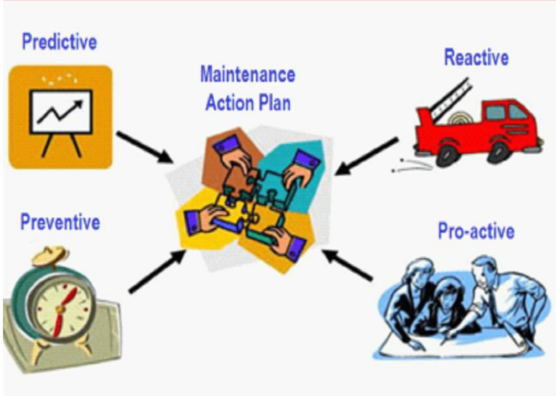

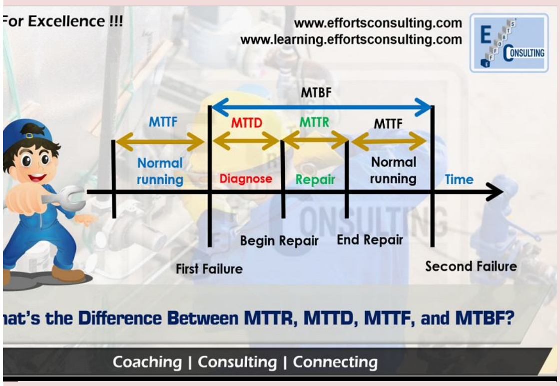

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Mohammed Seddik Benyahia University - Jijel
Faculty of Sciences and Technologie
Automatic Departement

COURSE of

MAINTENANCE and RELIABILITY

Intended for third –year bachelor's students in Automatic control

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Associate Professor

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Foreword

This course, titled *Maintenance and Reliability*, is primarily intended for third-year Bachelor's students in Automatic. It aims to provide students with a solid foundation of knowledge and key definitions, enabling them to understand, master, and effectively engage in the field of system maintenance and reliability.

The course is structured into five chapters; the first chapter focuses on the maintenance function. It covers key definitions, the various maintenance strategies, as well as the different levels of maintenance. The second chapter addresses failure mechanisms and modes. It introduces the concepts of failure, its causes, modes, and mechanisms. The third chapter is dedicated to the quantitative analysis of maintenance. It includes tools such as ABC analysis, decision trees, criticality matrices, and correlation relationships. The fourth chapter deals with diagnostics. It presents definitions, methodologies, and diagnostic tools (such as cause-effect diagrams, fault trees, diagnostic charts, etc.), and offers a comparative analysis of these tools. Finally, the fifth chapter focuses on predictive failure analysis; presenting methods that help anticipate breakdowns and improve maintenance planning.

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Guidance Notes On Failure Mode and Effects Analysis (FMEA) for Classification ABS 2015

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Chapter 1
Maintenance function

1 Introduction

In today's increasingly demanding industrial environment, maintenance plays a strategic role in the management of equipment and infrastructure. It is no longer limited to simply fixing breakdowns but encompasses a wide range of activities aimed at ensuring the availability, reliability, and performance of systems. This chapter provides a comprehensive overview of maintenance, beginning with its definition and exploring the different strategies—corrective and preventive—along with the specific operations involved, the various levels of intervention, and related activities. Through this exploration, we will also present practical examples to better understand the challenges and best practices associated with maintenance management.

2 Definition

Maintenance is the set of actions required to maintain or restore an asset in a specified condition, or capable of providing a given service. Good maintenance means carrying out all these operations at optimum cost.

The definition of maintenance thus reveals 4 concepts:

- Maintain, which presupposes follow-up and monitoring
- Restore, which implies the idea of fault correction
- Specified state and determined service, which specifies the level of skills and objectives expected of maintenance
- Optimum cost, which conditions all operations with a view to economic efficiency

The role of the maintenance function in a company (whatever its type and sector of activity) is therefore to guarantee the highest possible availability of equipment at the best efficiency, while respecting the allocated budget.

The three main concepts of maintenance as defined by the Standards Association

- *Reliability* Reliability is the ability or probability of a device to perform a required function under given conditions and for a given period of time.
- *Maintenability* Under given conditions of use, the ability of a device to be maintained or restored in a state in which it can perform its required function, when maintenance is carried out under given conditions, with prescribed procedures and means.
- *Availability* Availability is the ability to perform a required function under given conditions at a given moment or during a given time interval, assuming that the necessary external resources are available.

3 The role of maintenance

The maintenance function will then need to draw up targeted forecasts:

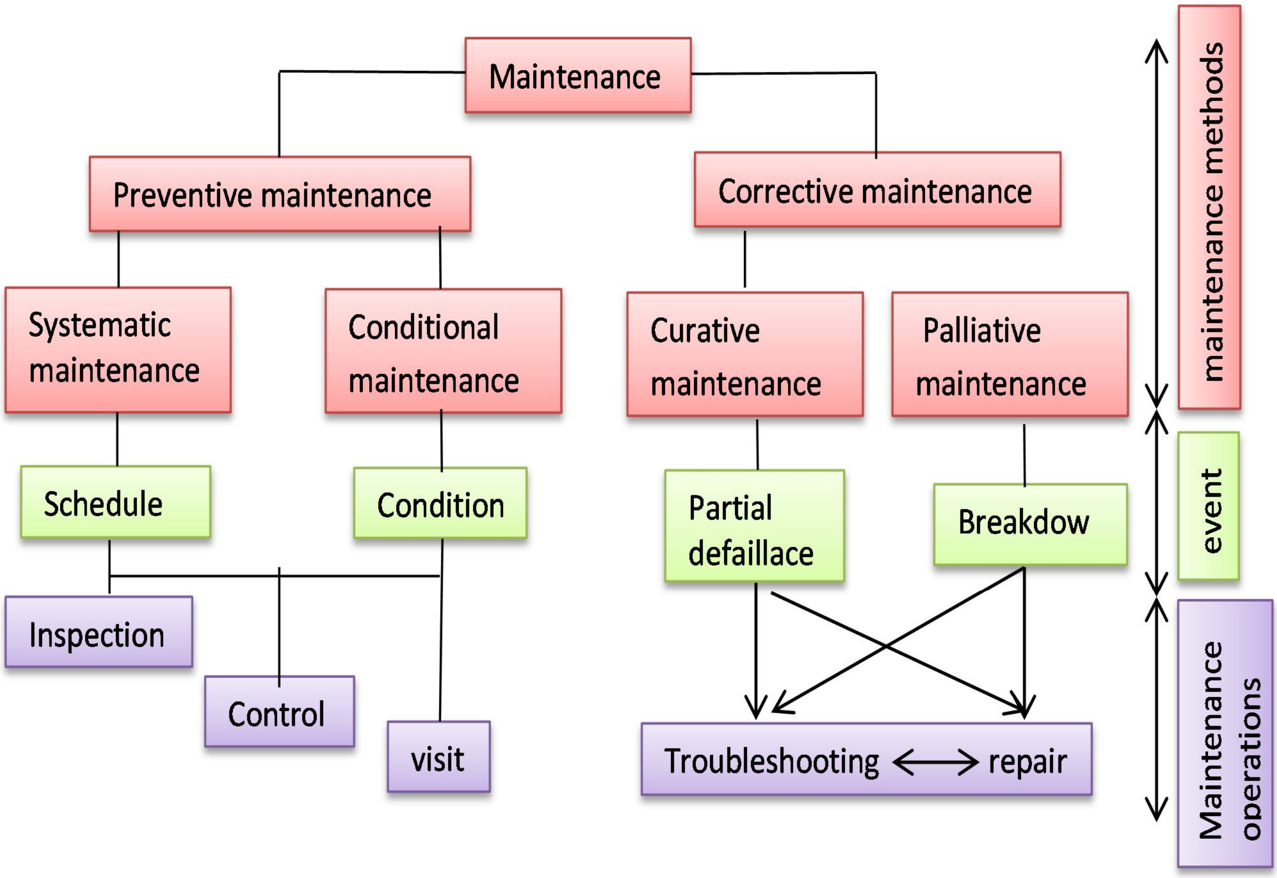
- Long-term forecasts: these concern major investments or long-term projects. These forecasts are usually dictated by the company's overall policy.
- Medium-term forecasts: maintenance needs to be as unobtrusive as possible in the production workload schedule. It is therefore necessary to anticipate, as far as possible, its interventions in line with production schedules. Production must also take into account the need to monitor equipment.
- Short-term forecasts: these can be weekly, daily or even hourly. Even in this case, with a view to minimizing disruption to production, interventions must also have undergone a minimum of preparation.

4 Maintenance strategies

Analysis of the various forms of maintenance is based on 4 concepts:

- The events that trigger action: reference to a schedule, subordination to a type of event (self-diagnosis, sensor information, measuring damage, etc., etc.), the occurrence of a fault
- The maintenance methods associated with them: systematic preventive maintenance, conditional preventive maintenance, corrective maintenance.
- Maintenance operations as such: inspection, control, troubleshooting, repair, etc.
- Related activities : improvement maintenance, renovation, reconstruction, modernization, new work, safety, etc.

Maintenance strategies are summarized in the following diagram



Maintenance methods, event and operations

4.1 Corrective maintenance:

a Definition: Failure: alteration or cessation of an asset's ability to perform its required function. There are 2 types of failure:

- *Partial failure*: alteration of an asset's ability to perform its required function
- *Complete failure*: cessation of an asset's ability to perform its required function.

The aim of corrective maintenance, sometimes called curative maintenance (a non-standardized term), is to restore the lost qualities necessary for the use of the equipment. Defects, breakdowns or damage of any kind requiring corrective maintenance lead to immediate or very short-term unavailability of the equipment concerned and/or a reduction in the quantity and/or quality of services rendered.

b Palliative maintenance:

Corrective maintenance activities designed to enable an asset to temporarily perform all or part of a required function. Commonly referred to as "troubleshooting", palliative maintenance is mainly made up of provisional actions to be followed by corrective actions.

c Curative maintenance:

Corrective maintenance activity aimed at restoring an asset to a state or enabling it to perform a required "repair" function.

4.2 Preventive maintenance

a Definition: Maintenance carried out according to predetermined criteria, with the intention of reducing the probability of failure of an asset or the degradation of a service rendered. Preventive maintenance is intended to prevent equipment failure during use. The cost analysis must show a gain in relation to the failures avoided.

b **Aims of preventive maintenance**

- Increase the service life of equipment
- Reduce the probability of in-service failures
- Reduce downtime in the event of overhaul or breakdown
- Prevent and also anticipate costly corrective maintenance interventions
- Enable corrective maintenance decisions to be taken under the right conditions
- Avoid abnormal consumption of energy, lubricants, etc.
- Improve working conditions for production staff
- Reduce the maintenance budget
- Eliminate the causes of serious accidents

c Systematic preventive maintenance: Preventive maintenance carried out according to a schedule based on time or the number of units in use.

This method requires knowledge of :

- The behavior of the equipment
- The modes of deterioration
- The average time of good operation between 2 breakdowns

d Application cases

- Equipment subject to current legislation (regulated safety): lifting equipment, fire extinguishers, pressure tanks, conveyors, elevators, etc.
- Equipment whose breakdown could cause serious accidents: all public transport equipment, aircraft, trains, etc.
- Equipment with a high failure cost: elements of an automated production line, continuous processes (chemical or metallurgical industries).
- Equipment whose operating costs become abnormally high over the course of its service life: excessive energy consumption, lighting from old lamps, incorrect ignition and carburation (combustion engines), etc.

e Conditional preventive maintenance: preventive maintenance dependent on a predetermined event (self-diagnosis, sensor information, wear measurement, etc.). Note: conditional maintenance is therefore maintenance that depends on experience, using information gathered in real time. This conditional preventive maintenance is carried out by means of relevant measurements on equipment in operation. The parameters measured may relate to :

- Oil level and quality
- Temperatures and pressures
- Voltage and current of electrical equipment
- Vibrations and mechanical play

5 Maintenance operations

5.1 Corrective maintenance operations

a. Troubleshooting: Action taken on a faulty item to restore it to working order. Given the objective, a troubleshooting operation can be carried out with provisional results and under conditions which are outside the rules of procedure, cost and quality, and in this case will be followed by repair. Often, troubleshooting operations are of short duration, but can be numerous.

b. Repair: Definitive and limited corrective maintenance intervention after a breakdown or failure. Repair is a definitive action. The repaired equipment must provide the performance for which it was designed.

5.2 Preventive maintenance operations :

a. Inspections: monitoring activities consisting in periodically identifying anomalies and carrying out simple adjustments, which do not require special tools or a shutdown of the production tool or equipment.

b. Visits: monitoring operations which, as part of systematic preventive maintenance, are carried out at set intervals. These interventions correspond to a list of operations defined in advance, which may involve the dismantling of components and the immobilization of equipment. A visit may lead to corrective maintenance action.

c. Controls: conformity checks against pre-established data, followed by a judgement. Controls may :

- Include an information activity
- Include a decision: acceptance, rejection, postponement
- Like visits, lead to corrective maintenance operations.

5.3 Other operations

a. Overhaul: All examinations, controls and interventions carried out with a view to protecting the asset against any major or critical failure, for a given period of time or for a given number of usage units. The term "overhaul" should never be confused with the terms "visit", 'control' or "inspection".

b. Standard exchange: The trade-in of a used part, component or subassembly, and the sale to the same customer of an identical part, component or subassembly, either new or reconditioned to the manufacturer's specifications, subject to payment of a balance based on the cost of reconditioning.

6 Maintenance levels

Level 1 Simple actions required for operation and carried out on easily accessible components in complete safety using support equipment integrated into the asset.

Operator The user of the asset

Example of corrective maintenance Replacement of light bulbs; Adjustment, replacement of worn or damaged parts, on simple and accessible elements or components.

Example in preventive maintenance Condition monitoring round; Daily lubrication; Manual operation of mechanical components; Recording of status values or usage units; Lamp test on console; Purging of filter elements; Filter clogging check.

Level 2 Actions requiring simple procedures and/or support equipment (integrated into the asset or external) that is easy to use or implement.

Operator Operator Qualified personnel. Personnel are qualified when they have received training enabling them to work safely on an asset presenting certain potential risks, and are recognized as fit to carry out the work entrusted to them, given their knowledge and skills.

Example of corrective maintenance Replacement of parts by standard exchange: fuses, belts, air filters, etc.; Replacement of braids, cable glands, etc.; Reading of troubleshooting 7ogograms for re-cycling; Replacement of worn or deteriorated individual components by standard exchange (rail, slide, roller, chain, fuse, belt, etc.).

Example of preventive maintenance Checking parameters on equipment in operation, using measurement equipment integrated into the asset; Simple adjustments (pulley alignment, pump-motor alignment, etc.); Checking switching devices (sensors, circuit breakers, fuses), safety devices, etc.; Descaling run-off surfaces (cooling towers); Greasing at short intervals (weekly, monthly); Replacing filters that are difficult to access.

Level 3 Operations requiring complex procedures and/or portable support equipment.

Operator Qualified technician

Example of corrective maintenance Diagnosis; Repair of a refrigerant leak (refrigeration unit); Insulation repair; Condition diagnosis using portable and individual support equipment (PLC pocket, multimeter); Replacement of parts and components by standard exchange of general technicality, without use of common or specialized support equipment (PLC card, cylinder, pump, motors, gears, bearings, etc.); Troubleshooting of production equipment using individual measurement and diagnostic equipment.

Example of preventive maintenance Control and adjustments involving the use of measuring equipment external to the goods; Preventive maintenance visits to complex equipment; Ignition and combustion control (boilers); Intrusive preventive maintenance intervention; Recording of technical parameters of goods condition using individual measuring equipment (fluid or material sampling, etc.).

Level 4 Operations whose procedures require mastery of a particular technique or technology and/or the use of specialized support equipment.

Operator Technician or specialized team

Example of corrective maintenance Replacement of compressor valves; Replacement of BTA cable head; Overhaul of a pump in a specialized workshop following preventive removal; Repair of a pump on site, following a fault; Troubleshooting of production equipment using collective and/or highly complex measuring or diagnostic equipment (PLC programming set, digital control and regulation system, drives, etc.); Repair of external fencing; Overhaul of external fencing. Repairs to cracks and leaks in the roof.

Example of preventive maintenance Partial or general overhauls not requiring complete dismantling of the machine; Vibration analysis; Lubricant analysis; Infrared thermography (electrical, mechanical, thermal installations, etc.); Recording of technical parameters requiring collective measuring equipment (oscilloscope, vibration data collector) with data analysis; Overhaul of a pump in the workshop, following preventive removal.

Level 5 Operations whose procedures involve know-how, calling on specific techniques or technologies, processes and/or industrial support equipment. These are operations involving renovation, rebuilding, etc.

Operator Manufacturer or specialized company

Example General overhauls involving complete dismantling of the machine; dimensional and geometrical overhauls; major repairs carried out by the manufacturer or reconditioning of his goods; replacement of obsolete or worn-out goods.

7 Related activities

These activities complement the maintenance actions mentioned above, and play a significant role in optimizing operating costs.

Upgrade maintenance	Upgrading capital goods involves making modifications, changes or transformations to equipment.
Renovation	Complete inspection of all components, complete dimensional adjustment or replacement of deformed parts, verification of characteristics and possible repair of defective parts and sub-assemblies, conservation of good parts. Renovation is one of the possible outcomes of a general overhaul in the strict sense of the term.
Reconstruction	Restoration to the state defined by the initial specifications, requiring the

	replacement of vital parts with original parts or equivalent new parts. Reconstruction may be accompanied by modernization or modifications.
Modernization	Replacement of equipment, accessories and devices, or possibly software, which, thanks to technical improvements not found on the original product, improves the product's suitability for use. This operation can be carried out in the case of renovation or reconstruction.
New works	The addition of responsibility for new works to the maintenance function is widespread, particularly in medium-sized companies. It's based on the principle that, for any additional investment in replacement or extension, it makes sense to consult maintenance specialists who, on the one hand, are familiar with the old equipment and, on the other, will have to keep the new equipment in working order.
Safety	Safety is the set of methods designed, if not to eliminate, at least to minimize the consequences of failures or incidents to which a device or installation may be subject, consequences which have a destructive effect on personnel, equipment or the environment of both.

8 Example

Automobile maintenance	Corrective maintenance		Preventive maintenance		Related activities (Improvement maintenance)
	Trouble-shooting	repair	systematics	Conditional	
Fill up with petrol					
Change oil					
Install a car radio					
Change brake pads at wear indicator					
Change a punctured					

wheel					
Repair punctured wheel					
Renovate shock absorbers					
Change timing belt					
Check oil level every month					
Repainting					
Change exhaust pipe					

9 Conclusion

Maintenance is far more than a support function—it is a vital driver of industrial performance. Whether corrective or preventive, it involves specific, context-based operations at different intervention levels. This chapter has highlighted the importance of a well-defined maintenance strategy, supported by targeted and scheduled actions. When properly managed, maintenance can extend the lifespan of equipment, improve productivity, reduce costs, and enhance safety. Therefore, efficient maintenance is a key asset for any organization aiming to maintain its competitiveness and long-term sustainability.

Chapter 2
Failure Mechanisms and Modes

1 Introduction

Failures are an inevitable aspect of any engineering system or industrial process. Understanding their nature, causes, and mechanisms is crucial to improving system reliability, safety, and performance. This chapter explores the fundamental concepts related to failure, starting with its general definition and classification. It then delves into the underlying causes, common failure modes, and the physical mechanisms that lead to component or system breakdowns. Special attention is given to mechanical failures—such as fatigue, wear, and fracture—as well as electrical and corrosion-related failures. By examining these aspects in detail, this chapter provides essential knowledge for predicting, preventing, and managing failures in various technical contexts.

2 Notion of failure

Failure is the alteration or cessation of an asset's ability to perform its required function. There are several ways of classifying failures.

3 Failure classification

Failures can be classified as follows:

a. According to the speed of occurrence

Progressive failure Evolution over time of certain characteristics of an entity

Sudden failure Almost instantaneous evolution of the characteristics of an entity

b. According to the time of occurrence

Failure in operation Occurs when the required function is in use.

Failure at standstill Occurs when the required function is not in use.

Failure on request Occurs when the required function is requested.

c. Depending on the degree of importance

Partial failure Entails the inability of an entity to perform certain required functions *Total failure* Entails the total inability of an entity to perform the required function to perform the required function

d. Depending on the speed of onset and degree of importance

Failure by degradation Which is both progressive and partial

Catalectic failure Which is both sudden and complete

e. Depending on the causes

Failure by inherent weakness Due to the design or manufacture of the entity

Failure by inappropriate use Stresses applied exceed the entity's capabilities

Failure due to incorrect operation Incorrect operation in the use of the entity

Failure due to ageing Degradation over time of the entity's characteristics

f. Depending on its origin

Failure internal to the entity The origin is attributed to the entity itself. itself.

Failure external to the entity The cause is attributed to factors external to the entity itself.

g. As a function of consequences

Critical failure Suspected of causing damage (to people, property, environment)

Major failure Affects a major function of the entity

Minor failure Does not affect a major function of the entity

h. As a function of character

Systematic failure Definitely linked to a cause

Reproducible failure Can be provoked at will by simulating or reproducing the cause

Non-reproducible failure The cause never reproduces the failure

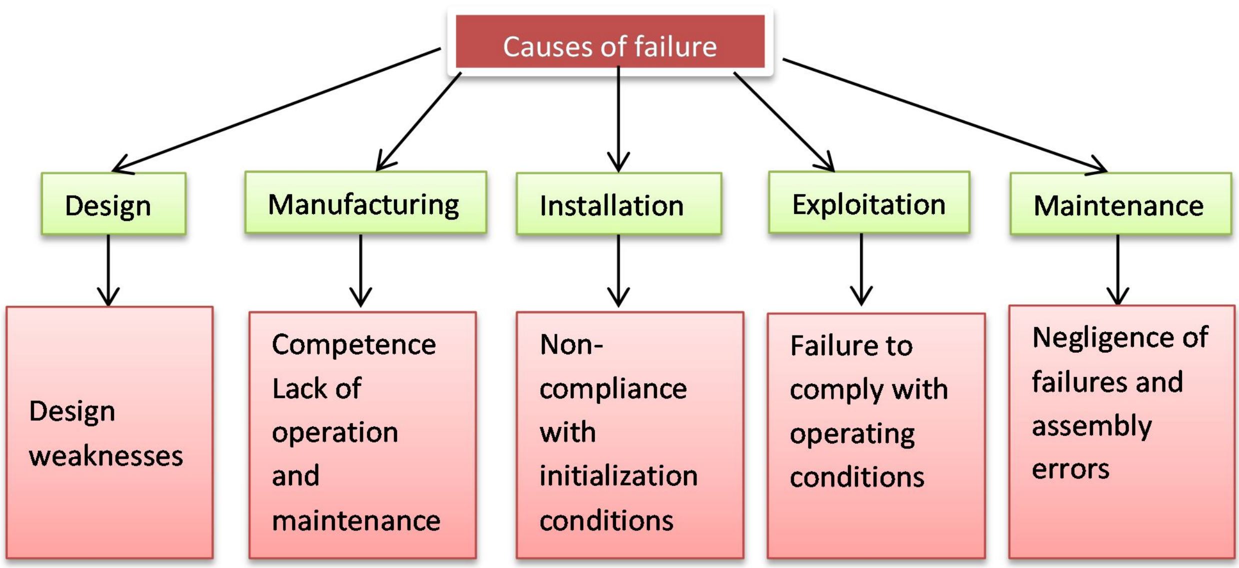
4 Causes of failure

These are the reasons for failure. The reasons may be the result of at least one of the following factors: failure due to design, manufacture, installation, misuse, faulty operation or maintenance.

The causes of system failure can be either external or internal:

External causes - Raw materials (missing, non-conforming) - Energy (missing, non-conforming) - Operating conditions: non-conforming operation and adjustment - Maintenance (missing, non-conforming) - Disturbance (environment).

Internal causes - System elements (components, links) Internal causes are system elements that perform a function. Supplying energy, processing information and ensuring safety are common functions. The failure of one of these functions leads to the failure of the others. Generally.

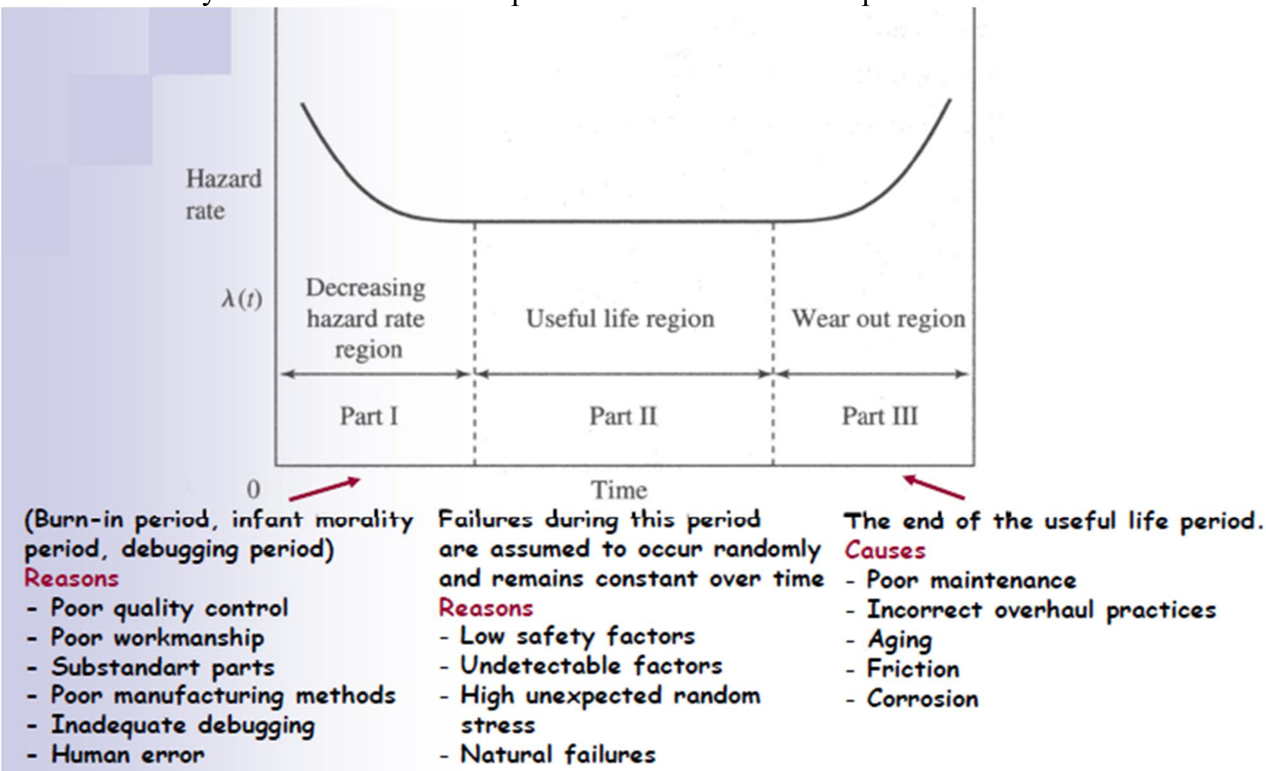


Failure causes

5 Failure modes

The way in which a failure manifests itself. It is the way in which a system fails to function. There are 4 ways in which a function can fail to perform correctly:

- No function: the function ceases to perform,
- No function: the function does not perform when called upon,
- Degraded function: the function does not perform perfectly, impairment of performance
- Untimely function: the function performs when not called upon.



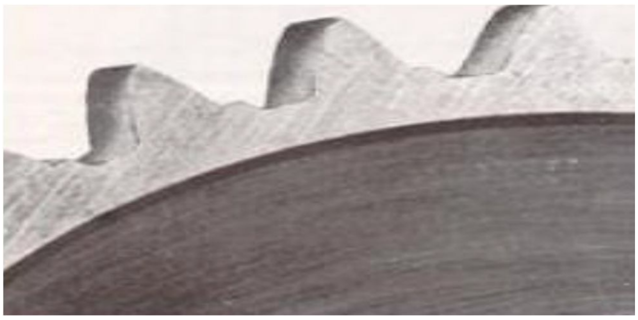
Failure mode

6 Failure mechanism

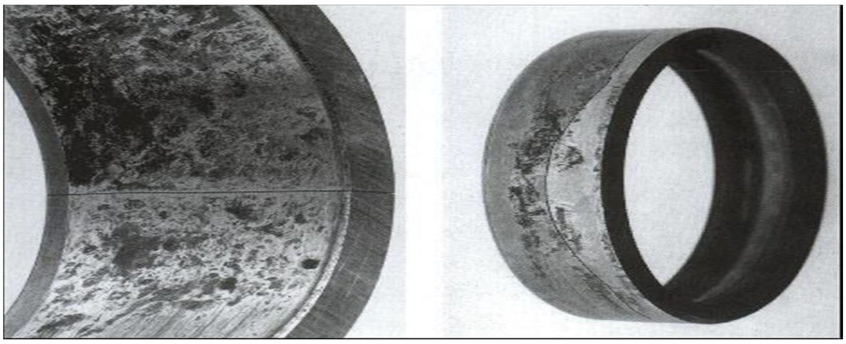
The failure mechanism corresponds to the physical, chemical or other processes that lead or have led to a failure.

6.1 Mechanical failure due to surface deterioration: Fatigue and wear

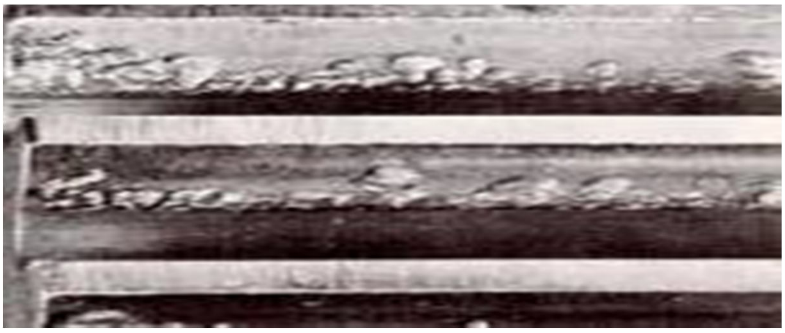
Wear: progressive removal of material from the surface of the parts of a kinematic couple in relative sliding.



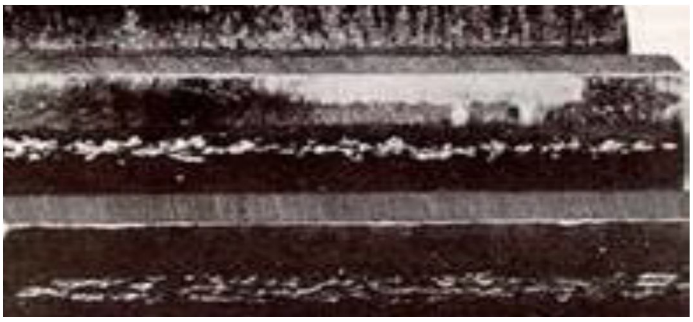
Fretting-corrosion: special wear occurring when 2 static parts come into contact, but are subjected to small oscillating movements (vibrations). This is the case with shrink-fitted parts and keyed joints.



Scaling: removal of large flakes of material.



Seizure: welding of large areas of contact surface, with massive material removal wear: action of impurities or waste (dust, sand, etc.)



Cavitation: implosion of incondensable micro-gas bubbles caused by a sudden drop in pressure within a liquid. The shock wave generates craters in the cavitation zone (pumps, propellers, etc.).

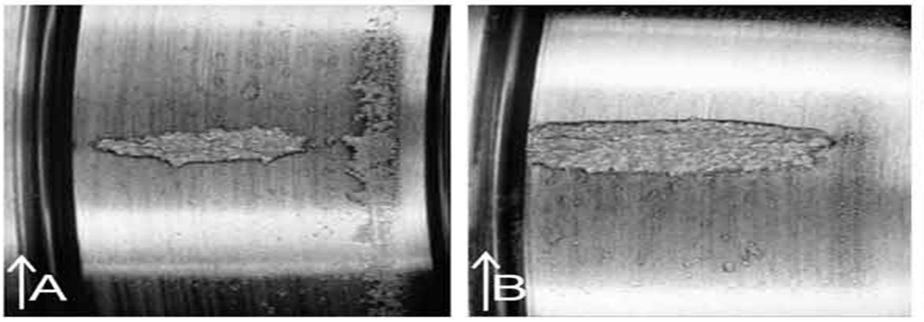
Erosion: removal of material by the impact of a fluid or solid particles in suspension, or by electrical phenomena (arcing)

Crazing: network of surface cracks due to thermal fatigue

Marking: localized indentation due to a point load

Scraping: trace left by the passage of a hard body

Bearings and contact fatigue: ball and needle roller bearings inherently deteriorate through contact fatigue. Hertz pressure at the ball/raceway contact causes shear stresses on the rings, leading to surface cracking and pitting.



6.2 Friction and wear

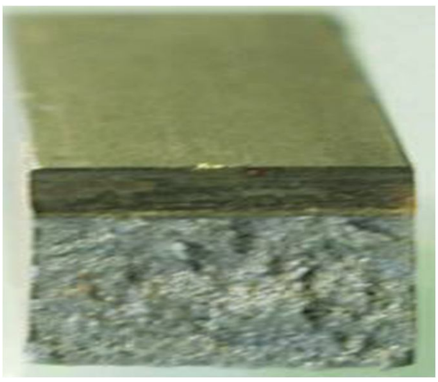
This mode of failure is inexorable when 2 surfaces in contact move relative to each other. Mechanical failure due to plastic deformation

Plastic deformation under mechanical stress: due to exceeding the material's elastic limit.

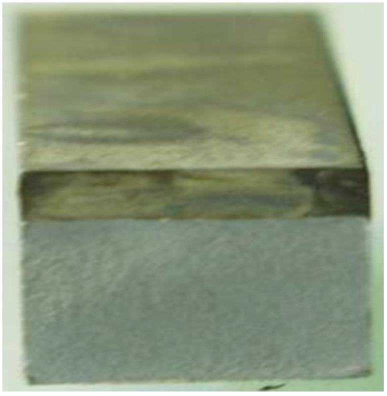
Plastic deformation under thermal stress and over time: this is creep, a deformation occurring under mechanical stress associated with service temperatures.

6.3 Mechanical failure due to ductile, brittle or fatigue fracture

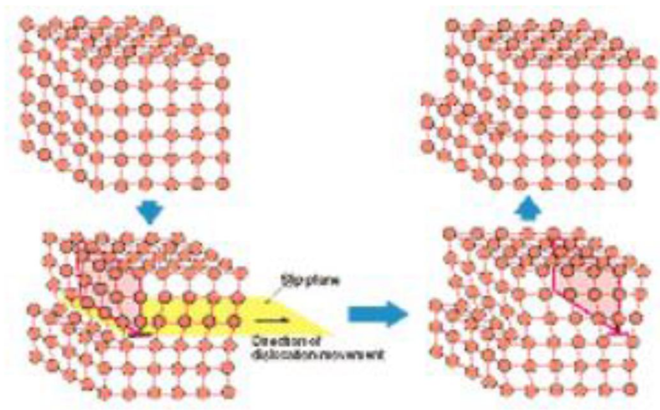
Ductile fracture: occurs after a phase of appreciable plastic deformation, with elongation of the material and striction at the fracture point.



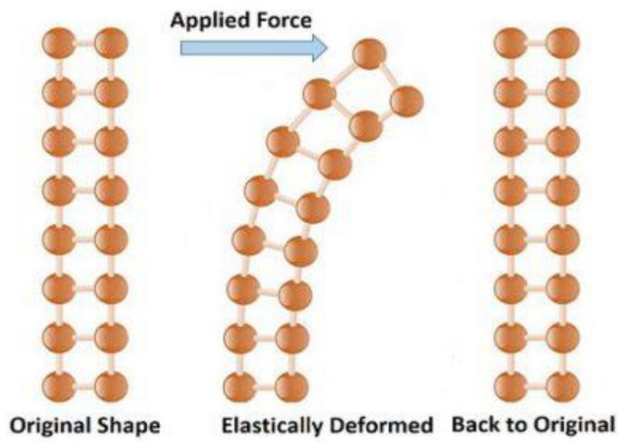
<u>*Brittle fracture*</u>: occurs after very little plastic deformation. It is often the result of an impact and is favored by the material's intrinsic fragility.



Fatigue failure: when a part has reached its endurance limit.



Plastic Deformation



Elastic Deformation

6.4 Electrical failure modes

- *Electrical connection failure*: this is most often the result of an extrinsic cause (shock, overheating, vibration).

- *Contact sticking or wear*: through various failure modes, contacts are often the “weak links” in an electrical circuit.

- *Component breakdown*, such as resistors, transistors, etc.

6.5 Corrosion failure modes

<u>*Electrochemical corrosion:*</u> This affects metals (often iron) in aqueous media.

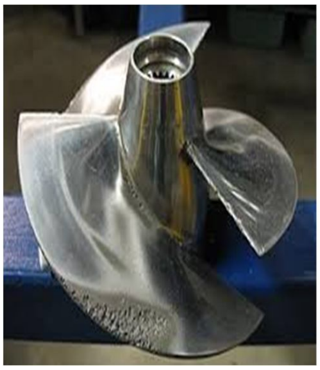
Chemical corrosion: The accidental or normal, temporary or permanent contact of equipment with aggressive products leads to chemical corrosion: a chemical reaction with regular loss of material, pitting or intergranular corrosion cracking. Corrosive agents may be acids (sulfuric, nitric, hydrochloric, etc.), detergents or even lubricants (whose mission is to protect surfaces, but whose additives create certain incompatibilities, and whose oxidation produces organic acids).

Electrical corrosion: under the effect of "stray currents", 2 adjacent metal surfaces can be subjected to a sufficiently high DDP to create an electric arc, resulting in abrasion. The causes may be poor earthing, induced currents on electrical machines, or electrostatic charges from friction (belts, textiles, etc.).

Bacterial corrosion: cutting oils and industrial water often contain "ferro-bacteria" which divide every 20 minutes (1 bacterium gives rise to 1 billion bacteria in 12 hours).


Contact corrosion: occurs when 2 parts are in contact and subjected to vibrations. Example: outer ring of a bearing in its housing. In this complex process, Fe_2O_3 forms a reddish, highly abrasive dust.

Cavitation: this occurs on parts in contact with a zone of liquid turbulence. Bubbles form in the mass of liquid in turbulent flow. Under the effect of external pressure, these bubbles implode, generating a shock wave accompanied by a high point temperature. This explains the degradation of turbines, propellers, engine liners, etc.




7 Conclusion

Failure analysis is a cornerstone of effective engineering design and maintenance. By classifying failures and understanding their causes and mechanisms—whether mechanical, electrical, or chemical—engineers can implement better preventive strategies and extend the life of equipment and systems. This chapter has outlined the main types and sources of failure, providing a structured approach to identify and mitigate them. Mastering these concepts is key to enhancing reliability, reducing downtime, and ensuring the overall efficiency and safety of industrial operations.

Chapter 3
Quantitative maintenance analysis

1 Introduction

Effective failure analysis is essential for identifying, understanding, and eliminating the root causes of problems in industrial systems. This chapter introduces a range of tools and methods used to systematically analyze failures and support decision-making processes. Beginning with the importance of timing in failure assessment, it then presents the ABC Method (Pareto Chart), which helps prioritize issues based on their impact. The chapter also explores the Noiret Abacus—a visual and analytical tool for failure classification—along with its principles and applications. Additional methods such as decision trees, correlation analysis, and the Fishbone diagram are also covered, offering a comprehensive approach to identifying cause-effect relationships. Through these tools, engineers and technicians can develop more targeted and effective solutions to reduce downtime and improve system reliability.

2 Failure analysis

Failure analysis can be carried out:

- either quantitatively, then qualitatively, using the equipment's history and the qualitative data from diagnostics and failure analysis.

- Or in a predictive way, during the design phase, or a posteriori, after experience feedback.

3 Failure metrics

Quantitative analysis of a history will enable us to identify improvement actions, and thus failures that need to be further investigated in order to correct or prevent them. Quantitative analysis of diagnostic results is therefore a key area for progress. Dates of interventions (days, hours) and number N of failures; these data will be used to calculate

a. *Mean time to failure (MTTF)*. This measure is used to assess the reliability of an item equipment or a system. The longer the MTTF, the more reliable the equipment.

b. *Up Time (UT)*

c. *Time intervals between two consecutive failures* (TBF: Time Between Failures).

d. *Mean Time Between Failures (MTBF).* This measure is used to assess the effectiveness of maintenance strategies. A long MTBF indicates that maintenance interventions are spaced out over time, implying reduced maintenance costs and optimum equipment availability.

$$MTBF = \frac{Up\ Time}{Number\ of\ periods\ of\ uptime}$$

e. *Failure rate*, often denoted λ, can be defined as the probability that a component or system fails at a given time to perform its required function. When constant, it can be calculated by the following formula:

$$\mu = \frac{1}{MTTR}$$

f. Downtime (DT).

g. Time to Repair (TTR).

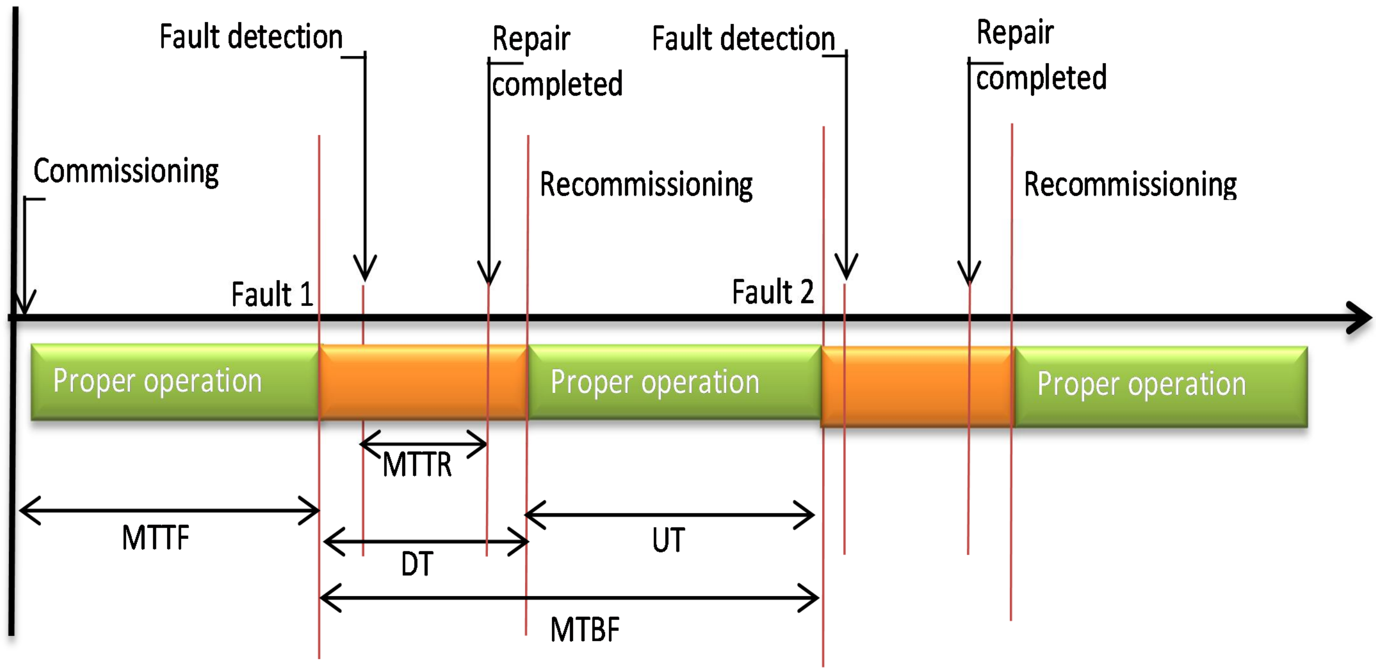
*h. Mean Time to Repair (MTTR).*This metric is used to assess an organization's ability to effectively respond to failures and restore equipment to normal operation. A short MTTR indicates high responsiveness and an ability to minimize downtime.

$$\mathrm{MTTR} = \frac{\sum Response\ time\ for\ n\ breakdowns}{Number\ of\ breakdowns}$$

Each of the above data is then associated with the failure families defined in the previous chapter:

- Location of sensitive elements based on structural decomposition,

- Most frequently observed failure modes.



Failure metrics

4 Decision-making method

4.1 ABC Method (Pareto Chart)

a Principle

The ABC method is a decision-making method, based on an investigation that highlights the most important elements of a problem in order to facilitate choices and priorities. Events (breakdowns, for example) are classified in descending order of cost (downtime, financial cost, number, etc.), with each event relating to one entity. A graph is then drawn up, corresponding the percentages of accumulated costs to the percentages of accumulated types of breakdown or failure. The diagram shows three zones.

1. Zone A: 20% of failures generate 80% of costs;

2. Zone B: the additional 30% of breakdowns cost only an additional 15%;

3. Zone C: the remaining 50% of breakdowns account for only 5% of overall costs.

Conclusion: it's clear that maintenance planning should focus on Zone A breakdowns.

Pareto principle

b Method

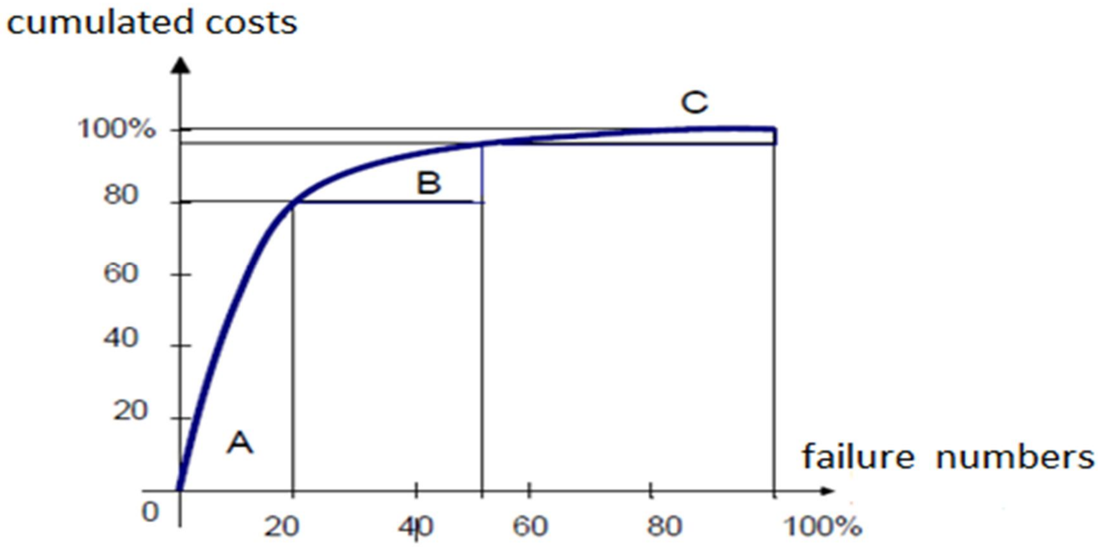
To construct a Pareto Chart, you need to start with meaningful data which you have collected and categorized. You may want to turn to the Data Collection module at this point to review the process of collecting and categorizing data.

Step 1 - Record the raw data. List each category and its associated data count.

Step 2 - Order the data, putting the categories in order and placing the one with the largest count first.

Step 3 - Find the cumulative counts. Each category's cumulative count is the count for that category added to the counts for all larger categories.

Step 4 - Add a cumulative line. This is optional. Label the right axis from 0 to 100%, and line up the 100% with the grand total on the left axis. For each category, put a dot as high as the cumulative total and in line with the right edge of that category's bar. Connect all the dots with straight lines.



In maintenance, this method is very useful for determining the most urgent or profitable tasks, for example:

- Pay particular attention to the preparation of interventions on the most frequent and/or most costly failures (documentation, operating ranges, contracts, scheduling, etc.),
- Search for causes and possible improvements for these same failures,
- Organize a warehouse according to the frequency of parts removal (number of parts and location),
- Decide on the maintenance policy to be applied to certain equipment, based on maintenance hours and costs.

The maintenance department can take this method much further:

- A table is drawn up showing the sub-assemblies, the number of failures N, the downtime per sub-assembly Nt and the average downtime t ;
- N, Nt and t bar charts are drawn up; these will be used to determine the priority for the maintenance department in taking charge of the sub-assemblies,
- The N-graph focuses on improving reliability;
- The graph in Nt is an availability indicator, since Nt estimates the loss of availability of each sub-assembly;
- The graph in t is oriented towards maintainability, i.e. improving serviceability.

c Example

A company wants to increase productivity by reducing the number of serious breakdowns. To achieve this, it asks the maintenance department to prioritize the improvements to be made to the production line. To do this, the maintenance manager uses the breakdown history recorded over a 2-year period in the workshop to each type of equipment. The data are summarized in the following table:

Types of equipment	Repair time (h)	No. of faults
Boiler (CH)	100	2
Air compressor (C)	35	10
Manual valve (VM)	175	6
Centrifugal pump(PC)	145	2
Automatic valve (VA)	60	7
Electric motor(M)	52	6
Speed reducer(R)	36	15
Heat exchangers(E)	200	2
Transmission system(S)	12	20
Gear pump (PE)	250	5

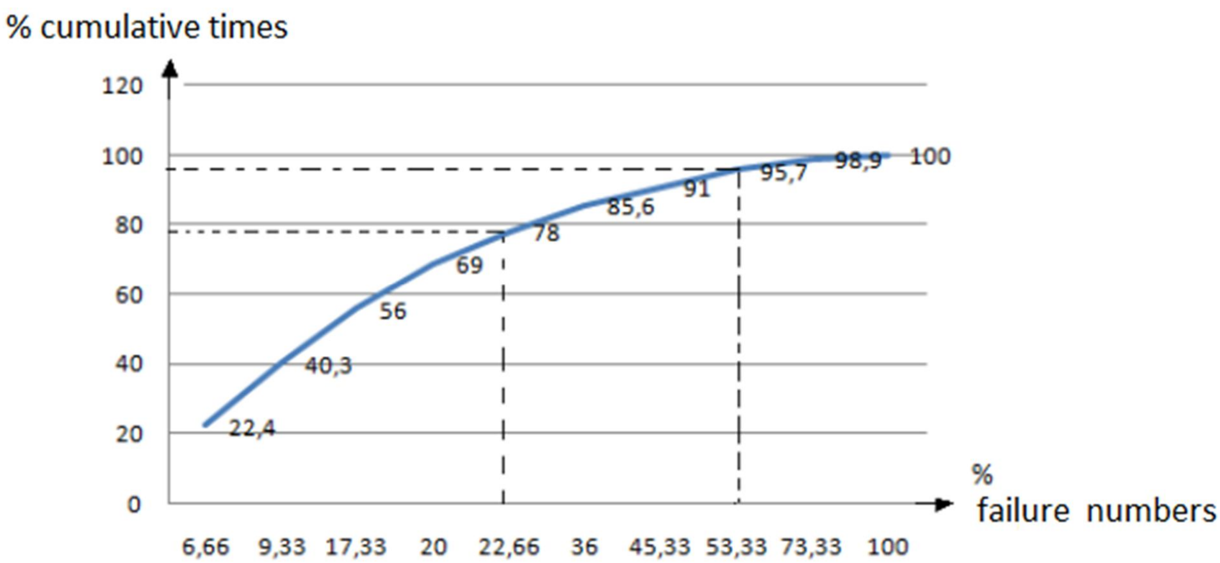
The ABC steps are summarized by the following table

Machine no.	Breakdown cost (in DA) :	Cumulative costs :	% of cumulative costs :	Number of breakdowns	Cumulative number of breakdowns	% of cumulative breakdowns:
Gear pumps	250	250	22.4%	5	5	6.66%
Heat exchangers	200	450	40.3%	2	7	9.33%
Manual valve	175	625	56%	6	13	17.33%
Centrifugal pump	145	770	69%	2	15	20%

Boiler	100	870	78%	2	17	22.66%
Air compressor	85	955	85.6%	10	27	36%
Automatic valve	60	1015	91%	7	34	45.33%
Electric motor	52	1067	95.7%	6	40	53.33%
Speed reducer	36	1103	98.9%	15	55	73.33%
Transmission system	12	1115	100%	20	75	100%

From the above table, we construct the Pareto diagram. The limits of zones A, B and are illustrated in the table and in the diagram (22.66% , 53.33%).

It is therefore clear that an improvement in the reliability of the following sub-assemblies: gear pumps, heat exchangers, manual valve, centrifugal pump and boiler can provide up to 78% fewer breakdowns.



Diagrammes en N, Nt et $\bar{t}$

Types of equipment	Repair time (h) N	No. of faults Nt	$\bar{t}$
Boiler (CH)	100	2	50
Air compressor (C)	35	10	3.5
Manual valve (VM)	175	6	29.16
Centrifugal pump(PC)	145	2	72.5
Automatic valve (VA)	60	7	8.75
Electric motor(M)	52	6	8.66
Speed reducer(R)	36	15	2.4
Heat exchangers(E)	200	2	100
Transmission system(S)	12	20	0.6
Gear pump (PE)	250	5	50

The N-shaped graph focuses on improving reliability: here we can see that the Transmission system(S) and Speed reducer(R) sub-assemblies are the ones on which priority action needs to be taken. Various actions can be envisaged: technical modifications (component quality), operating instructions, increased surveillance (round-the-clock maintenance), systematic preventive actions initially, then conditional actions.

The Nt graph is an availability indicator, since Nt estimates the loss of availability of each sub-assembly. It can therefore be used to select the order in which failure types are handled, according to their criticality.

The graph in t¯focuses on maintainability, i.e. improving serviceability. Here, sub-assemblies E and D account for almost 80% of repair difficulties.

4.2 Noiret abacus

a Definition

The Noiret abacus is a tool used in the maintenance field to facilitate quantitative analysis and informed decision-making concerning maintenance, taking into account the specific characteristics of the equipment. It is mainly used to determine the periodicity of preventive maintenance actions, but also to determine, as a first approximation, the form of maintenance (preventive or corrective).

This method is based on the idea of optimizing maintenance decisions by balancing the costs of maintenance with the costs associated with acquisition and failures. It therefore takes several criteria into consideration, and can be broken down into three possible recommendations in the case of preventive maintenance:

- Preventive recommended: Preventive maintenance is strongly recommended.
- Preventive possible: Preventive maintenance is possible, but other factors must be taken into account.
- Preventive not necessary: Preventive maintenance is not justified.

b Basic principles of the Noiret chart

- Identify the equipment or systems for which you wish to determine the optimum preventive maintenance options.
- Take into consideration the following criteria, which can be broken down into several options, each with a corresponding number of points in ascending order:
    - Age of the equipment: From least recent to most recent.
    - Interdependence (importance for production): e.g. independent, semi-independent, essential and discontinuous operation, essential and semi-discontinuous operation or essential and continuous operation.
    - Cost: draw up a table of the different cost ranges from least to most expensive.
    - Complexity and accessibility: we can have three to four levels of complexity, going from the least complex to the most complex with
    - Robustness: From the most robust to the least robust.
    - Origin: Country of origin/ with or without after-sales service.

- ❖ Working conditions: Durations of use from least to most stressed.
- ❖ Consequences of its failures on production: Depending on the quality of the products if there is production, so options such as saleable products, products to be taken back, lost products or no products can be declined
- ❖ Production lead times for associated products: Ranging from free and flexible lead times to the tightest and most imperative lead times.

- ➢ Gather the relevant data on each piece of equipment according to the various criteria
- ➢ Evaluate each piece of equipment and match the data to the various possible options.
- ➢ Calculate a score for each item by adding the points of the corresponding options according to the evaluation made.
- ➢ Classify equipment according to its score, so that equipment with the highest scores is considered to require more frequent or more intensive preventive maintenance. Alternatively, divide the possible range of scores into several point intervals and associate them with the three possible preventive maintenance recommendations, thus identifying equipment for which preventive maintenance is not necessary, possible or recommended, depending on its position.
- ➢ Prioritize actions and determine appropriate preventive maintenance options for each piece of equipment.

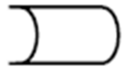
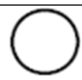
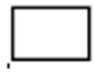
4.3 Decision tree

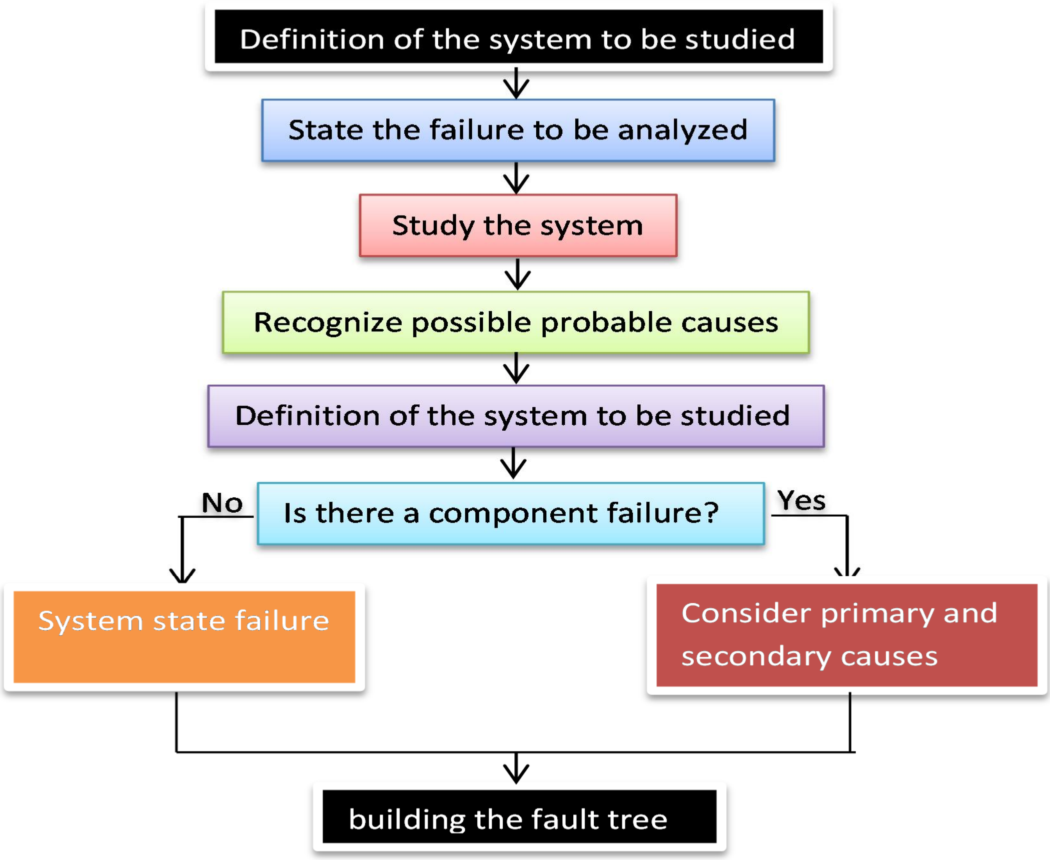
a Principle

This is a deductive diagram which goes from effect to cause, and whose purpose is to find all the combinations of elementary (primary) failures which could lead to a breakdown.

A fault tree is a powerful tool for evaluating the reliability of systems during their design phase.

Basic symbols used to construct the fault tree:

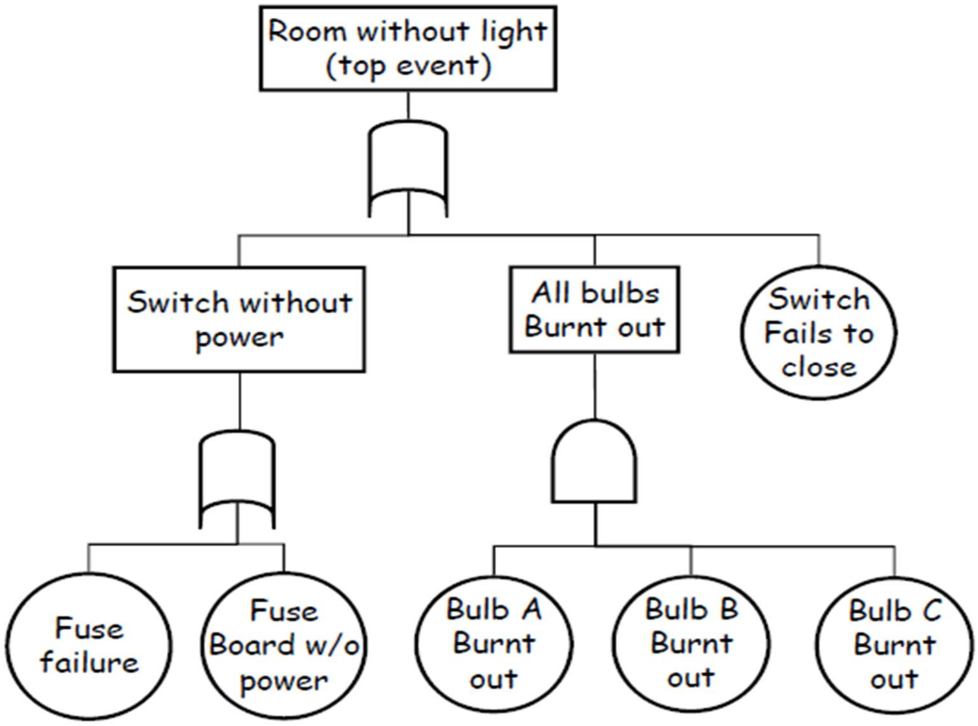
OR Gate: This symbol denotes that an output fault event occurs if one or more of the input fault events occur	
AND Gate: This symbol denotes that an output fault event occurs if all the input fault events accur.	
Basic fault event: A circle denotes a basic fault event or the failure of an elementary component.	
Resultant fault error: A rectangle denotes a fault event that results from a combination of failure events through the input of a logic gate.	



Decision tree

b Example

Develope a fault tree for a system comprising a windowless room with one switch and three light bulbs. The switch can only fail to close, and the top undesirable event is the room without light.



4.4 Correlation relationships

In quantitative maintenance analysis, correlation relationships refer to the statistical links between maintenance variables and the operational performance of equipment, such as downtime, preventive and corrective maintenance interventions, and the cost of replacement parts. They enable us to understand how different aspects of maintenance affect equipment reliability, availability and durability.

Principle:

A correlation study examines the relationship between two variables at the same time. The principle is to collect all the statistical data linked to the variables and plot the values on an XY graph. The relationships obtained can then be

- Functional relationships: which denote direct, predictable and uncertainty-free relationships between variables (deterministic).
- Stochastic links: which designate probabilistic, statistical relationships with some uncertainty between variables (non-deterministic).

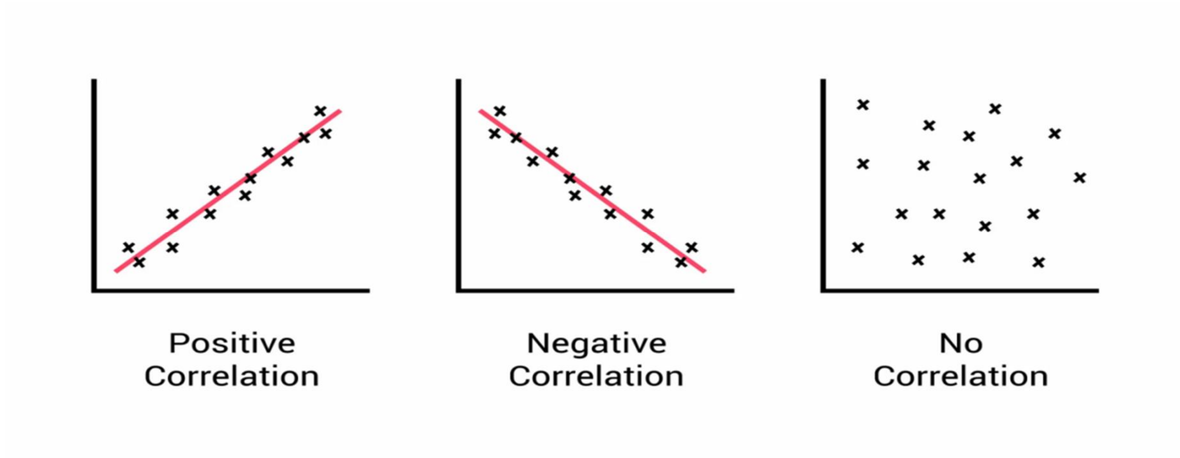
When the link is stochastic, the question is whether there is an influential relationship between the variables, and if so, which one (perhaps a functional relationship), and what the risk of error is.

N.B.: It is possible to perform multiple analyses to explore relationships between several pairs of variables in a single study. In this case, it would be wise to rank them in order of importance.

Based on this data, the correlation coefficient is calculated and interpreted to determine the strength and direction of the relationship between the variables.

The correlation coefficient ranges from -1 to +1:

- A correlation close to +1 indicates a strong positive correlation, meaning that the variables are moving in the same direction.
- A correlation close to -1 indicates a strong negative correlation, meaning that the variables are moving in opposite directions.
- A coefficient close to 0 indicates weak or no correlation between the variables.



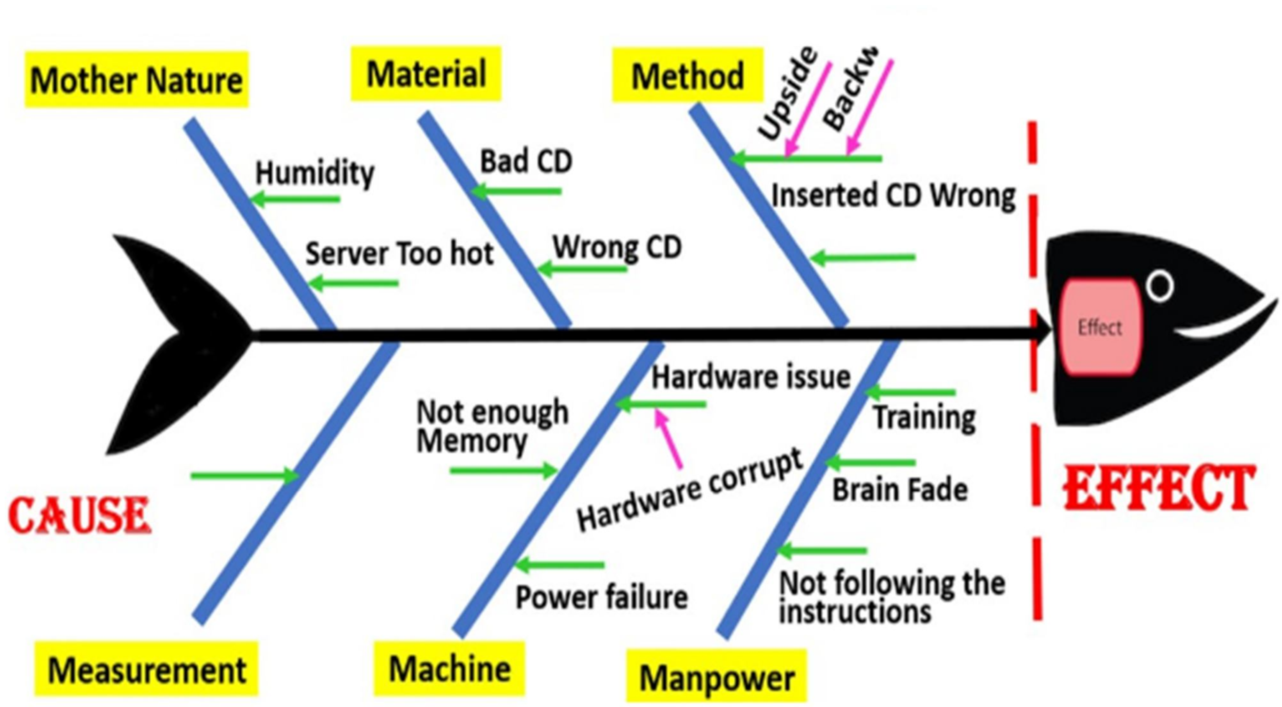
4.5 Fishbone diagram

Principle

Also known as the Ishikawa Diagram or Cause-and-Effect Diagram, the Fishbone diagram typically consists of six main elements, represented as "bones", that help categorise potential causes of a problem.

- **Problem or Effect:** Displayed at the head or the mouth of the fishbone, this is the issue or undesired outcome that the team aims to investigate and address. The problem statement should be clear, specific, and measurable.
- **Major Cause Categories:** The primary branches extend from the main arrow of the diagram, representing major categories of potential causes. The categories may vary depending on the specific context, but common ones include:

- ❖ **Man** - Refers to the people involved in the process or task.
- ❖ **Methods** - Involves the procedures or standard work used in the process.
- ❖ **Machines** - Encompasses the equipment and tools used in the process.
- ❖ **Materials** - Involves the raw materials or inputs used in the process.
- ❖ **Measurements** - Represents the data and metrics used to evaluate the process.
- ❖ **Mother Nature (Environment)** - Includes external factors or conditions affecting the process.



5 Conclusion

Understanding and applying structured failure analysis methods is key to continuous improvement in industrial systems. This chapter has presented several valuable tools—including the Pareto Chart, Noiret Abacus, decision trees, correlation relationships, and the Fishbone diagram—that aid in visualizing, organizing, and prioritizing failure data. Each method offers unique insights, enabling a deeper understanding of root causes and supporting better decision-making. By integrating these tools into maintenance and quality management practices, organizations can significantly enhance operational efficiency, reduce recurring issues, and promote a culture of proactive problem-solving.

Chapter 4
Diagnostic

1 Introduction

In the context of complex systems, the ability to accurately diagnose malfunctions and inefficiencies is crucial for ensuring reliability and optimal performance. This chapter introduces the fundamentals of diagnostic processes and explores the structured methods used to analyze system functionality. Starting with a definition of diagnostic approaches, the chapter outlines the key stages involved in conducting a diagnosis and presents several essential analysis tools. These include functional analysis methods such as SADT (Structured Analysis and Design Technique) and FAST (Function Analysis System Technique), as well as visual and logical tools like block diagrams, functional chains, logic equations, and Grafcet diagrams. By leveraging these tools, engineers can break down system operations, identify root causes of failure, and develop targeted corrective actions.

2 Definition:

identification of the cause of a failure using logical reasoning.

A failure is anything that is abnormal, anything that deviates from a standard of correct operation (alarm, untimely stop, defective product, etc.). The defect that appears is called a symptom.

A symptom is a discrepancy between what is and what should be. The symptom is the fault that the maintenance engineer observes. It is from the symptom that he will look for the causes. The symptom must be described as precisely as possible, i.e. the failure must be characterized:

- An engine that suddenly stops;
- A loud, muffled noise (difficult to locate);
- A smell of burnt brakes.

3 Diagnosis

This requires a large amount of information to be gathered:

- From users (detection, manifestation and symptoms)

- Manufacturer and/or maintenance department documents.

But there is also field experience and know-how.

a. Manifestation of the failure: The manifestation (or effect) of the failure is manifested by its amplitude (partial or complete), its speed (it is progressive or sudden), its character (it is permanent, fugitive or intermittent).

b. Symptoms: Symptoms can be observed in situ, without dismantling, by users of the equipment or by the maintainer: VTSAT, measurements, quality defects. VTSAT is the natural use of an individual's five senses. They should never be neglected, as they are capable of contributing to the establishment of a diagnosis.

Sight (V):

- Detection of cracks, leaks, disconnections,
- Detection of mechanical damage.

Touch (T):

- Sensation of heat, vibration,
- Estimation of surface condition.

Smell (S):

- Detection of the presence of particular products,
- Burnt smell", hot clutch,...

Auditory (A):

- Detection of characteristic noises (rubbing, whistling).

Taste (T):

- Identification of a product (leak).

Symptoms can also be observed after disassembly: measurements, observations of breakage, surface condition, non-destructive testing, etc.

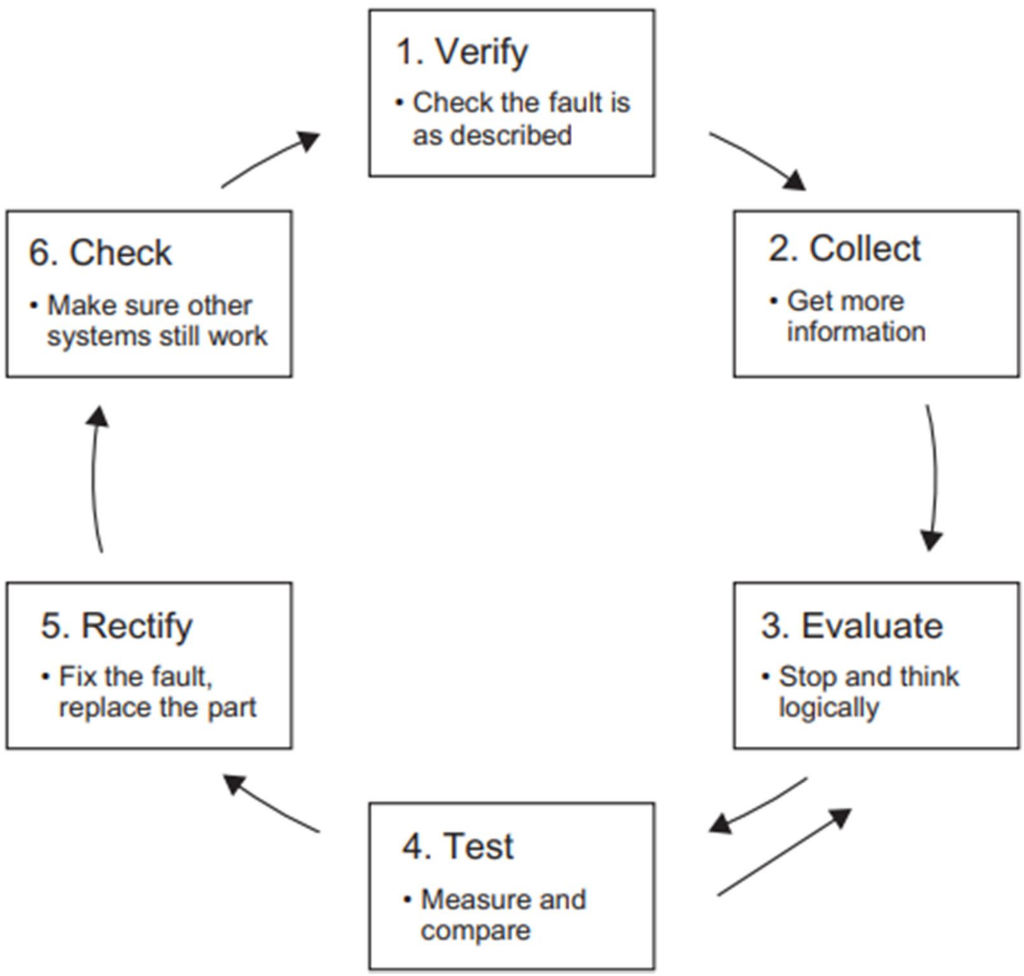
c. Experience: When tackling a failure problem on a piece of equipment, the maintainer cannot afford to navigate by sight. He already knows the probabilities of failure on a piece of equipment. For example, on an SAP (Automated Production System), we know that it's the operating part that will cause the most breakdowns.

d. Know-how: Diagnosis is like a police investigation: the maintainer starts from information and symptoms, and on the basis of his experience, he formulates hypotheses assigned with a greater or lesser degree of probability, and tests these hypotheses in order to build up a certainty.

4 Stage diagnostic process

The diagnostic stage process is recommended but there are others that are similar – the important thing is to follow any 'process' logically:

1. Verify: Is there actually a problem, can you confirm the symptoms
2. Collect: Get further information about the problem, by observation and research
3. Evaluate: Stop and think about the evidence
4. Test: Carry out further tests in a logical sequence
5. Rectify: Fix the problem
6. Check: Make sure all systems now work correctly



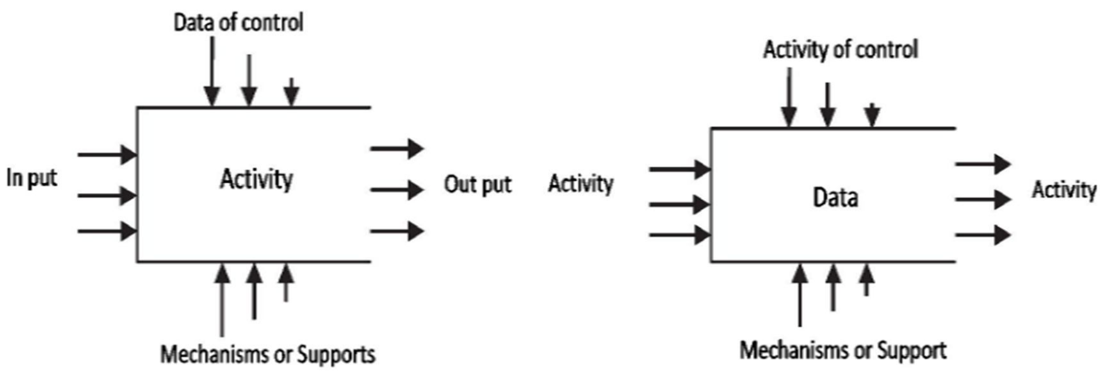
Diagnostic stage

5 Analysis tools

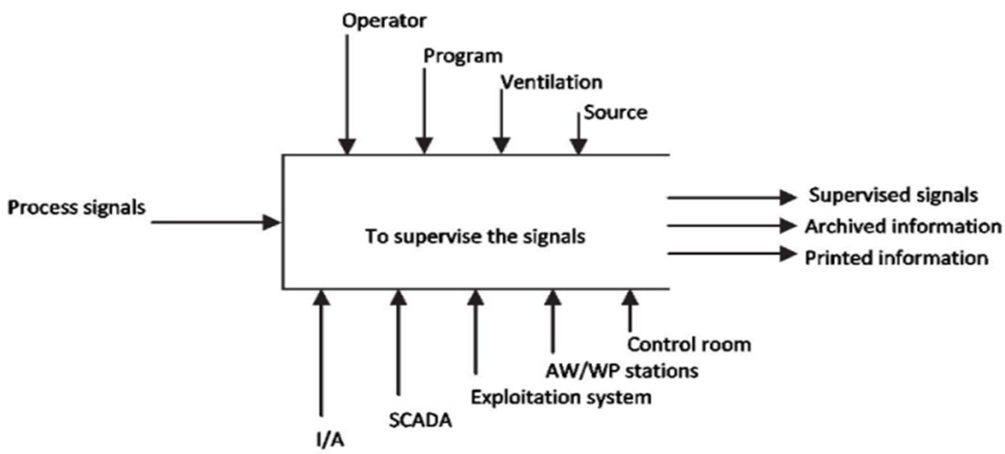
The aim is to understand the system and how it works. Several tools can be used. The choice will depend on the type of machine to be studied and the assumed type of failure. Here is a list of tools and how they can be used.

a. Functional analysis using the SADT (Structured Analysis and Design Technique)

The SADT method is a graphical method which starts with the general and works down to the details. The method, applied industrially, is a tool for communication between people from different backgrounds. It enables the flow of materials and energy through a system to be described in a common language. The representation model takes the form of Actigrams, rectangles based on the system's activities or functions.



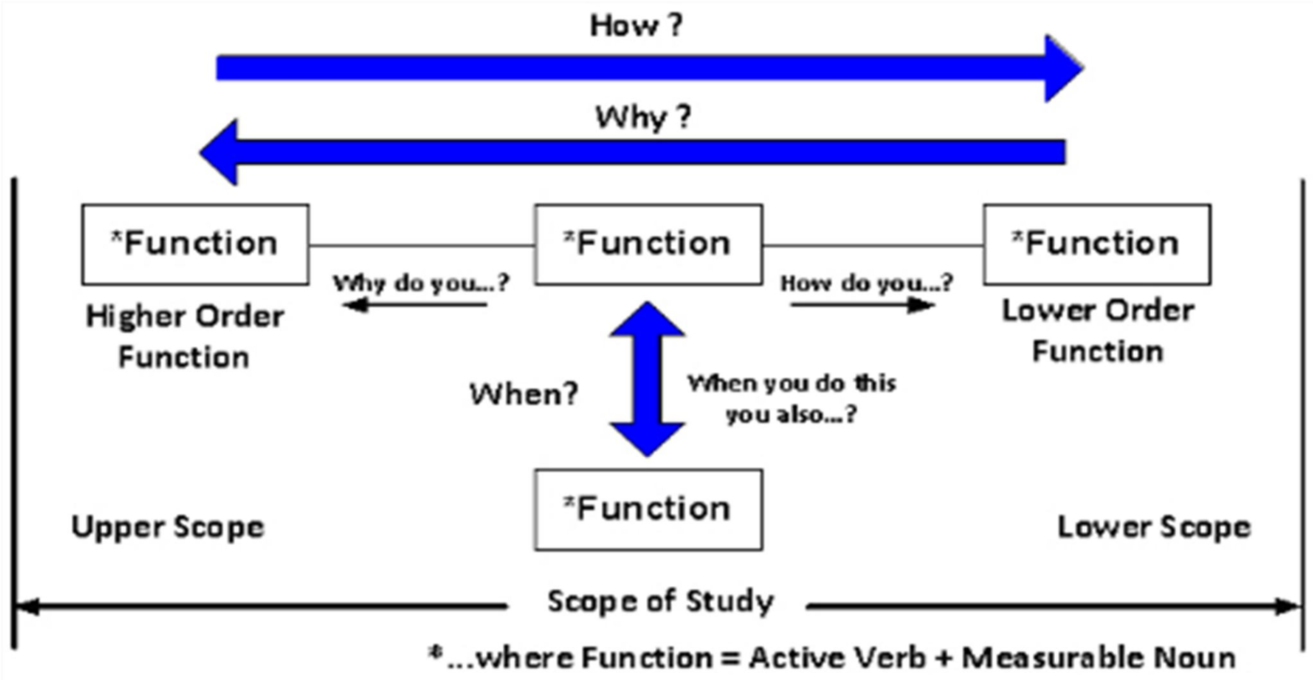
Organization of the SADT model



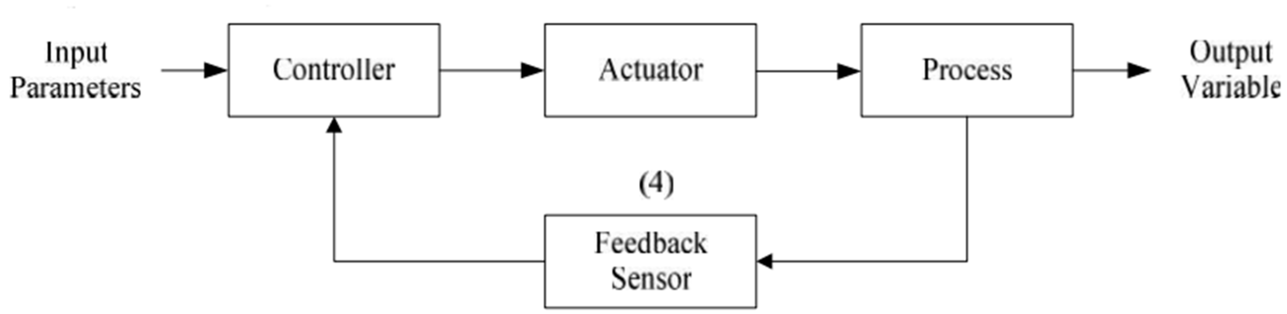
A-0 level of the SADT model

b. Functional analysis using the FAST (Function Analysis System Technique)

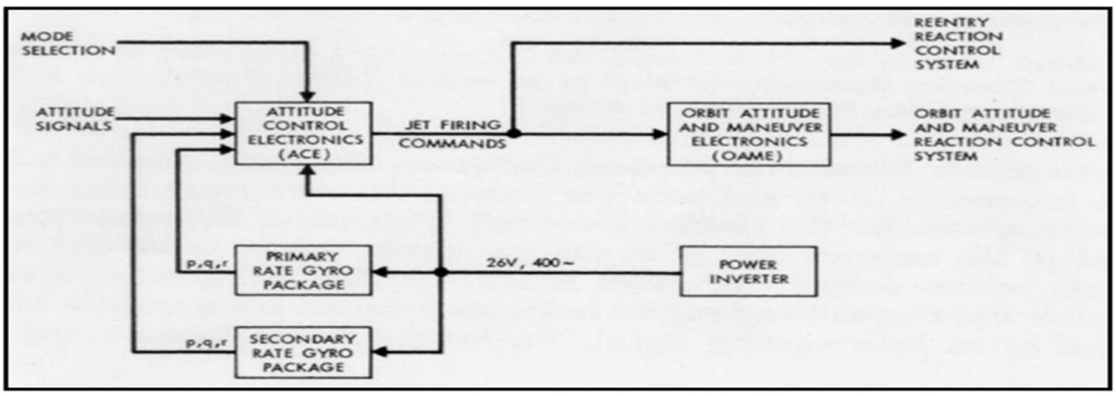
The FAST (Function Analysis System Technique) diagram translates each service function into technical function(s), and then into technical solution(s). It is constructed from left to right, in a logic of why and how. The FAST diagram provides essential data for understanding a complex product and improving the proposed solution.



c. Block diagrams: Well suited to mechanical assemblies for describing the kinematics of a movement. Use for mechanical faults

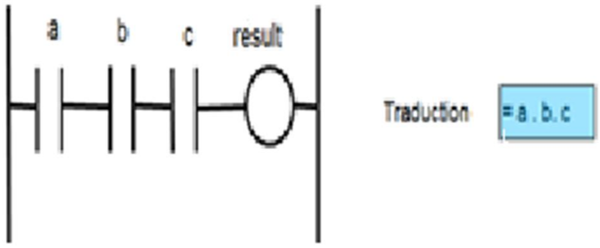


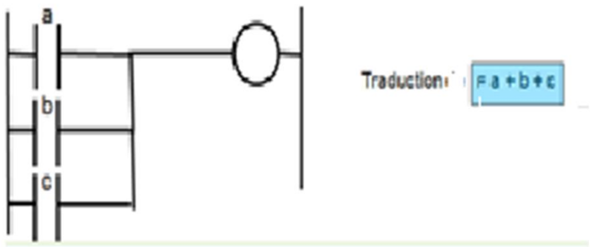
d. Functional chain: Well suited to automated systems, to describe the transmission of energy and information flows in an automated system.



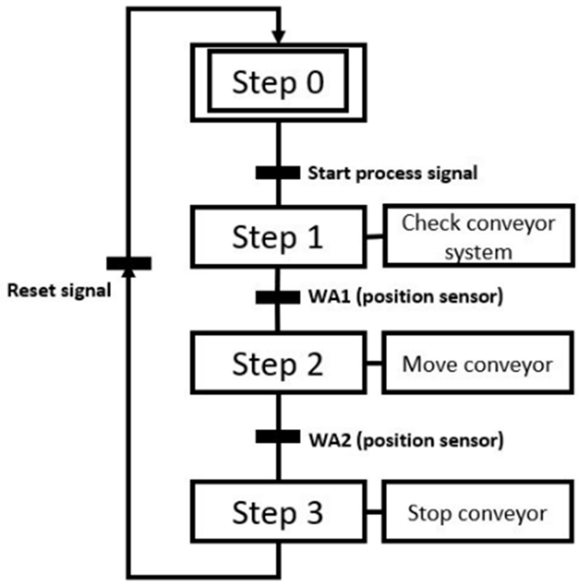
Functionel block diagram

e. Logic equations: Well suited to describing the operating conditions of systems in wired logic (electrical cabinet of a tower, freight elevator) or programmed in “ladder”.

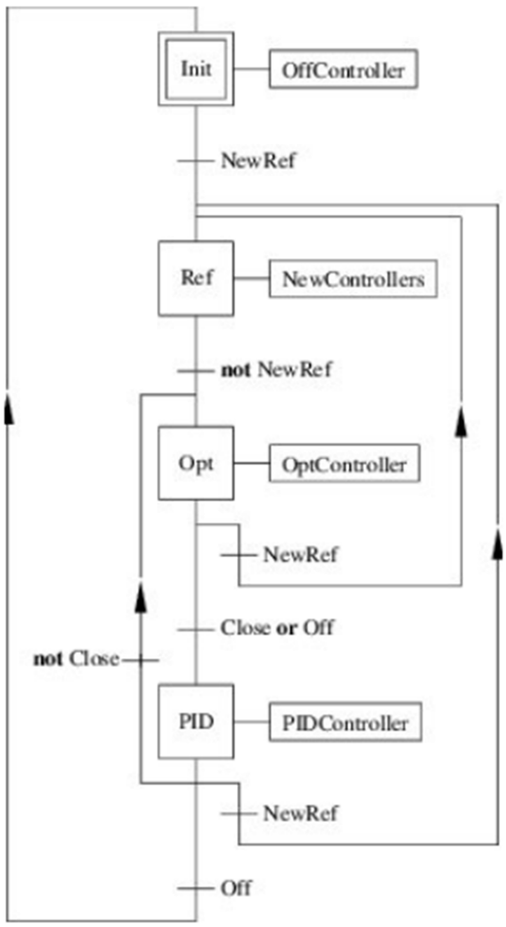




f. Grafcet: Ideal tool for describing any sequential operation.



Grafcet diagram for Switching car task.



Grafcet diagram describing the control algorithm

6 Conclusion

A well-structured diagnostic process is indispensable for understanding system behavior and resolving complex issues effectively. Throughout this chapter, we have examined both the stages of diagnosis and a variety of analytical tools that support functional analysis. Techniques such as SADT, FAST, block diagrams, logic equations, and Grafcet offer complementary perspectives that help clarify system structure and identify weak points. When integrated into maintenance and design workflows, these tools enhance decision-making, reduce errors, and improve system reliability. Mastering them is a key step toward more efficient and intelligent problem-solving in technical and industrial contexts.

Chapter 5
Predictive failure analysis

1 Introduction

Failure Modes, Effects, and Criticality Analysis (FMECA) is a systematic and structured approach used to evaluate potential failure modes within a system, their causes and effects, and the severity of their consequences. This chapter provides a comprehensive overview of FMECA, beginning with its definition and scope of application. It explores the different categories of FMECA, the detailed steps involved in its implementation, and how criticality ratings are assigned and interpreted. Additionally, the chapter discusses the advantages and limitations of this method, offering valuable insights into its practical utility in risk management and system reliability improvement.

2 Definition

Initially, the FMECA was called FMEA (Failure modes and analysis). The C in FMECA indicates that the criticality (or severity) of the various failure are considered and ranked. Today, FMEA is oen used as a synonym for FMECA. The distinction between the two terms has become blurred. However, there are certain differences between the two processes

FMEA	FMECA
FMEA is used for process	FMECA is used for system
Criticality analysis is not performed	Criticality analysis is performed
Problem prevention is the major aim of FMEA	Detection and controlling the measures contributing to failure mode by providing management information is the major aim of FMECA
Human errors are examined to a certain limit and the output is dependent on the operation	Human errors are not considered

mode	
Less time consuming compared to FMEA	FMECA are more time consuming

FMEA (FMECA) is a predictive analysis technique that allows for the estimation of the risks of failure and the consequences for the proper functioning of the production system, and for the initiation of necessary corrective actions, to resolve potential problems in a system before they occur.

The following table describes the four questions, which are sufficient to provide an overview of the logic followed and help understand that FMEA (FMECA).

Failure modes/Potential	Possible effects	Possible causes	Monitoring plan
What could go wrong?	What could be the effects?	What could be the causes?	How can we see this?

3 Scope of Application

FMECA has proven its worth in the following industries: space, weapons, mechanical engineering, electronics, electrical engineering, automotive, nuclear, aeronautics, chemistry, and IT. More recently, it has begun to gain interest in services. Since FMECA is considered a total quality tool, it is now possible to anticipate problems in all systems of the business process and seek preventive solutions in advance.

4 Categories of FMECA

There are several types of FMECA, including the following

1. *Organizational FMECA*: This is a study that applies to the different levels of business processes: from the first level, which encompasses management, information, production, personnel management, marketing, and financial processes, to the final level, such as the organization of a work task.

2. *Product FMECA*: This is used to study in detail the design phase of a product or project.

3. *System or production means FMECA*: This is a study that analyzes the design and/or operation of production equipment to improve its reliability and availability, and sometimes even its safety.

4. *Service FMECA*: This is used to verify that the added value in the service meets customer expectations and that the service delivery process does not cause failures.

5. *Safety FMECA*: This aims to analyze failures and predictable risks on equipment in order to improve its safety and reliability. 6. Process FMEA: It allows the validation of the manufacturing range of a product. It is used to analyze and evaluate the criticality of all potential failures of a product caused by its process. In other words, it allows the analysis of production operations to improve the manufacturing quality of the product.

6. *Machine FMECA* (or production equipment): this identifies production equipment failures whose effects have a direct impact on the company's productivity. This involves failure analysis and maintenance optimization.

7. *Process FMECA*: this identifies failures in the manufacturing process whose effects have a direct impact on the quality of the manufactured product (failures are not taken into account).

5 Steps of FMECA

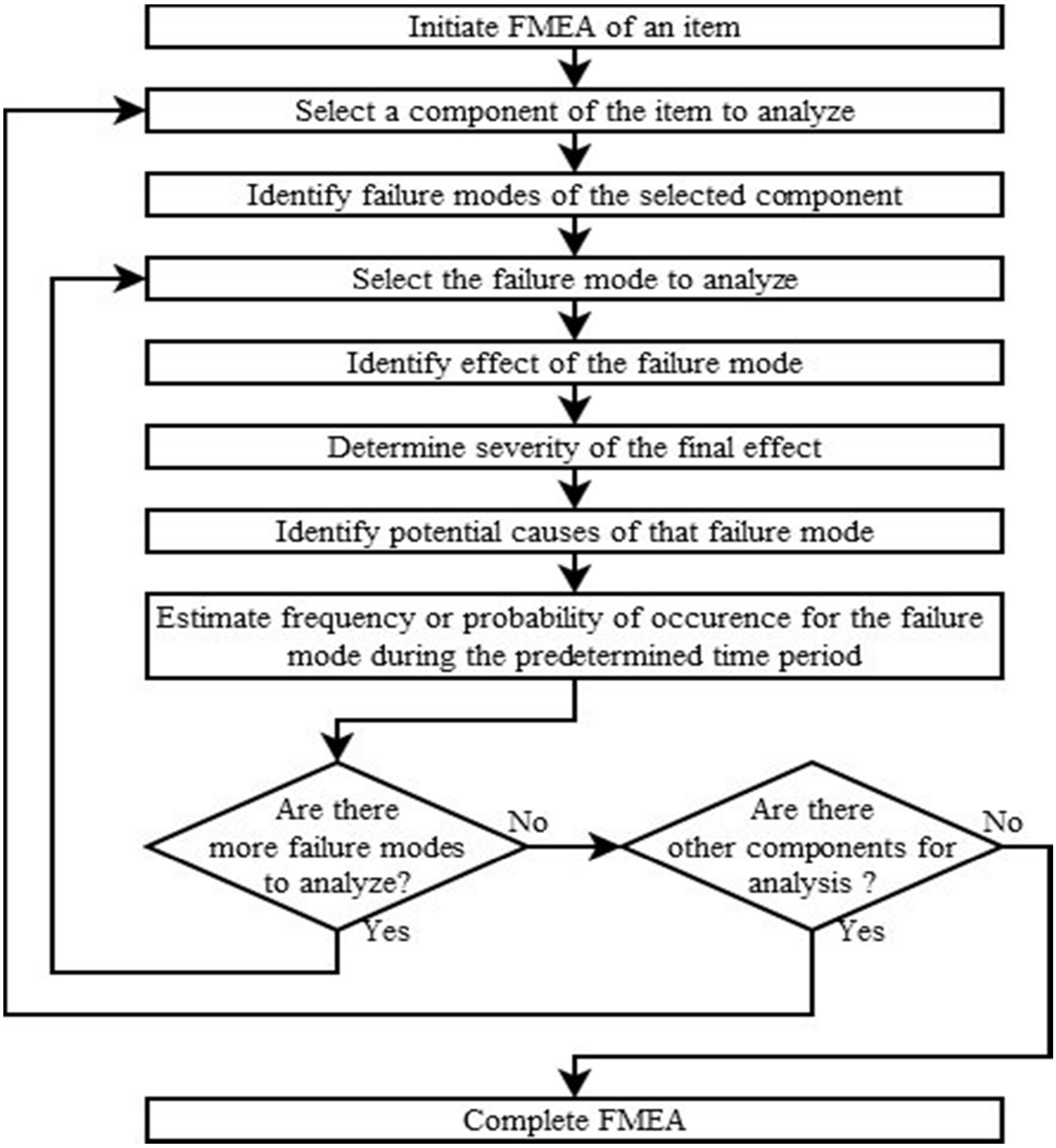
The FMECA is carried out in several steps, which include:

a- System Breakdown

The system is broken down into subsystems based on interrelationships among its various subsystems. The number of levels used in the breakdown depends on the objective of the FMECA study. Subsequently, the components of each subsystem are identified.

b- Define the Operational Mode and Function of each Component

For each component, the operational mode, describing the specific state or condition in which the component operates, and the function, referring to the specific role or task the component performs within the system, are defined.



Steps of FMEA (FMECA)

c- Identify Failure Modes, Causes, and Detection Methods (Controls)

For each component, relevant failure modes, indicating how a component could fail to meet its intended function or purpose, as well as the causes of failures, underlying reasons or mechanisms leading to a failure mode, are identified. Additionally, the methods of failure detection (controls), which encompass possible ways to detect, prevent and mitigate the consequences and frequency of each identified failure mode, are recorded.

d- Determine Failure Modes Consequences

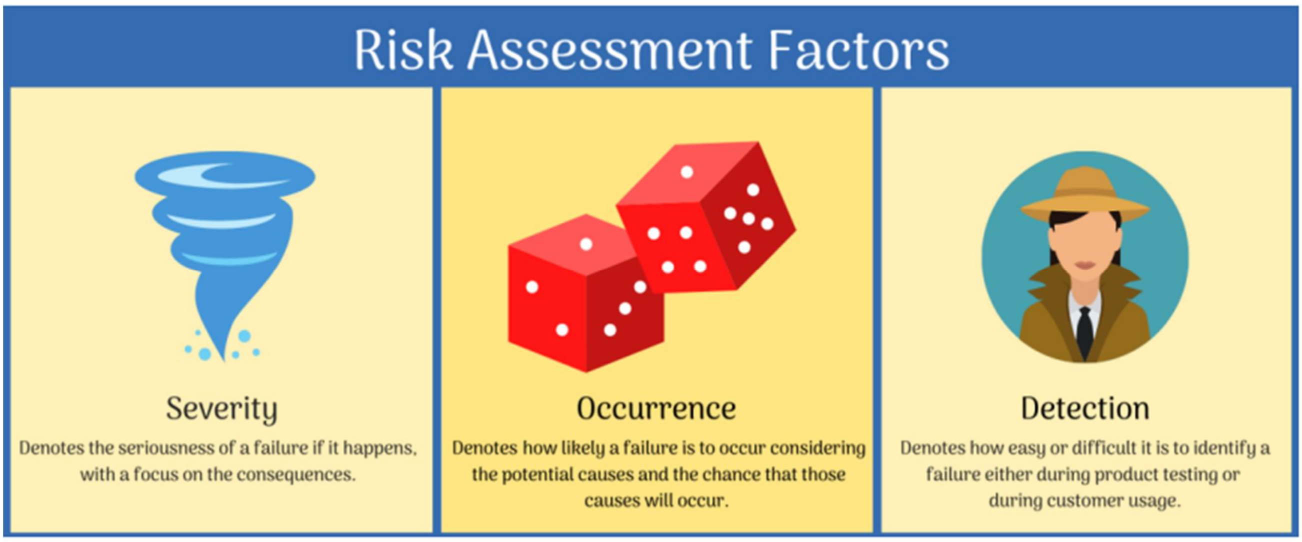
For each failure mode, credible consequences are determined and recorded. These consequences are divided into parts: local consequences, representing the impact of the failure mode on the next higher level in the hierarchy, and global consequences, representing the impact of failure mode on the entire system.

e- Assign Criticality Level (Risk) for each Failure Mode

- Notion of criticality : Criticality enables us to quantify the notion of risk. In an FMECA study, criticality is assessed on the basis of failure frequency, severity and probability of non-detection. It determines the choice of corrective and preventive actions to be taken, and sets the priority between these actions. It is a criterion for monitoring the predicted reliability of equipment.
- Criticality rating: For each failure mode i the criticality is quantified by the Risk Priority Number (RPN) defined as: $RPN = S * O * D$. The RPN is a product of severity (S), occurrence (O) and detection (D).

6 Risk Priority Number

RPN provides a numerical result, and therefore, offers an intuitive approach to risk assessment: the higher the RPN value, the higher the risk. This makes it easier for companies to develop processes for handling risk. For example, an organization may institute a rule that no RPNs can be above a certain level prior to product release. In this manner, RPNs provide an easy way to assess risk and help in developing your risk mitigation plan. RPN is determined based on three factors:



a Severity: Denotes the seriousness of the problem if it happens, with a focus on the consequences. The higher the number, the greater the severity. The Severity rating scale:

Severity	Description
10	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.
9	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.
8	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).
7	Degradation of primary function (vehicle operable, but at reduced level of performance).
6	Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable).
5	Degradation of secondary function (vehicle operable, but comfort / convenience functions at reduced level of performance).
4	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by most customers (> 75%).
3	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by many customers (50%).
2	Appearance or Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (< 25%).
1	No discernible effect.

b Occurrence*:* Denotes how likely the issue is to occur. To determine the rate of occurrence, you'll want to look at all the potential causes of a failure and the chance that those causes will occur. The higher the number, the greater the probability of occurrence.

The Occurrence rating scale:

Occurrence	Description
10	New technology/new design with no history.
9	Failure is inevitable with new design, new application, or change in duty

	cycle/operating conditions.
8	Failure is likely with new design, new application, or change in duty cycle/operating conditions.
7	Failure is uncertain with new design, new application, or change in duty cycle/operating conditions.
6	Frequent failures associated with similar designs or in design simulation and testing.
5	Occasional failures associated with similar designs or in design simulation and testing.
4	Isolated failures associated with similar design or in design simulation and testing.
3	Only isolated failures associated with almost identical design or in design simulation and testing.
2	No observed failures associated with almost identical design or in design simulation and testing.
1	Failure is eliminated through preventive control.

c Detection*:* Denotes how easy or difficult it is to identify the problem. A higher rating means an issue is less likely to be detected either by engineers during the test phases of product development or by customers after product release. Therefore, the higher the number, the less likely the failure is detected. The Detection rating scale:

Detection	Description
10	No current design control; Cannot detect or is not analyzed.
9	Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g., CAE, FEA, etc.) is not correlated to expected actual operating conditions.
8	Product verification/validation after design freeze and prior to launch with pass/fail testing (Subsystem or system testing with acceptance criteria such as ride and handling, shipping evaluation, etc.).
7	Product verification/validation after design freeze and prior to launch with test to failure

	testing (Subsystem or system testing until failure occurs, testing of system interactions, etc.).
6	Product verification/validation after design freeze and prior to launch with degradation testing (Subsystem or system testing after durability test, e.g., function check).
5	Product validation (reliability testing, development or validation tests) prior to design freeze using pass/fail testing (e.g., acceptance criteria for performance, function checks, etc.).
4	Product validation (reliability testing, development or validation tests) prior to design freeze using test to failure (e.g., until leaks, yields, cracks, etc.).
3	Product validation (reliability testing, development or validation tests) prior to design freeze using degradation testing (e.g., data trends, before/after values, etc.).
2	Design analysis/detection controls have a strong detection capability. Virtual analysis (e.g., CAE, FEA, etc.) is highly correlated with actual or expected operating conditions prior to design freeze.
1	Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g., proven design standard, best practice or common material, etc.).

d Example

The best way to understand how RPN is used is through an example. For our sample scenario, we'll consider a FMEA performed by a manufacturer of car batteries.

In this case, we'll zone in on one particular failure mode: the battery goes dead. For this failure mode, there are several causes and effects. For this example, one obvious effect is that the car does not start. One of the causes is that the driver failed to turn the headlights off.

We determine the RPN by analyzing the component factors:

1. Severity. Using the 1-10 scale, we determine the severity level is a 5. It is not a catastrophic failure, but one that is an annoyance, and clearly impacts customer satisfaction.

2. Occurrence. Using the 1-10 scale, we determine the occurrence level is a 7 due to the fact that if the headlights are left on there is a high likelihood this failure will occur.

3. Detection. In this case, there is no method of detection, so our Detection value is a 10, indicative of no detection.

The resulting RPN = Severity * Occurrence * Detection = 5 * 7 * 10 = 350.

7 Criticality matrix

a. principle

To prioritize possible failure modes, a risk priority number is assigned to each failure mode, indicating the degree of importance. Typically, this number is determined through criticality analysis by using a Criticality Matrix (Risk Matrix), which comprises two axes: Severity and Likelihood of occurrence.

The severity axis, the potential impact or consequences of each failure mode are assessed, often categorized into levels such as minor, moderate, major, and critical, based on specific analysis needs.

The likelihood of occurrence (Probability of Occurrence) *axis* evaluates the probability or frequency of each failure mode occurring, typically categorized into levels such as unlikely, possible, occasional, and frequent. The Probability of Occurrence is determined based on failure mode probabilities. Failure mode probability is computed by:

Failure mode probability $= 1 - e^{(-\lambda t)}$

where

λ = mode failure rate

t = time: the amount of the mission phase time of the failure mode

In FMECA, there are two criticality values: mode criticality and item criticality. Both are useful when analyzing risk levels.

Mode criticality is a numerical value determined for each failure mode. The equation for mode criticality is:

*Mode Criticality = Mode Failure Rate * Operating Time * Failure Effect Probability*

Where mode failure rate is computed by:

*Mode Failure Rate = Item Failure Rate * Failure Mode Percentage*

Essentially, mode failure rate is the percentage of the failure rate attributable to a given failure mode. Consider an example of an item with a failure rate of 50 FPMH (Failures per Million Hours) with two failure modes: one failure mode has a failure mode percentage of 80%, and the other is 20%. In this case, the mode failure rate of the first failure mode is 40 FPMH, and of the second is 10 FPMH.

b. Levels

Essentially, for each item, there is a set of criticality values. The number of criticality values is based on the number of levels used when determining the Severity rating. For example, the most commonly used Severity Classification is a 4-level scale defined in MIL-STD-1629:

I. Catastrophic (Category I): A failure which may cause death or weapon system loss (i.e. aircraft, tank, missile, ship, etc.).

II. Critical (Category II): A failure which may cause severe injury, major property damage, or major system damage which will result in mission loss.

III. Marginal (Category III): A failure which may cause minor injury, minor property damage, or minor system damage which will result in delay or loss of availability or mission degradation.

IV. Negligible (Category IV): A failure not serious enough to cause injury, property damage or system damage, but which will result in unscheduled maintenance or repair.

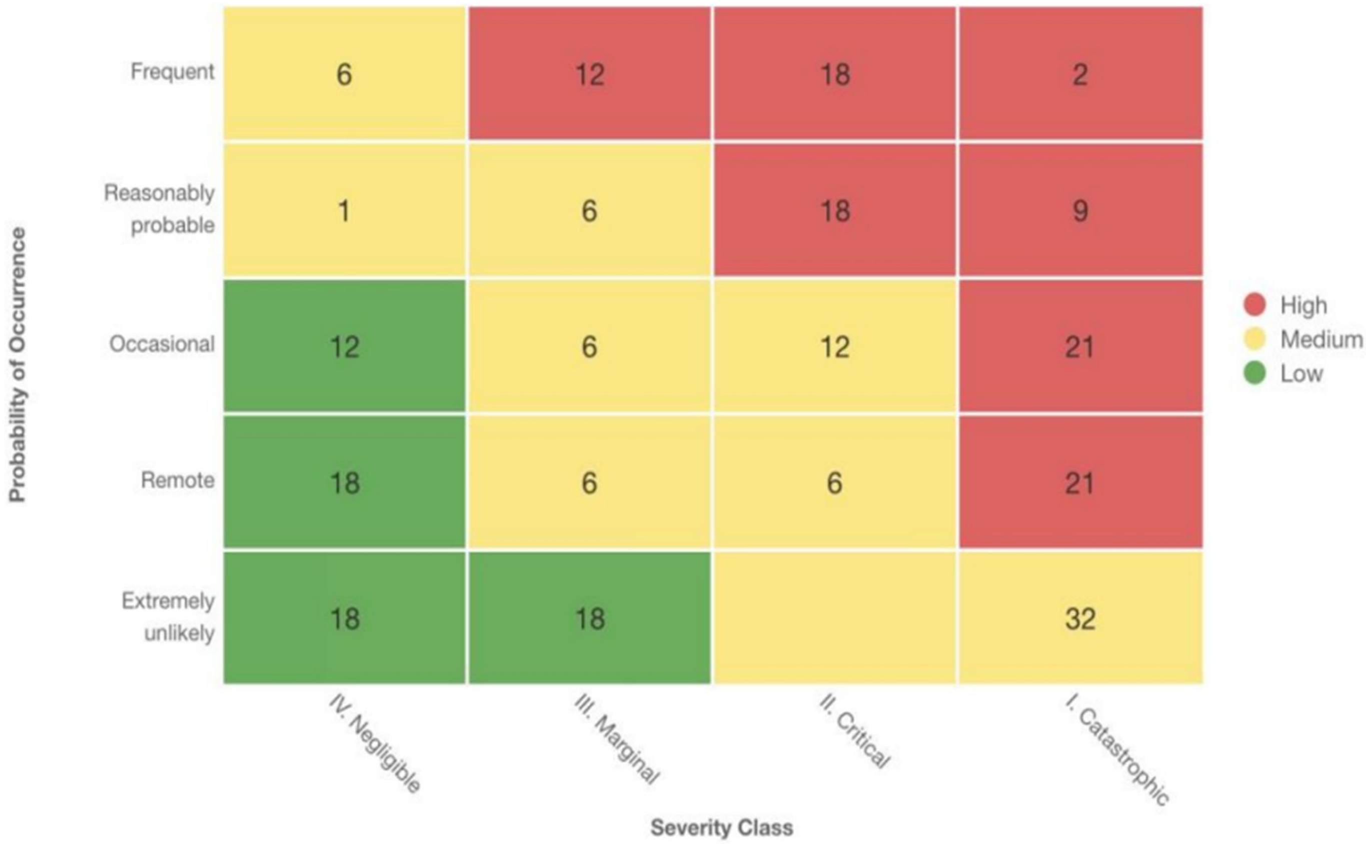
Similar to the way a risk matrix is used for analyses employing RPN values, a FMECA criticality matrix can be used for analysis purposes.

Using these values, the Probability of Occurrence is designated as one of these five levels per MIL-STD-1629A:

- Frequent (Level A): A high probability of occurrence, defined as a single failure mode probability greater than 0.20 of the overall probability of failure during the item operating time.
- Reasonably probable (Level B): A moderate probability of occurrence, defined as a single failure mode probability which is more than 0.10 but less than 0.20 of the overall probability of failure during the item operating time.

- Occasional (Level C): An occasional probability of occurrence, defined as a single failure mode probability which is more than 0.01 but less than 0.10 of the overall probability of failure during the item operating time.
- Remote (Level D): An unlikely probability of occurrence, defined as a single failure mode probability which is more than 0.001 but less than 0.01 of the overall probability of failure during the item operating time.
- Extremely unlikely (Level E): A failure whose probability of occurrence is essentially zero during the operating time interval, defined as a single failure mode probability less than 0.001 of the overall probability of failure during the item operating time.

The FMECA criticality matrix graphs Severity Classification vs. Probability of Occurrence. Again, the number of failure modes in each category is designated in the boxes on the graph. The green/yellow/red color coding is utilized to designate failures of low, medium, and high risk. Those in the red range are the most critical items to address.



While the criticality analysis using FMECAs is much more complex, it offers the unique advantage of being comprehensive, quantifiable, and robust. It is a much more precise risk assessment technique in contrast to the more qualitative approaches of RPN

c. Example

Returning to our car battery manufacturer used in our previous examples, let's determine criticality values. Again, the failure mode under analysis is that the battery goes dead. The effect is that the car does not start, and one of the causes is that the driver failed to turn the headlights off.

For criticality analysis, we need additional information: the failure rate of the item and the operating time. We'll say we've determined the failure rate of the item using a Reliability Prediction analysis as 57.5 FPMH. We determined that this failure mode percentage is 75%.

For the time, we need to determine the operating time for this particular failure mode. For this example, we are going to look at the probability of failure over a year. We'll make the assumption that the car is driven about 2 hours/day and the lights are on for nighttime driving about 1/3 of the time. Therefore:

Operating Time = 2 hours/day * 365 days/year * 1/3 = 243.33 hours

We also need to identify the failure effect probability. In this case, the probability of the car not starting is high due to the lights being left on, so we'll say it is 0.8.

Our Mode Failure Rate = Item Failure Rate * Failure Mode Percentage =

57.5 * 75% = 43.125 FPMH

*Our Mode Criticality = Mode Failure Rate * Operating Time * Failure Effect Probability =*

*43.125 * 243.33 * 0.8 = 8394.885*

In FMECAs Mode Criticality values can widely vary. They all depend on the factors and failure rates of the system being analyzed. To use it effectively, you must review

In this example, using the Severity Classification list from MIL-STD-1629, this failure would be Marginal. In the computation of Item Criticality, this failure mode's Mode Criticality would be included in the Marginal level value.

To compute the Failure Mode Probability in order to assess Probability of Occurrence:

Failure mode probability

$$1 - e\ (-\lambda t)\ =\ 1 - e^{(-43.125\text{ failures}/1000000\text{ hours} * 243.33\text{ hours})}\ =\ 0.0104$$

So, for Probability of Occurrence, this example would fall into the Occasional level. Therefore, with the Severity as Marginal and the Probability of Occurrence as Occasional, finding the point of intersection on the Criticality Matrix, this mode would fall into the Medium (yellow) range using our example risk matrix color coded levels.

8 Advantages and Limitations of FMECA

Building on the preceding description, the advantages and limitations of FMECA can be succinctly identified and clarified as follows.

The advantages of FMECA are:

- Improve the quality, reliability and safety of a product/process
- Improve company image and competitiveness
- Increase user satisfaction
- Reduce system development timing and cost
- Collect information to reduce future failures, capture engineering knowledge
- Reduce the potential for warranty concerns
- Early identification and elimination of potential failure modes
- Emphasize problem prevention
- Minimize late changes and associated cost
- Catalyst for teamwork and idea exchange between functions
- Reduce the possibility of same kind of failure in future
- Reduce impact of profit margin company
- Reduce possible scrap in production
- Ensuring that any failure that could occur will not injure the customer or seriously impact a system.
- To produce world class quality products

The limitations of FMECA are:

- It is heavily dependent on the expertise and judgment of the individuals conducting the analysis. Varying analysts may prioritize each failure mode differently during criticality analysis, resulting in inconsistent outcomes.

- It can become complex, particularly for large and interconnected systems when the number of potential failure modes is extensive. Handling and analyzing the substantial volume of data produced by FMECA can pose challenges and be time-consuming.
- It demands significant time, effort, and resources when conducted comprehensively. Organizations should deploy dedicated personnel to effectively carry out the analysis.
- It aims to identify potential failure modes based on historical data and expert knowledge. However, it may not accurately predict future failures, especially for complex systems with unforeseen interactions or environmental factors.
- It is typically performed as a one-time analysis at a specific point in time. It may not account for changes in the system over its lifecycle or new failures that may arise due to evolving technologies or operating conditions.

9 Conclucion

In summary, FMECA serves as a powerful analytical tool for identifying and mitigating risks in complex systems. By systematically assessing failure modes and their potential consequences, organizations can prioritize critical issues and implement effective control measures. While FMECA offers significant benefits in enhancing safety and reliability, it also has certain limitations, such as its dependence on expert judgment and time-intensive nature. Nevertheless, when applied correctly, FMECA remains an essential technique for proactive risk management across a wide range of industries.