6: calculate** NSP_i and NSN_i

$$NSP_i = \frac{SP_i}{max_i(SP_i)} \quad (30)$$

$$NSN_i = 1 - \frac{SN_i}{max_i(SN_i)} \quad (31)$$

- **Phase 7:** Determine the Appraisal Score (AS_i) for each alternative

$$AS_i = \frac{1}{2}(NSP_i + NSN_i) \quad (32)$$

$$0 \leq AS_i \leq 1$$

- **Phase 8:** The best selection is determined by identifying the alternative with the maximum Appraisal Score (ASi).

6.2.2. FUZZY-TOPSIS

Hwang and Yoon introduced TOPSIS, a ranking technique for alternatives based on distances from ideal solutions, using Fuzzy TOPSIS to identify the best option based on NIS and PIS criteria. [26]

The decision matrix DM, with m alternatives and n criteria, is constructed using equation (23) to measure the criteria's performance:

$$DM = [x_{ij}] = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (23)$$

Where $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$

a) $R = [\tilde{r}_{ij}]_{m\times n}$:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \qquad j \in B \tag{24}$$

$$\tilde{r}_{ij} = \left(\frac{a_i^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \qquad j \in C \tag{25}$$

B stands for a benefit criterion and C for a cost criterion. in addition, $c_j^* = \max_i c_{ij}$ if $j \in C$ and $a_j^- = \min_i a_{ij}$ if $j \in B$.

b) indicate the fuzzy negative ideal solution (FNIS) and fuzzy positive ideal solution (FPIS):

c)

$$FPIS = (r_1^+, r_2^+, r_3^+, \ldots . . r_n^+) \tag{26}$$

$$FNIS = (r_1^-, r_2^-, r_3^-, \ldots . . r_n^-) \tag{27}$$

Where

$$v_j^+ = (p, p, p) \ \forall j = (1, 1, 1) \tag{28}$$

$$v_j^- = (k, k, k) \ \forall j = (0, 0, 0) \tag{29}$$

d) Compute the weighted distance of every alternative from both positive and negative ideal solutions.

$$d(A, B) = \frac{1}{2}\{max(|a_1 - b_1|, |a_3 - b_3|) + |a_2 - b_2|\} \tag{30}$$

If we suppose the weight matrix $w_j = (w_{xj}, w_{yj}, w_{zj})$ and each of our normalized Matrix arrays are $r_{ij} = (r_{xij}, r_{yij}, r_{zij})$

so then distance from FPIS can be calculate by formula (31):

$$d_i^+ = \sum_{j=1}^{n} \frac{1}{2}\{max(w_{xj}|r_{xij} - 1|, w_{zj}|r_{zij} - 1|) + w_{yj}|r_{yij} - 1|\} \tag{31}$$

And formula (32) for the Distance from the (FNIS)

$$d_i^- = \sum_{j=1}^{n} \frac{1}{2}\{max(w_{xj}|r_{xij} - 0|, w_{zj}|r_{zij} - 0|) + w_{yj}|r_{yij} - 0|\} \tag{32}$$

e) Finally, using formula (33), the relative proximity coefficient to the ideal solution is calculated. A higher value indicates that the alternative has a better rank.

$$CR = \frac{d_i^-}{d_i^+ + d_i^-} \tag{33}$$

6.2.3. Hybrid RPI-RPN-MCDM based FMEA model

Various approaches might provide different results. When all alternatives have the same ranking across all ranking techniques, decision-making becomes easier. A few studies [27–31] examine the hybrid MCDM strategy, which has emerged as an acceptable approach for classification. This research employs five distinct approaches for classifying failures. The entropy technique is utilized to ascertain the weights of the risk factors. However, employing an appropriate integration technique is necessary to determine the criticality position of each alternative. The suggested integrated model streamlines decision-making processes. Thus, to achieve a comprehensive outcome, it is recommended for risk managers to integrate multiple classification methodologies. The subsequent explanation delineates the specific steps of numerous integrated MCDM, RPI, and fuzzy MCDM techniques, which are founded on the TOPSIS concept used to merge the evaluation rankings.

- Step 1: The failure mode scores are translated into a 0–1 index. The RRPN, REDAS, RVIKOR, and RFUZZY TOPSIS (ranking indices) are converted by: Create a normalized matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}}, \tag{34}$$

a) Create the weighted Normalized Matrix.

$$V_{ij} = r_{ij} \times W_j \tag{35}$$

Where Wj is the entropy method's weighted criterion.

- Step 2 Obtain the z^+ and z^- (maximum and minimum scores for each column)

$$Z^+ = \underbrace{max}_{n}\{\text{RRPN, RRPI, REDAS, RVIKOR, RFTOPSIS}\} = \{Z_1^+, Z_2^+, Z_3^+, Z_4^+, Z_5^-\} \tag{36}$$

$$Z^- = \underbrace{max}_{n}\{\text{RRPN, RRPI, REDAS, RVIKOR, RFTOPSIS}\} = \{Z_1^-, Z_2^-, Z_3^-, Z_4^-, Z_5^-\} \tag{37}$$

- Step 3 Determine the distance between each method rank and (z+ and z-).

It is possible to determine the distance between each failure mode and the positive (z+) and negative (z-) ideal solutions, abbreviated PIS ($\boldsymbol{\alpha}_n^+$) and NIS ($\boldsymbol{\alpha}_n^-$), respectively:

$$\boldsymbol{\alpha}_n^+ = \sqrt{(\boldsymbol{R}RPN - Z_1^+)^2 + (\boldsymbol{R}RPI - Z_2^+)^2 + (\boldsymbol{R}EDAS - Z_3^+)^2 + (\boldsymbol{R}VIKOR - Z_4^+)^2 + (\boldsymbol{R}FTOPSIS - Z_5^+)^2} \tag{38}$$

$$\boldsymbol{\alpha}_n^- = \sqrt{(\boldsymbol{R}RPN - Z_1^-)^2 + (\boldsymbol{R}RPI - Z_2^-)^2 + (\boldsymbol{R}EDAS - Z_3^-)^2 + (\boldsymbol{R}VIKOR - Z_4^-)^2 + (\boldsymbol{R}FTOPSIS - Z_5^-)^2} \tag{39}$$

$$n = 1,2,\dots,m$$

- Step 4. Creating the final ranking index is necessary.

The final classification standard is established by the reliable classification index FRIn [32]. This index is determined as follows:

$$FRI_n = \left(\frac{\alpha_n^-}{\sum_{n=1}^{m} \alpha_n^-}\right) - \left(\frac{\alpha_n^+}{\sum_{n=1}^{m} \alpha_n^+}\right) \quad (40)$$

$$-1 \leq FRI_n \leq 1$$

6.3. Case study

The analysis focused on failure data over a one-year period, listing in Table 1 all functional failures of the tramway air conditioning system, along with several types of 'Fti' failures. Twelve different failure mechanisms were identified, according to tramway specialists. Table IV4 presents the language descriptors and values for St, Ot, and Dt. Notably, in Table 3 related to the classical FMEA, failure modes Ft10 and Ft11 are ranked sixth.

Table IV.3: FMEA Sheet and Failure Modes of the Air Conditioning System.

FMEA (Failure Modes and Effects Analysis) Machine - Evaluation of Failure Modes, Their Consequences, and Their Importance SYSTEM: Tramway						
Element	**Function**	**Failure mode**	**Causes of failure**	**Effect of failure**	**Detection**	**Failure number**
Compressor	Ensures air pumping from LP to the HP	HP Failure overheated	- BP and HP pressure switch deteriorates - High gas temperature - The oil level is too low	- Loss of compressor -Total breakdown of the air conditioner	Visual	Ft1
Pressure switches HP	- Protect the compressor in the event of an HP and LP fault. - Regulated the condensing pressure of an air condenser.	- HP Failure - Blocked circuit	- Working continuously due to high temperature in summer	- Damaged compressor - Total breakdown of the air conditioner	- Air conditioning software (IHM IOS 17 IOS 18 IOS 19)	Ft2
Solenoid valve	Maintains the pressure difference between the condenser and evaporator during shutdown periods	HP Failure crash/clogged	- damaged coil -Teflon valve and blocked spring	- Total breakdown of the air conditioner	Air conditioning software	Ft3
Condenser	- Conversion of the refrigerant gas to the liquid state before going to the filter drier -Reduce the temperature of the r134A gas sent by compressor	HP Failure crash/clogged	- A lack of ventilation bearing problem lack of lubrication due to sand and high outside temperature in summer	- High gas temperature -Total breakdown of the air conditioner	Air conditioning software	Ft4
Filter drier	- Remove moisture. - Neutralize acids. - Filter fine particles (copper...etc.)	Blockage	Filter contamination and blockage	- Lack of cooling inside ram room - Total breakdown of air conditioning	Air conditioning software	Ft5
Liquid indicator light	- Humidity detector inside the refrigeration circuit using chemical salt. -The green color the circuit is healthy and free of humidity. -The yellow color of the circuit indicates the presence of humidity.	Damaged	Too high humidity	- High humidity - The formation of acids detrimental to the proper functioning of the air conditioner	Visual	Ft6
Regulator	- Transported r134A liquid from HP to BP (liquid/vapor mixture). - Maintaining a constant difference between the evaporation temperature of the refrigerant and the temperature of the gases leaving the evaporator.	LP Failure crash/clogged	The spring deteriorates	- Lack of cooling inside ram room - Total breakdown of air conditioning	- Analysis Vibratory - Air conditioning software	Ft7
Evaporator	- Cool the outside air with a refrigerant before sending it to the RAM room. - Filters the air inside RAM room.	LP Failure	- Clogged air filter - Evaporator contamination - The regulator blocked	- A block of ice forms on the evaporator - Lack of cooling	- Visual - Air conditioning software	Ft8
Lack of refrigerant	R134A gas the basic element in the refrigeration and heat conversion process.	HP and LP Failure	- Damaged compressor valve solenoid valve failure - Damaged charging connection - Flexible vibrator deteriorated	- Lack of cooling. - High compressor temperature. - Total breakdown of air conditioning.	- Air conditioner pressure gauge. - Air conditioning software.	Ft9
Pressure Switch LP	-Regulate the movement of hot/cold air between the turbine and the evaporator (open/closed) -Detection of turbine and evaporator malfunctions	- LP Failure - Blocked circuit	-Work continuously due to high temperature in summer - Pressure switch plug poorly connected	- Damaged compressor - total breakdown of the air conditioner	- Air conditioning software	Ft10
Turbine	sucking the humidity present inside the ram room then will blow the air flow cooled by the evaporator	LP Failure	- Fan deteriorates - Bearing problem due to sand - Work continues	- Total breakdown of air conditioning	- Air conditioning software (IHM IOS 17 IOS 18 IOS 19)	Ft11
Canal beck	- Air conditioning water passage circuit outside	Corking	Sand	Water leak inside RAM room	Visual	Ft12

Table IV.4: Linguistic Terms and Values for Severity (St), Occurrence (Ot), Detectability (Dt)

Linguistic terms			**Score**
Severity (St)	**Occurrence (Ot)**	**Detection (Dt)**	
Hazardously dangerous (HD)	Almost Certainly (AC	Absolute uncertainty (AU)	10
Hazardous (H)	significantly elevated (SE)	Extremely distant (ED)	9
Serious (S	recurring errors (RE)	Remote (R)	8
Predominance (P)	Excellent (E)	Extremely low (EL)	7
Important (I)	Quite high (QH)	Minimal (M)	6
Moderate (MO)	medium (M)	Moderate (M)	5
Low (Lo)	comparatively little (RL)	Moderately high (MH)	4
Minimal (MI)	Minimal (L)	High (H)	3
Very little (VL)	Distant (R)	Very high (VH)	2
None (N) essentially	nearly unattainable (NU)	certain (AC)	1

Table IV.5: Conventional FMEA Ranking.

	S t	**O t**	**D t**	**RPNt**	**RANG**
FT1	**2**	**10**	**5**	100	9
FT2	**4**	**10**	**5**	200	3
FT3	**8**	**8**	**5**	320	2
FT4	**3**	**10**	**6**	180	5
FT5	**10**	**10**	**10**	1000	1
FT6	**5**	**3**	**3**	45	12
FT7	**3**	**8**	**8**	192	4
FT8	**3**	**8**	**3**	72	10
FT9	**8**	**5**	**3**	120	8
FT10	**3**	**10**	**5**	150	6
FT11	**5**	**10**	**3**	150	6
FT12	**8**	**3**	**3**	72	10

By examining Ft8 and Ft12, a similar scenario is revealed, highlighting a common limitation often discussed when using FMEA to identify failure scenarios. Additionally, it identifies Ft2, Ft3, and Ft5 as the three most critical failure modes.

When comparing the risk variable values assigned to Ft5 (10, 10, 10), Ft3 (8, 8, 5), and Ft2 (4, 10, 5) with their RPN rankings, it becomes evident that the reduced severity score influenced the classification of Ft2, despite higher Ot and St values for the previous failures.These results illustrate how the traditional FMEA method influences the relative weighting of each risk indicator in a way that is not fully controlled by experts. The entropy method is used to determine the weights, as shown in Table IV.4.

Table IV.6: Estimated Weights Using the Entropy Method.

	S t	O t	D t	
WJ	0,43824861	0,2401209	0,32163049	1
WJ%	44%	24%	32%	100%

To establish the final ranking, this study proposes a more reliable methodology that combines the Fuzzy TOPSIS, EDAS, RPN, RPI, and VIKOR rankings. Table IV.5 provides a summary of the failure mode rankings, calculated using equations (1)–(40), while Figure 4 illustrates a classification diagram of the results obtained using different methods. According to the analysis, the most critical failure mode is Ft5, followed sequentially by Ft3 and Ft2.

Table IV.7: Results of the Ranking by the Six Integrated Methods.

	FMEA	RPI	EDAS	VIKOR	FUZZY TOPSIS	PROPOSED MODEL
Ft1	9	10	10	6	6	8
Ft2	3	3	3	3	3	3
Ft3	2	2	2	2	2	2
Ft4	5	4	7	8	9	7
Ft5	1	1	1	1	1	1
Ft6	12	11	11	11	12	12
Ft 7	4	6	4	7	5	4
Ft8	10	12	12	12	11	11
Ft9	8	7	6	5	4	6
Ft 0	6	8	8	10	9	9
Ft11	6	5	5	4	7	5

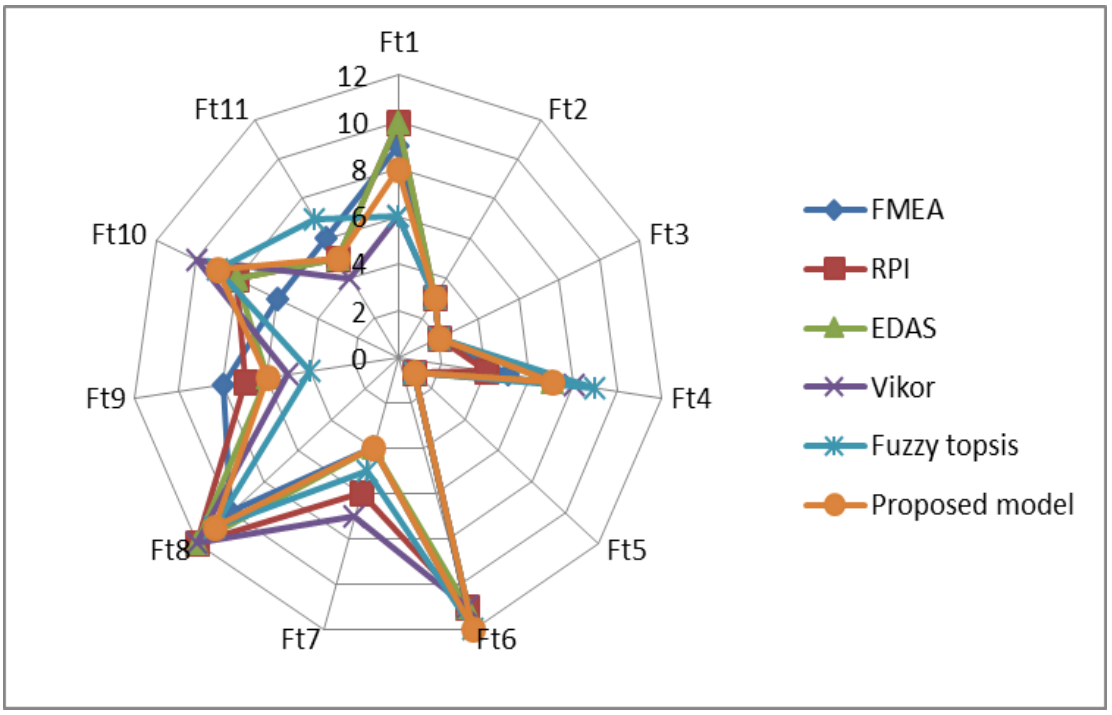


Figure IV.23: Ranking of Failure Modes Obtained by Various Methods

Table IV.6 illustrates how different approaches yield varying rankings for the failure types. As a result, ranking methods such as RRPN, REDAS, and RVIKOR prioritize failure modes Ft5, Ft3, Ft2, and Ft7 (positions 1 to 4), while other methods (RPI, Fuzzy TOPSIS) assign different positions, especially from the fourth rank onward. However, it is difficult to resolve or evaluate such problems using a single approach. It is clear that no single evaluation method can provide a comprehensive and ideal solution

Table IV.8: Top 6 Failure Modes

models	**Top 6 ranking of failure modes**
The proposed model	Ft5>Ft3>Ft2>Ft7>Ft11> Ft9
FMEA	Ft5>Ft3>Ft2>Ft7>Ft4> Ft10
RPI	Ft5>Ft3>Ft2>Ft4>Ft11> Ft7
EDAS	Ft5>Ft3>Ft2>Ft7>Ft11> Ft9
Vikor	Ft5>Ft3>Ft2>Ft7>Ft11> Ft1
Fuzzy topsis	Ft5>Ft3>Ft2>Ft9>Ft7> Ft1

The final ranking of failure modes obtained using equations (34) to (40) is presented in Table 7. It is clearly shown that Ft5 emerges as the most critical failure mode, followed by Ft3 and Ft2.

Table IV.10: Results of the Proposed Integrated Ranking Method

FAILURES	α_n^-	α_n^+	FRIH	RANKING
FT1	0,13152	0,074481	0,05024	8
FT2	0,035376	0,159191	-0,10127	3
FT3	0,017688	0,176878	-0,13087	2
FT4	0,104147	0,101163	0,004989	7
FT5	0	0,194566	-0,16048	1
FT6	0,184187	0,013682	0,145107	12
FT7	0,07702	0,122123	-0,03533	4
FT8	0,184406	0,017804	0,141893	11
FT9	0,092124	0,108834	-0,01155	6
FT10	0,129323	0,07141	0,050908	9
FT11	0,079879	0,118118	-0,0296	5
FT12	0,142053	0,05413	0,075969	10

6.3.1. Results and Discussion

The proposed model is based on practical applications of risk analysis and management. For reliable evaluation, it is recommended to involve specialized professionals to assess potential risks. Based on assessments of severity (St), occurrence (Ot), and detectability (Dt), six main failure types are identified, namely: Ft5 > Ft3 > Ft2 > Ft7 > Ft11 > Ft9, related to the condenser (Ft4), the control valve (Pt3), the pressure switches (FT2), the expansion valve (Fts7), the turbine (Ftt11), and the evaporator (Ft9). The main system failures related to pressure, along with their root causes, are as follows:

- The refrigerant gas undergoes a phase change to a liquid state before entering the filter dryer.
- The temperature of the R134A gas released by the compressor decreases.
- Coil damage.
- Teflon valve and spring blockage.
- Continuous operation, particularly during high summer temperatures.
- Fan failure, mainly due to bearing wear caused by sand accumulation.

The hybrid model, developed using the Failure Mode and Effects Analysis (FMEA) framework, can generate consistent information and assist professionals and decision-makers in predicting the most critical failure modes.

Undoubtedly, failure modes Ft5, Ft3, Ft2, Ft7, Ft11, and Ft9 are classified as relatively high-risk. As a result, risk managers should prioritize implementing improvement plans that specifically address these six failures. As for failure modes Ft1, Ft4, Ft6, Ft8, Ft10, and Ft12, they may be categorized as secondary groups to be considered and reviewed later when conditions allow.

The proposed method integrates multiple risk assessment techniques, offering higher reliability and accuracy than any single method, despite the ongoing development of such techniques.

7. Conclusion and Future Research

A failure in the air conditioning system of a tramway was diagnosed in desert areas. The findings are summarized as follows:

- The air conditioning system is both efficient and sensitive.
- Desert regions with hot and dry climates are among the areas where industrial equipment failures and malfunctions—especially in air conditioning systems—are common.
- Failure to comply with assembly recommendations for industrial components leads to malfunctions of unknown origin, resulting in increased maintenance costs.
- Industrial safety prevention systems act as a protective wall for industrial equipment, facilitating faster fault detection and lower maintenance costs.
- Reliability is a key factor in the manufacturing world. The higher the reliability of vehicles and machines, the greater the production and revenue percentages.
- Transport vehicles are among the most influential machines in the industrial sector due to their direct impact on economic indicators; thus, they must always be protected.

The purpose of this study is to enhance the FMEA approach by addressing its shortcomings and producing deeper, more accurate, and widely accepted results. The proposed hybrid MCDM RPI-Fuzzy model is used to evaluate failure modes and analyze the importance weights and associated risks, effectively mitigating the limitations of traditional FMEA. The evaluation model is designed to improve the identification and classification of failure modes in the tramway air conditioning system located in the southern Saharan region of Algeria.

The results reveal that **wear**, **phase changes in the refrigerant gas**, and **extended operation at high temperatures** are the main causes of major failures.

Various risk estimation methods can yield different results from similar input data due to the use of distinct concepts and calculations. The objectivity and stability of an analysis can be improved by employing a range of methodologies. The proposed model is feasible and suitable for various classification methods. Moreover, it considers the interaction between evaluation elements and different weights using the entropy method. To enhance risk ranking efficiency, it combines the hybrid MCDM method with the RPI, EDAS, VIKOR, and FUZZY TOPSIS models. The results obtained were conclusive and open new avenues for further research.

In the future, we recommend updating data in real time for more objective results and relying on expert interviews and statistical data. Future research could involve deeper exploration of additional variables and the use of other theories, such as machine learning

General Conclusion

Through this study, it becomes clear that traditional preventive maintenance plans and programs applied to rotating machinery and vehicles in the industrial sector have not significantly lost their effectiveness. Despite major technological advances, these approaches remain the core and foundational basis for modern technologies that have greatly contributed to the development of preventive maintenance and the significant reduction of error rates. They have also proven to be effective and accurate in detecting and identifying failures with greater precision and speed.

This study focused on tramway vehicles operating in southern Algeria, specifically on the air conditioning systems of these vehicles, which have experienced significant deterioration and operational issues since the launch of the tramway. As a preliminary step, a preventive maintenance program for the air conditioning system was established, taking into account both the operating hours of the tramway and the periods of intensive use of the air conditioning system. It was then confirmed that the scheduled preventive maintenance plan successfully met the objectives of identifying the root causes of failures.

The maintenance plan was divided into two parts: the first aimed to determine the reliability of the air conditioning system and identify failure causes, while the second part focused on confirming previous results and assessing future outcomes.

Based on our findings, we concluded that there is a need to revise the structure of the preventive maintenance strategy. The results also highlight the necessity of adopting a new preventive maintenance approach for the air conditioning system one that is aligned with the high frequency of failures affecting these vehicles, due to the faster-than-expected deterioration of components, particularly during summer and under high-temperature conditions. As such, conditional maintenance has been linked to preventive and reliability-based predictive maintenance. All of the results obtained aim to achieve and stabilize the required level of reliability for these vehicles, especially concerning their air conditioning systems.

Finally, based on these results, a revised preventive maintenance plan was proposed, tailored to the specific needs of these vehicles. It was confirmed that the scope of each task was appropriate and effective when implementing the maintenance operations.

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