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Industrial Maintenance

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Abstract :

Les mathématiques appliquées jouent un rôle essentiel dans la maintenance industrielle en offrant des outils pour analyser, prévoir et optimiser les processus de maintenance. Les statistiques permettent de suivre la fiabilité des équipements, tandis que les probabilités aident à prédire les défaillances et à planifier les interventions. La modélisation mathématique est utilisée pour simuler les systèmes de maintenance, et les outils d'optimisation permettent de minimiser les coûts tout en maximisant l'efficacité opérationnelle. Ces éléments mathématiques sont fondamentaux pour garantir la durabilité et la performance des équipements industriels.

Mots -clés : Statistiques industrielles, Fiabilité, Optimisation, Modélisation, mathématique; Probabilités

Abstract :

Applied mathematics plays a crucial role in industrial maintenance by providing tools to analyze, forecast, and optimize maintenance processes. Statistics are used to monitor equipment reliability, while probabilities help predict failures and plan interventions. Mathematical modeling is employed to simulate maintenance systems, and optimization tools minimize costs while maximizing operational efficiency. These mathematical elements are fundamental to ensuring the sustainability and performance of industrial equipment.

Keywords : Industrial; Probabilities statistics, Reliability; Optimization, Mathematical modeling

Chapter 1: General Overview of Maintenance

I.1 Introduction:

In the modern competitive landscape, companies must continuously find ways to improve their production processes while maintaining high standards of quality. This is crucial because customers demand not only products that meet or exceed expectations but also reasonable prices. Reducing production costs becomes a key factor in sustaining profitability, and achieving this involves streamlining operations to eliminate waste, reduce downtime, and maintain consistent output. Speeding up production while ensuring the absence of defects requires a delicate balance. Any deviation from this can lead to increased costs, rework, or loss of customer trust. Therefore, the maintenance function of a company is not just about fixing machines when they break down but about ensuring that all assets are operating at peak efficiency to avoid disruptions.

The maintenance function plays a strategic role in the overall success of production. It's about making sure that every piece of equipment, every system, and every tool is in optimal condition to support continuous, high-quality production. This requires a proactive approach to maintaining machinery, including preventive maintenance routines that can predict and prevent potential issues before they cause failures. Integrating data and mathematical analysis into maintenance processes further enhances this by allowing companies to anticipate wear and tear, predict when maintenance is needed, and avoid costly unplanned downtime.

By utilizing mathematical models, companies can better understand the performance of their machinery, assess potential risks, and make data-driven decisions. This not only optimizes equipment use but also extends its lifecycle, which in turn contributes to cost reduction. Ultimately, maintenance becomes a key contributor to achieving a company's productivity goals, ensuring that production continues without interruption, and delivering products at the desired quality while keeping costs as low as possible.

I.2 History (Standardized Concepts and Terminology, etc.):

The term "maintenance," rooted in the Latin words *manus* (hand) and *tenere* (to hold), first appeared in the French language in the 12th century. The etymologist Wace identified the form *mainteneor* (one who supports) in 1169, an archaic form of "mainteneur"

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(maintainer). This early use emphasized the concept of support or keeping things in order, a notion that has evolved significantly over the centuries.

Before the 1900s, what we now refer to as maintenance was simply called "repair." Equipment or machinery was repaired only after it broke down, with no systematic approach to preventing such failures. Between 1900 and 1970, the idea of *entretien* (maintenance or upkeep) emerged, driven by the rapid development of railroads, automobiles, aviation, and military hardware during both world wars. During this time, maintenance practices began to take shape as industrial systems became more complex and essential to national infrastructure.

After 1970, with the rise of high-risk industries and the advent of modern tools and technologies, the concept of maintenance as we understand it today was formalized. Maintenance no longer merely responded to failures; it became a proactive function, essential to ensuring operational continuity and reducing risks in sectors like nuclear energy, aerospace, and advanced manufacturing. This marked a shift from the simple repair and upkeep of machinery to a more strategic role in managing the lifecycle of equipment.

The Anglo-Saxon use of the term "maintenance" came later. In modern times, the word reappeared in military contexts, defined as "maintaining personnel and equipment in combat units at a constant level." This definition was later adapted by the industrial world to refer to maintaining production units in an ongoing "economic battle." The evolution of this terminology reflects the increasing complexity of modern industries and the critical role maintenance plays in sustaining productivity.

Key reasons for the shift from *entretien* (upkeep) to maintenance include:

Technological evolution: As technology advanced, machinery became more complex, necessitating more sophisticated maintenance strategies.

Cost considerations: The cost of downtime and repairs grew, making preventive and predictive maintenance more cost-effective.

Automation: The rise of automation required continuous monitoring and maintenance of systems to prevent breakdowns and ensure efficiency.

Depreciation: As equipment became more expensive, maximizing its lifespan became essential to amortizing the investment.

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Regulatory constraints: Increasingly stringent safety and environmental regulations imposed new requirements for equipment maintenance and reliability.

In summary, maintenance has evolved from a reactive process to a proactive and essential aspect of modern industrial operations, ensuring not only the longevity of machinery but also compliance with economic, technological, and regulatory demands.

I.2.1 AFNOR and CEN Definitions of Maintenance:

The **AFNOR** (French Association for Standardization) and the **CEN** (European Committee for Standardization) provide definitions of maintenance, though there are currently no **ISO** (International Standardization Organization) standards specifically for maintenance functions.

Definitions

According to **AFNOR**, maintenance is defined as the set of actions aimed at maintaining or restoring an asset to a specified condition or to a state where it can ensure a determined level of service. Maintenance involves a strategic approach that encompasses:

Selection of maintenance methods: This includes various modes of maintenance, such as preventive, corrective, and predictive strategies.

b) **Improvements:** Continuous enhancement of the system and its components.

c) **Positioning of equipment in the manufacturing process:** The prioritization and criticality of equipment are considered, ensuring that the most important assets receive the necessary attention.

d) **Training of maintenance and production personnel:** A focus on educating workers to ensure they are equipped with the skills required to maintain and operate the equipment effectively.

a) AFNOR's Definitions of Maintenance by Standard X 60-000:

AFNOR Definitions of Maintenance:

According to **AFNOR** under the standard **X 60-000**, maintenance is defined as the set of all technical, administrative, and managerial actions taken throughout the lifecycle of an asset. These actions are aimed at maintaining or restoring the asset to a condition where it can perform its required function. This definition highlights that maintenance is not limited to

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fixing broken equipment but involves an ongoing effort to ensure that an asset remains functional and efficient over its entire lifecycle.

This comprehensive approach to maintenance emphasizes that various factors must be addressed, from the technical aspects—like repairs, adjustments, and upgrades—to the administrative tasks, such as scheduling and documentation. In addition, management practices play a crucial role in making strategic decisions about when and how maintenance activities should be conducted to ensure equipment operates smoothly. The goal is to optimize the performance of assets and extend their useful life, preventing costly failures and maximizing productivity.

b) AFNOR's Definition of Maintenance According to Standard NF X 60-010:

This standard defines maintenance as the set of actions taken to keep or restore an asset to a specified condition or to a state where it can continue providing a determined level of service. Proper maintenance means ensuring all operations are performed at **optimal cost**.

It highlights four key concepts central to effective maintenance:

Maintaining: This concept involves ongoing **monitoring** and **surveillance** of assets to ensure they are functioning as expected. Maintenance goes beyond fixing issues—it includes preventive measures like regular inspections, real-time monitoring, and condition-based maintenance. These practices are aimed at anticipating potential failures and taking preemptive action, thus reducing unexpected downtime and extending the life of the asset. By continuously observing performance indicators, organizations can maintain equipment in peak condition, preventing minor issues from becoming major problems.

Restoring: Restoration implies the correction of defects or faults that prevent the asset from functioning properly. When equipment deviates from its normal state, maintenance efforts are directed towards bringing it back to its specified condition. This can involve repairs, part replacements, recalibrations, or software updates. The goal of restoring is to ensure the asset regains full operational capacity as efficiently as possible. This reactive aspect of maintenance is crucial for minimizing downtime and ensuring that equipment can quickly return to service after a failure.

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Specified Condition and Determined Service: The concept of **specified condition** refers to the predetermined standards or performance levels that an asset must meet to perform its intended function. Maintenance activities are designed to ensure that equipment consistently meets these standards, whether in terms of safety, productivity, or quality. The idea of a **determined service** highlights the importance of understanding the specific role that an asset plays within the overall system, allowing maintenance teams to prioritize actions based on the criticality of the equipment. This requires a clear definition of the expected output or service level of the asset, ensuring that it performs its function reliably and efficiently.

Optimal Cost: One of the most important aspects of modern maintenance is the idea of balancing performance with cost-effectiveness. **Optimal cost** means ensuring that maintenance activities are economically viable, without overspending on unnecessary interventions while avoiding the higher costs associated with reactive maintenance (such as unplanned downtime or emergency repairs). The goal is to minimize the total cost of ownership over the asset's lifecycle by carefully planning and executing maintenance activities. This involves a strategic approach to decision-making, where the timing, frequency, and intensity of maintenance tasks are determined based on cost-benefit analyses. The objective is to achieve the best possible performance while maintaining financial efficiency.

c) The Importance of These Notions in Practice:

AFNOR's definition underlines the importance of **strategy** in maintenance management. Instead of just fixing things when they break, modern maintenance is about **prevention, optimization, and efficiency**. In practice, this means developing maintenance plans that include regular inspections, predictive analytics, and continuous improvements to ensure assets are always ready to perform their tasks.

For example, **predictive maintenance** systems, enabled by data analysis and advanced monitoring technologies, allow organizations to predict equipment failures before they happen. This can significantly reduce costs and improve efficiency compared to traditional reactive maintenance approaches. By knowing when a piece of equipment is likely to fail, maintenance can be scheduled in advance, preventing unplanned downtime and reducing the need for emergency repairs.

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Additionally, **optimal cost management** requires a careful balance between **preventive maintenance** (which avoids breakdowns but can be expensive if overdone) and **corrective maintenance** (which addresses problems after they occur but can lead to costly downtime). To strike this balance, many organizations employ **condition-based maintenance**, where maintenance actions are triggered based on real-time data about the condition of the equipment, rather than on a fixed schedule.

c) Broader Implications:

Effective maintenance plays a critical role in the **efficiency and profitability** of any organization that relies on equipment or machinery. Whether in manufacturing, transportation, energy, or other sectors, poor maintenance can lead to significant operational disruptions, safety risks, and financial losses. By adhering to AFNOR's standards and focusing on the four key concepts—monitoring, restoring, maintaining specified conditions, and optimizing costs—organizations can maximize the performance and lifespan of their assets.

In conclusion, AFNOR's definition of maintenance according to the NF X 60-010 standard emphasizes a holistic approach that incorporates **technical, economic, and strategic** considerations. It advocates for maintenance as an integral part of operational success, aiming to ensure that assets are always available and functioning at their best, all while keeping costs under control. This approach not only improves operational reliability but also enhances overall **organizational efficiency and competitiveness**.

I.3 Role of Maintenance and Equipment Repair in Industry:

The role of the maintenance and repair function in a company (regardless of its type and sector) is to ensure the highest availability of equipment at optimal performance while respecting the allocated budget. To achieve these objectives, the maintenance and repair policy for equipment in industry must adhere to the following points:

a. The maintenance service (or "repair service") primarily intervenes in the event of a problem:

- It responds to emergencies.
- It performs repairs in the workshop.

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- It conducts daily maintenance of equipment.
- b. The maintenance service (or "repair service") is there to prevent breakdowns and slowdowns in production: Since emergency interventions lead to costly production stoppages, systematic preventive procedures must be established to avoid major failures.
- c. The maintenance service (or "repair service") must generate profits: The maintenance service prevents breakdowns, which translates into cost savings. However, it also incurs expenses: salaries, maintenance materials, spare parts inventory, and production stoppages for preventive maintenance.
- d. The maintenance service (or "repair service") competes with subcontracted maintenance providers: After proving its profitability, the maintenance service must demonstrate greater cost-effectiveness than outsourcing to specialized maintenance companies.

The maintenance service must implement the maintenance policy defined by the company's management, which should enable the achievement of maximum production system efficiency. However, not all equipment has the same level of importance from a maintenance perspective. Therefore, the service must, within the framework of the overall policy, define strategies that are best suited to various situations.

The maintenance function will then be required to establish targeted forecasts:

- **Long-term forecasts:** These relate to major investments or long-term projects. They are often dictated by the company's overall policy.
- **Medium-term forecasts:** Maintenance should be as unobtrusive as possible within the production workload planning. Thus, it needs to anticipate its interventions as much as possible based on production schedules. Production must also consider the monitoring imperatives of the equipment.
- **Short-term forecasts:** These may range from weekly to daily or even hourly.

Even in this case, with the goal of disrupting production as little as possible, interventions must also undergo a minimum level of preparation.

I.4 Mathematical concepts used in Industrial Maintenance :

In the field of industrial maintenance , it is common to need to determine certain measurements based on a limited set of known values. This section will help consolidate some mathematical concepts learned in secondary school and apply them in contexts related to industrial maintenance. Additionally, it promotes the development of skills such as using functions and graphs in a spreadsheet, determining the desired dimensions of the represented object from data on a drawing, recognizing and utilizing the appropriate mathematical model for a given situation, and analyzing situations using vector calculus.

- **Functions and Variations:**

This section primarily aims to introduce the analysis of how the variation of one quantity influences another, which is crucial for solving various problems. Understanding functions and their variations is fundamental in mathematics and serves as a bridge to apply mathematical concepts in real-world contexts, especially in industrial maintenance. In the industrial maintenance setting, the ability to express problems mathematically allows professionals to model systems, analyze performance, and make informed decisions based on quantitative data. For instance, if a piece of machinery's efficiency decreases as wear and tear increase, understanding the function that relates the two can help predict maintenance needs and optimize operational schedules.

- **Statics and Material Resistance:**

The second aspect of physics focuses on the study of forces within a static equilibrium context, which is vital for diagnostic purposes. This includes understanding how various forces interact and balance when machinery and structures are at rest. Additionally, the concepts of stress and strain are crucial in the field of material resistance, which pertains to how materials deform under applied forces. In preventive maintenance, assessing the material's strength is essential, as this helps identify when components are likely to fail. For example, the resistance of joints and welds in electromechanical systems must be determined to ensure that they can withstand operational loads. Such measurements are not just necessary; they are often mandated to initiate preventive maintenance, ensuring safety and reliability in industrial operations.

- **Statistics in Industrial Maintenance:**

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This section focuses on integrating statistical concepts into the context of industrial maintenance. By employing statistical tools, maintenance professionals can accurately interpret data and derive insights that inform their decisions. For instance, understanding the distribution of machine failures can help identify patterns and predict future breakdowns. The topics covered include statistical methods, which encompass techniques for analyzing data, creating tables and graphs to visualize trends, and calculating key measures of central tendency (mean, median, mode) and dispersion (variance, standard deviation). Additionally, understanding probabilities allows professionals to assess risks associated with equipment failure, while statistical inferences help in making predictions based on sample data. Correlation and regression analysis further aid in understanding relationships between variables, enabling better forecasting and resource allocation.

- **Mechanism Analysis:**

In the context of industrial maintenance, mechanism analysis plays a critical role in diagnosing and resolving issues with faulty machinery. This involves a systematic approach to understanding how different components of a machine interact and function together. When a mechanism fails, it is essential to disassemble it carefully to identify the root cause of the failure. This process may include examining wear patterns, analyzing broken parts, and understanding the conditions that led to the malfunction. Once the defective components are identified, maintenance professionals must decide whether to repair or replace them. This decision-making process is crucial for restoring the machinery to its optimal operating condition and ensuring that it functions effectively in its intended application. Proper analysis not only enhances the longevity of the equipment but also minimizes downtime and increases overall productivity.

I.5 Behavior of Equipment in Service

The equipment designer is often a company that does not operate the facilities it designs. As a result, it inevitably faces challenges in considering the specific operating conditions of its clients in its designs. Generally, the designer pays little attention to the maintainability of the installations. Thus, the choice of a material behavior law (reliability calculation) becomes a very complicated task. The operational safety of a machine, considering safety aspects and criteria aimed at avoiding frequent, difficult, and costly maintenance, can be summarized in

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three points known as the F.M.D. concept that the designer should take into account during engineering studies:

- Operational safety
- Maintainability
- Availability
- Reliability

I.5.1. What is a System?

A complex set of hardware, software, personnel, and usage processes, organized in such a way as to satisfy needs and fulfill expected services within a given environment.

I.5.2. Operational Safety

The operational safety of a system can be defined as the property that allows its users to place justified trust in the service it provides. The user can be an individual, such as an Operator or Supervisor, or another hardware/software system interacting with the system in question. Operational safety includes activities for evaluating the Reliability, Availability, Maintainability, and Safety (FDMS) of an organization, system, product, or facility. These properties are different but complementary.

- **The Maintenance Environment:** Maintenance is integrated into the overall concept of Operational Safety, which, in turn, is part of Product Assurance.
- **Product Assurance:** The concept of Operational Safety encompasses four disciplines:



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- **Reliability** (AFNOR X-06-501): "The ability of a device to perform a required function under given operating conditions at a specific moment."
- **Availability** (AFNOR X-06-010): "The ability of a device to perform a required function under given operating conditions over a specified period."
- **Maintainability** (AFNOR X-06-010): "The ability of a device to be maintained or restored to a state in which it can perform a required function when maintenance is carried out under given conditions, with prescribed means and procedures."
- **Safety** (AFNOR X-06-010): "The ability of a device to prevent the occurrence of critical or catastrophic events."

I.6 MAINTENANCE TOOLS

The tools used in maintenance are critical to ensuring that maintenance operations are effective, efficient, and aligned with both organizational goals and the specific needs of each type of equipment.

Below we present each category and explain it in detail:

I.6.1 Mathematical Tools:

Mathematical tools help organizations make data-driven decisions in maintenance management. By using mathematical models, it becomes possible to estimate the **reliability** of equipment, determine the optimal frequency of maintenance interventions, and predict failures. For example:

- **Probability theory** helps estimate the likelihood of equipment failure within a certain time frame.
- **Statistical laws and distributions** (such as Weibull or exponential distributions) are useful for modeling the failure rates of machines and planning preventive maintenance actions accordingly.
- **Markovian analysis** is used to model systems that transition between various states (e.g., operational, under repair, etc.) and calculate long-term availability and reliability.
- **Algebra of events** assists in identifying combinations of system states that lead to failures, helping in the design of more resilient systems. Mathematical tools enable maintenance

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managers to plan interventions, ensuring equipment is maintained at the right time, neither too early (wasting resources) nor too late (risking failure).

I.6.2 Organizational Tools:

Maintenance requires clear procedures and decision-making frameworks to ensure smooth operations and minimize downtime. Some common tools in this domain include:

- **FMEA (Failure Modes and Effects Analysis):** This tool is used to systematically evaluate where and how systems might fail, identifying failure modes and their impact on operations, and ranking them to prioritize preventive actions.
- **Flowcharts and Synoptics:** These provide visual representations of processes, making it easier to understand the sequence of maintenance steps, decision points, and interdependencies within a system.
- **Preventive maintenance techniques:** These include **condition monitoring** tools (like vibration analysis or thermal imaging) that help predict when equipment might fail, allowing for timely preventive action.
- **Operational procedures:** These detail the exact steps for repairs or routine checks, ensuring that the maintenance staff follows a standardized approach, minimizing the risk of errors and improving efficiency.

I.6.3 IT Tools:

As industrial systems become more complex, **computerized maintenance management systems (CMMS)** and other IT solutions play an increasingly important role in tracking and optimizing maintenance efforts:

- **CMMS:** This software helps track maintenance tasks, schedule preventive actions, record equipment history, and manage spare parts inventories. It ensures that resources are efficiently allocated, and maintenance actions are recorded for future reference.
- **GMAO (Gestion de la Maintenance Assistée par Ordinateur):** A French acronym for CMMS, this system integrates maintenance planning, resource allocation, and reporting, helping businesses manage maintenance activities in a structured way.
- **ERP (Enterprise Resource Planning)** systems, such as **GTP (Gestion des Temps de Production)** or **GTB (Gestion Technique de Bâtiment)**, assist in broader resource

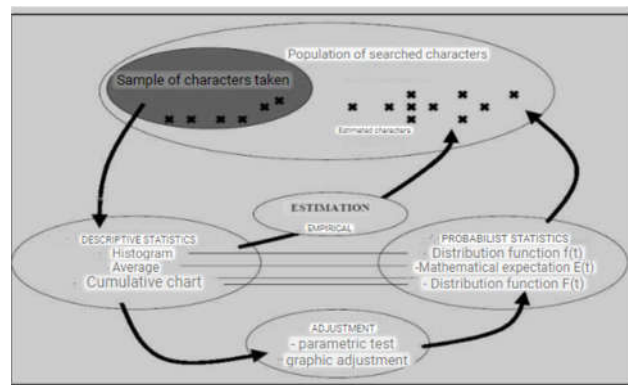
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management, integrating maintenance with production planning, human resources, and financial systems.

- **Expert systems:** These decision-support systems use artificial intelligence to provide advanced analysis and recommendations for maintenance actions. They can help identify root causes of issues and suggest optimized intervention strategies based on historical data.

I.6.4 Mathematical methods and tools for implementing maintenance actions:

Mathematics is deeply embedded in maintenance strategies, especially when it comes to reliability and risk analysis. Statistical studies and mathematical methods provide essential insights into equipment behavior and future performance:



I.7 STATISTICAL STUDIES:

By analysing data collected from a sample of equipment, statistical studies estimate the behaviour of similar equipment within the same category. This allows maintenance teams to predict failure rates and plan accordingly.

Note: Reliability research: Through statistical reliability methods, teams can establish models that predict equipment behavior over time. These methods consider historical data on failures, environmental conditions, and usage patterns to forecast when equipment is likely to fail or require maintenance.

Overall, the integration of mathematical, organizational, and IT tools ensures a comprehensive approach to maintenance, making it possible to improve the lifespan of equipment, optimize costs, and maintain operational efficiency. This multi-faceted approach

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allows organizations to keep their systems running reliably while reducing downtime and costs associated with equipment failure.

I.7.1 GROUPING OF CLASSES:

If $N > 50$, it is necessary to group into classes of value Δt . To determine the number K of classes to create, several empirical rules exist:

$$K \leq \frac{N}{10} \quad \text{et } K \geq 5 \text{ (Gnedenko)}$$

$$K \approx \sqrt{N} \text{ (Chapouille and De Pazzis)}$$

- **Case of large samples $N > 50$**

Class intervals	Frequencies	Relative frequency	Cumulative frequency
t_{i-1}, t_i	n_i	$f_i = \frac{n_i}{N}$	$F_i = \frac{\sum n_i}{N} = (Ft)$

- **Case of small samples $N < 50$**

TBF croissants	Effectifs	Ordre (rang)	Fréquence cumulée
t_i	n_i	$\sum n_i = i^{\text{ième}}$	$F_i = \frac{i}{N}$

In this last case, an approximation of the cumulative distribution function $F(t)$ will be necessary:

- If $20 < N < 50$, we will use the approximation by the average ranks according to the formula:

$$F(i) = \frac{i}{N + 1}$$

- If $N < 20$, we will use the approximation by the median ranks according to the formula:

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

I.8 Measuring and Designing for Reliability and Maintainability

Asset reliability is an important focal point for many organizations. It's a source of competitive advantage for many visionary companies. It is the central theme for maintenance departments trying to improve their bottom line. To some, reliability identifies the right work and is synonymous with reliability centered maintenance (RCM). Reliability is not just RCM, however; it has a much broader meaning. Understanding the term reliability and how it differs from maintenance is key to establishing a successful program for improving reliability in any organization. In this chapter, we will define key terms related to reliability and discuss important factors that will help realize higher reliability of assets and plants.

What and Why Reliability?

Reliability is a broad term that focuses on the ability of an asset to perform its intended function to support manufacturing or to provide a service. Many books written about reliability tend to focus on Reliability Centered Maintenance (RCM). Reliability is not just RCM. RCM is a proactive methodology utilizing reliability principles for identifying the right work to be done to maintain an asset in a desired condition so that it can keep performing its intended function. In fact, RCM is basically a PM optimizing tool to define the "right" maintenance actions. In its most effective and widely-accepted form, it consists of seven structured steps for building a maintenance program for a specific asset. When organizations first try to improve reliability, they label this undertaking as RCM, but RCM really differs from a reliability improvement initiative. Details of the RCM process will be discussed in chapter 8.

Improving asset reliability is important to the success of any organization, particularly to its operation and maintenance activities. To do this, we need to understand both reliability and maintenance, and how they're interrelated. Reliability is the ability of an asset to perform a required function under a stated set of conditions for a stated period of time, called mission time. Three key elements of asset reliability are the asset function, the conditions under which the asset operates, and mission time. The term *reliable assets* means that the equipment and plant are available as and when needed, and they will perform their intended function over a predetermined period without failure. Reliability is a design attribute and should be "designed in" when an asset is designed, built, and installed.

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On the other hand, maintenance is an act of maintaining, or the work of keeping an asset in proper operating condition. It may consist of performing maintenance inspection and repair to keep assets operating in a safe manner to produce or provide designed capabilities. These actions can be preventive maintenance (PM) and corrective maintenance (CM) actions. So, maintenance keeps assets in an acceptable working condition, prevents them from failing, and, if they fail, brings them back to their operational level effectively and as quickly as possible.

Maintainability is another term we need to understand with reliability. It is another design attribute which goes hand in hand with reliability. It reflects the ease of maintenance. The objective of maintainability is to insure maintenance tasks can be performed easily, safely, and effectively. Reliability and maintainability attributes are usually designed into the asset to minimize maintenance needs by using reliable components, simpler replacement, and easier inspections.

With these definitions, the differences start to become clear. Reliability is designed in and is a strategic task. Maintenance keeps assets functioning and is a tactical task. Maintenance does not improve reliability, it just sustains it. Improving reliability requires redesign or replacement with better and reliable components. Improving reliability needs a new thinking — a new paradigm. Rather than asking how to restore the capability of a failed asset efficiently and effectively, we need to ask what we can do proactively to guarantee that the asset does not fail within the context of meeting the business needs of the overall operation.

A challenge in this transition is the belief that we should strive to maximize asset reliability. However, it has been found that insuring 100% reliability — although a great goal — often results in high acquisition costs and may require a high level of maintenance to sustain high reliability. It may not be a cost-effective strategy and may not be affordable. We need to define an asset's or plant's reliability requirements in the context of supporting the underlying business needs. Then, we inevitably realize that we may need a different reliability and an affordable maintenance program.

As shown in Figure I.3, we need to find the right level of reliability required to give us the optimum total cost. This graph illustrates the production or use cost, which is operations and downtime cost versus the reliability (and maintenance) cost.

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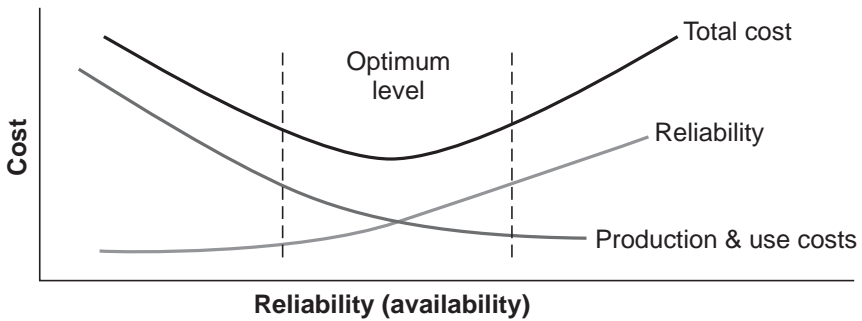


Figure 1.3 Reliability/ Availability Economics

Why is Reliability Important?

Asset reliability is an important attribute for several reasons, including:

- **Customer Satisfaction.** Reliable assets will perform to meet the customer's needs on time and every time. An unreliable asset will negatively affect the customer's satisfaction severely. Thus, high reliability is a mandatory requirement for customer satisfaction.
- **Reputation.** An organization's reputation is very closely related to the reliability of their services. The more reliable that plant assets are, the more likely the organization is to have a favorable reputation.
- **O & M Costs.** Poor asset performance will cost more to operate and maintain.
- **Repeat Business.** Reliable assets and plant will insure that customer's needs are being met in a timely manner. Customer satisfaction will bring repeat business and also have a positive impact on future business.
- **Competitive Advantage.** Many leading and visionary companies have begun achieving high reliability / availability of their plants and assets. As a result of their greater emphasis on plant reliability improvement programs, they gain an advantage over their competition.

Reliability vs. Quality Control

In a manufacturing process, quality control (QC) is concerned with how the process is meeting specifications to guarantee consistent product quality. Its objective is to see that both an asset and its components are manufactured and assembled with high quality standards and meet the designed specifications. Thus, QC is a snapshot of the manufacturing process' quality program at a specific time. Reliability is usually concerned with failures after an asset has been put in operation for its whole life. The QC of manufacturing processes for building assets makes an essential contribution to the reliability of an asset — it can be considered as an integral part of an overall reliability program.

The same way that a chain is only as strong as its weakest link, an asset is only as good as the inherent reliability of the asset, and the quality of the manufacturing process used to build or assemble this asset. Even though an asset may have a reliable design, its reliability may still be unsatisfactory when the asset is built and installed or used in the field. The reason for this low reliability may be that the asset or its components were poorly built. This could be the result of a substandard manufacturing process to build the asset. For example, cold solder joints could pass initial testing at the manufacturer, but fail in the field as the result of thermal cycling or vibration. This type of failure does not occur due to poor design, but as a result of an inferior manufacturing process.

Usually assets are designed with a level of reliability based on the effective use of reliable components and their configurations. Some components may be working in series and others in parallel arrangements to provide the desired overall reliability. This level of reliability is called inherent reliability. After the asset has been installed, the reliability of an asset cannot be changed without redesigning or replacing it with better and improved components. However, asset availability can be improved by repairing or replacing bad components before they fail, and by implementing a good reliability-based PM plan.

Evaluating and finding ways to attain high asset reliability are key aspects of reliability engineering. There are a number of practices we can apply to improve the reliability of assets. We will be discussing these practices to improve reliability later in this chapter, as well as in other chapters.

I.9 Key Terms and Definitions

Availability (A)

The probability that an asset is capable of performing its intended function satisfactorily, when needed, in a stated environment. Availability is a function of reliability and maintainability.

Failure

Failure is the inability of an asset / component to meet its expected performance. It does not require the asset to be inoperable. The failure could also mean reduced speed, or not meeting operational or quality requirements.

Failure Rate

The number of failures of an asset over a period of time. Failure rate is considered constant over the useful life of an asset. It is normally expressed as the number of failures per unit time. Denoted by Lambda (λ), failure rate is the inverse of Mean Time Between Failure (MTBF).

Maintainability (M)

The ease and speed with which a maintenance activity can be carried out on an asset. Maintainability is a function of equipment design and usually is measured by MTTR.

Mean Time Between Failures (MTBF)

MTBF is a basic measure of asset reliability. It is calculated by dividing total operating time of the asset by the number of failures over some period of time. MTBF is the inverse of failure rate (λ).

Mean Time to Repair (MTTR)

MTTR is the average time needed to restore an asset to its full operational condition upon a failure. It is calculated by dividing total repair time of the asset by the number of failures over some period of time. It is a basic measure of maintainability.

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Reliability (R)

The probability that an asset or item will perform its intended functions for a specific period of time under stated conditions. It is usually expressed as a percentage and measured by the mean time between failures (MTBF).

Reliability Centered Maintenance (RCM)

A systematic and structured process to develop an efficient and effective maintenance plan for an asset to minimize the probability of failures. The process insures safety and mission compliance.

Uptime

Uptime is the time during which an asset or system is either fully operational or is ready to perform its intended function. It is the opposite of downtime.

1.10 Defining and Measuring Reliability and Other Terms

There are two types of assets: repairable and non-repairable.

Assets or components that can be repaired when they fail are called repairable, e.g., compressors, hydraulic systems, pumps, motors, and valves. Reliability of these repairable systems is characterized by the term MTBF (Mean Time Between Failure).

Assets or components that can't be repaired when they fail are called non-repairable, e.g., bulbs, rocket motors, and circuit boards. Some components such as integrated circuit boards could be repaired, but the repair work will cost more than the replacement cost of a new component. Therefore, they're considered non-repairable. Reliability of non-repairable systems is characterized by the term MTTF (Mean Time to Failure).

1-Reliability, Maintainability and Availability

Reliability (R), as defined in military standard (*MIL-STD-721C*), is "the probability that an item will perform its intended function for a specific interval under stated conditions."

As defined here, an item or asset could be an electronic or mechanical hardware product, software, or a manufacturing process. The reliability is usually measured by MTBF and calculated by dividing operating

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time by the number of failures. Suppose an asset was in operation for 2000 hours (or for 12 months) and during this period there were 10 failures. The MTBF for this asset is:

$$\text{MTBF} = 2000 \text{ hours} / 10 \text{ failures} = 200 \text{ hours per failure}$$

or

$$12 \text{ months} / 10 \text{ failures} = 1.2 \text{ months per failure}$$

A larger MTBF generally indicates a more reliable asset or component.

Maintainability (M), is the measure of an item's or asset's ability to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources at each stage of maintenance and repair. Maintainability is usually expressed in hours by Mean Time to Repair (MTTR), or sometimes by Mean Downtime (MDT). MTTR is the average time to repair assets. It is pure repair time (called by some *wrench time*). In contrast, MDT is the total time the asset is down, which includes repair time plus additional waiting delays.

In simple terms, maintainability usually refers to those features of assets, components, or total systems that contribute to the *ease* of maintenance and repair. A lower MTTR generally indicates easier maintenance and repair.

Figures I.4 a, b, and c show trends of MTBF and MTTR data in hours. The baseline should be based on at least one year of data, dependent on your operations (could require as much as three years of data for assets

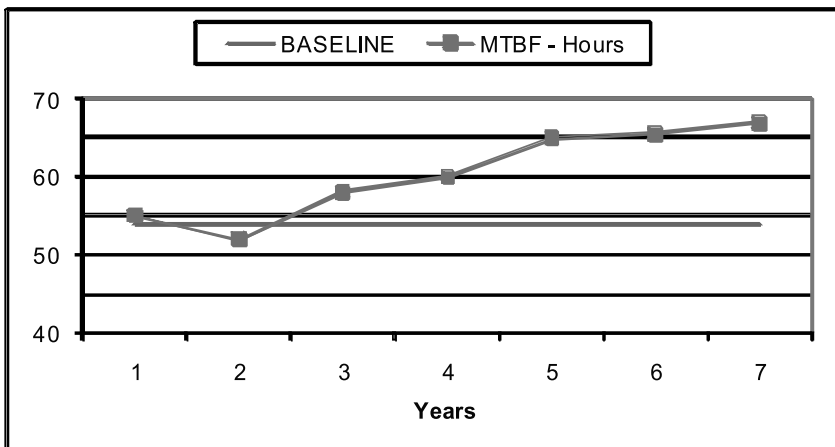


Figure I.4a Trending of MTBF Data

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with minimal operating time). This type of trend line is essential for tracking impact of improvements. Figure I.4a shows MTBF trend data, which is increasing. This trend is a good one.

Figure I.4b shows MTTR trend data, which is increasing. It is going in the wrong direction. We need to evaluate why MTTR is increasing by asking: Do we have the right set of skills in our work force? Do we identify and provide the right materials, tools, and work instructions? What can we do to reverse the trend?

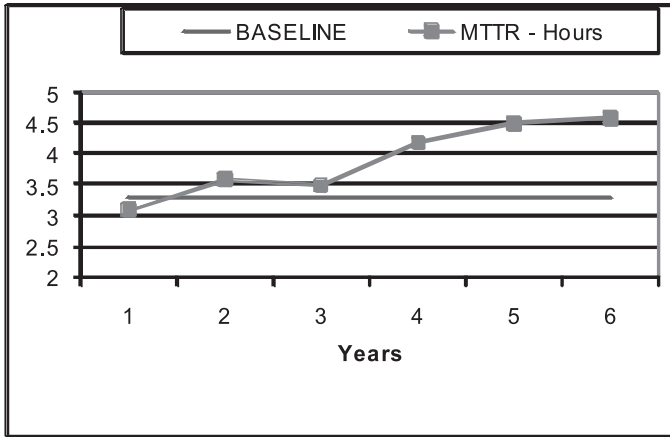


Figure I.4b Trending of MTTR (I) Data

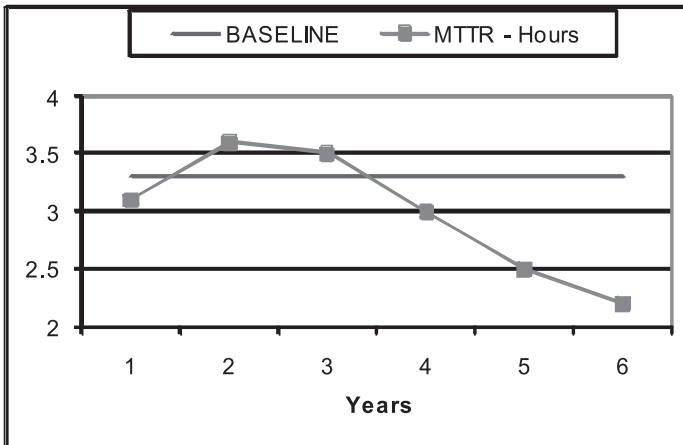


Figure I.4c Trending of MTTR (D) Data

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Figure I.4c shows MTTR trend data, which is decreasing. In this case, the trending is in the right direction. To continue this trend, we need to ask the questions: What caused this to happen? What changes did we make? Trending of this type of data can help to improve the decision process.

2-Availability

Availability (A) is a function of reliability and maintainability of the asset. It is measured by the degree to which an item or asset is in an operable and committable state at the start of the mission when the mission is called at an unspecified (random) time.

In simple terms, the availability may be stated as the probability that an asset will be in operating condition when needed. Mathematically, the availability is defined:

$$\text{Availability (A)} = \frac{MTBF}{MTBF+MTTR} = \frac{Uptime}{Uptime + Downtime}$$

The availability defined above is usually referred to as inherent availability (A_i). It is the designer's best possible option.

In reality, actual availability will be lower than inherent availability as the asset will be down due to preventive and corrective maintenance actions. Another term, Operational Availability (A_o), considers both preventive and corrective maintenance and includes all delays — administrative, materials and tools, travel, information gathering, etc. — that keep the asset unavailable. Achieved Availability (A_a) includes preventive maintenance, but not delays for getting materials and tools, information, etc.

Naturally, the designer or the manufacturer of the asset should be responsible for inherent or achieved availability. The user of the asset should be interested in operational availability. The inherent availability will be degraded as we use the asset and it can never be improved upon without changes to the hardware and software. Availability can be improved by increasing reliability and maintainability. Trade-off studies should be performed to evaluate cost effectiveness of increasing MTBF (reliability) or decreasing MTTR (maintainability). For the sake of simplicity and to reduce confusion, we will be using the term *Availability* in this book to represent inherent availability.

The standard for availability is about 95%, meaning that the asset is available for 9.5 hours out of 10. This is based on general industry expect-

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tations. In some cases, if assets are not very critical, the standard may be lower. But in case of critical assets such as aero-engines or assets involved with 24-7 operations, the standard may require 99% or higher availability.

In general, the cost to achieve availability above 95% increases exponentially. Therefore, we need to perform operational analysis to justify high availability requirements, particularly if it's over 97 percent.

I.11. The Bathtub Curve and Reliability Distribution

The bathtub curve seen in Figure 6.3 is widely used in reliability engineering, although the general concept is also applicable to people as well. The curve describes a particular form of the hazard function which comprises three parts:

- The first part is a decreasing failure rate, known as early failures or infant mortality. It's similar to our childhood.
- The second part is a constant failure rate, known as random failures. It's similar to our adult life.
- The third part is an increasing failure rate, known as wear-out failures. It's similar to our old age.

The bathtub curve is generated by mapping the rate of early infant mortality failures when first introduced, the rate of low random failures with constant failure rate during its useful life, and finally the rate of wear out failures as the asset approaches its design lifetime.

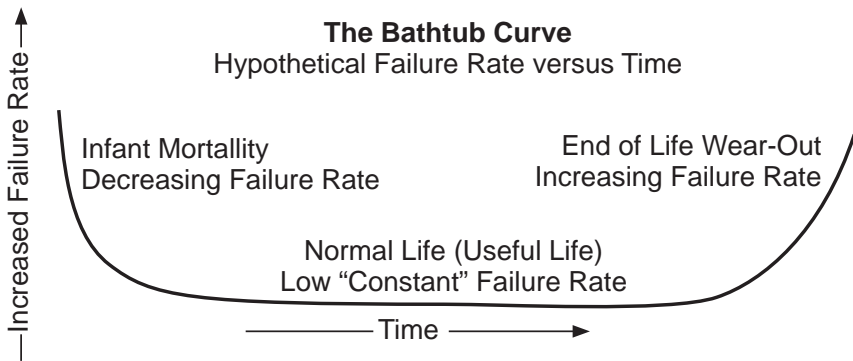


Figure I.5 The Bathtub Curve

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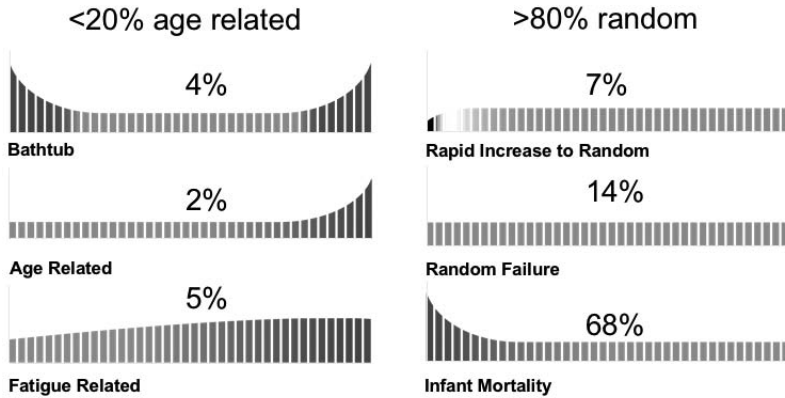


Figure I.6 Failure Patterns

In less technical terms, in the early life of an asset adhering to the bathtub curve, the failure rate is high. However, it quickly decreases as defective components are identified and discarded, and early sources of potential failure, including installation errors, are eliminated. In the mid-life of an asset, the failure rate is generally low and constant. In the late life of the asset, the failure rate increases, as age and wear take its toll.

The airline industry and the U.S. Navy performed studies in the 1960s and 1970s to have a better understanding of asset failures. These studies showed that these types of assets remain fairly close, even though they do not all follow the bathtub curve failure concept exactly. All assets followed a constant or slightly increasing failure rate for most of their life. Some didn't follow early mortality rate and some didn't have a wear out region either. Figure I.6 shows a series of these failure patterns based on original study data. The failure patterns are categorized into two groups — age-related and random. Fewer than 20% of failures follow an age degradation pattern; the remaining follow a random pattern with constant failure rate.

1- Reliability Failure Distribution

The exponential distribution is one of the most common distributions used to describe the reliability of an asset or a component in a system. It models an asset or component with the constant failure rate, or the flat section of the bathtub curve. Most of the assets, consumer or industrial, follow the constant failure rate for their useful life, so exponential distribution is widely used to estimate the reliability. The basic equation for

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estimating reliability, $R(t)$, is

$$R(t) = e^{-\lambda t}$$

where

λ (lambda) = Failure rate = $1/\text{MTBF}$

t = mission time, in cycles, hours, miles, etc.

(Note: e is base of the natural logarithm = 2.71828)

2- Calculating Reliability and Availability

Example 1

A hydraulic system, which supports a machining center, has operated 3600 hours in the last two years. The plant's CMMS system indicated that there were 12 failures during this period. What is the reliability of this hydraulic system if it is required to operate for 20 hours or for 100 hours?

MTBF = operating time / # of failures = $3600 / 12 = 300$ hours

Failure rate = $1 / \text{MTBF} = 1 / 300 = 0.003334$ failures / hour

Reliability for 20 hours of operations,

$$R(t) = e^{(-\lambda t)}$$

$$R(20) = e^{-(0.003334)(20)} = 93.55\%$$

Reliability for 100 hours of operations,

$$R(100) = e^{-(0.003334)(100)} = 71.65\%$$

For 100 hours of operation, the reliability of the hydraulic system is 71.65%. This means that there is a 71.65% probability that the hydraulic system will operate without a failure. If we need to operate the system for only 20 hours, however, the probability of failure-free operations will increase to 93.55%.

Now, let us suppose that there is a need to operate this hydraulic system for 100 hours to meet a key customer's needs and the current reliabil-

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ity of 71.65% is not acceptable. The system needs to have 95% or better assurance (probability) to meet the customer's need.

To have reliability requirements of 95% for 100 hours of mission time, we need to calculate a new failure rate, λ . We use the reliability equation,

$$\text{Required Reliability} = 0.95 = R_{(100)} = e^{(-\lambda \times 100)}$$

Solving this equation, gives us

$$\begin{aligned}(\lambda \times 100) &= 0.05 \\ 100 \lambda &= 0.05\end{aligned}$$

Thus,

$$\text{Failure rate } \lambda = 0.0005 \text{ or MTBF} = 2000 \text{ hours}$$

This indicates that the failure rate needs to be dropped from 0.00334 (or an MTBF of 300 hours) to a new failure rate of 0.0005 (or an MTBF of 2000 hours). If we consider the same 3600 operating hours, then the number of failures needs to be reduced from 12 to 1.8. A root cause failure or FMEA analysis needs to be performed on this hydraulic system to identify unreliable components. Some components may need to be re-designed or replaced to achieve the new MTBF of 2000 hours.

3- Example 2

A plant's air compressor system operated for 1000 hours last year. The plant's CMMS system provided the following data on this system:

Operating time = 1000 hours
Number of failures, random = 10
Total hours of repair time = 50 hours

What's the availability and reliability of this compressor system if we have to operate this unit for 10, 20, or 100 hours? Figure I.7 shows the failure data and Figure I.8 shows repair time data for those failures.

Figure I.7 shows that the first failure happened at 100 hours of operation, the second at 152 hours of operation, and so forth. Figure I.8 shows that the first failure happened at 100 hours of operation and took 2 hours to repair; the second failure happened at 152 hours of operation

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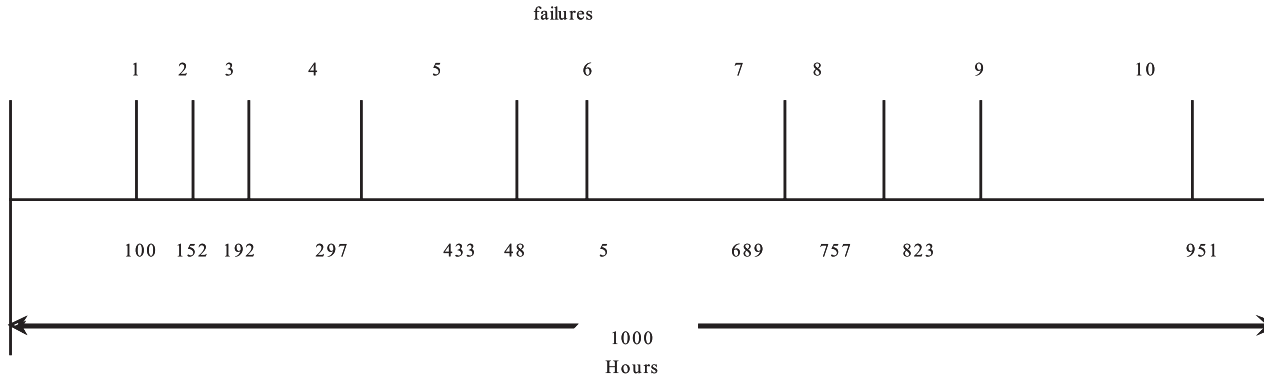


Figure I.7 Compressor Failure Data

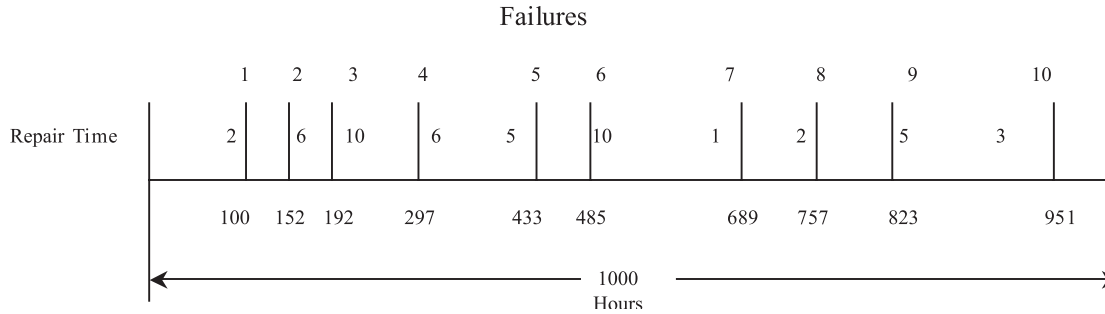


Figure I.8
Compressor
Failure and
Repair Time
Data

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and took 6 hours to repair; and so forth. The total repair time for 10 failures is 50 hours.

Calculating MTBF and Failure Rate

$$MTBF = \frac{\text{Operating Time}}{\# \text{ of Failures}} = \frac{1000 \text{ hours}}{10 \text{ failures}} = 100 \text{ hours}$$

This indicates that the average time between failures is 100 hours.

$$\text{Failure Rate } (\lambda - \text{Lambda}) = \frac{1}{MTBF} = \frac{1}{100} = 0.01 \text{ Failures /Hour}$$

Calculating MTTR and Repair Rate

$$MTTR = \frac{\text{Total Repair Time}}{\# \text{ of Failures}} = \frac{50 \text{ hours}}{10 \text{ failures}} = 5 \text{ hours}$$

$$\text{Repair Rate } (\mu) = \frac{1}{MTTR} = \frac{1}{5} = 0.2$$

Calculating Availability

Earlier, we calculated,

Mean Time Between Failures (MTBF) = 100 hours

Mean Time To Repair (MTTR) = 5 hours

Then,

$$\text{Availability (A)} = \frac{MTBF}{MTBF + MTTR} = \frac{Uptime}{Uptime + Downtime}$$

$$\text{Availability} = \frac{MTBF}{MTBF + MTTR} = \frac{100}{100 + 5} = 0.95 = 95\%$$

or

$$\frac{Uptime}{Uptime + Downtime} = \frac{1000 - 50 = 950}{950 + 50} = 0.95 = 95\%$$

This means that the asset is available 95% of the time and is down for 5% of the time for repair.

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Calculating Reliability

As calculated earlier for the compressor unit,

$$\text{MTBF} = 100 \text{ hours}$$

$$\text{Failure Rate } \lambda \text{ (FR)} = \frac{1}{\text{MTBF}} = \frac{1}{100} = 0.01 \text{ Failures / Hour}$$

$$\text{Reliability } R(t) = e^{-\lambda t}$$

If $t = \text{time} = 10 \text{ hours}$ and $\lambda = 0.01$, then

$$\text{Reliability } (R_{10}) = e^{-\lambda t} = e^{-(.01)(10)} = e^{-(.1)} = 0.90 \text{ or } 90\%$$

If $t = 20 \text{ hours}$ and $\lambda = 0.01$, then

$$\text{Reliability } (R_{20}) = e^{-\lambda t} = e^{-(.01)(20)} = e^{-(0.2)} = 0.81 \text{ or } 81.8\%$$

If $t = \text{time} = 100 \text{ hours}$ and $\lambda = 0.01$, then

$$\text{Reliability } (R_{100}) = e^{-\lambda t} = e^{-(.01)(100)} = e^{-1} = 0.3678 \text{ or } 36.78\%$$

So, for this compressor system with MTBF of 100 hours,

Reliability for 10 hours of operation = 90%

Reliability for 20 hours of operation = 82%

Reliability for 100 hours of operation = 37%

This data indicates that the reliability of the air compressor unit in this example is 90% for 10 hours of operation. However, reliability drops to 37% if we decide to operate the unit for 100 hours. For 20 hours of operation, reliability is 82%. If this level of reliability is not acceptable, then we need to perform root cause failure or FMEA analysis to determine what component needs to be redesigned or changed to reduce the number of failures, thereby increasing reliability.

I.12 Reliability Block Diagram (RBD)

The failure logic of an asset, components, or a group of assets and components called a system can be shown as a reliability block diagram

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(RBD). This diagram shows logical connections among the system's components and assets. The RBD is not necessarily the same as a schematic diagram of the system's functional layout. The system is usually made of several components and assets which may be in series, parallel, or combination configurations to provide us the designed (inherent) reliability. The RBD analysis consists of reducing the system to simple series and parallel component and asset blocks which can be analyzed using the mathematical formulas.

Figure I.9 shows a simple diagram, using two independent components and assets to form a system in series.

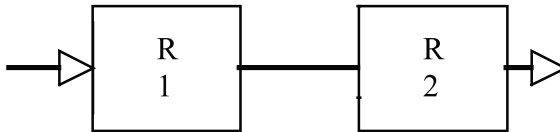


Figure I.9 An Example of Series System

The reliability of a system with multiple components in series is calculated by multiplying individual component reliabilities,

$$R_{\text{sys}} = R_1 \times R_2 \times R_3 \times R_4 \times \dots \times R_n,$$

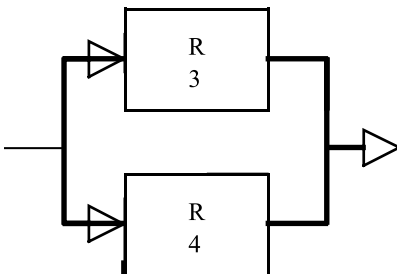
And the reliability of system $R_{\text{sys}12}$ as shown in Figure 6.7

$$R_{\text{sys}12} = R_1 \times R_2$$

or

$$R_{\text{sys}12} = e^{-(\lambda_1 + \lambda_2)t}$$

where λ is failure rate and t is the mission time.



*Figure I.10
An Example of a Parallel System*

Active Redundancy or Parallel System

The RBD for the simplest redundant system is shown in Figure 6.8.

This system is composed of two independent components and assets with reliability of R_3 and R_4

The reliability of a parallel system as shown is often written as

$$R_{\text{sys}34} = 1 - (1 - R_3)(1 - R_4)$$

or

$$R_{\text{sys}34} = R_3 + R_4 - (R_3 \times R_4)$$

or

$$R_{\text{sys}34} = e^{-(\lambda_3)t} + e^{-(\lambda_4)t} - e^{-(\lambda_3 + \lambda_4)t}$$

In this arrangement, the reliability of the system, $R_{\text{sys}34}$ is equal to the probability of component 3 or 4 surviving. It simply means that one of the components is needed to operate the system and the other component is in active state and available if the first one fails. Therefore, the reliability of the whole system in parallel configuration is much higher than in series configuration. The components in parallel improve system reliability whereas components in series lower system reliability.

Standby redundancy is achieved when, in a redundant system, the spare component is not in an active mode continuously, but gets switched on only when the primary component fails. In standby mode, the resultant reliability is a little higher in comparison to active mode. However, the assumption is made that switching is done without failure or without any delay. The reliability of a two component system in standby mode is:

$$R_{\text{sys-standby}} = e^{-(\lambda)t} + \lambda t e^{-(\lambda)t}$$

Example 3

In a two-component parallel system with a failure rate of 0.1 /hour of each component, what would be the active and standby reliability of the system for one hour of operation?

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In this example, $\lambda_3 = \lambda_4 = 0.1$ and $t = 1$ hour. Then active reliability

$$R_{\text{active}} = e^{-(\lambda_3)t} + e^{-(\lambda_4)t} - e^{-(\lambda_3 + \lambda_4)t}$$

or

$$= R_3 + R_4 - (R_3 R_4)$$

Note that

$$R_3 = R_4 = e^{-(\lambda_3)t} = e^{-(0.1)1} = 0.9048$$

and therefore

$$= 0.9048 + 0.9048 - 0.8187 = 0.9909$$

$$R_{\text{standby}} = e^{-(\lambda)t} + \lambda t e^{-(\lambda)t} \text{ or } R + \lambda t R \\ = 0.9048 + (0.1 \times 1 \times 0.9048) = 0.9953$$

m – out – of – n Reliability Models

In real application, there will be many components and assets in series and parallel arrangements, depending upon design requirements. For example, Figure I.11 shows a typical system comprised of 13 components, or individual assets, arranged in a combination of series and parallel configuration. The system reliability can be determined by calculating first the individual component and asset reliability, then the system's subsystems, and finally the system as a whole. Reliability of some of the subsystems that are in parallel arrangements can be calculated using *m-out-of-n* reliability formulas. This means how many *m* legs (components in series) are necessary out of *n* legs for the system to operate properly. In Figure I.11, subsystem B has three legs, but we need only one to operate the system. Similarly, subsystem C has three components and assets in parallel, and we need two to operate.

A simple approach for calculating the reliability of *m-out-of-n* systems is utilizing the binomial distribution and the relationship $(R + Q)^n = 1$, where *R* is reliability, *Q* is unreliability, and *n* is the number of elements. Figure I.12 shows the formula for 2-, 3-, and 4-element systems to calculate system reliability.

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The reliability of the system, as shown in Figure 6.9, is

$$R_{\text{sys}} = R_1 \times R_2 \times R_B \times R_{10} \times R_C$$

R_B is an active parallel configuration which is equal to

$$R_B = 1 - [1 - (R_3 \times R_4 \times R_5)] [1 - (R_6 \times R_7 \times R_8)] (1 - R_9)$$

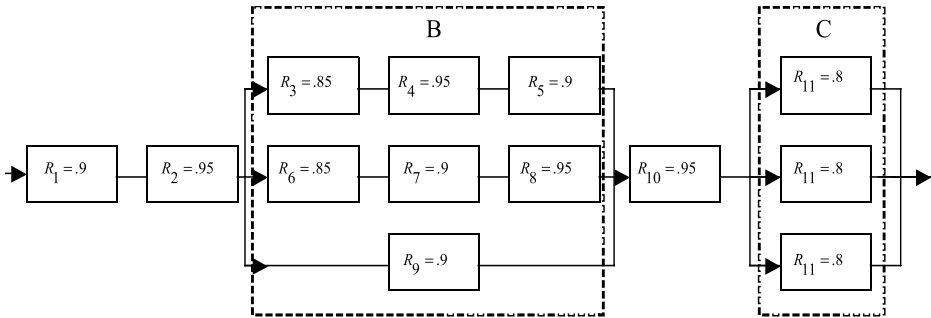


Figure 1.11 An Example of Multiple Component System RBD

m - # of Working element	Overall System Reliability
1 out of 2 2 out of 2	$R^2 + 2R(1-R) = 1 - (1-R)^2$ R^2
1 out of 3 2 out of 3 3 out of 3	$R^3 + 3R^2(1-R) + 3R(1-R)^2 = 1 - (1-R)^3$ $R^3 + 3R^2(1-R)$ R^3
1 out of 4 2 out of 4 3 out of 4 4 out of 4	$R^4 + 4R^3(1-R) + 6R^2(1-R)^2 + 4R(1-R)^3 = 1 - (1-R)^4$ $R^4 + 4R^3(1-R) + 6R^2(1-R)^2$ $R^4 + 4R^3(1-R)$ R^4

Assumption: each element/component's reliability is the same (R)

Figure 1.12 System Reliability for m-out-of-n components

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$$\begin{aligned} &= 1 - [1 - (0.85 \times 0.95 \times 0.9)] [1 - (0.85 \times 0.9 \times 0.95)] (1 - 0.9) \\ &= 1 - (1 - 0.7267) (1 - 0.7267) (0.1) \\ &= 1 - 0.00746 \\ &= 0.9925 \end{aligned}$$

R_c is another active parallel configuration, but it requires 2 (m) out-of-3(n) to operate. We could also use the binomial distribution, from Figure I.12 to calculate R_c

$$\begin{aligned} R_c &= R^3 + 3R^2 (1 - R) \\ &= (0.8)^3 + 3 (0.8)^2 (1 - 0.8) \\ &= (0.512) + (0.384) \\ &= 0.896 \end{aligned}$$

The whole system reliability

$$\begin{aligned} R_{sys} &= 0.9 \times 0.95 \times 0.9925 \times 0.95 \times 0.896 \\ &= 0.7223 \end{aligned}$$

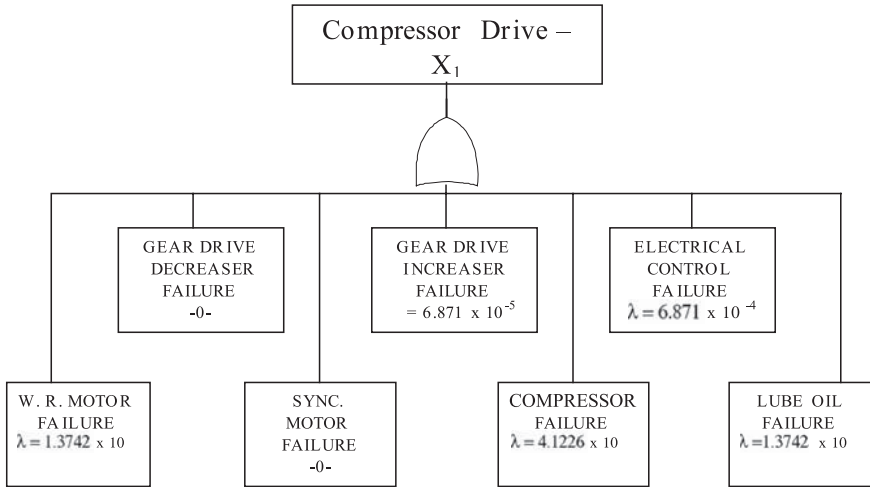
Example 4

Figure 6.11 shows a compressor drive system consisting of seven components, motors, gear boxes, the compressor itself, electrical controls, and lube oil system, with failure rates based on four years of data. All components are assumed to be in series arrangement. Figure I.14 shows the same compressor system in RBD format.

The total system failure rate based on the last 4 years of data,

$$\begin{aligned} \lambda_{X1} &= 1.3742 \times 10^{-4} + 0 + 0 + 6.871 \times 10^{-5} + 4.1226 \times 10^{-4} + 6.871 \times 10^{-4} + \\ &\quad 1.3742 \times 10^{-4} \\ &= 1.443 \times 10^{-3} = 0.001443 \end{aligned}$$

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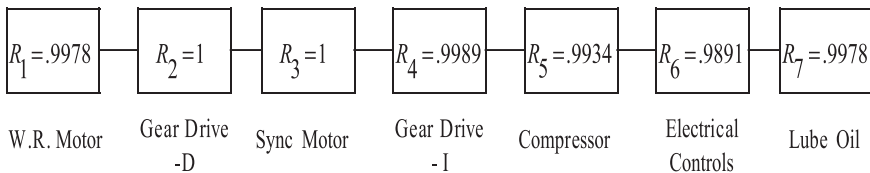
Figures I.13 Compressor X1 system with major components and failure rates

Therefore,

$$\text{MTBF of total system} = 1/\lambda = 1/0.001443 = 693 \text{ hours}$$

Based on 16 hours of operation, the reliability of each component is calculated and shown in the reliability block diagram in Figure I.14. The system reliability

$$R_{\text{sys}} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \times R_7$$



Figures I.14 Reliability Block Diagram for Compressor X1 System

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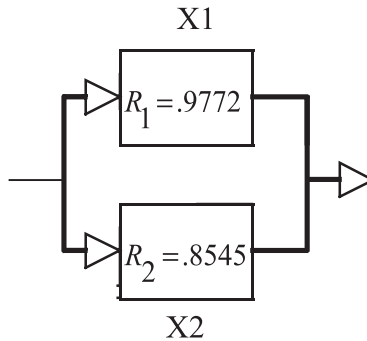
Substituting individual reliability, the system reliability

$$R_{\text{sys}} = 0.9978 \times 1 \times 1 \times 0.9989 \times 0.9934 \times 0.9891 \times 0.9978 = 0.9772$$

Thus the reliability of the compressor unit is 97.72% based on 16 hours of operation. Now, let us assume that there are two compressor systems X1 and X2 in the facility, as shown in Figure I.15, with reliability of

$$X1 = 0.9772$$

$$X2 = 0.8545$$



Figures I.15 Two compressors system arrangement

These **reliability** levels are based on 16 hours, 2-shift operation scenarios. Let us also assume that most of the time, say 85%, we need only one compressor to meet our production needs. The second compressor will work as active standby. However, for 15 percent of the time, we may need both of the compressor units. During that time, both compressors will be in series arrangement.

The reliability of one unit (85% of time needing only one compressor)

$$\begin{aligned} &= R_{X1} + R_{X2} - (R_{X1} \times R_{X2}) \\ &= 0.9772 + 0.8545 - (0.9772 \times 0.8545) \\ &= 1.8317 - 0.8350 \\ &= 0.9967 \text{ or } 99.67\% \end{aligned}$$

Chapter 1: General Overview of Maintenance

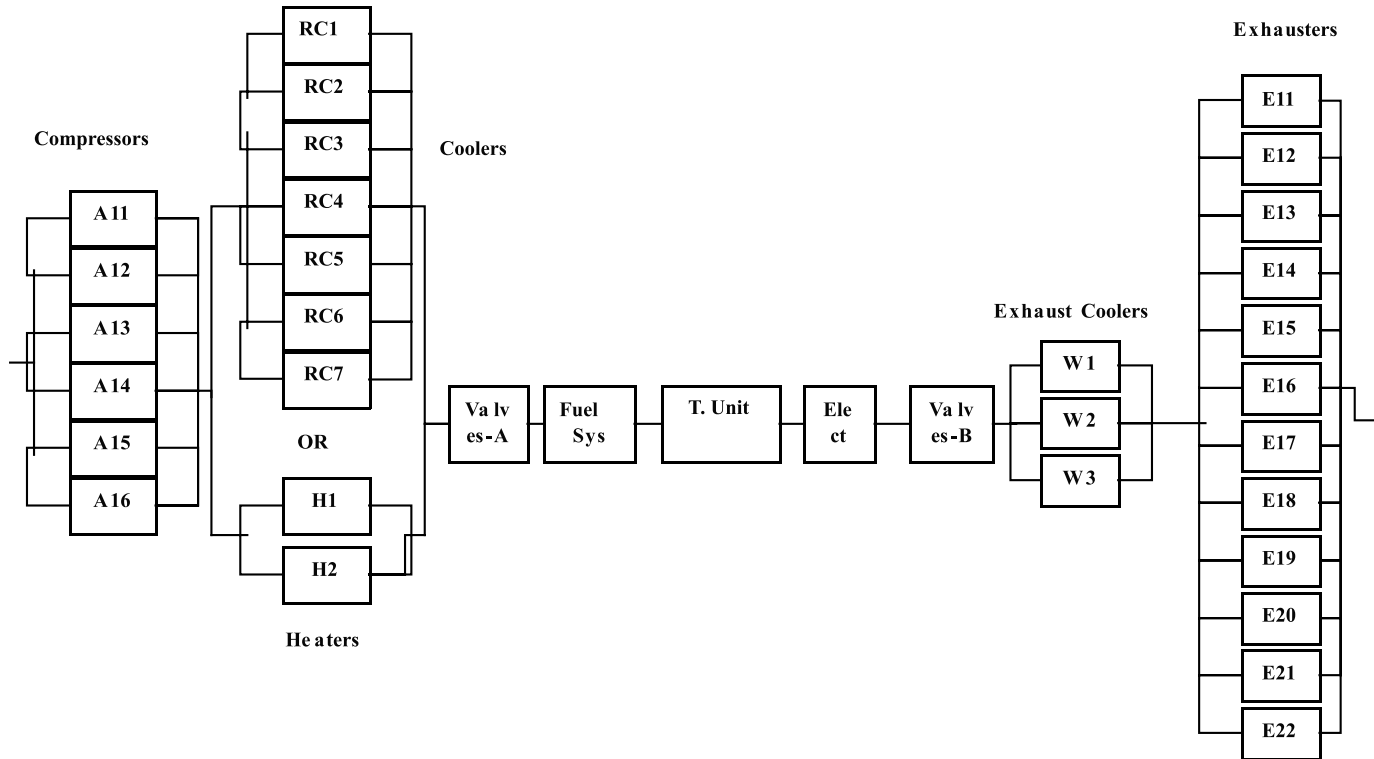


Figure I.16 Example of a Reliability Block Diagram at Plant Systems

Chapter 1: General Overview of Maintenance

The reliability of two units (15% of time needing both compressors)

$$\begin{aligned} &= R_{X1} \times R_{X2} \\ &= 0.9772 \times 0.8545 \\ &= 0.8350 \end{aligned}$$

So, when there is need for only one compressor unit, we are 98% reliable. However, when there is need for both compressors, we are only 85% reliable to meet the customer's needs. This level may be acceptable. If not, we may need to redesign or replace some of the components in compressor X2 to make it more reliable.

Similarly, a reliability block diagram for a process, a manufacturing line, or a plant could be developed, as shown in Figure I.16. This type of reliability block diagram can provide the information needed to improve the reliability of systems in the plant.

***Chapter 2:
Organization and Management of
Maintenance***

II.1 Introduction

Organizing is the process of arranging resources (people, materials, technology *etc.*) together to achieve the organization's strategies and goals. The way in which the various parts of an organization are formally arranged is referred to as the organization structure. It is a system involving the interaction of inputs and outputs. It is characterized by task assignments, workflow, reporting relationships, and communication channels that link together the work of diverse individuals and groups. Any structure must allocate tasks through a division of labor and facilitate the coordination of the performance results. Nevertheless, we have to admit that there is no one best structure that meets the needs of all circumstances. Organization structures should be viewed as dynamic entities that continuously evolve to respond to changes in technology, processes and environment, (Daft, 1989 and Schermerhorn, 2007).

Frederick W. Taylor introduced the concept of scientific management (time study and division of labor), while Frank and Lilian Gilbreth founded the concept of modern motion study techniques. The contributions of Taylor and the Gilbreths are considered as the basis for modern organization management. Until the middle of the twentieth century maintenance has been carried out in an unplanned reactive way and for a long time it has lagged behind other areas of industrial management in the application of formal techniques and/or information technology. With realization of the impact of poor maintenance on enterprises' profitability, many managers are revising the organization of maintenance and have developed new approaches that foster effective maintenance organization.

Maintenance cost can be a significant factor in an organization's profitability. In manufacturing, maintenance cost could consume 2–10% of the company's revenue and may reach up to 24% in the transport industry (Chelson, Payne and Reavill, 2005). So, contemporary management considers maintenance as an integral function in achieving productive operations and high-quality products, while maintaining satisfactory equipment and machines reliability as demanded by

Chapter 2: Organization and Management of Maintenance

the era of automation, flexible manufacturing systems (FMS), “lean manufacturing”, and “just-in-time” operations.

However, there is no universally accepted methodology for designing maintenance systems, *i.e.*, no fully structured approach leading to an optimal maintenance system (*i.e.*, organizational structure with a defined hierarchy of authority and span of control; defined maintenance procedures and policies, *etc.*). Identical product organizations, but different in technology advancement and production size, may apply different maintenance systems and the different systems may run successfully. So, maintenance systems are designed using experience and judgment supported by a number of formal decision tools and techniques. Nevertheless, two vital considerations should be considered: strategy that decides on which level within the plant to perform maintenance, and hence outlining a structure that will support the maintenance; planning that handles day-to-day decisions on what maintenance tasks to perform and providing the resources to undertake these tasks.

The maintenance organizing function can be viewed as one of the basic and integral parts of the maintenance management function (MMF). The MMF consists of planning, organizing, implementing and controlling maintenance activities. The management organizes, provides resources (personnel, capital, assets, material and hardware, *etc.*) and leads to performing tasks and accomplishing targets. Figure II.1 shows the role organizing plays in the management process. Once the plans are created, the management’s task is to ensure that they are carried out in an effective and efficient manner. Having a clear mission, strategy, and objectives facilitated by a corporate culture, organizing starts the process of implementation by clarifying job and working relations (chain of command, span of control, delegation of authority, *etc.*).

In designing the maintenance organization there are important determinants that must be considered. The determinants include the capacity of maintenance, centralization *vs* decentralization and in-house maintenance *vs* outsourcing. A number of criteria can be used to design the maintenance organization. The criteria include clear roles and responsibilities, effective span of control, facilitation of good supervision and effective reporting, and minimization of costs.

Maintenance managers must have the capabilities to create a division of labor for maintenance tasks to be performed and then coordinate results to achieve a common purpose. Solving performance problems and capitalizing on opportunities could be attained through selection of the right persons, with the appropriate capabilities, supported by continuous training and good incentive schemes, in order to achieve organization success in terms of performance effectiveness and efficiency.

This chapter covers the organizational structure of maintenance activities. Section II.2 describes the organization objectives and the responsibilities of maintenance, followed by the determinants of a maintenance organization in Section II.3. Section II.4 outlines the design of maintenance organization and Section II.5 presents basic models for organization. The description of function of material and spare parts management is given in Section II.6, and Section II.7 outlines the process of establishing authority. The role of the quality of leadership and supervision is presented in Section II.8 followed by the role of incentives in

Section II.9. Sections II.10 and II.11 present education and training, and management and labor relations, respectively. A summary of the chapter is provided in Section II.12.

II.2 Maintenance Organization Objectives and Responsibility

A maintenance organization and its position in the plant/whole organization is heavily impacted by the following elements or factors:

- Type of business, *e.g.*, whether it is high tech, labor intensive, production or service;
- Objectives: may include profit maximization, increasing market share and other social objectives;
- Size and structure of the organization;
- Culture of the organization; and
- Range of responsibility assigned to maintenance.

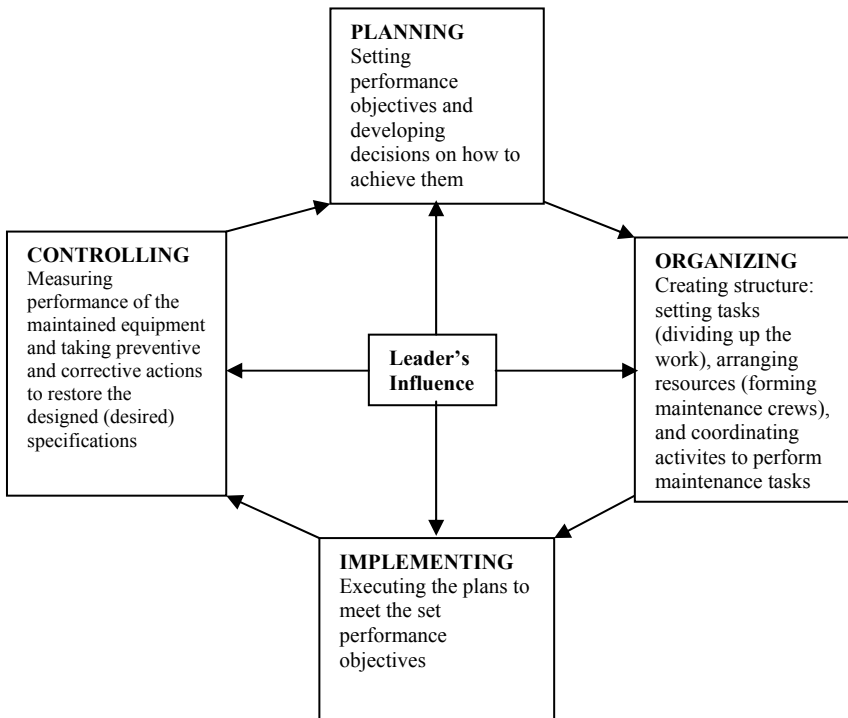


Figure II.1. Maintenance organizing as a function of the management process

Organizations seek one or several of the following objectives: profit maximization, specific quality level of service or products, minimizing costs, safe and clean environment, or human resource development. It is clear that all of these

Chapter 2: Organization and Management of Maintenance

objectives are heavily impacted by maintenance and therefore the objectives of maintenance must be aligned with the objectives of the organization.

The principal responsibility of maintenance is to provide a service to enable an organization to achieve its objectives. The specific responsibilities vary from one organization to another; however they generally include the following according to Duffuaa *et al.* (1998):

1. Keeping assets and equipment in good condition, well configured and safe to perform their intended functions;
2. Perform all maintenance activities including preventive, predictive; corrective, overhauls, design modification and emergency maintenance in an efficient and effective manner;
3. Conserve and control the use of spare parts and material;
4. Commission new plants and plant expansions; and
5. Operate utilities and conserve energy.

The above responsibilities and objectives impact the organization structure for maintenance as will be shown in the coming sections.

II.3 Determinants of a Maintenance Organization

The maintenance organization's structure is determined after planning the maintenance capacity. The maintenance capacity is heavily influenced by the level of centralization or decentralization adopted. In this section the main issues that must be addressed when forming the maintenance organization's structure are presented. The issues are: capacity planning, centralization vs decentralization and in-house vs outsourcing.

II.3.1 Maintenance Capacity Planning

Maintenance capacity planning determines the required resources for maintenance including the required crafts, administration, equipment, tools and space to execute the maintenance load efficiently and meet the objectives of the maintenance department. Critical aspects of maintenance capacity are the numbers and skills of craftsmen required to execute the maintenance load. It is difficult to determine the exact number of various types of craftsmen, since the maintenance load is uncertain. Therefore accurate forecasts for the future maintenance work demand are essential for determining the maintenance capacity. In order to have better utilization of manpower, organizations tend to reduce the number of available craftsmen below their expected need. This is likely to result in a backlog of uncompleted maintenance work. This backlog can also be cleared when the maintenance load is less than the capacity. Making long run estimations is one of the areas in maintenance capacity planning that is both critical and not well developed in practice. Techniques for maintenance forecasting and capacity planning are presented in a separate chapter in this handbook.

II.3.2 Centralization vs Decentralization

The decision to organize maintenance in a centralized, decentralized or a hybrid form depends to a greater extent on the organization is philosophy, maintenance load, size of the plant and skills of craftsmen. The advantages of centralization are:

1. Provides more flexibility and improves utilization of resources such highly skilled crafts and special equipment and therefore results in more efficiency;
2. Allows more efficient line supervision;
3. Allows more effective on the job training; and
4. Permits the purchasing of modern equipment.

However it has the following disadvantages:

1. Less utilization of crafts since more time is required for getting to and from jobs;
2. Supervision of crafts becomes more difficult and as such less maintenance control is achieved;
3. Less specialization on complex hardware is achieved since different persons work on the same hardware; and
4. More costs of transportation are incurred due to remoteness of some of the maintenance work.

In a decentralized maintenance organization, departments are assigned to specific areas or units. This tends to reduce the flexibility of the maintenance system as a whole. The range of skills available becomes reduced and manpower utilization is usually less efficient than in a centralized maintenance. In some cases a compromise solution that combines centralization and decentralization is better. This type of hybrid is called a cascade system. The cascade system organizes maintenance in areas and what ever exceeds the capacity of each area is challenged to a centralized unit. In this fashion the advantages of both systems may be reaped. For more on the advantages and disadvantages of centralization and decentralization see Duffuaa *et al.* (1998) and Niebel (1994).

II.3.3 In-house vs Outsourcing

At this level management considers the sources for building the maintenance capacity. The main sources or options available are in-house by direct hiring, outsourcing, or a combination of in-house and outsourcing. The criteria for selecting sources for building and maintaining maintenance capacity include strategic considerations, technological and economic factors. The following are criteria that can be employed to select among sources for maintenance capacity:

1. Availability and dependability of the source on a long term basis;
2. Capability of the source to achieve the objectives set for maintenance by the organization and its ability to carry out the maintenance tasks;

Chapter 2: Organization and Management of Maintenance

3. Short term and long term costs;
4. Organizational secrecy in some cases may be subjected to leakage;
5. Long term impact on maintenance personnel expertise; and
6. Special agreement by manufacturer or regulatory bodies that set certain specifications for maintenance and environmental emissions.

Examples of maintenance tasks which could be outsourced are:

1. Work for which the skill of specialists is required on a routine basis and which is readily available in the market on a competitive basis, *e.g.*,:
 - Installation and periodic inspection and repair of automatic fire sprinkler systems;
 - Inspection and repair of air conditioning systems;
 - Inspection and repair of heating systems; and
 - Inspection and repair of main frame computers *etc.*
2. When it is cheaper than recruiting your own staff and accessible at a short notice of time.

The issues and criteria presented in the above section may help organizations in designing or re-designing their maintenance organization.

II.4 Design of the Maintenance Organization

A maintenance organization is subjected to frequent changes due to uncertainty and desire for excellence in maintenance. Maintenance and plant managers are always swinging from supporters of centralized maintenance to decentralized ones, and back again. The result of this frequent change is the creation of responsibility channels and direction of the new organization's accomplishments *vs* the accomplishments of the former structure. So, the craftsmen have to adjust to the new roles. To establish a maintenance organization an objective method that caters for factors that influence the effectiveness of the organization is needed. Competencies and continuous improvement should be the driving considerations behind an organization's design and re-design.

II.4.1 Current Criteria for Organizational Change

Many organizations were re-designed to fix a perceived problem. This approach in many cases may raise more issues than solve the specific problem (Bradley, 2002). Among the reasons to change a specific maintenance organization's design are:

1. Dissatisfaction with maintenance performance by the organization or plant management;
2. A desire for increased accountability;

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3. A desire to minimize manufacturing costs, so maintenance resources are moved to report to a production supervisor, thereby eliminating the (perceived) need for the maintenance supervisor;
4. Many plant managers are frustrated that maintenance seems slow paced, that is, every job requires excessive time to get done. Maintenance people fail to understand the business of manufacturing, and don't seem to be part of the team. This failure results in decentralization or distribution of maintenance resources between production units; and
5. Maintenance costs seem to rise remarkably, so more and more contractors are brought in for larger jobs that used to get done in-house.

II.4.2 Criteria to Assess Organizational Effectiveness

Rather than designing the organization to solve a specific problem, it is more important to establish a set of criteria to identify an effective organization. The following could be considered as the most important criteria:

1. Roles and responsibilities are clearly defined and assigned;
2. The organization puts maintenance in the right place in the organization;
3. Flow of information is both from top-down and bottom-up;
4. Span of control is effective and supported with well trained personal;
5. Maintenance work is effectively controlled;
6. Continuous improvement is built in the structure;
7. Maintenance costs are minimized; and
8. Motivation and organization culture.

II.5 Basic Types of Organizational Models

To provide consistently the capabilities listed above we have to consider three types of organizational designs.

- **Entralized maintenance.** All crafts and related maintenance functions report to a central maintenance manager as depicted in Figure II.2. The strengths of this structure are: allows economies of scale; enables in-depth skill development ; and enables departments (*i.e.*, a maintenance department) to accomplish their functional goals (not the overall organizational goals). This structure is best suited for small to medium - size organizations . The weaknesses of this structure are: it has slow response time to environmental changes; may cause delays in decision making and hence longer response time; leads to poor horizontal coordination among departments and involves a restricted view of organizational goals.
- **Decentralized maintenance.** All crafts and maintenance craft support staff report to operations or area maintenance as described in Figure II.3. The strengths of this structure are that it allows the organization to achieve adaptability and coordination in production units and efficiency in a

centralized overhaul group and it facilitates effective coordination both within and between maintenance and other departments. The weaknesses of this structure are that it has potential for excessive administrative overheads and may lead to conflict between departments.

- Matrix structure, a form of a hybrid structure. Crafts are allocated in some proportion to production units or area maintenance and to a central maintenance function that supports the whole plant or organization as depicted in Figure II.4. The strengths of this matrix structure are: it allows the organization to achieve coordination necessary to meet dual demands from the environment and flexible sharing of human resources. The weaknesses of this structure are: it causes maintenance employees to experience dual authority which can be frustrating and confusing; it is time consuming and requires frequent meetings and conflict resolution sessions. To remedy the weaknesses of this structure a management with good interpersonal skills and extensive training is required.

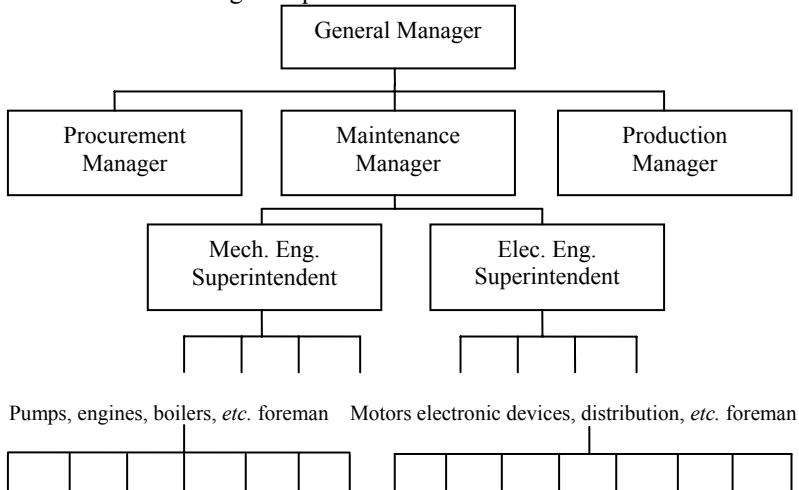
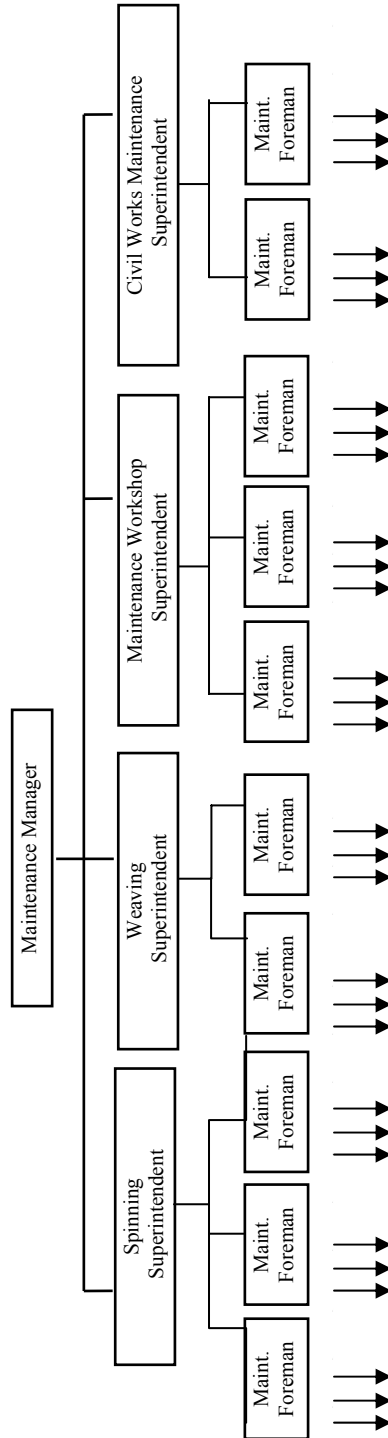


Figure II.2. Centralized (functional) organizational structure

II.6 Material and Spare Parts Management

The responsibility of this unit is to ensure the availability of material and spare parts in the right quality and quantity at the right time at the minimum cost. In large or medium size organizations this unit may be independent of the maintenance organization; however in many circumstances it is part of maintenance. It is a service that supports the maintenance programs. Its effectiveness depends to a large extent on the standards maintained within the stores system. The duties of a material and spare parts unit include:



T E C H N I C I A N S

Figure II.3. Functionally de-centralized organizational structure of maintenance in a textile factory

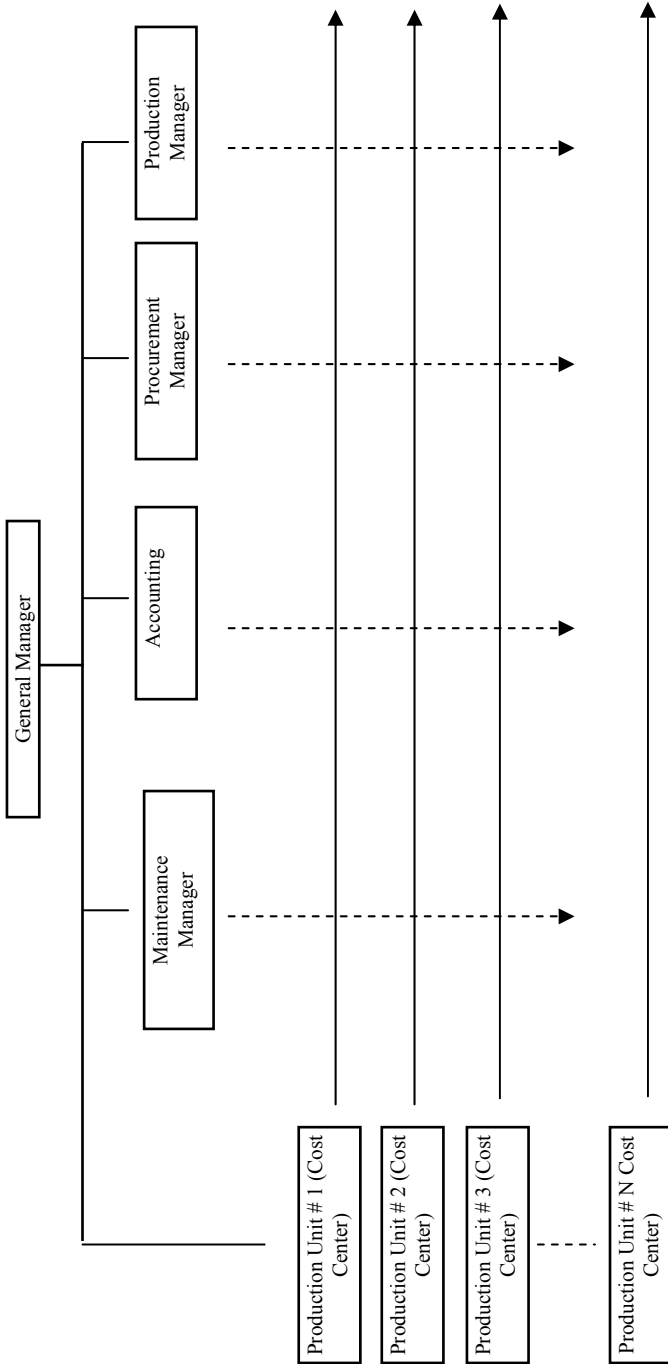


Figure II.4. Matrix (de-centralized) organizational structures

1. Develop in coordination with maintenance effective stocking policies to minimize ordering, holding and shortages costs;
2. Coordinate effectively with suppliers to maximize organization benefits;
3. Keep good inward, receiving, and safe keeping of all supplies;
4. Issue materials and supplies;
5. Maintain and update records; and
6. Keep the stores orderly and clean.

II.7 Establishment of Authority and Reporting

Overall administrative control usually rests with the maintenance department, with its head reporting to top management. This responsibility may be delegated within the maintenance establishment. The relationships and responsibility of each maintenance division/section must be clearly specified together with the reporting channels. Each job title must have a job description prescribing the qualifications and the experience needed for the job, in addition to the reporting channels for the job.

II.8 Quality of Leadership and Supervision

The organization, procedures, and practices instituted to regulate the maintenance activities and demands in an industrial undertaking are not in themselves a guarantee of satisfactory results. The senior executive and his staff must influence the whole functional activity. Maintenance performance can never rise above the quality of its leadership and supervision. From good leadership stems the teamwork which is the essence of success in any enterprise. Talent and ability must be recognized and fostered; good work must be noticed and commended; and carelessness must be exposed and addressed.

II.9 Incentives

The varied nature of the maintenance tasks, and differing needs and conditions arising, together with the influence of production activity, are not attuned to the adoption of incentive systems of payment. There are, however, some directions in which incentive applications can be usefully considered. One obvious case is that of repetitive work. The forward planning of maintenance work can sometimes lead to an incentive payment arrangement, based on the completion of known tasks in a given period, but care must be taken to ensure that the required standards of work are not compromised. In some case, maintenance incentives can be included in output bonus schemes, by arranging that continuity of production, and attainment of targets, provides rewards to both production and maintenance personnel.

II.10 Education and Training

Nowadays it is also recognized that the employers should not only select and place personnel, but should promote schemes and provide facilities for their further education and training, so as to increase individual proficiency, and provide recruits for the supervisory and senior grades. For senior staff, refresher courses comprise lectures on specific aspects of their work; they also encourage the interchange of ideas and discussion.

The further education of technical grades, craft workers, and apprentices is usually achieved through joint schemes, sponsored by employers in conjunction with the local education authority. Employees should be encouraged to take advantage of these schemes, to improve proficiency and promotion prospects.

A normal trade background is often inadequate to cope with the continuing developments in technology. The increasing complexity and importance of maintenance engineering warrants a marked increase in training of machine operators and maintenance craftsmen through formal school courses, reinforced by informed instruction by experienced supervisors.

The organization must have a well defined training program for each employee. The following provides guidelines for developing and assessing the effectiveness of the training program:

- Evaluate current personnel performance;
- Assess training need analysis;
- Design the training program;
- Implement the program; and
- Evaluate the program effectiveness.

The evaluation is done either through a certification program or by assessing the ability to achieve desired performance by persons who have taken a particular training program.

The implementation of the above five steps provides the organization with a framework to motivate personnel and improve performance.

II.11 Management and Labor Relations

The success of an undertaking depends significantly on the care taken to form a community of well-informed, keen, and lively people working harmoniously together. Participation creates satisfaction and the necessary team spirit. In modern industry, quality of work life (QWL) programs have been applied with considerable success, in the form of management conferences, work councils, quality circles, and joint conferences identified with the activities. The joint activities help the organization more fully achieve its purposes.

II.12 Summary

This chapter considered organizing as one of the four functions of management. It is the process of arranging resources (people, materials, technology, *etc.*) together to achieve the organization's strategies and goals. Maintenance organization structure is the way various part of the maintenance organization is formed including defining responsibilities and roles of units and individuals. A set of criteria are provided to assess and design organization structures and the main issues to be addressed are outlined. The issues include centralization, decentralization and outsourcing. The chapter describes three types of organization structures. In addition, several functions that could support maintenance organization such as material and spare management, training and the management of labor relations are presented.

***Chapter 3:
Troubleshooting Different Parts
of Electrical Machines***

III.1. Introduction

This chapter gives an overview of faults found in electrical machines and their diagnosis, with a special reference to induction machines and their fault detection. These techniques may be easily extended to other types of electrical machines.

Electrical machine fault diagnosis has greatly benefited from an intense interest from research domains. Monitoring electrical machines for diagnosis and predicting breakdowns has spurred the writing of several studies, due to its significant influence on the operational continuity of many industrial processes.

A good diagnosis and early fault detection enable minimized shutdown time as well as maintenance time of the process in question. This also means that the harmful, sometimes devastating, consequences of such faults can be avoided, and there is a reduction in incurring financial losses.

A good detection procedure must use necessary minimalist measures using the process in question, as well as obtain a diagnosis which gives a clear indication of the failure modes by analyzing data in a small time frame.

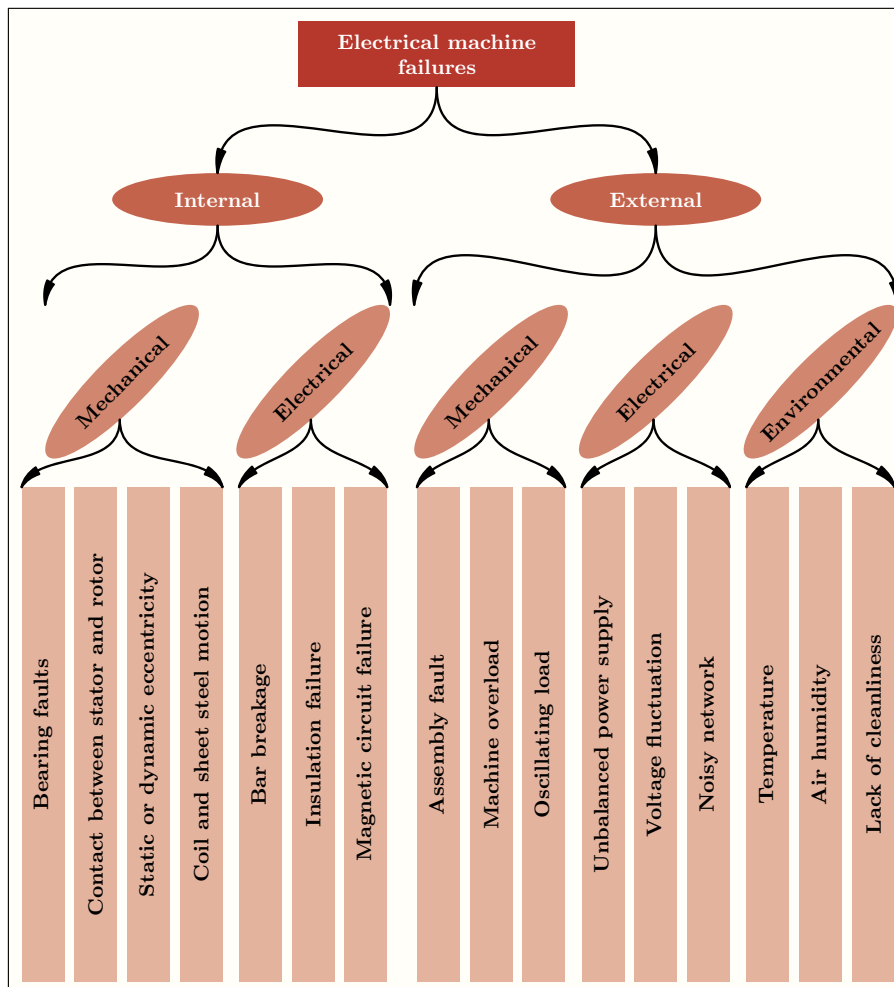


Figure III.1. Cause-based fault categorization

Electrical machines and drive systems often have several types of faults. These can be categorized into two groups according to their causes (Figure III.1): internal causes and external causes [KAZ 03, CAS 05]. External faults are caused by power supply voltage, mechanical loads, as well as by the machine's usage environment. Internal causes are generated by the machine's components (magnetic circuits, stator and rotor coils, mechanical air-gaps, rotor's cage, etc.). As an example, let us draw up a non-exhaustive list of the faults shown in Figure III.1:

- electrical faults on the stator, manifested by a phase opening or a short-circuit within the same phase, between two phases, or between one phase and the stator frame;

Chapter 3: Troubleshooting Different Parts of Electrical Machines

- electrical faults on the rotor, which include an opening or a short-circuit on the coils for wound rotor machines, or bar and/or short-circuit ring breakages or cracks for squirrel-cage machines;
- mechanical faults on the stator bore or the rotor, such as bearing faults, eccentricity, and alignment;
- failure on the power electronic components of the drive system.

Due to the symmetry in electrical machines, any fault will induce a level of distortion in the rotating magnetic field in the machine's air-gap. It causes harmonics to appear on the measured signals which characterize these faults. Measuring relevant signals enables us to non-invasively monitor the machine's operation. These signals may be electrical or mechanical such as currents, voltages, flux, torque and speed. Fault detection and identification techniques have been widely studied because there are still some questions left unanswered:

- the definition of a single diagnostic procedure for detecting and identifying any type of fault;
- an increase in the robustness of detection techniques, making them unsusceptible to operation conditions;
- the reliable detection of breakdowns for a position, speed, and torque control;
- reliable detection of breakdowns in different working conditions.

An efficient diagnosis opens up a pathway for a tolerant fault control and must, consequently, increase the robustness of the industrial process. Over these last few decades, the advent of power electronics has made it possible to envisage new applications, as well as drawing the best performances from electrical machine operations. Nonetheless, this technological advancement has brought other failure risks with it in terms of electrical drive processes.

Currently, several research laboratories are looking into the design and development of new control strategies [BIA 07, AKI 08], making it possible to make up for performance losses which follow the appearance of failures on the machine or the control system.

This chapter has been set out in three main sections which present the composition of induction machines, the different types of faults which can occur within, and finally, the diagnosis techniques of electrical machines.

III.2. Composition of induction machines

In this section, we wish to briefly outline the composition of the induction machine. This description will enable us to better understand induction machine failures in their physical dimensions.

Chapter 3: Troubleshooting Different Parts of Electrical Machines

From a mechanical point of view, induction machines can be composed of three distinct parts:

- the stator: the fixed component where the electrical power supply is connected;
- the rotor: the rotating part which rotates the mechanical load;
- the bearings: the mechanical component which guides the shaft rotation.

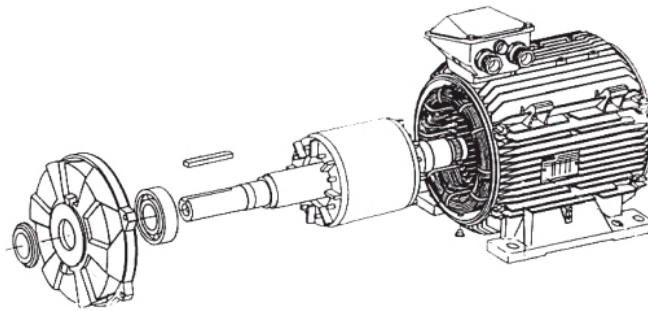


Figure III.2. *Leroy-Somer induction squirrel-cage motor*

III.2.1. The stator

The induction machine stator is composed of steel sheets, where the stator coils are located. For small machines, these sheets are cut out from a single sheet, whereas for more high-powered machines, they are cut out into sections. These sheets are usually varnished to limit the Foucault current effects; they are assembled on top of each other by rivets or welding, to form the stator magnetic circuit. Stator coils are positioned in the pre-designed slots. It is into these slots that the stator coils are positioned, according to a distributed or a concentric winding [GRE 89, LOU 69].

Concentric winding is often used when the induction machine's winding mechanism is performed mechanically. The insulation between the electrical winding and the stator core is made using insulating materials, which may differ depending on the use of the machine.

The stator of the induction machine is also equipped with a terminal box where the electrical power supply is connected. Figure III.2 shows the different components which make up the induction machine stator.

III.2.2. The rotor

The rotor magnetic circuit is composed of steel sheets which, generally, originate from the same place as those used to build the stator. There are two types of rotors in induction machines: wound and squirrel-cage rotors.

Chapter 3: Troubleshooting Different Parts of Electrical Machines

The wound rotors are built in the same way as the stator coil¹. The rotor phases are therefore available with the help of a brush/slip ring assembly located in the machine's shaft.

With regard to squirrel-cage rotors, the winding is composed of copper bars for high-power motors, and aluminum bars for lower-powered motors. These bars are short-circuited at each end by two short-circuit rings, made of copper or aluminum. In Figure III.2, we show the different elements composing a squirrel-cage rotor.

For squirrel-cage rotors (Figure III.2), the conductors are made by molding an aluminum alloy or by large bars of precast copper hooped into the rotor's core. Generally, there is no insulation between the rotor bars and the magnetic circuit. But the resistance of the alloy used to build this cage is low enough so the currents do not flow across the magnetic sheets, except when the rotor cage shows bar breakage [MUL 94].

III.2.3. Bearings

Bearings are composed of ball bearings and flanges. The ball bearings are inserted when hot on the shaft, for rotation guiding of the motor shaft. The flanges, molded in cast iron alloys, are fixed onto the stator body using bolts or tightening rods as shown in Figure III.2. All these components arranged in this way compose the induction machine.

III.3. Failures in induction machines

Although the induction machine is said to be robust, it may sometimes present different types of faults. These faults are found in the different parts of the machine, starting with the stator phase connection and finishing with the mechanical coupling between the rotating shaft and the load. These failures can be predicted or unexpected, mechanical, electrical or magnetic, and they have very different causes.

A statistical study led by [BON 08] on squirrel-cage induction machines operated in the petrochemical industry, shows that some breakdowns occur more frequently than others (see diagram in Figure III.3 displaying the percentage of faults likely to affect these high-powered machines).

This distribution shows that faults in high-powered machines mainly stem from the bearings and the stator coil, which is due to larger mechanical constraints in the case of this machine.

¹ Inserting windings in the rotor slots.

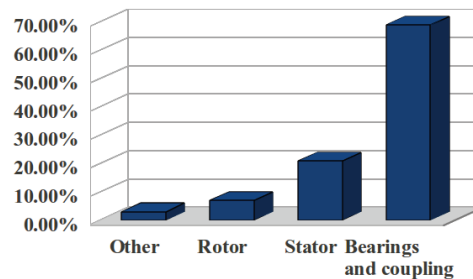


Figure III.3. *Fault percentages (2008)*

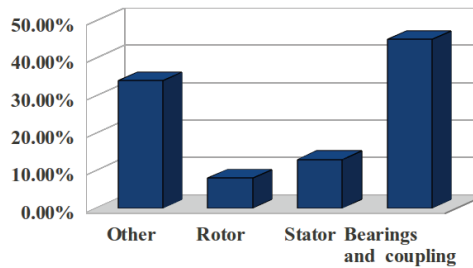


Figure III.4. *Fault percentages (1995)*

By comparing these results to those taken from older studies carried out by [THO 95] in Figure III.4 on same-type machines (100 kW to 1 MW), we notice that over the last few years, the distribution of the fault percentages has changed due to the manufacturing conditions in which the motors are constructed. Faults in the stator and rotor are less frequent now, with the main source of failure currently coming from the bearings. Technological advances in power electronics has also made it possible to introduce new control techniques for electrical machines. For machines controlled by power converters, the bearings are excited by voltages including high-rank harmonics. This last option has become standard for controlling electrical systems. This type of power supply accelerates ageing in the stator winding insulator. One solution is to develop a better material insulator. These statistics are not valid for all circumstances, and we must note here that these faults are highly sensitive to the machine's operating conditions, and that they may stem from very different reasons [THO 97]. For instance, let us now make a list of the different causes:

- mechanical: bad manufacturing, machine vibrations, unbalanced electromagnetic forces, centrifugal forces, load fluctuations;
- electrical: insulation damage, partial discharging, sparks;

- thermal: copper losses, lack of general or localized cooling;
- environmental: air humidity, dust.

Table III.1 [KAZ 03] shows a summary of the causes leading to stator and rotor faults.

	Faults	Causes
Stator fault	Frame vibration	Magnetic imbalance, coil vibration, power supply imbalance, overload, bad installation, contact with the rotor.
	Fault between coils and the stator frame	Coil pressured by the frame, thermal cycle, bad insulation, angular points in the slots, shock.
	Insulation fault	Insulation damage during installation, frequent starting, extreme temperature condition.
	Inter turn short-circuit	excessive temperature, high humidity, vibration, over-voltage.
	Inter-phase short-circuit	insulation failure, high temperature, imbalanced supply, slacking of coils.
	Conductor displacement	Shock, frequent starting, winding vibration.
	Connector failure	conductor pressure, excessive vibration.
Rotor fault	Bearing fault	bad installation, magnetic imbalance, overload, loss of lubricant, high temperature, lack of cleanliness, unbalanced load.
	Bar breaks	magnetic imbalance, overload, loss of lubricant, high temperature, lack of cleanliness, unbalanced load, thermal fatigue.
	Magnetic circuit failure	manufacturing fault, thermal fatigue, overload.
	Misalignment	bad installation, bearing failure, overload, magnetic imbalance.
	Bearing lubricated badly	excessive temperature, bad quality of lubricant.
	Mechanical imbalance	short-circuit ring movement, alignment problem.

Table III.1. *Causes of failure in the induction machine*

These faults display one or many “symptoms”, which can be:

- unbalanced line currents and voltages;
- increased torque oscillations;
- decreased average torque;
- increased losses and therefore reduced energy efficiency;
- excessive heating and therefore accelerated aging.

Thus, as a brief summary, we have categorized these faults into two main groups: mechanical faults and electrical faults. These faults are briefly shown in the flow chart in Figure III.1.

There are two reasons for studying induction machine faults:

- to understand their evolution so as to predict their gravity and development;
- to analyze their impact on the machine’s behavior and to deduce from this the signatures making it possible to go back to the cause of failure, *a posteriori*.

III.3.1. Mechanical failures

More than 40% of induction motor faults are mechanical. These can be bearing faults and eccentricity faults.

III.3.1.1. Bearing faults

The main reason for machine failures concerns faults in the ball bearing [STA 05] which have several causes, such as lubricant contamination, an excessive load, or even electrical causes such as leakage current induced by multilevel inverters (MLI) [STA 05].

Bearing faults generally lead to several different mechanical effects in machines, such as an increased noise level and vibrations. It has also been shown that bearing failure leads to variations in the torque load in induction machines.

III.3.1.2. Eccentricity faults

The effects of mechanical faults are generally displayed at the air-gap, by static, dynamic [SAH 08] (Figure III.5), or mixed eccentricity faults:

- static eccentricity faults are generally caused by a misalignment in the rotor’s rotation pin in relation to the stator pin, where the most frequent cause is a fault in the flange centering;
- dynamic eccentricity faults can be caused by a bend in the rotor cylinder and in the stator cylinder or deterioration in the ball bearings;

– mixed eccentricity, the most common kind of fault, is a combination of static and dynamic eccentricity.



Figure III.5. *Static and dynamic eccentricity faults*

A vibration, ultrasound, or frequential analysis of the absorbed currents, or simply a visual analysis of the machine's shaft makes it possible to detect these failure types. We can find very comprehensive studies in various works which deal with these various problems, such as those mentioned in [BIG 95, BON 99, BON 00].

III.3.2. Electrical failures

Electrical failures, either on the stator or on the rotor, may be of different types or have several different causes. Let us cite an example: an unbalanced power supply voltage in the machine or even frequent starting can lead to overheating in the stator coils, finally leading to a local destruction of the insulator. In the same way, the electrodynamic strains exerted on the phase conductors result in mechanical vibrations which may deteriorate the insulator. In terms of electrics, voltage fronts generated by static converters aggravate the phenomenon and consequently, the lifespan of the conductor insulators. With regard to environmental causes, we may cite air humidity, corrosive or abrasive products.

III.3.2.1. Stator faults

Stator faults are displayed as an inter-coil short-circuit between two phases, or a short-circuit between a phase and the stator frame [BAZ 09b]. This can be simplified by the clear connection between two points on the coil. Inter-phase short-circuits appear preferentially in the coil heads, as it is here that the different phase conductors flow together. Inter-coil short-circuits in the same phase may appear, either on the coil heads or in the notches, which leads to a reduction in the number of actual coils in the winding.

An inter-phase short-circuit would cause the machine to shutdown. However, a short-circuit between a phase and the neutral (via the yoke) or between the coils of the same phase does not have such an extreme effect. It will lead to a phase imbalance, which will have a direct effect on the torque. This type of fault also interferes with the controls developed by using the Park model (hypothesis for a balanced model).

III.3.2.2. Rotor faults

A wound rotor may be affected by the same faults as the stator. For a cage rotor, the faults can be summarized as bar breakages or short-circuit ring breakages (Figure III.6).

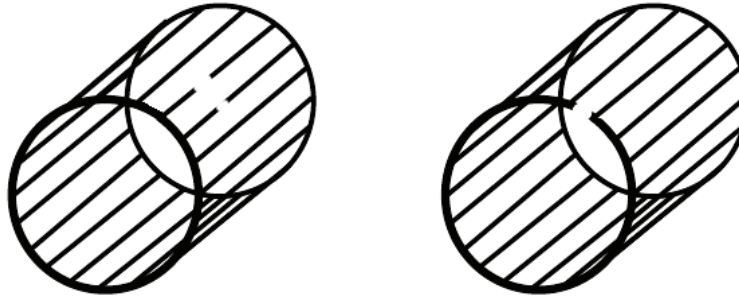


Figure III.6. Fault by bar and short-circuit ring breakage

These bar or short-circuit ring breakages can be due, for example, to a mechanical overload (frequent starting up), local excessive overheating, or even a manufacturing fault (air bubbles or bad welds) [BON 92, CAS 05]. This fault will induce oscillations in the currents and the electromagnetic torque, which are more noticeable when the inertia is high (constant speed). When the drive inertia is lower, then oscillations occur in the mechanical speed and in the stator current amplitudes.

The ring section break is a fault which occurs as frequently as bar breaks. In fact, these breaks are either due to bubbles in the casting or due to different dilations between the bars and the rings, especially as the short-circuit rings conduct larger currents than the rotor bars. Due to this phenomenon, a bad ring sizing, deterioration in the operating conditions or a torque overload, and therefore a current overload, may lead to their breaking.

A bar break fault will not cause the machine to shut down because the current which runs through the broken bar is distributed over the adjacent bars. Thus, these bars are then overloaded, which can break them and a large number of broken bars causes a shutdown.

Faced with the multitude of possible faults and their consequences, monitoring techniques have rapidly been imposed on electrical machine users. They are also beginning to interest the designers.

III.4. Overview of methods for diagnosing induction machines

Electrical machines, and induction machines in particular, play a vital role today in all industrial applications. Guaranteeing availability and operating safety of these

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machines is a fundamental task. It is, then, necessary to develop systems which enable monitoring and diagnosis of the health condition of these devices.

Monitoring and supervision must not be limited to the electrical machine alone. In fact, this machine is still part of an entire industrial process. Ensuring the operating safety is part of the supervision process of the whole industrial process itself. The diagram showing the supervision and accommodation of the control in Figure III.7 shows the different stages and functionalities that a supervised system must contain.

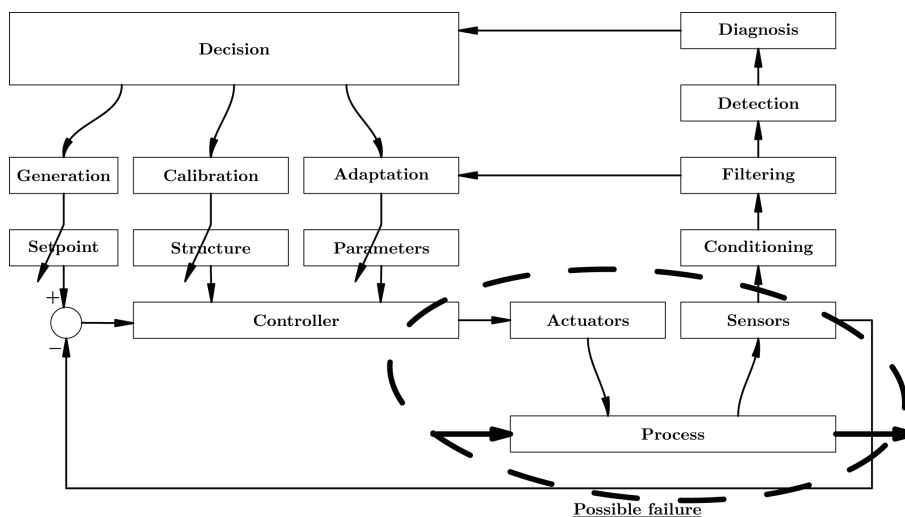


Figure III.7. Control supervision and accommodation

This diagram is applicable to the induction machine and its control, or to the integrating process. The final objective for any supervision is to increase the reliability of the process, by looking to catch failures which may occur when the system is in operation. Once the levels of supervision and diagnosis have fulfilled their role by detecting and identifying the failure, then the second stage is to act on the controls to catch this operational decline. This intervention stage takes place on several different levels (Figure III.7) according to the severity and the destructive nature of the failure.

For some highly important systems where even the smallest breakdown may be impossible (nuclear plants, aerospace industry, air transport, etc.), the designers multiply the systems so that, for a failure in one system, another system will immediately replace it. If one of the systems displays behavior which is very different from the others, then it is excluded from the set of systems. This type of maintenance (material redundancy) is clearly too expensive to implement for the most common types of industrial systems.

The aim of this section is to present an overview of diagnosis methods applied to electrical machines. These methods are classified into two large categories: those which use an analytical model of the system, and those which do not use it. The analytical approach is rather inspired by control engineers, whereas those from the electrical engineering and signal processing domains prefer to make use of more heuristic methods.

III.4.1. Diagnosis methods using an analytical model

These detection methods rely on a prior knowledge of the system. They assume knowledge of the models and parameters representing the system's operations. Signals generated by the models (or estimated parameters) enable detection as well as the identification of the failure which is likely to occur. These techniques assume a prior knowledge of the range of variations within these models and parameters, according to the system's operating conditions. These techniques can be categorized into three groups.

III.4.1.1. State estimation techniques

Analytical models involve a finite number of internal variables, called state variables. These variables are generally immeasurable for reasons concerning accessibility: they might lack physical meaning or the cost of installing sensors is too high. As the system's evolution through time is characterized by the evolution of these variables, then we often use estimation techniques (software sensor) to follow the evolution of their values. Figure III.8 shows the diagram of the principle of state estimation using measured signals (system's input and output signals).

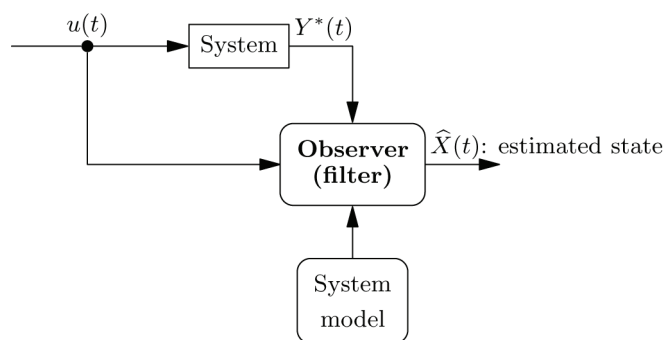


Figure III.8. Principle of state estimation

Fundamental studies done by [KAL 60] and [LUE 71] offer two different approaches to reconstruct the system's state through knowing its mathematical model. The techniques which stem from these two concepts are the Kalman filter and

the Luenberger observer. Techniques based on a linear representation around the system's operating point have made it possible to adapt these techniques to non-linear models. We can cite the extended Kalman filter and the extended Luenberger observer [SAÏ 00, CHE 06, BES 07]. We can also cite other techniques which may be applied to systems which cannot be linearized by coordinate changes, such as high-gain observers [RAJ 98, GAU 92], adaptive-gain observers [RAG 94], or a combination of high-gain observers and the Kalman filter [GAU 92]. . . The extended Kalman filter, estimating state variables and parameters, refers us back to identification techniques. As an example, in the domain of monitoring and diagnosing the induction machine, we may use rotor currents² or flux, based on the Park model of the induction machine, which may inform us about the presence of certain types of faults, as these estimations are used by control algorithms.

III.4.1.2. *Residual generation technique*

Residuals are signals which reflect the deviation between a model and the system to be monitored , as shown in Figure III.9. These residuals depend on the technique they are generated from . These techniques for extracting residuals aim to provide important and exploitable signals to detect a specific failure. When the residuals are in healthy operating mode , they must be close to zero and reflect a fault by taking important values.

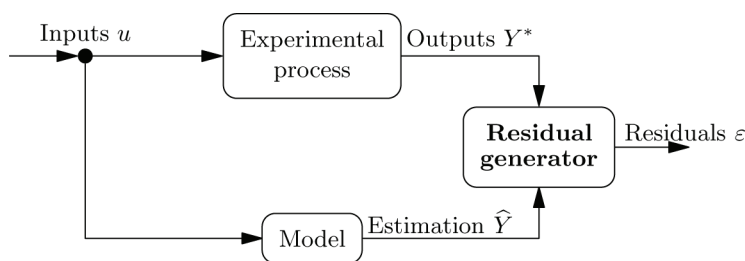


Figure III.9. *Residual generation*

Another generation technique is based on analytical redundancy relationships (ARR) [CHR 99] in order to provide the machine's variations in stator and rotor resistance with robust residuals, which has made it possible to provide a reliable malfunction detector on the stator or rotor.

However, several studies have shown that these residual generation techniques are more suited to detect actuator, and above all sensor, faults [CHR 99]. In practice, internal faults are detected better by identification techniques.

² For a squirrel-cage rotor.

III.4.1.3. Identification techniques

Identification techniques aim to determine a dynamic model of the system to be monitored using experimental input and output measures. The fundamental idea is that the parameters which characterize this identified model will be sensitive to the faults affecting the machine, and will therefore make it possible to characterize these faults through their variations; in [ISE 93], we find a formalization of this principle.

Estimating the model's parameters is ensured by an algorithm to minimize the error between the model's output and the machine's output. Figure III.10 presents this process, which is also known as the model method [RIC 71].

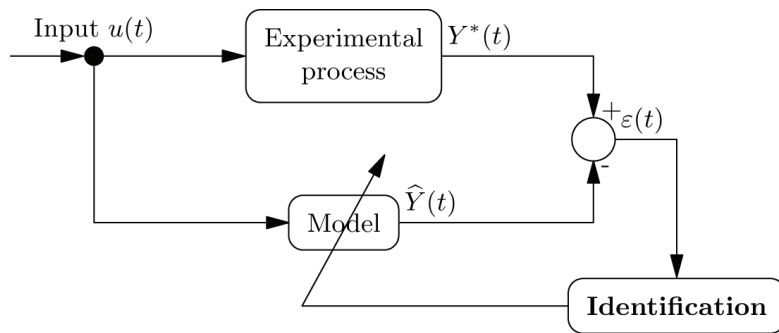


Figure III.10. Principle of identification techniques

Many identification techniques based on the minimization of quadratic criteria may be used. We will categorize them according to:

- equation error techniques [LJU 87];
- output error techniques [RIC 71, TRI 96, TRI 01];
- the extended Kalman filter [LJU 87, LOR 98].

Equation error techniques are the simplest to implement. Moreover, they adapt perfectly to real time, therefore to the monitoring of parametric variations. Their main fault is providing biased estimations by noises affecting the system. Furthermore, it is important to adapt them to cases of continuous representation systems [YOU 81, MEN 99].

Output error techniques are more laborious to implement and are limited to offline operations. On the other hand, they give unbiased information which is well adapted to diagnostics via parametric monitoring, potentially with prior knowledge [MOR 99].

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The extended Kalman filter [LOR 98] combines state observation and parametric estimation. Its estimations are also unbiased. Moreover, this estimator is perfectly well adapted to real-time operations. However, optimum operation requires a good level of prior knowledge regarding noises affecting the system.

The electrical parameters which characterize the induction machine can be very good fault indicators. One of the most commonly studied failures in the squirrel-cage induction machine is the rotor bar break. Although this can be identified using a spectral analysis of stator currents, monitoring the rotor resistance can also be a good failure indicator.

In fact, several studies have proven that the resistance R_r is highly sensitive to rotor faults, and that the variation in this resistance is increased when the number of broken bars is also increased. Many techniques make it possible to estimate the value of this resistance, for example, here we can cite the output error estimation [MOR 99, BAC 02], the extended Kalman filter estimation [SAÏ 00, BAZ 09a], or the non-linear high-gain observer estimation [BOU 01].

However, due to the fact that the value of this resistance is also linked to the variation in the rotor temperature, a natural cause (for instance, operation at full load) could be enough to make the resistance change. A single estimation of R_r does not allow us to detect the presence of one or many faulty bars. This ambiguity can be alleviated by taking account of the machine's internal temperature using identification algorithms and having prior knowledge [BAC 02].

These methods of diagnosis through identification are generally used for monitoring and detecting failures, most often by using precise models of [SCH 99, BAC 02]:

- broken bars or short-circuit rings;
- static and dynamic eccentricity;
- reduced coils or inter-coil short-circuit in the same stator phase.

The main limitation of identification-based techniques is the need for persistent excitation, i.e. an input $u(t)$ (Figure III.10) which stimulates the system enough so as to generate signals which can be used by the identification algorithm. This persistent excitation [LJU 87] is clearly incompatible with controlled operation (at constant speed, for instance).

The first group of diagnostic models requires knowledge of the machine's dynamic behavior, using a knowledge model. However, these methods do not allow us to study all the faults in the machine (bearing faults, for example). In the following section, we will focus on diagnostic methods without a model, based on monitoring and analyzing magnitudes such as currents, vibrations, flux, and torques.

III.4.2. Diagnostic methods with no analytical model

These methods do not necessarily require a specific model of the system, but rather rely on knowledge of signatures. Fault signatures, obtained through modeling or measurements, are generally categorized in a database. The analysis is carried out by a signal-type interpretation or by an expert system.

The following faults are studied by these diagnostic methods:

- breakages in the bars or slice of the rotor ring;
- static and dynamic eccentricity;
- bearing failures;
- inter-coil short-circuit.

III.4.2.1. Signal processing method

For reasons of simplicity and efficiency, the signal approach is currently being widely used in diagnostics. This approach is based on knowledge of the healthy system's behavior, and it is then compared to the measured signals. The common methods of analyzing diagnostic signals in a transitory and permanent regime are spectral analysis, spectrogram, temporal analysis, and the Wigner-Ville distribution [AND 94].

Approaches based on spectral signature analysis are the most commonly found methods used for detecting an anomaly. The main fault in spectral analysis is that it is highly sensitive to the measurement quality, as well as the sampling frequency and the number of samples. The procedures for monitoring operations are generally directed toward specific failures in one of the three parts of the machine: the stator, the rotor, or the bearings.

To accurately draw out information relating to faults, research has been carried out, in particular, toward the spectrum of stator currents, for two reasons. Currents are easy to measure and they provide a lot of information on a lot of different faults. But measuring signals and then processing them in the "FFT" spectral domain can only be used, in terms of identification, if the frequential components defined for each fault are known [BEN 00, KAZ 03, SAH 08]. Besides this limitation, this method requires a sufficient number of acquisition points to guarantee a minimum frequential accuracy. This technique is generally used during the machine's permanent regime [DID 04].

The spectrogram technique means that we can carry out frequential analysis of signals in the dynamic regime of the system's operation. This technique consists of carrying out a repetitive calculation of the FFT on a temporal drop window, which makes this technique sensitive to the window length, to the window type, to the total duration of the supervision process and the step of the sliding window [FLA 93]. Although this technique means that we can analyze signals in the dynamic regime, the

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speed of the dynamic regime for induction machines at 150 m/s significantly reduces the accuracy of this technique.

We must also refer to the temporal analysis, which consists of comparing temporal signals coming from the system's healthy operation to the temporal signals of the current operation [CAS 03, KRA 04, OND 06]. The phase shift introduced by the measurement instruments makes the direct comparison of these instruments insignificant. Thus, it is common practice to transform the signals before comparing them. Despite this transformation, this method does not allow us to efficiently identify the failures which could affect electrical machines.

Time-frequency methods, based on the Wigner-Ville analysis, combine the temporal analysis and the frequential analysis. [AND 94] proved that this technique will allow us to extract information from a system's dynamic regime, and that this regime is more comprehensive than the stationary process in question.

III.4.2.2. *Artificial intelligence (AI) method*

Artificial intelligence is being used widely in the supervision and diagnostics domain. It has increased the efficiency and reliability of diagnostics. In the domain of supervising electrical machines, industrialists and researchers are using this type of technique more often in order to increase the system's efficiency [ALT 99, AWA 03].

In fact, the term "artificial intelligence" involves various different techniques, such as expert systems, neural networks, and fuzzy logic, which can all be used independently or in a combination, to improve their efficiency. These methods are interesting, even if they require an initial training phase which is vital for optimal operation. The training phase requires an important set of examples, as it may be erroneous or produce results which are limited to a set of systems.

Once the training phase has been completed, these techniques are displayed as being efficient and simple, and can be successfully adopted for diagnosing failure in electrical systems. Artificial intelligence techniques may contribute to accelerating the decision-making process with a reduced amount of human intervention. But they are not a cure for solving all diagnostic problems.

Artificial intelligence-based techniques try to imitate human reasoning in different ways, which we will describe below:

Artificial neural networks imitate the neural structure of the human brain; they are formed by a complex network of simple arithmetic blocks. They can easily represent the non-linear, multi-input, multi-output systems.

This technique was widely used in the domain of diagnosing electrical machines [SAL 00, AWA 03] according to several different approaches and techniques:

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- training using temporal or frequency signals drawn from simulations or experiments;
- real-time self-diagnosis;
- dynamic updating of the network structure;
- filtering transients, disturbances, and noise;
- detecting faults as soon as they occur.

Fuzzy logic translates the human perception of values. It is not limited to values such as “true or false” like traditional logic. It offers a wide variety of intermediate values. Fuzzy systems can process natural variables through fuzzy “if-then” conditions. Adaptive fuzzy systems use the training faculties of neural networks, or the robustness of genetic algorithms in the domain of optimizing the parameters of the studied system, in order to consider prior knowledge and human expertise in this domain.

In the following studies [ALT 99, BAL 07, ZID 08], we can find several articles which exploit this technique in diagnosing and monitoring electrical machines. They have varied objectives:

- detection of abnormal functioning and locating failure;
- evaluation of performance indexes;
- constructing a database taken from human expertise, and formulating a set of conditional “if-then” rules;
- design of adaptive systems for diagnostics.

The *neuro-fuzzy technique* is the combination of the two previous techniques. [ALT 99] and [BAL 07] have shown that this combination is very interesting for diagnosing and monitoring induction machines. In fact, the adaptive neuron networks may generate the corresponding fuzzy system alone. This generation of rules is performed using training examples, by minimizing expert intervention during the formulation of conditional rules.

Applying AI is of great use in automating the diagnosis procedure. It makes it possible to take advantage of human expertise in the domain at hand.

III.5. Conclusion

Electrical machine diagnosis has been, and still is, an important topic for research over the last few decades, such that it has been presented in the non-exhaustive bibliography which can be found at the end of this chapter. The advent of monitoring has revolutionized system maintenance based on electrical machines. In fact, this term refers to a monitored system, making it possible to diagnose the state of an AC motor

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in order to determine the failure types and their seriousness when the motor is within its normal operating conditions.

We started this chapter by reminding readers of the composition of the induction machine. We then categorized the failures likely to affect the different components of electrical machines. Next, we drew up a non-exhaustive list of the causes which could lead to mechanical and electrical failure in these machines.

We have tried to present an outline of the methods and techniques for monitoring and diagnosing electrical machines. Two large categories of methods were reviewed: those based on an analytical model of the machine (with particular focus on the identification approach), and the methods with no model, based on the Fourier analysis and a heuristic approach.

***Chapter 4:
Overview of Computer-Aided
Maintenance (CAM)***



IV.1 Introduction

It has been said that:

- To manage, you must have controls.
- To have controls, you must have measurement.
- To have measurement, you must have information.
- To have information, you must collect data.

Data...information...facts. Whatever term you use, you need knowledge to make good decisions.

IV.2 Computerized Maintenance Management Systems (CMMS) and Enterprise Asset Management (EAM) Systems

In the maintenance / reliability community, the terms CMMS and EAM are used interchangeably. For a point of reference, a CMMS tends to be a departmental system and an EAM system tends to be more of a corporate system. For the purpose of this text, we will use the CMMS acronym, except where the material is specific to an EAM system.

Chapter 4: Overview of Computer-Aided Maintenance (CAM)

The goal of a computerized maintenance management system (CMMS) is to produce quality data to help maintenance/reliability professionals make good decisions.

IV.2.1 CMMS MODULES

Even as a company implements a CMMS, data collection begins. Consider the various modules that make up a comprehensive CMMS:

- Equipment
- Inventory
- Purchasing
- Personnel
- Preventive maintenance
- Predictive maintenance
- Work orders
- Contractors
- Rebuilds

The data for reporting in a CMMS is derived from accurate data input into all of the CMMS modules.

Figure IV.1 shows the basic relationship of these modules to one another. The relationship of some of the modules will be discussed in the following section.

Equipment. To use this module properly, you must identify each piece of equipment—or facility location—that you want to track for costs and repairs. For example, you need the financial information stored in the equipment history when making repair/replacement and other cost decisions. Data provided by the other modules can determine the accuracy of the financial information.

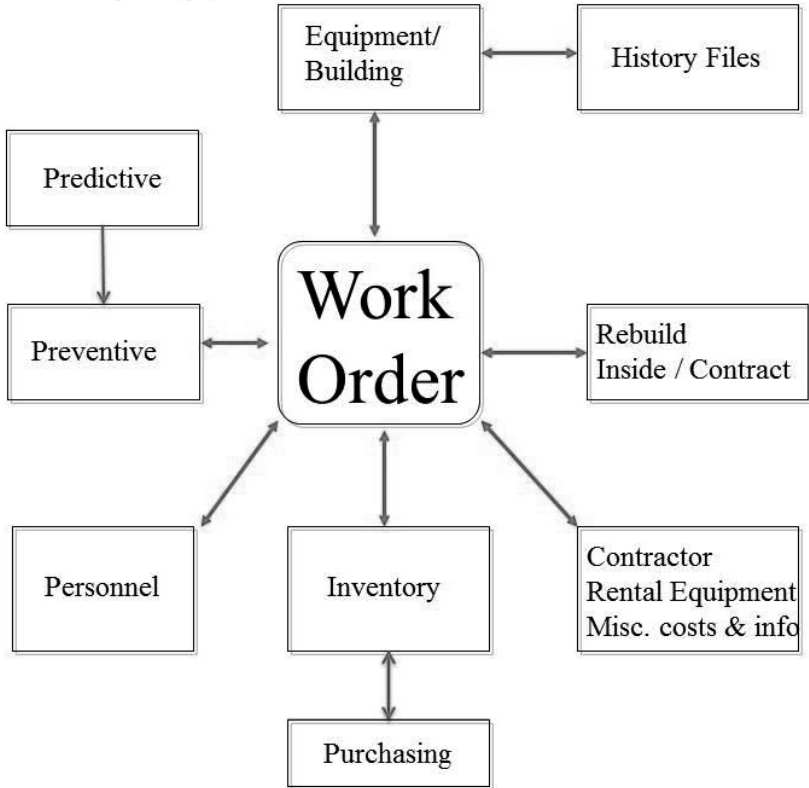


Figure IV.1, CMMS Basic Modules

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Inventory. To use this module, you must identify the spare parts carried in each store at your facility. The data you need includes, but is not limited to:

- Part number
- Part description (short and extended)
- On-hand, reserved, on-order, max-min, etc.
- Locations
- Part-costing information
- Historical use

Information from the inventory module ensures that your CMMS will contain accurate material-costing information for each piece of equipment or facility location.

Purchasing. This module is associated with the inventory module. It provides planners with a window into the ordering information. This module includes the following information:

- Part number
- Part description
- Part-costing information
- Delivery information, including the date
- Related vendor information
- The ability to order non-stock materials

The importance of this module becomes clear when you begin to plan a job and do not know when you will receive the part. Furthermore, this module is important for estimating job costs without knowing new part costs.

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Personnel. This component allows a company to track specific information about each employee. The required data includes:

- Employee number
- Employee name and personal information
- Pay rate
- Job skills
- Training history
- Safety history

The data from the personnel module insures that the facility will post accurate labor costs to work orders and equipment history.

Preventive Maintenance (PM). This module allows you to track all PM-specific costs. The costing information comes from the personnel and inventory databases. Important information stored in this module includes:

- Type of PM (lubrication, calibration, testing, etc.)
- Frequency required
- Estimated labor costs (from the personnel module)
- Estimated parts costs (from the inventory module)
- Detailed task description.

The collection of this data insures accurate service information and costing each time a worker performs a PM task. A CMMS can also project labor at material resource requirements for calendar-based PM tasks.

Work Orders. With this installment, a user can initiate different types of work orders, or track the work through completion. This mod-

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ule also allows you to allot costing and repair information to the correct piece of equipment or facility location . The use of the work order requires information from all other modules of the CMMS . Information required on a work order includes:

- Identifying the equipment or facility location where the work is being performed
- Identifying the labor requirements (personnel)
- Identifying the parts requirements (inventory)
- The priority of the work
- The date the work must be finished
- Contractor information
- Detailed instructions

In order to be effective , the work order requires information from all the modules. Without accurate information, the work order cannot collect the required data. Therefore, the work order cannot post accurate information to the equipment history . In turn, without accurate data in the equipment history , the maintenance manager cannot make timely and cost effective decisions . All other reports, which are derived from the data stored in the various CMMS modules, also require accurate information.

The success of a CMMS depends on the timeliness and accuracy of collected data and the use of that data by the company. If information is inaccurate or used incorrectly, the system fails.

IV.3 Time Frame for Reports

Once a company purchases a CMMS, how long does it take before accurate and informative reports can be produced? The answer

depends on how long the company needs to develop accurate data. In a survey conducted by Engineer's Digest, 52% of the respondents indicated that 1 to 11 months were needed to make their system fully operational. (Detailed results of this survey were published in a special insert in the April 1992 issue of Engineer's Digest.) ReliabilityWeb (www.reliabilityweb.com) has conducted a more recent survey (in 2008) with almost the exact results. More specifically, the survey showed that 40% of respondents took more than one year to make their system fully operational (see Figure IV.2).

How Long Before Full Operation?

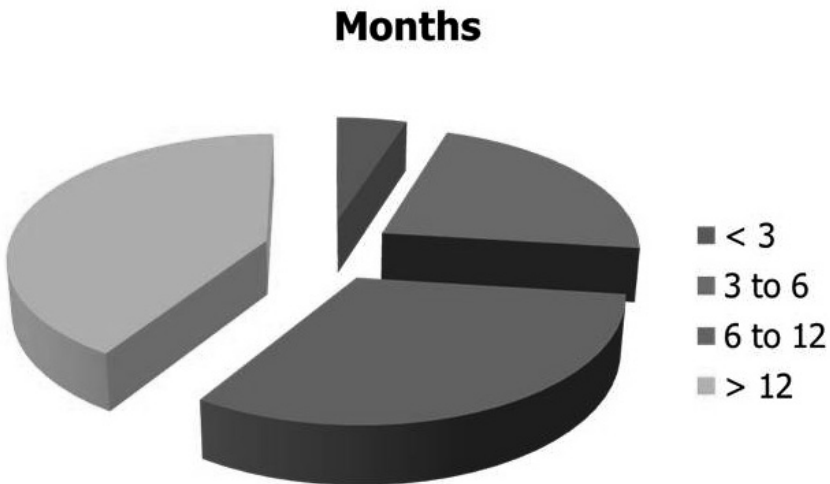


Figure IV.2, How Long Before Full Operation ?

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Even before a facility implements a CMMS, the information collected will still have some value. But until the system is fully utilized, the data will not be accurate. For example, if only certain departments are on a CMMS (a typical pilot implementation problem), then the data from these departments may be accurate. However, in areas where a crossover or combination with another area or craft exists, the data may be incomplete or distorted.

A CMMS should provide a completely integrated data collection system. However, even many mature users are not getting complete—and thus accurate—data from their CMMS. In the Engineer's Digest survey, 921 respondents were asked about the use of the inventory, purchasing, and personnel modules of their systems. The majority of the respondents indicated they were using less than 70 percent of their systems. The ReliabilityWeb survey showed a similar trend with only 1/3 of the survey respondents effectively using their CMMS for inventory and purchasing functions.

When companies use corporate systems, such as the EAM system, the data may not be posted accurately in the equipment history. In fact, in most cases, the data are inaccurate or not posted. Thus, the equipment history is incomplete or inaccurate. Consider this example. When you take your car in for repairs, the service manager estimates the time and cost of the job (work-order planning). You accept the estimate, and the service shop begins the work. When the job is complete, you receive a shop order with a complete breakdown of each part used and its related cost. The bill (work order) also shows the number of hours the mechanic worked and the hourly rate. The total equals labor and parts. You expect this bill each time you go to the garage for any work. If your bill showed only the final price with no breakdown, you would not accept it. Apply that concept to your EAM System. Are your EAM system reports giving you accurate cost breakdowns for your equipment?

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Here's another example. When using a CMMS, if you do not supply planners with closely integrated inventory information, then they cannot be sure the stores' information is accurate. This is especially true if the information is updated only once a day or once a week. This situation arises many times when other corporate systems are interfaced to a CMMS. Workers can waste time looking for a part that is supposed to be in the stores, when, in fact, another worker used that part the previous day or shift. This delay may seem inconsequential. However, when downtime can cost \$1,000 or even \$100,000/hour, these types of delays may mean the difference between profit and loss for the entire company.

When it comes time to consider replacing your car, do you look only at the labor charges you have made against it for its life? Do you look only at the parts used? No, you consider the whole picture — labor, materials, its present condition, etc. These same principles must carry over in the asset-management programs at companies. However, companies have set the CMMS information flow so the material or labor costs are not shown on the work order or equipment history. Therefore, decisions are based on inaccurate or incomplete data, and such decisions will include mistakes. The financial implications of these decisions can spell disaster for a company. They can force that company into a condition where it cannot compete against other companies that make full use of a CMMS and, thus, obtain the subsequent cost benefits.

IV.4 THE SOLUTION

If a company is collecting data incorrectly, it needs to re-evaluate the system, determining also if the data is incomplete or missing. In addition, it needs to determine what parts of the CMMS are being used incorrectly or not at all.

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By evaluating the answers and then working to provide accurate data collection, a company's CMMS use will benefit its bottom line. In today's competitive marketplace, it is unacceptable to make guesses when data is available. The cost benefits obtained making correct decisions will help make a company more competitive. Wrong decisions can put a company out of business by taking away a competitive position.

What CMMS reports should a company use? Some systems are available with no reports, while others have hundreds of "canned" reports. The deciding factor is to use reports that are needed to manage the maintenance function. If the report does not support or verify an indicator used to manage maintenance, it is not beneficial. Reports produce hundreds of pages of data that can overload the maintenance manager. If maintenance is measured by the estimated vs. actual budget, but the CMMS cannot produce a budget report, then the system is not supporting the organization. With CMMS reports, too many can be just as bad as too few.

Because management requires measurement and measurement requires data, each company must use its CMMS fully to obtain data. Without data, it is just someone's opinion. Discussions require factual data. Arguments occur when emotions and opinions enter the discussion, not factual data. Whether employees at a company have discussions or arguments may mean the difference between being a world-class competitor or a second-rate company.

Preceding chapters have shown where data is collected in a maintenance organization. The work order is the key document for collecting maintenance information. But having the information is not important. It must be in a usable form. The work order information should be used to produce reports, providing management with the information necessary to control and manage the maintenance func-

tion. The information should be concise and specific. Broad lists of information can be too time consuming for a manager to study. Analysis and exception reports using the information are vital to the management of maintenance. Beyond just maintenance's needs, there are the needs of the entire company. Inventory, purchasing, engineering, and plant management all need from maintenance.

Reports are time consuming to compile manually. In organizations with any appreciably-sized staff, a computer will be necessary to compile them. The reports may be output from a simple database or spreadsheet, sorted and compiled. Companies using a CMMS have an advantage because many of these reports are included in the system. If they are not, a report writer can be used to construct these reports. Computerized reports have another advantage, especially with the relational databases; they can produce meaningful graphic representations of the information. These graphs can be more helpful in describing trends and patterns than columns of figures. They can also be included in reports to upper management. As many reports as possible should be graphed.

IV.5 Maintenance Reporting

The following maintenance reports are organized into five groups. The first three groups are reports that need to be reviewed by the maintenance staff daily, weekly, or monthly. The fourth group is made up of general information reports and the fifth group by reports that should be produced on an "as needed" basis.

DAILY REPORTS

This group of reports should be produced daily for review by the appropriate maintenance personnel and managers.

IV.5.1 WORK SUMMARY REPORT

This report lists work orders currently in progress as well as work orders that have been closed out in the last day. It provides a quick look at the prior day's activity. The report should show estimated vs. actual totals for the following categories:

- Maintenance labor
- Maintenance materials
- Equipment downtime

The report should be divided into two sections: work orders completed and work orders still in process. Each section should be sorted by priority of the work: emergency, planned and scheduled, preventive maintenance, and routine. This summary of work performed allows managers to quickly answer any questions that operations may ask during a daily review meeting.

IV.5.2 SCHEDULE PROGRESS REPORT

This report lists only the work scheduled for the week with the present status of each work order. Like the work summary report, it should show actual vs. estimate figures. The difference is that only work orders appearing on the schedule will be listed in this report. This report should conclude with a summary showing the number of work orders scheduled to be closed out during the week versus those that have been closed out. A percentage could even be included as percent of scheduled work completed. This report allows the manager to monitor the progress of the schedule completion and make any adjustments necessary during the week to insure schedule completion.

IV.5.3 EMERGENCY REPORT

The emergency report lists all emergency or reactive work requests in the last day. It should be a two-part report. The first should be a line summary showing labor hours and materials dollars used. The second part should show which craft technicians worked on the job, what parts were used, and any other detail or completion notes. This report gives managers a quick look at the breakdowns and emergency work for the last day. If a particular job needs clarification, they can reference the second part of the report to get the required details.

IV.5.4 REORDER REPORT

This report lists all inventory items that have reached their reorder point during the last day. Depending on the maintenance and purchasing relationship, this list is used to generate purchase requisitions or purchase orders. If maintenance is not involved in the ordering, the report may be only an information report for maintenance. If the organization is multi-warehouse, this report should be divided by warehouse, allowing the option of transferring between warehouses instead of placing new orders. The report should show on-hand, reserved, and minimum quantities for each item listed.

IV.5.5 METER-BASED/PREDICTIVE WORK ORDER REPORT

This report lists all meter-based, predictive, and condition based preventive maintenance work orders generated during the prior day. Depending on the sophistication of the PM system in use, these may be manually generated or automatically generated through real-time interfaces to computer systems. In either case, these work orders need quick attention, usually within a week. Some may even require breaking in to the present schedule to avoid a serious failure. This report

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should list the equipment, type of PM, type of work to be performed , and labor and material requirements.

IV.5.6 PERSONNEL SUMMARY REPORT

The personnel summary report lists all employees who worked during the previous day, the hours they worked on each work order, and any overtime that was worked during the period . The report gives supervisors a quick review of the previous day's activity . The purpose is to insure that each employee worked and was credited for the proper number of hours worked the prior day.

IV.5.7 WORK ORDER LISTING

This report lists work orders currently in the backlog. It should be available in several different ways , for example by requesting depart - ment , by equipment ID, by craft , by supervisor , and by planner Each report should be sorted in descending order from work orders in process to work orders just requested , allowing for complete informa- tion on all work when required.

IV.5.7 WEEKLY REPORTS

In addition to the daily reports , each week additional reports are required to properly manage maintenance. This section provide ex- amples of these reports.

IV.5.8 SCHEDULE COMPLIANCE REPORT

This report compares results from the previous week's activity to the schedule for the same (current) week. It should begin with all work completed , all work not completed , and finally all work not started. This format allows for detailed analysis of the week's activity . The re-

port should also compare time allotted for emergency activities versus the time actually used for emergency activities . This comparison indicate why more or less work was completed than scheduled. The report also compares work scheduled to be worked on versus total work completed. This summary figure can be used as the efficiency percentage. Tracking this percentage over a 6- to 12-month time period provides a complete picture of scheduling efficiency.

IV.5.9 PM COMPLIANCE REPORT

This report lists the PMs scheduled to be completed for the previous week and their present status. It may be broken down by:

- PMs completed as scheduled
- PMs started as scheduled, but not completed
- PMs scheduled, but not started

The report gives a quick overview of the status of the preventive maintenance program for the previous week. A detailed section of the report may also show who performed the work, what parts were used, completion comments, any related work orders that were written because of the PM, etc.

IV.5.10 PM DUE/OVERDUE REPORT

This report lists all overdue PMs. It should sort the PMs from oldest to newest. If possible, the report should start with a specified time period, for example, PMs that are over eight weeks overdue, and then sort the remaining PMs down to the ones that just became overdue last week. This structure allows for a quick look first at numbers that are critically overdue, and eventually at ones just overdue. The report

is most beneficial when a summary line of the numbers and percent - age of work contained in each overdue category is listed. The report can be a good indicator of the condition of the PM program.

IV.5.11 SCHEDULE PROJECTION REPORTS

These reports are a related series that should be produced upon setting the next week's schedule. With the work orders identified for the schedule, the information for these reports should be pulled from the work order estimates.

Required Manpower. This report should show the required craft hours for the work scheduled. The report should first list, by craft, a summary of total hours required. The second part of the report should be the detailed description of the work. The report gives supervisors a quick or detailed overview of their craft groups for the next week. If the schedule is produced by crew or department, then the report should be listed the same way.

Required Downtime. This report lists all equipment downtime required for the work scheduled for next week. It should be divided by equipment, department, and line or plant, depending on the layout of the plant or facility. The report is extremely important, especially for JIT, MRP, MRPII, and CIM installations. Inputting this information into the production control system begins the process of integrating maintenance management.

Required Parts. This report lists all parts required for the work that is scheduled for next week. It should be given to the stores/ inven- tory personnel to insure that parts are ready. If the company practices staging, this report is good to use to pick the materials and send to the staging area.

Required Contractors. This report lists all contractors required for the next week's schedule. It should match the contractors with the

work orders they are required to complete. This format reduces the report's size when individual contracts have multiple work orders.

Required Equipment. This report lists all rental, lease, or specialized in-house equipment required to complete the work on next week's schedule. It allows planners or coordinators to insure that the equipment is either ready for delivery or delivered before the work is started.

Required Tools. Companies that have tool rooms for storing general maintenance tools generate this report, which lists the required tools for the week and the work orders for which they will be needed. This information enables the tools room to insure that all the tools required will be in good repair and ready for use.

IV.5.12 WORK ORDER STATUS REPORT

This report lists all work orders in the backlog. It should be available in the several formats listed below along with a brief explanation of each:

By Department. This report is distributed to the departmental supervisors so they can see the status of all work requested for their department. Thus, they can see the status of their "pet" projects without continually calling maintenance.

By Equipment. This report allows quick access to all work presently requested for all equipment. As a quick reference report for anyone requesting work, it helps prevent duplicate work orders in the system by allowing recipients to review if a similar job is requested for the equipment.

By Planner/Supervisor. This report indicates the workload for both planners and supervisors. Balance can be achieved in the organization by offloading work from one planner or supervisor to others during peak work times.

IV.5.13 PAST DUE WORK ORDER REPORT

This report lists all work orders in the current backlog sorted by the date needed, ideally from the most overdue to the least overdue. Work orders without this information should not be included. All status work orders, except those completed, should be included. If, for example, a work order is being held up due to materials unavailable, planners may be able to find some way of expediting or substituting the materials to complete the work order. The report can also provide good feedback information to engineering, stores, and operations.

IV.5.13 BACKLOG BY CRAFT/CREW/DEPARTMENT

This report tracks the amount of work for each craft or crew group. In some organizations, the work may even be backlogged by department. It should be a summary type report, showing the total hours for each craft group and then the number of weeks' work. It could also be a trending report, showing the weekly backlog for each craft group for the last year. In this way, it can highlight trends and seasonal peaks, helping management make good, justifiable staffing decisions.

IV.5.14 MONTHLY REPORTS

In addition to daily and weekly information, other information becomes more meaningful looked at on a monthly basis. Some of these reports are described in this section.

1- COMPLETED WORK ORDERS REPORT

This report is a two-part report of all work orders completed during the month. The summary portion shows total work orders closed, actuals versus estimates for man-hours, labor costs, material costs,

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contractor costs. This information should be available in several ways: sorted by requesting department, by equipment type, by equipment ID. The summary will help in spotting trouble areas. The detail portion is a work order by work order listing, sorted in the same way as the summary portion. This information helps managers investigate any discrepancies in detail.

2- PLANNING EFFECTIVENESS REPORT

This report highlights the effectiveness of the planners. It shows all the work orders for each planner, comparing actual costs with planned costs. In some computerized systems, it may also specify a tolerance percentage, reducing the amount of information that managers would have to review. A summary by planner is beneficial, concluding with a listing of the most effective to least effective planner. Any major discrepancies should be reviewed at a detailed level.

3- SUPERVISORY EFFECTIVENESS REPORT

This report is identical to the planner's report except it focuses on the effectiveness of the supervisors. It should show all the work orders for each supervisor, comparing actual costs with planned costs. In some CMMS, it may be helpful to specify a tolerance percentage, reducing the amount of information that managers would have to review. A summary by supervisor is beneficial, concluding with a listing of the most effective to least effective supervisor. Any major discrepancies should be reviewed at a detailed level.

4- DOWNTIME REPORT

This report compares actual downtime with estimated downtime for all closed work orders for the month. The report is important be-

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cause it includes not only the planned and scheduled work, but also the emergency and breakdown work. Rather than measuring planning and supervising effectiveness, it measures the effectiveness of the entire organization. PM programs, planning, supervising, stores, purchasing, and organizational coordination all play a part in controlling downtime. A specified tolerance could help keep the report shorter. Any major discrepancies should be investigated, with appropriate correctional measures taken.

5- BUDGET VARIANCE REPORT

This report compares the actual figures for all maintenance expenses to the budgeted figures for each category. Depending on the plant or facility budgeting procedures, they may be broken into categories such as labor, material, contractor, and tools. The report provides an opportunity for managers to correct potential problems before it is too late.

6- CRAFT USAGE SUMMARY REPORT (BY DEPARTMENT AND TYPE OF WORK)

This is one of the most meaningful reports that can be produced for analyzing a maintenance organization. It first summarizes the work that was performed in each department (line, building, cost center, etc.) by craft. The summary should include the total resource expenditures. The second part should list percentages of the total resources expended for the entire plant or facility and what percentage was used by each department. The final part should show what percentage of the work done in each department was emergency work, planned work, PM work, or other, as tracked by maintenance managers.

IV.5.15 GENERAL INFORMATION REPORTS

Some reports list general information and are kept for reference. Although by themselves they do not provide analysis capability, they form the catalog for each category of information.

1- EQUIPMENT LISTING

This report lists all equipment that maintenance is responsible to maintain. It has two formats — summary and detailed. The summary is a one-line-per-item list of equipment, including categories such as ID, name, type, and location. The detailed format lists one item per page (or more pages, depending on the level of detail kept). Each page should include all of the information kept on the equipment. This report can be anything from a file folder to a computerized database.

2- CROSS REFERENCE LISTING

This report lists all parts stocked in inventory as spares. It may be a listing by equipment of all spares used for an equipment item or by part number, the latter which then lists all the equipment on which the part is used. Both formats have value. The equipment listing helps planners know what parts are carried as spares whereas the parts/equipment listing helps inventory find items that may otherwise be of questionable value to carry as spare parts.

3- PARTS MASTER LIST

This report lists all spare parts carried in inventory. It may be produced in two formats: by part number or by part description. Both formats are necessary because there will be times the part number is known and times when it is not. The descriptive lookup helps craft technicians or other personnel who are not familiar with the part num-

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ber. Each listing includes most of the information about the spare part and may require a page or more.

4- EMPLOYEE/CRAFT/CREW LISTING

This report lists all the information about the maintenance personnel. It may be produced by employee ID number or on a last name/first name basis. Each listing then has all the personnel information, which may require a page or more per employee.

5- ANALYSIS/DECISION JUSTIFICATION REPORTS

This last series of reports are prepared for management on an as-needed basis. They are not simple lists, but instead use advance statistical calculations to produce intelligent output. These reports do not make decisions, but the information, combined with good management skills and insight, can help manage maintenance successfully.

6- STATISTICS REPORT

This report is useful for spotting trends in breakdowns. It lists, either by equipment ID or by type of equipment, the downtime, what caused the downtime, and what effect it had on operations. For example, a report could look at all air conditioning units to see what the most common cause of failure was for a certain time period. Another report may focus on plant lathes to consider the most common cause of breakdowns that led to operational delays of ten hours or more. Careful analysis of this report can lead to improvements in preventive maintenance programs, and even in purchasing policies.

IV.5.16 RESOURCE REQUIREMENTS FORECAST (OPEN)

This report forecasts the known requirements for maintenance activities for a specified period. If the specified time period exceeds the

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work backlog, it basically becomes a PM forecast. The report lists the work in the backlog, from the oldest to the newest requests. (PMs that are forecast to come due in the specified time period will be included.) Labor, materials, contractor, and other costs will be listed for the forecast period. This information can help in short range (4 to 8 weeks) financial planning. It can also help related groups if they know what portion of their resources will be required from maintenance in the short term.

1- EQUIPMENT HISTORY REPORT

This report allows the detailing of any work performed on any specified equipment. The report should offer users selection criteria, so they do not have to go through all the work orders to find the desired information. Some categories for sorting the information include:

- Type of work (PM, emergency, planned, etc.)
- Equipment component
- Type of failure
- Type of activity (adjustment, calibration, part change, etc.)
- Date range

This report can help identify specific problems and the number of occurrences for any given equipment item.

2- REPAIR LENGTH REPORT

This report identifies any repair — whether emergency, P.M., or routine — that has a downtime greater than the amount specified at the start of the report. This information enables users to look at just the repairs that had a measurable effect on operations or facilities. The

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report should be able to be sorted by equipment, type of equipment, department, craft, or any other field that is important to a particular organization.

3- REPETITIVE REPAIRS REPORT

This report analyzes repairs that have been performed on the same equipment component when the repairs have been conducted more than the number of times the user enters. The report should list the number of times the repair occurred, how long the equipment was down each time, and what caused the equipment to fail each time. The report is useful for analyzing repetitive failures for any equipment component. If the report is expanded, it can show the failure rate for similar components on various equipment items. This information may be useful for supporting purchasing or outage activities.

4- MTBF/MTTR REPORT

This report calculates the Mean Time Between Failures (MTBF) and the Mean Time To Repair (MTTR) for a piece of equipment. The report should be able to break the information down to the component level. This information is useful for setting frequencies for PM programs and planning production schedules. The report can produce the MTBF and MTTR information for failure causes and equipment components. These sections help to highlight any problem component or consistent failure problem. Because trouble areas will be clearly highlighted, the report also helps plan the use of maintenance resources.

5- BREAKDOWN ANALYSIS REPORT

This report analyzes all breakdown and emergency work requests. It can be prepared for a specific equipment item or for all the equipment plant wide. It should include, and be able to be sorted by, the

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following specification fields: equipment type, line, shop, building, account code, failure, cause, repair, and solution. The report enables maintenance managers to find specific problem areas and work to correct them. By knowing the largest problems first, resource usage can be optimized.

6- TOP TEN REPORT

The previous report highlights specific problems on equipment, this report highlights the top ten equipment items in equipment downtime, labor costs, material costs, or contractor use. It should be available by plant, department, building, line, account code, or other appropriate field. This report highlights the specific problem equipment, whereas the previous report can then be used to further analyze the problem.

7- PM ROUTE LISTING

In some plants and facilities, PM tasks are arranged in a route for optimizing travel time on the part of the maintenance technicians. This report lists a particular route and all of the PM tasks associated with it. By analyzing this route with others in the same areas, managers may be able to make adjustments or changes that optimize the technician's travel time.

8- OVERDUE PM REPORT

This report shows all overdue PMs currently outstanding for any equipment item. The report can be sorted by fields such as individual equipment ID, department, line, building, and account code. It should be used to highlight problems with missed or overdue PMs. Coupled with the breakdown analysis report, it can spot breakdown problems that are related to poor PM follow-up.

9- OUTAGE/SHUTDOWN REPORT

This report allows users to specify the shutdown or outage; it then lists all of the work orders planned for that outage. Users then have all the work orders, the requirements for the work orders, and the resources necessary to perform the work. The information can be fed into the project management program for detailed scheduling with PERT or GANTT charts.

10- PM EFFICIENCY AND COMPLIANCE REPORT

This report has two parts. The first part compares the planned versus the actual for completed PMs. It can be sorted by equipment, department, crew/craft, building, or individual equipment item. The comparisons should include the following areas: planned vs. actual hours, planned vs. actual materials, and planned vs. actual downtime. Users should be able to specify a percentage deviation, allowing for a specific report to highlight problem areas. The second part of this report is the compliance report for the PM frequency. By specifying a percentage deviation allowed, the user should then get a report selected by the same parameters as the first part of the report. This report will then list the scheduled frequency for the PM versus the actual frequency. This information helps the manager in examining compliance and scheduling accuracy for the PM program.

11- PARTS ACTIVITY

The parts activity report shows the inventory activity for either a specific warehouse or for all warehouses. It can list activity for a specific part, range of parts, or all parts. The report helps managers analyze the activity of a given location in order to insure proper staffing of inventory and warehouse distribution personnel.

12- SLOW MOVING PARTS

This report is used to find those spare parts that are carried in inventory, but that are not having sufficient activity to maintain in stock. Managers would not include critical spares in this analysis; by definition, they should be slow moving. But others not having activity in a specified time period could be marked for reduction in on-hand quantities or elimination from inventory. This report can be organized by warehouse or for all warehouses as well as for part groups or types of parts.

13- ISSUE/RETURNS REPORT

The issues/returns report shows the parts issued to a work order compared to the items returned to the stores as not needed for the work order. The report should also list any materials issued to the work order that were not planned. The report becomes a measure of the effectiveness of the planner's ability to estimate the parts required for a work order. The report should be sorted by planner. The columns for each planner can then be totaled and an effectiveness percentage calculated. This report will benefit both inventory managers and the maintenance manager.

IV.5.17 INVENTORY OVER MAX REPORT

Almost all inventory items have maximum/minimum levels set for them. This report lists any stock items whose on-hand quantities are higher than the pre-set maximum quantity. It will highlight any overages. Then appropriate measures can be taken to reduce these quantities.

1- EOQ REPORT

The economic order quantity is the optimum quantity to be ordered when purchasing an item. It is beyond the scope and purpose of this text to go into an explanation of the formulas used to calculate this number. The EOQ is an effective method for ordering maintenance spares. This report examines the inventory and lists the EOQ for the inventory items. The information from this report can be then used to adjust this quantity in the part record.

2- STOCK OUT REPORT

This report will sort in descending order the inventory items that have had stock outs during the specified time period for the report. Items having multiple stock-outs give an indication of a problem. These should be cross-referenced to the activity and planning reports in order to find and correct the problem. Stock outs can have high downtime-related costs and should be corrected as quickly as possible.

3- INVENTORY OPTIMIZATION REPORT

Because there are cost trade-offs in inventory, this report looks at the entire picture and recommends stock levels. It is similar to the EOQ report except it highlights the financial penalties associated with the decision. For example, it uses carrying costs, desired service level, downtime costs, lead times, and other categories to calculate the differing costs of maintaining stock levels. It should list several options for the user, highlighting the costs for more or fewer items in stock.

4- REORDER LIST

This report lists all inventory items that are in need of re-order. It is often used where maintenance does not have a computerized tie-

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in to the purchasing department. It will list by warehouse all parts below their minimum quantity. The report can then be reviewed and forward to purchasing for action.

5- PARTS RECEIPT LIST

This report lists all parts that have arrived and been processed by receiving. The quantity received, where they have been stored, and the date should all appear on the report.

6- A-B-C CLASSIFICATION REPORT

Chapter 8 on inventory described the A-B-C classification system. This report categorizes the inventory items into the appropriate classification. Combined with several of the activity reports, it can help managers adjust inventory levels.

7- PRICE CHANGE REPORT

This report lists all items that were ordered at one price, but received at a different one. This difference indicates either a change in price or a mistake by the vendor. The purchasing buyer can then take appropriate action to determine the cause of the price change. Once the matter has been resolved, the inventory records can be updated with the correct price.

8- PARTS WARRANTY REPORT

This report lists the warranty of each part in the inventory. This information can be useful if high activity is shown on a part with a lengthy warranty. Investigation may show the justification for a claim against the manufacturer for a refund. Close monitoring of the warranties can result in sizable refunds in some cases.

9- RESTOCKING REPORT

This report is used in a multiple warehouse plant or facility. It shows items in stock at the main warehouse that need to be distributed to satellite stores locations. It lists the parts and where they need to go. After this report is run, the reorder report also needs to be run because some items may now fall below their minimum.

10- LIST PARTS ISSUES

This report is similar to the parts activity listing, except it lists what work order goes with each part. It is often listed by work order number. More often, it is listed by part, with each work order the part was issued to also listed.

11- PARTS ADJUSTMENT TRANSACTION

This report is a listing made after a physical count inventory has been taken. It shows the difference between what was counted and what the inventory record indicates was on-hand. In some computerized systems, this report is used to accept the physical count; it then lists the cost variance for each item and finally the report.

12- OVERDUE P.R. REPORT

This report lists the purchase requests that are older than a time period specified by the requestor of the report. This report insures that buyers consolidate the purchase requests into a purchase order in a timely manner. Because many maintenance activities are dependent on quick turnaround times, this is a key performance measurement report.

13- OVERDUE P.O. REPORT

This report shows all purchase order that are past the expected delivery date. This report is important in that many maintenance activities are based on these dates. When purchase orders are overdue, the buyer must call the vendor, check the status of the order, and do what is necessary to expedite the order.

14- VENDOR PERFORMANCE ANALYSIS

This report analyzes the on-time delivery, price, and total amount of business conducted with each vendor. This information can be used to work for discounts, insist on quality, or other performance related issues. The report helps determine vendor of choice for purchasing critical items.

15- P.O. HISTORY REPORT

This report is for tracking the receipt history of a purchase order. Because many purchase orders contain multiple line items, the parts are received in partial shipments. This report lists each purchase order and all shipments received to date against it. It also serves as an indicator of the vendor performance.

16- OUTSTANDING P.O. REPORT

This report lists all outstanding purchase orders for any or all vendors. These may or may not be overdue purchase orders. The report also complements the vendor performance report, which has historical information whereas this report provides the current outstanding purchase orders.

17- COST VARIANCE REPORT

This report helps to synchronize all of the part prices throughout the inventory /purchasing /receiving process. Any parts with a difference in price in any of these areas should appear on this report. This information helps insure accurate parts costing in the maintenance work order system.

18- OVERTIME REPORT

This is a two -part report , the first part being a listing of employees with the total overtime they have worked for the specified reporting period. The second part of the report is a call list; it is based on com- pany policy for contacting employees to work overtime. These reports can be time savers for supervisors.

19- CANCELED PM WORK

This report is a selective report organized by equipment ID. It highlights any canceled PMs for a specific equipment ID. This report is used to check PM compliance when a breakdown occurs. Neglect - ing the PM program could be the reason for the failure. This report is invaluable in justifying that PM programs are necessary to upper man- agement.

IV.6. Conclusion

This chapter does not present a complete list of reports that a manager might need to review . However, the reports presented here should be sufficient for an organization to gather enough information so that it can begin the analysis part of the benchmarking process . Without information at this level of detail, organizations are unlikely to have sufficient data to begin benchmarking.

REFERENCES

REFERENCES

1. G.Zwingelstein,"Diagnostic de défaillance ",Hermès,Paris,1997.
2. "La maintenance basée sur la fiabilité ",Hermès, Paris,1997.
3. Jean Henq,"Pratique de la maintenance préventive ",Dunod,2000.
4. Raymond Magnan, "Pratique de la maintenance industrielle",Dunod,2003.
5. Yves Lavina,"Maintenance industrielle, Fonction de l'entreprise", 2005.
6. M. François,"Maintenance : méthode et organisation", Dunod, Paris, 2000.
7. M. François,"Maintenance:méthode et organisation", Dunod,Paris,2000.
8. A. Boulenger, C. Pachaud, "Diagnostic vibratoire en maintenance préventive",Dunod, Paris, 2000.
9. Jean Henq,"Pratique de la maintenance préventive", Dunod,, Paris,2002.
10. R. Cuigent, "Management de la maintenance" ,Dunod,Paris,2002.
11. Rachid Chaib,"La maintenance et la sécurité industrielle dans l'entreprise",Dar El Houda,,Alger,2007
12. S.Robert, S.Stéphane, "Maintenance : la méthode MAXER", Dunod, Paris,2008.
13. J.F.D.Beaufort,"Emploi des relais pour la protection des installations", 1972.
14. Michel Pierre Villoz, "Protection et environnement",Technique et ingénieur,2006.
- 15.Nichon Margossian,"Risques professionnelle",Technique et ingénieur,2006..