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Presented by:

YADDADEN Abdennour

GUENDOUZ Mohammed Laid

<u>Theme</u>

Failure analysis at industrial machine (Turbine) by FTA (Fault tree analysis)

Jury:

Mr. ZERROUKI.M	**President**	**UKM Ouargla**
Mr. KAREK.R	**Supervisor**	**UKM Ouargla**
Mr. ROUAGDIA.K	**Examiner**	**UKM Ouargla**

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I would like to warmly thank all the professors of the mechanical engineering department and all those who contributed from near or far to the outcome of this work.

Dedication

I dedicate this work:

To my dear mother and father,

To My dear brothers and sister especially Khaled, Ibrahim, Islam and

My dear fiancée Lylia. Bae.

For their patience, their love, their support and their encouragement

To the whole Yaddaden and Guendouz family.

To Our Friends Lahcen Fraga, L'Houcine Fraga, Lyes Hamani, Malik

Si hadj, Anis Moumni, Samir, Sidali Slimani, Sidali Merzouken

To all M2 Industrial Maintenance students.

CHAPTER III: APPLICATION

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V.A.W.T: Vertical-Axis Wind Turbine

H.A.W.T: Horizontal-Axis Wind Turbine

HP: Hight pressure

LP: Low pressure

RPM: Rounds per minute

CM: Corrective Maintenance

IM: Improvement Maintenance

PDM: Predictive Maintenance

PM: Preventive Maintenance

RTF: Run to failure maintenance

EFNMS: European Federation of National Maintenance Societies.

K-S : KOLMOGOROV SMIRNOV

MTTR: Mean time to Repair

MUT: Mean up time

S.A.D.T.: Structured Analysis Design Technic

FTA: Fault tree analysis

β : Shape Parameter.

γ : Location Parameter.

η : Scale Parameter

A : WEIBULL Parameter

λ (**t**) : Failure rate

f(t): Probability density function

F(t): Distribution function

R(t): Reliability

M(t): Maintainability

μ: Repair rate

Di: Intrinsic Availability

D(t): Instant Availability

Abstract

Industrial maintenance is becoming increasingly important and is considered to be one of the key functions of the modern production company. The whole problem for the maintenance engineer is knowing which failures to deal with first, some of which are of little importance in terms of effects and costs. The objective of the maintenance function is to ensure optimum availability of production facilities, involving minimum economic downtime.

The objective of this work is to exploit the failure history of a gas turbine and to experimentally study the FMD indicators, thus applying the Pareto, Ishikawa and fault tree methods.

Keywords: Ishikawa, Availability, Maintainability, Reliability, Pareto, Functional analysis

Résumé

La maintenance industrielle prend une importance croissante et se Considère comme une des fonctions clé de l'entreprise de production moderne. Tout le problème pour l'ingénieur de maintenance est de savoir quelles défaillances traiter en priorité, dont certaines sont de peu d'importance en matière d'effets et de coûts. L'objectif de la fonction de maintenance est d'assurer une disponibilité optimale des installations de production, impliquant un temps d'arrêt économique minimum.

L’objectif de ce travail est d’exploiter l’historique des pannes d’une turbine à gaz et d’étudier expérimentalement les indicateurs FMD, On appliquant ainsi les méthodes Pareto, Ishikawa et l’arbre de défaillance.

Mot clé : Ishikawa, Disponibilité, Maintenabilité, fiabilité, Pareto, Analyse fonctionnelle

ملخص

اصبحت الصيانة الصناعية ذات أهمية متزايدة وأثبتت أنها وظيفة رئيسية لشركات الإنتاج الحديثة. المشكلة العامة بالنسبة لرجل الصيانة هي الأعطال التي يجب عليه التعامل معها كأولوية، وبعضها ليس له أهمية تذكر من حيث الآثار والتكاليف.

الغرض من وظيفة الصيانة هو ضمان التوفر الأمثل لمرافق الإنتاج، التي تنطوي على الحد الأدنى من وقت التوقف

الهدف من هذا العمل هو استغلال قائمة محفوظات الأعطال الخاصة بالتوربين الغازية للدراسة التجريبية لمؤشرات الموثوقية وقابلية الصيانة والتوافر، وبالتالي تطبيق الاساليب وباريتو ويشيكوا وتحليل شجرة الأعطال

الكلمات المفتاحية: يشيكوا، التوفر، قابلية الصيانة، الموثوقية، باريتو، تحليل وظيفي

INTRODUCTION

In Algeria, gas turbines have a very important role in the hydrocarbon industry to produce energy. However, these machines are subject to major degradation mechanisms. The maintenance costs and machine availability are two of the most important concerns for a turbine equipment owner. Therefore, a well-thought-out maintenance program that reduces owner costs while increasing equipment availability should be in place. For this maintenance program to be effective, owners must develop a general understanding of the relationship between operating plans and plant priorities, the skill level of operations and maintenance personnel, and all the equipment manufacturer's recommendations regarding the number and types of inspections, parts planning and other important factors affecting component life and proper operation of the equipment.

Our work is structured into three chapters, followed by a general conclusion:

The first chapter presents a generality on turbines (gas, steam, hydraulic, and wind), and a general description of the DR900 gas turbine and these characteristics to exploit its history in the third chapter.

The second chapter presents a generality on maintenance, RMA concepts (Reliability, maintainability, availability), a theoretical study on functional analysis (horned beast, octopus, S.A.D.T.), and (PARETO, ISHIKAWA, FTA) diagrams.

The third chapter presents an analysis of the history of the DR 900 gas turbine, for the study of the RMA indicators of this turbine, and the application of (PARETO, ISHIKAWA, FTA) methods on this turbine.

CHAPTER 1: FUNDAMENTALS OF TURBINES

I.1. Introduction

A turbine is a rotary mechanical device that extracts energy from a fluid flow and converts it into useful work. The conversion is generally accomplished by passing the fluid through a system of stationary passages or vanes that alternate with passages consisting of finlike blades attached to a rotor. By arranging the flow so that a tangential force, or torque, is exerted on the rotor blades, the rotor turns, and work is extracted .[1]

The work produced by a turbine can be used for generating electrical power when combined with a generator. A turbine is a turbomachine with at least one moving part called a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades so that they move and impart rotational energy to the rotor. Early turbine examples are windmills and waterwheels.

Gas, steam, and hydraulic turbines have a casing around the blades that contains and controls the working fluid. [2]

I.2. Turbine Classification

Turbines can be classified into four general types according to the fluids used: hydraulic, steam, gas, and wind. Although the same principles apply to all turbines, their specific designs differ sufficiently to merit separate descriptions.

I.2.1. Hydraulic Turbine

The hydraulic turbine is a mechanical device that converts the potential energy contained in an elevated body of water (a river or reservoir) into rotational mechanical energy.

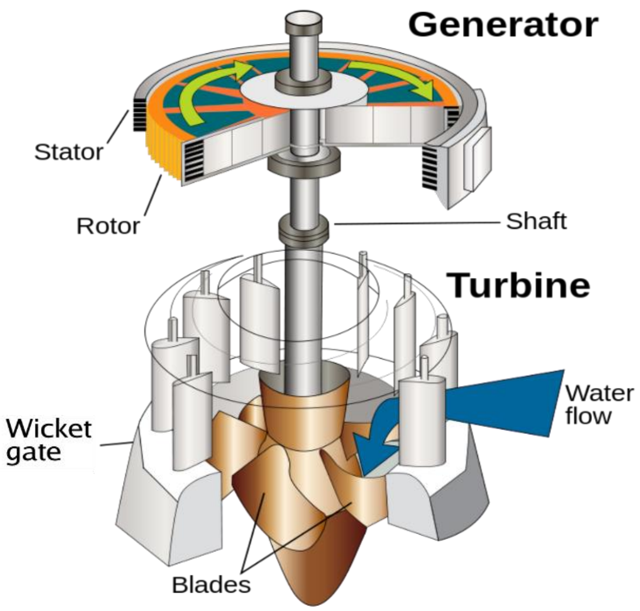


Figure I.1: Hydraulic turbine components [3]

I.2.1.1. History

Some of the key developments in hydropower technology happened in the first half of the nineteenth century. In 1827, French engineer Benoit Fourneyron developed a turbine capable of producing around 6 horsepower – the earliest version of the Fourneyron reaction turbine. In 1849, British–American engineer James Francis developed the first modern water turbine – the Francis turbine – which remains the most widely-used water turbine in the world today. In the 1870s, American inventor Lester Allan Pelton developed the Pelton wheel, an impulse water turbine, which he patented in 1880.Into the 20th century, Austrian professor Viktor Kaplan developed the Kaplan turbine in 1913 – a propeller-type turbine with adjustable blades. [4]

I.2.1.2. Hydraulic Turbine Classification

The hydraulic turbines can be classified based on type of energy at the inlet, direction of flow through the vanes, head available at the inlet, discharge through the vanes and specific speed. They can be arranged as per the following table: [5]

Table -I.1: Hydraulic turbine classification

Name	Type	Type of energy	Head	Discharge	Direction of flow	Specific speed
Pelton wheel	Impulse	Kinetic	High Head > 250 m to 1000m	Low	Tangential to runner	Low <35 single jet 35-60 Multiple jet
Francis turbine	Reaction Turbine	Kinetic + Pressure	Medium 60m to 150m	Medium	Radial/Mixed Flow	Medium 60 to 300
Kaplan Turbine	Reaction Turbine	Kinetic + Pressure	Low < 30 m	High	Axial Flow	High 300 to 1000

Figure I.2: Pelton wheel turbine

Figure I.3: Francis turbine

Figure I.4: Kaplan turbine

I.2.2. Wind Turbine

Wind turbines are systems that harness the kinetic energy of the wind for useful power. Wind flows over the rotor of a wind turbine, causing it to rotate on a shaft. The resulting shaft power can be used for mechanical work, like pumping water, or to turn a generator to produce electrical power.[6]

I.2.2.1. History

The idea of using the wind as an energy started by moving the boats along the Nile River in early time by 5000 B.C, while the first simple windmills were used in china in pumping water 200 B.C, however, Persia and the Middle East used the vertical axis windmills with woven reed sails for grinding the grain. Holland was best known for development in windmills design, by 14th century, which preformed many helpful functions in that time, including timber milling and the most important function was pumping water to drain marshy, low areas and reclaim large lands of Netherlands farming. At the end of 18th century, about 10,000 wind turbines were used in Netherland and Britain as well.

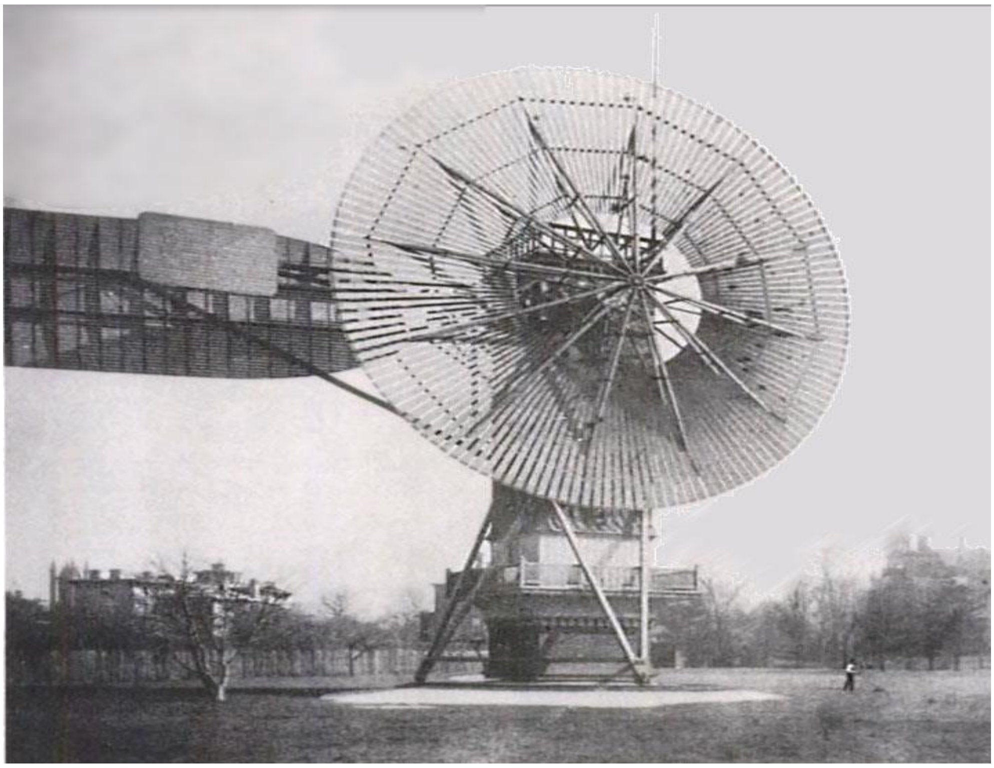


Figure I.5: History of wind turbine

By 1990 in Denmark there were about 2500 windmills for mechanical loads which were producing an estimated combined power approximately to 30MW.[7]

I.2.2.2. Wind Turbine Classifications

The wind turbine consists of two types based on the axis in which the turbine rotates. Turbine which rotates around a horizontal axis (HAWT) is more common than other the type of turbine which rotates around a vertical axis (VAWT).

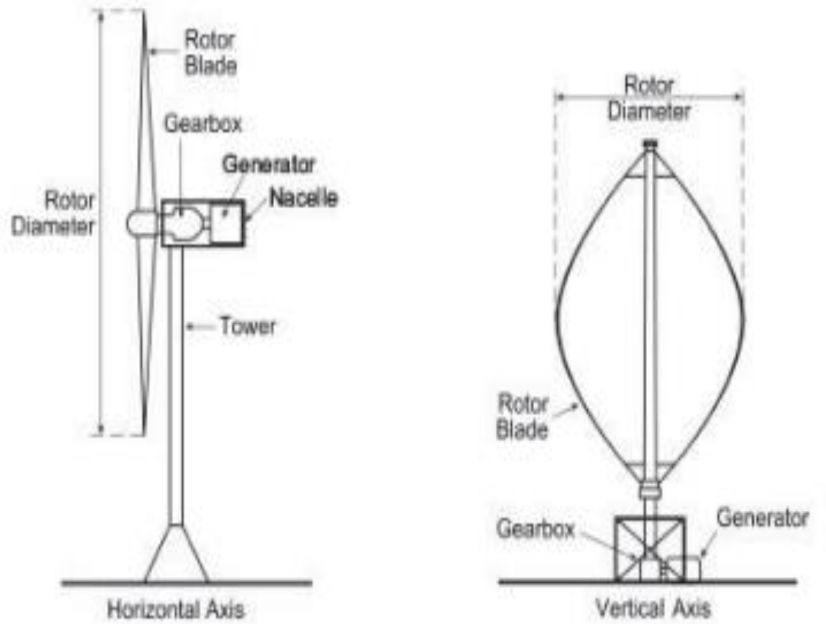


Figure I.6: Types of wind turbine

The two types are using a rotating motion to produce electricity, and this thesis concentrate on the horizontal axis wind turbine.

I.2.2.2.1. The Vertical-Axis Wind Turbine (VAWT)

There are two main types of VAWTs, the Savonius and the Darrieus. The Darrieus uses blades similar to those used on HAWTS, while the Savonius operates like a water wheel using drag forces. The blades rotate around a vertical axis, the turbine is in an optimal position to use this wind. The VAWT has an ingrained inefficiency because one blade is working well the wind, the other blades are effectively pulling in the wrong direction.

Figure I.7: VAWT components

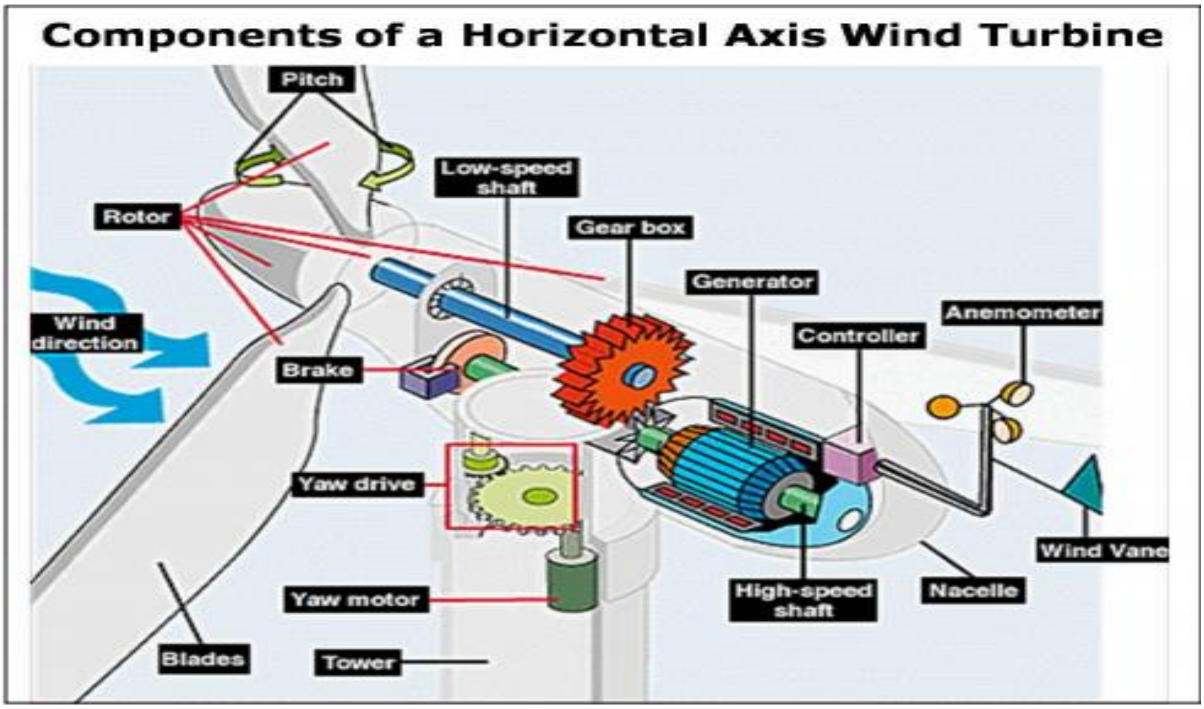
However, the VAWT resort to be larger than HAWT, also can be not easy to mount them on a tall enough tower to avail of higher and cleaner wind. One of the advantages of VAWT, it does not require a yaw mechanism, since it can harness the wind from any direction.

I.2.2.2.2. The Horizontal –Axis Wind Turbines (HAWT)

The electrical generator and the main rotor shaft are generally placed at the top of a tower for a HAWT. The HAWT has a design which is required that should be faced into the wind to obtain maximum power, this process is called yawing. In general, the turbine is connected to the shaft of the generator through a gearbox which moves the slow rotation of the blades into a faster rotation that is more suitable to drive an electrical generator.

HAWTs can be divided into three types:

- Dutch windmills.
- Multi blade Water pumping Windmills.
- High speed propeller type wind machines.



- *Figure I.8: Components of a HAWT*

Dutch windmills:

They were widely used for grinding grains. The blades of Dutch windmills were penchant at an angle to the wind to result in rotation, however, wooden slats or sails were used to industrialize these blades.

Figure I.9: Dutch windmills

Multi blade water pumping windmills:

They have a large number of blades, and wooden or metallic slats were used to manufacture these blades. This is used to rotate the shaft of a water pump. A tail vane is placed on the turbine to orient it to face the wind. However, the location of the mill does not dependent on the availability of the wind, but by the availability of water. Low cost and sturdiness are the main criteria for the design of these wind mills.

Figure I.10: Multi blade water pumping windmills

High speed propeller type wind machines:

This type of wind turbine is used most widely for the generation of electricity; this turbine operates on the aerodynamic forces of the wind. It has been found that the wind turbines that work on aerodynamic forces operate at higher efficiency than the ones which operate on thrust forces. Usually, the electrical generator is at the top of the tower, and directed into the wind. The gearbox turns the slow rotation of the blades till a quicker rotation to be suitable to drive an electrical generator.[7]

Figure I.11: High speed propeller type wind machines

I.2.3. Steam Turbine

A steam turbine consists of a rotor resting on bearings and enclosed in a cylindrical casing. The rotor is turned by steam impinging against attached vanes or blades on which it exerts a force in the tangential direction. Thus, a steam turbine could be viewed as a complex series of windmill-like arrangements, all assembled on the same shaft.[1]

I.2.3.1. History

The first device that may be classified as a reaction steam turbine was little more than a toy, the classic Aeolipile, described in the 1st century by Hero of Alexandria in Roman Egypt. In 1551, Taqi al-Din in Ottoman Egypt described a steam turbine with the practical application of rotating a spit. Steam turbines were also described by the Italian Giovanni Branca (1629) and John Wilkins in England (1648). The devices described by Taqi al-Din and Wilkins are today known as steam jacks. In 1672 an impulse steam turbine driven car was designed by Ferdinand Verbiest. A more modern version of this car was produced some time in the late 18th century by an unknown German mechanic. In 1775 at Soho James Watt designed a reaction turbine that was put to work there. In 1827 the Frenchmen Real and Pichon patented and constructed a compound impulse turbine.

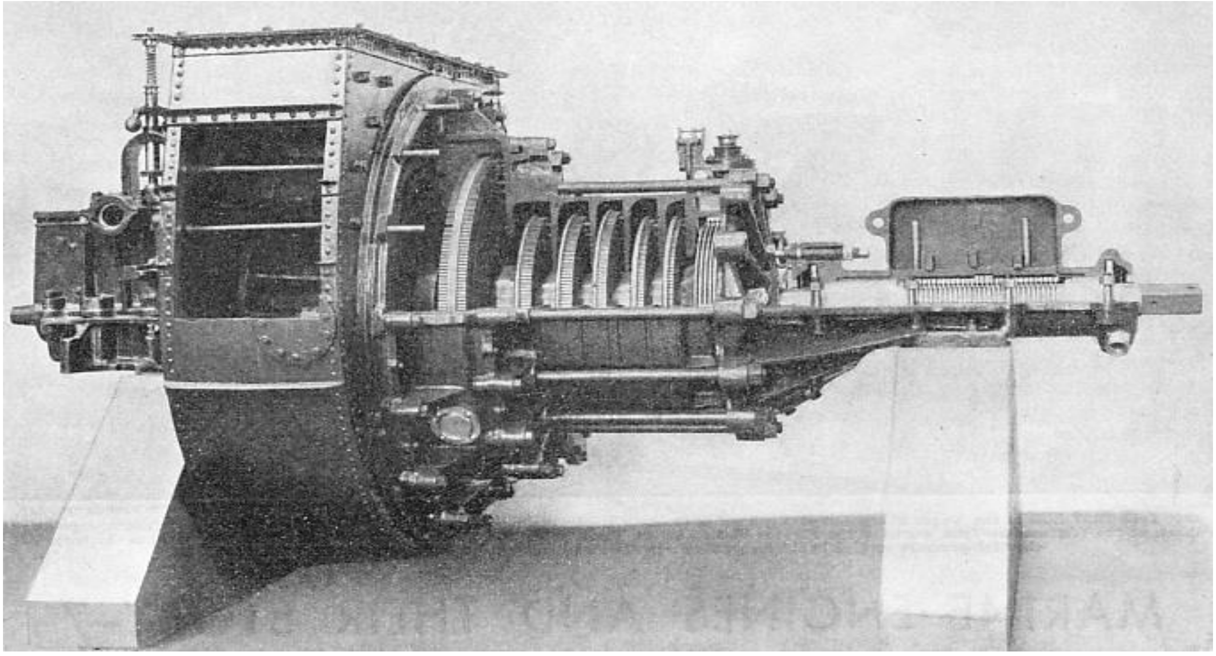


Figure I.12: Steam turbine engine

There are four people who may be considered to be pioneers of steam turbine technology (Constant, 1980):

- Carl Gustav De Laval (Patent date, 1883)
- Sir Charles Parsons (Patent date, 1884)
- Auguste Rateau (Patent date, 1894)
- Charles Curtis (Patent date, 1897) Steam turbine history and construction are detailed in Constant (1980) and Stodola (1927). [8]

Figure I.13: Steam power plant

I.2.3.2. Steam turbine classification

I.2.3.2.1. According to action of steam:

- Impulse turbine
- Reaction turbine
- Combination of both

I.2.3.2.2. According to direction of flow:

- Axial flow turbine
- Radial flow turbine

I.2.3.2.3. According to number of stages:

- Single stage turbine
- Multi stage turbine

I.2.3.2.4. According to steam pressure at inlet of Turbine:

- Low pressure turbine
- Medium pressure turbine.
- High pressure turbine
- Super critical pressure turbine.

I.2.3.2.5. According to usage in industry:

- Stationary turbine with constant speed.
- Stationary turbine with variable speed.
- Non stationary turbines. [9]

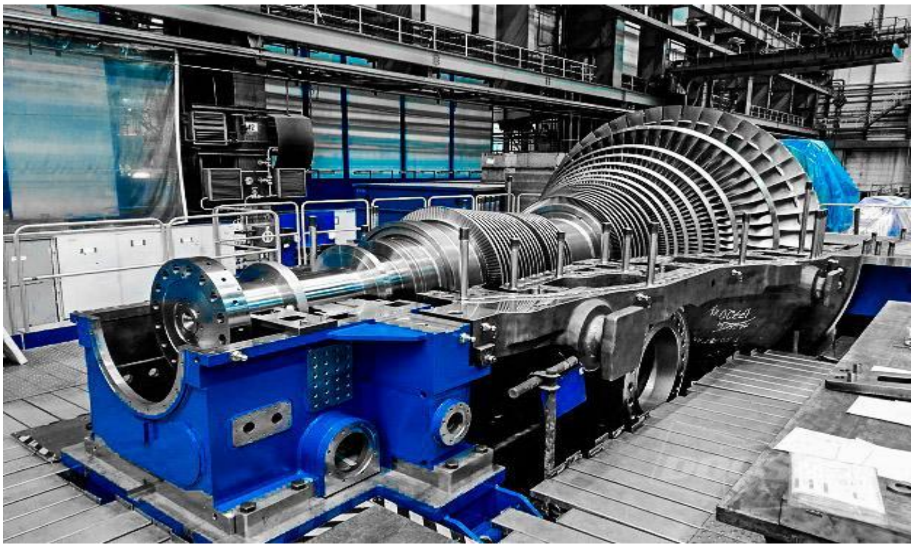


Figure I.14: Doosan Skoda Steam turbine

I.2.4. Gaz Turbine

Gas-turbine engine, any internal-combustion engine employing a gas as the working fluid used to turn a turbine. The term also is conventionally used to describe a complete internal-combustion engine consisting of at least a compressor, a combustion chamber, and a turbine.[1]

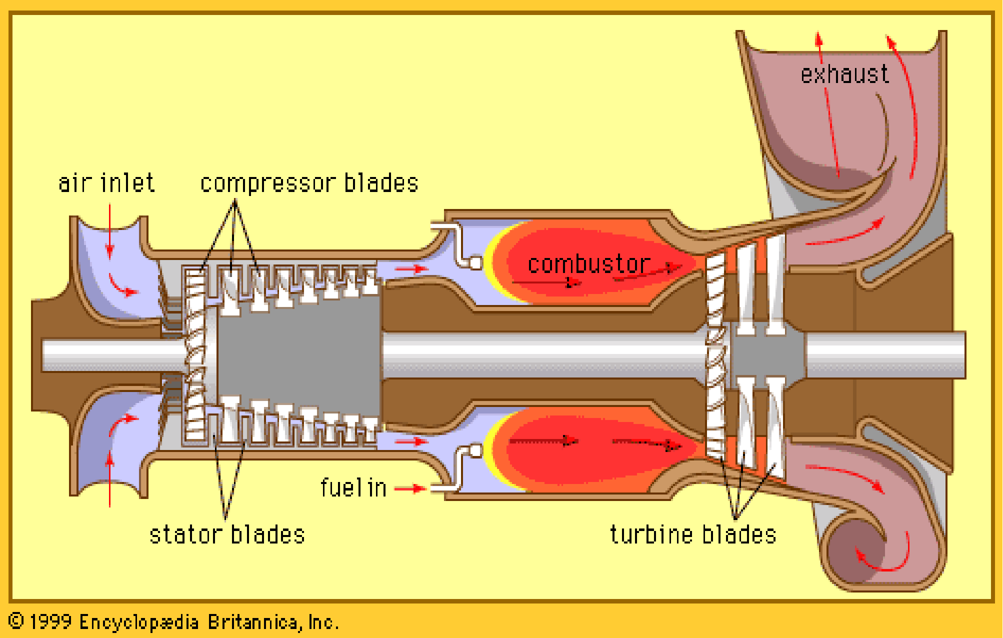


Figure I.15: Gas Turbine Engine

I.2.4.1. History

The first gas turbines were manufactured at the beginning of the 20th century, in France by a limited company of Turbomotos in Paris, and in Switzerland by the Brown Boweri Company in Neuchatel. The work produced by these machines is equal to the difference between the useful work provided by the turbine and the work required to compress the air, in the first realizations it was very low, and it was only from the 1930s that industrial applications really began to develop, thanks to the improvement of the performance of compressors and turbines. mainly due to advances in the understanding of gas flows, which continue to this day thanks to 3D modelling.

Over the past fifteen years, gas turbines have undergone a very strong development in many applications: air transport, electricity generation, cogeneration, machine drive (compressors and pumps), marine propulsion, where they are making a growing breakthrough, as arguments in their favor, these include their small footprint, their excellent power-to-weight ratio, their good efficiency, and their low emissions of pollutants [10]

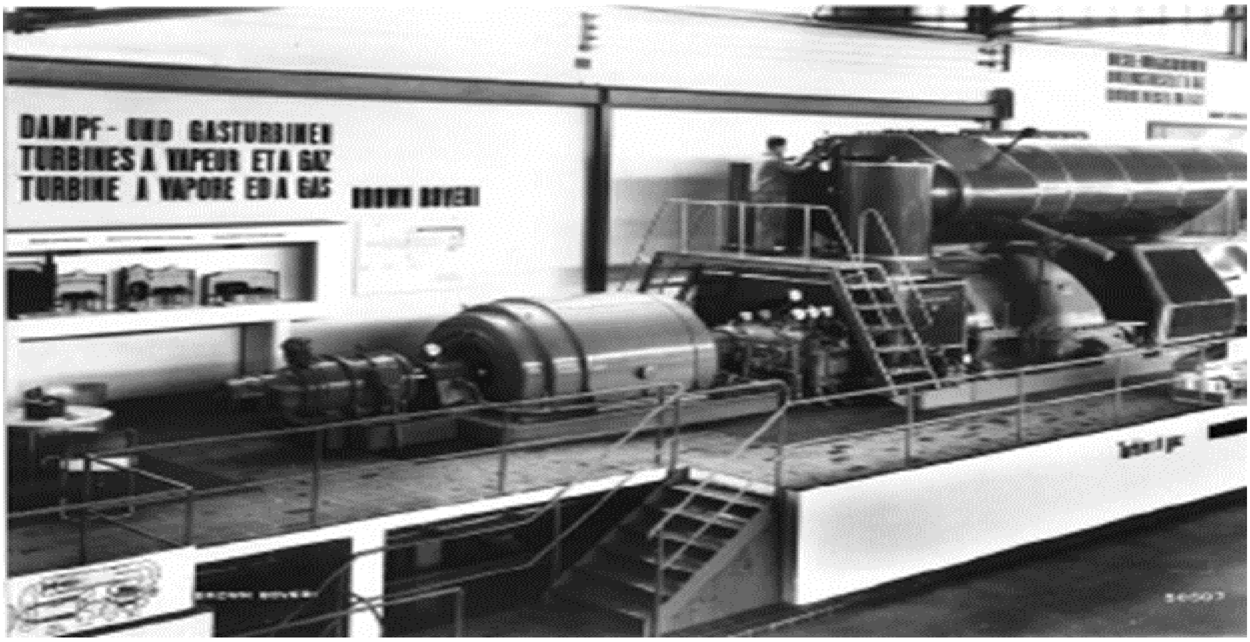


Figure I.16: Gaz Turbine – A brief History

I.2.4.2. Classification of Gas Turbine

The general characteristic of the gas turbines which are classified by the element of gas turbine is summarized as follow. The appropriate type of gas turbine shall be selected depending on the purpose, required output and circumstances. [11]

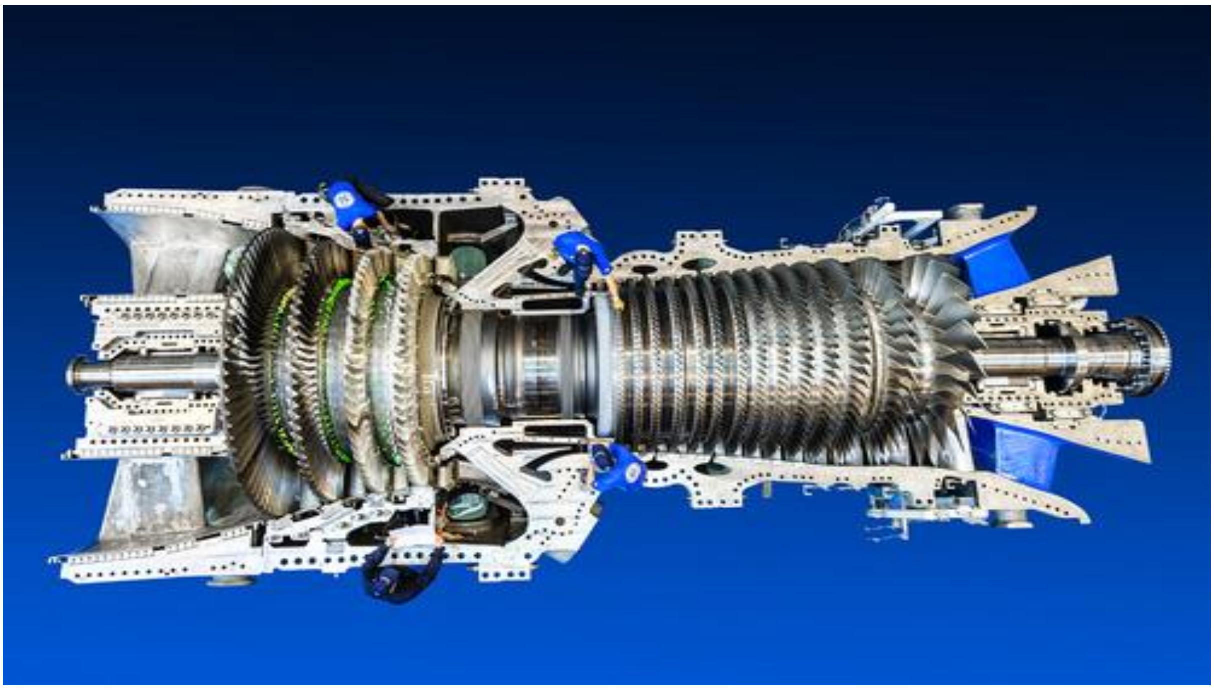


Figure I.17: the most powerful gas turbine in the world

I.2.4.2.1. Classification of Types by System

- **<u>Open Cycle:</u>** The energy of flue gas generated in the combustor work gas turbine, remaining energy is recovered by heat exchanger, if necessary, and is emitted to the atmosphere from chimney. The most cycle which is currently utilized is the "Open Cycle".

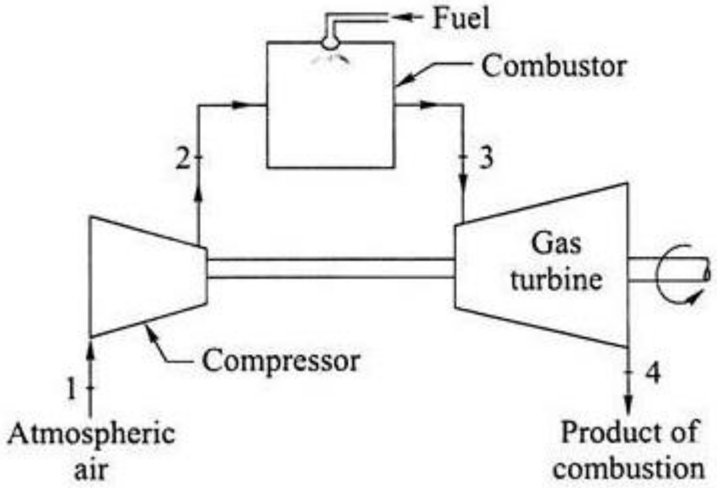


Figure I.18: Open cycle gas turbine

- **<u>Closed Cycle:</u>** The low boiling fluid such as nitrogen, helium, and carbon dioxide are applied to circulation medium for "Closed Cycle''

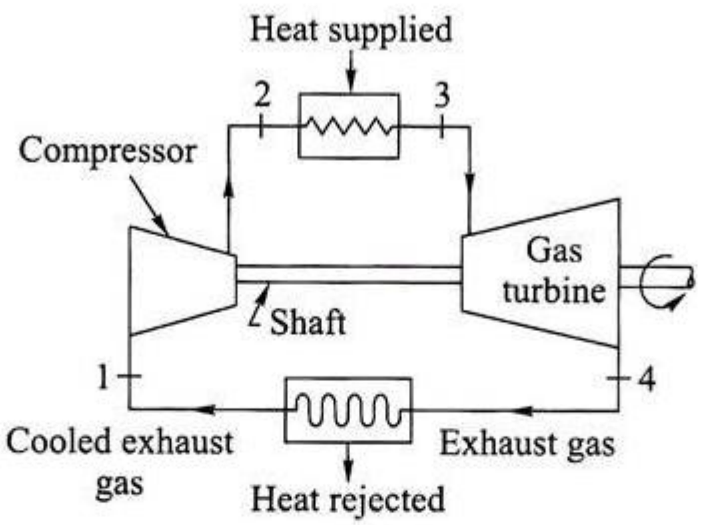


Figure I.19: Closed cycle gas turbine

I.2.4.2.2. Classification of Type by Heat Cycle

The gas turbine is based on the Brayton heat cycle and other options to perform higher performance, it can be divided into four types:

- **<u>Simple Cycle:</u>** The solid line in the T-S figure shows the ideal cycle without any losses (reversible adiabatic expansion). The actual gas turbines show the dotting line cycle which is under influence of compressor internal loss, turbine internal loss, pressure drop, heat loss and mechanical loss (irreversible process). This is the real baseline of gas turbine.

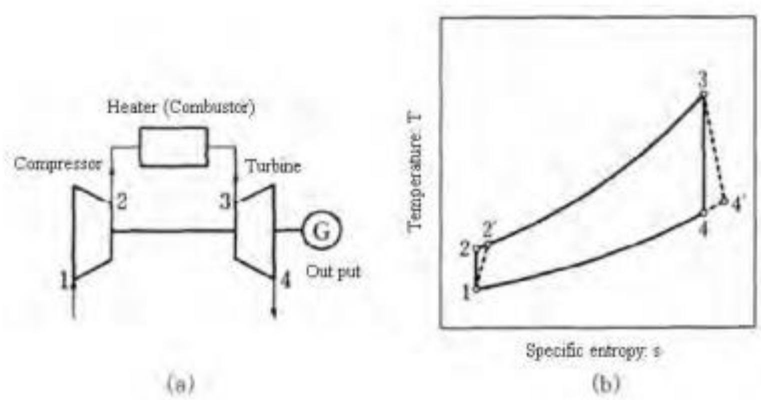


Figure I.20 : Simple heat cycle Gas turbine

- **Regenerative Cycle:** This system provides heat exchanger in the turbine outlet which exchange heat from flue gas to combustion air.
- **Reheat Cycle:** Generally, this system provides the HP combustor and re-heater to heat up HP flue gas temperature.

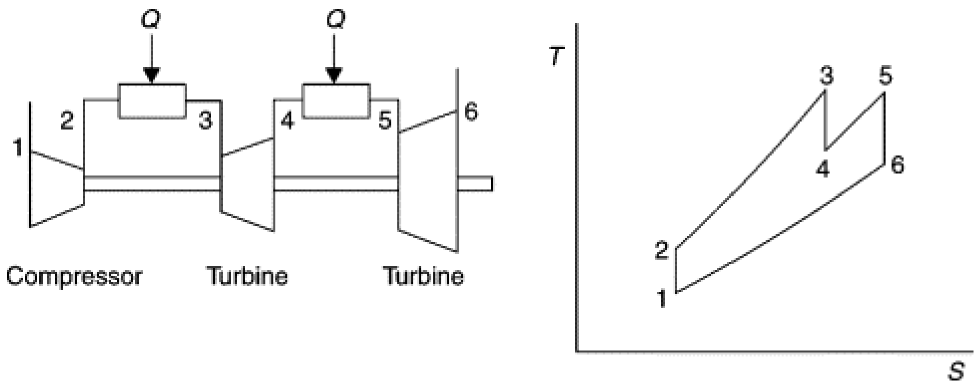


Figure I.21 : Reheat cycle gas turbine

- **Intermediate Cooling Cycle:** This system provides the intermediate cooler between air compressor

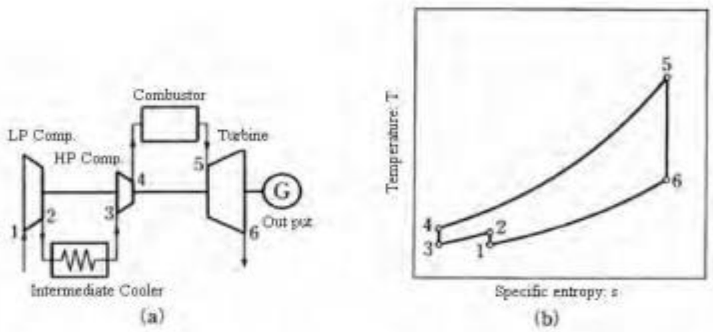


Figure I.22: Intermediate Cooling Cycle gas turbine

I.2.4.2.3. Classification of Types by Turbine

There are two types for the turbine which is used with compressor:

- **Axial Type:** Generally, the multistage axial flow turbine is applied to large gas turbine. The basic structure of the multi-stage axial-flow type is consisting of blades and vanes, the former has the role to convert the direction of gas flow and produce high gas flow, and the latter have the role to convert kinetic energy into rotational energy.
- **Centrifugal Type:** The centrifugal type is adopted for small scale gas turbine [11]

I.2.4.2.4. Classification of Types by Numbers of Shaft

- **Single shaft:** A single-shaft or two-shaft configuration may be used in gas turbines. The single-shaft structure consists of a shaft which connects a rotating part of the air compressor, gas turbine maker, and power turbine. This design is best suited for applications at constant speeds, such as electrical generators for constant frequencies.

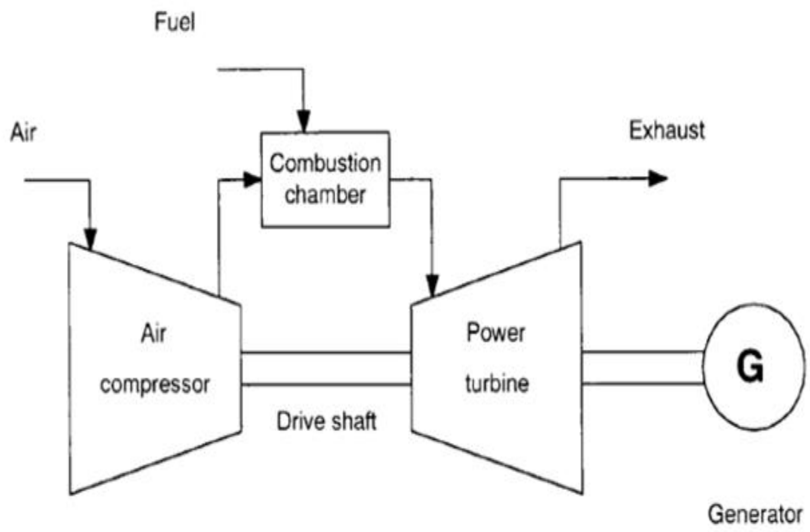


Figure I.23: Single shaft gas turbine

- **Two shafts:** The two-shaft configuration involves the air compressor, the gas supplier, and the power turbine on the second independent shaft. This design offers the speed in a flexible way needed to effectively cover a broader map of the powered system. The gas producer can, therefore, operates at the necessary speed to build the horsepower needed by the powered equipment including centrifugal compressors or pumps. [23]

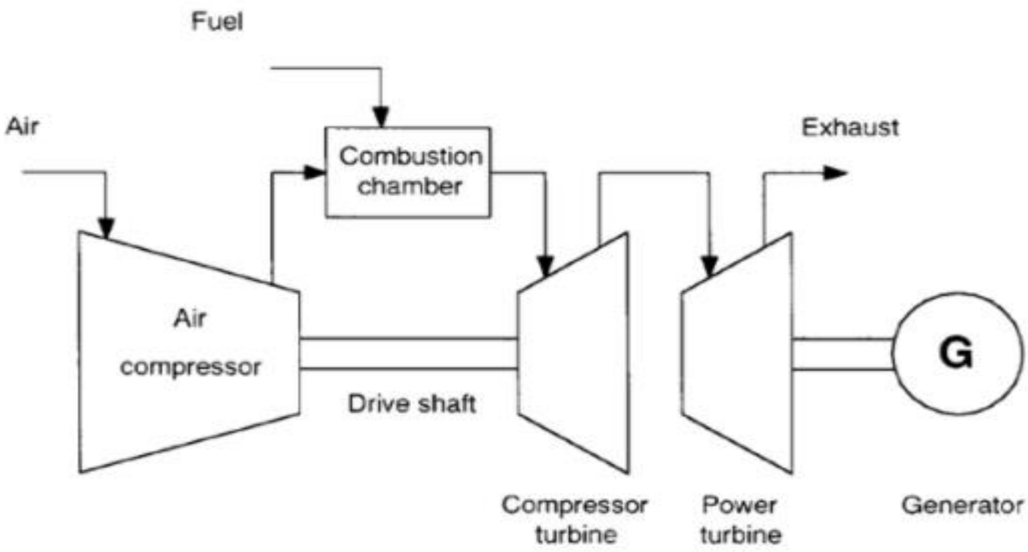


Figure I.24: Two-shaft gas turbine

I.2.4.3. Gaz Turbine Working Principle

1- The compressor ("C"), consisting of a set of fixed (stator) and mobile (rotor) fins, compresses the outdoor air ("E"), simply filtered, up to 10 to 15 bars, or even 30 bars for some models. Other types of machines use a centrifugal and non-axial compressor.
2- Fuel ("G") (gas or sprayed liquid) is injected into the combustion chamber ("Ch") where it mixes with compressed air to maintain continuous combustion.
3- Hot gases relax as they pass through the turbine ("T"), where the thermal and kinetic energy of hot gases is converted into mechanical energy. The turbine consists of one or more wheels also equipped with fins preceded by fixed blades (directors). The combustion gases escape through the chimney (Ec) through a diffuser.

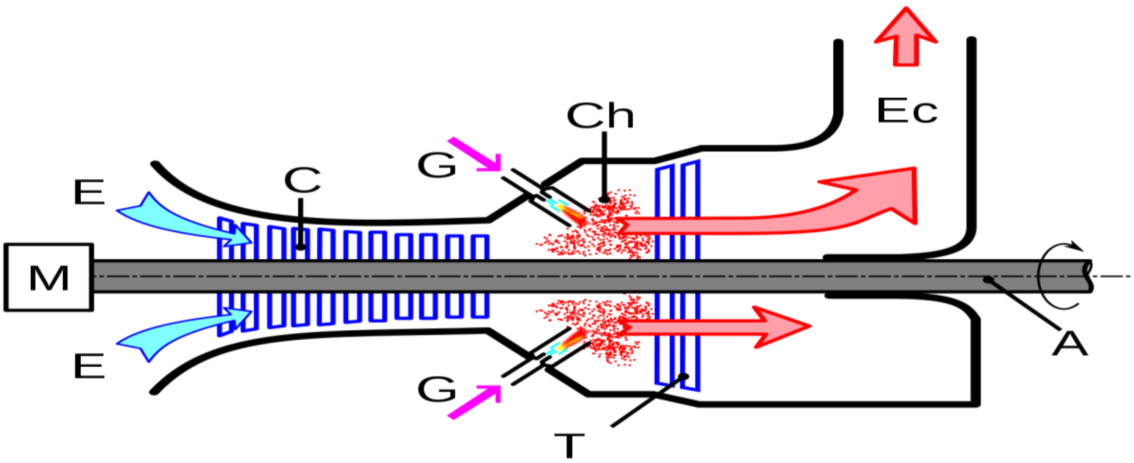


Figure I.25: Longitudinal section of a combustion turbine: main components

4- The rotational motion of the turbine is communicated to the shaft ("A"), which operates on the one hand the compressor, on the other hand a charge that is none other than a receiver (machine) (pump, alternator, compressor ...) mated at its end.

A launch engine ("M") is used to act as a starter; in some configurations, it is the alternator of the group itself that is used as an engine during the launch phase.[12]

I.3. DR 990 gas turbine

I.3.1. Description of the DR990 gas turbine

The DR990 gas turbine has a modular condition to facilitate the replacement of worn components and reduce on-site response time. Its rated power is 4400 KW. [13]

It consists of (Figure I.26):

- Admission system
- Gas generator
- Axial power turbine
- Exhaust system

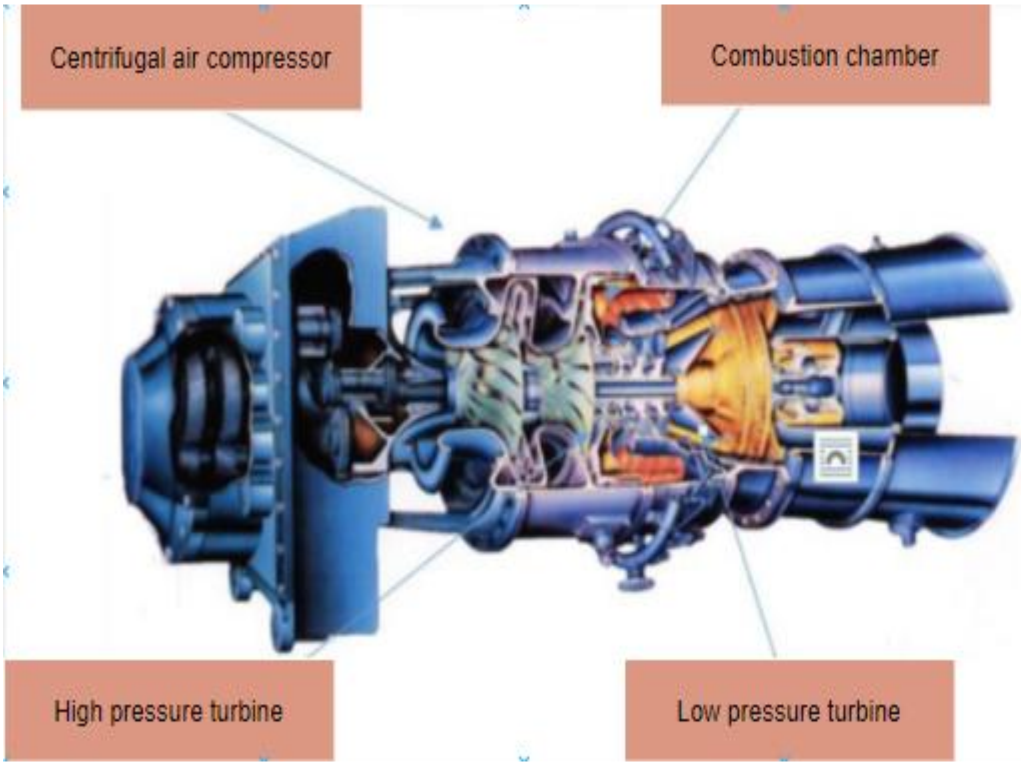


Figure I.26: DR 990 Gas turbine overview

I.3.2. Characteristic of a DR 990 Gas turbine

- SERIAL N ° ………………………. ………………………. C21-583A
- BRAND: ………………………… ……………………….. DRESSER RAND
- Shaft speed:
  - Gas generator (HP Turbine): …… ……………………..…… 18115 rpm
  - Power turbine (LP Turbine): … ……………………..…. .7200 rpm
- Intake temperature: ………………………………………... Ambient
- Compressor section:
  - Flow: …………………… ……… …………………..radial
  - Number of floors: ……… ……………………………...... 02 (two)
- Combustion section:
  - Type: ……………………..………… ……………..… A combustion chamber
  - Candles: ……………………………… ……………… 02 (two) candles
  - Flame detector: ………………………… ……………..02 (two)
- Turbine section:
  - Number of floors: ………………………………..……… 02 (two) Shafts
  - Starting system: …………………… ………………... Gas pneumatic starter

I.4. Conclusion

In this chapter we presented a fundamental of turbines (definition, history and classification) of the wind, Hydraulic, Steam and gas turbine.

Then the DR 990 gas turbine was described, and its characteristics was presented in order to exploit its history in the third chapter. In the next chapter, we will present a fundamental of maintenance.

CHAPITRE II: FUNDAMENTALS OF MAINTENANCE

II.1. Introduction

Although humans have felt the need to maintain their equipment since the beginning of time, the word Maintenance appeared in the industrial vocabulary in the 1950s, the maintenance of production equipment is a key issue for factory productivity as well as for product quality. The whole problem for maintenance man is what failures to deal with as a priority, some of which are of little importance in terms of effects and costs. The purpose of the maintenance function is to ensure the optimal availability of production facilities, implying a minimum economic downtime. In this chapter, a generality on maintenance is presented as well as the methods Pareto Ishikawa and fault tree analysis.

II.2. Maintenance

II.2.1. Maintenance Definition

European Federation of National Maintenance Societies ‘‘EFNMS’’ offers a similar definition in English: « All actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions ».[14]

II.2.2. Maintenance History

In the period of pre-World War II, people thought of maintenance as an added cost to the plant which did not increase the value of finished product. Therefore, the maintenance at that era was restricted to fixing the unit when it breaks because it was the cheapest alternative during and after World War II at the time when the advances of engineering and scientific technology developed, people developed other types of maintenance, which were much cheaper such as preventive maintenance. In addition, people in this era classified maintenance as a function of the production system.

Nowadays, increased awareness of such issues as environment safety, quality of product and services makes maintenance one of the most important functions that contribute to the success of the industry. World-class companies are in continuous need of a very well-organized maintenance programmed to compete world-wide.[15]

II.2.3. Types of Maintenance

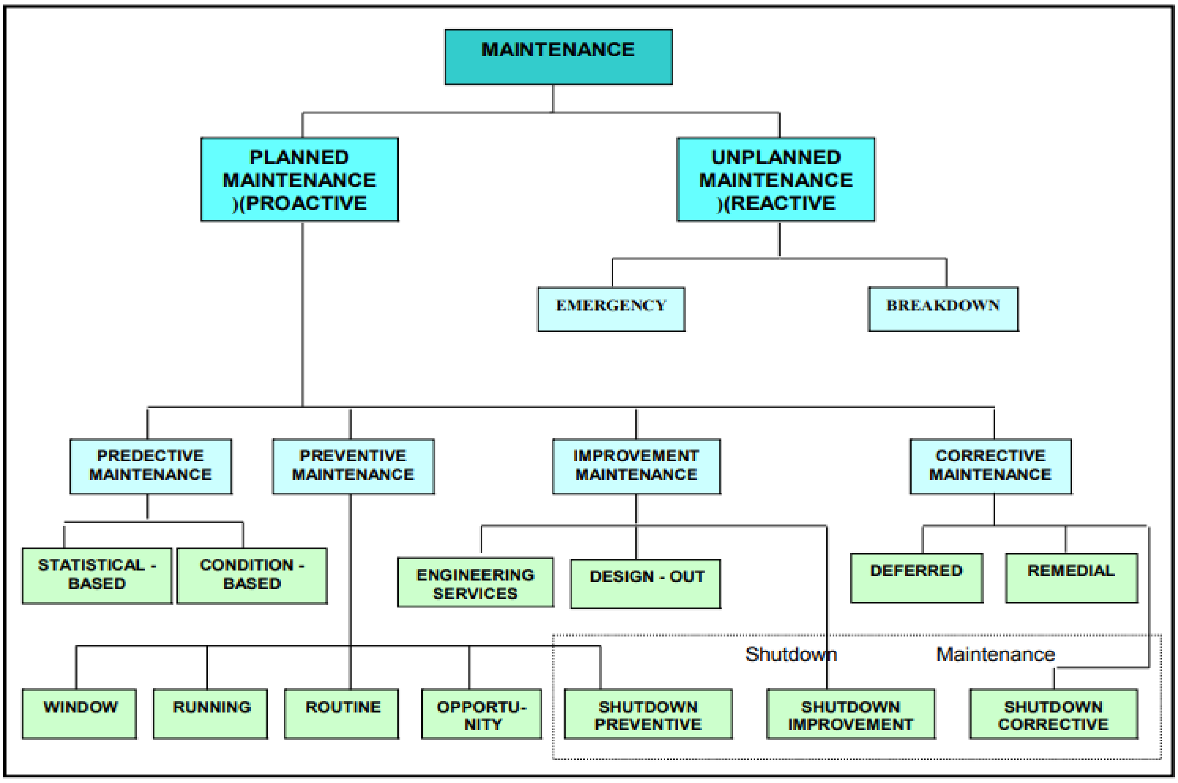


Figure II.1: Maintenance Type

In general, maintenance falls into two categories: reactive and proactive.

Reactive maintenance focuses on repairing an asset once failure occurs.

Proactive maintenance: focuses on avoiding repairs and asset failure through preventive and predictive methods.

II.2.3.1. Run to Failure Maintenance (RTF)

II.2.3.1.1. Definition

The required repair, replacement, or restore action performed on a machine or a facility after the occurrence of a failure in order to bring this machine or facility to at least its minimum acceptable condition. It is the oldest type of maintenance.

Run to Failure Maintenance (RTF) is subdivided into two types:

– ***Emergency maintenance***: it is carried out as fast as possible in order to bring a failed machine or facility to a safe and operationally efficient condition.

– ***Breakdown maintenance:*** it is performed after the occurrence of an advanced considered failure for which advanced provision has been made in the form of repair method, spares, materials and equipment.

II.2.3.1.2. Run to Failure Maintenance (RTF) Disadvantages

- Its activities are expensive in terms of both direct and indirect cost.
- Using this type of maintenance, the occurrence of a failure in a component can cause failures in other components in the same equipment, which leads to low production availability.
- Its activities are very difficult to plan and schedule in advance.

II.2.3.1.3. Run to Failure Maintenance (RTF) advantages

This type of maintenance is useful in the following situations:

- The failure of a component in a system is unpredictable.
- The cost of performing run to failure maintenance activities is lower than performing other activities of other types of maintenance.
- The equipment failure priority is too low in order to include the activities of preventing it within the planned maintenance budget.

II.2.3.2. Preventive Maintenance (PM)

II.2.3.2.1. Definition

It is a set of activities that are performed on plant equipment, machinery, and systems before the occurrence of a failure in order to protect them and to prevent or eliminate any degradation in their operating conditions. British Standard 3811:1993 Glossary of terms defined preventive maintenance as:

‘‘the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning and the effects limited’’.

Researchers subdivided preventive maintenance into different kinds according to the nature of its activities:

Routine maintenance: which includes those maintenance activities that are repetitive and periodic in nature such as lubrication, cleaning, and small adjustment.

Running maintenance: which includes those maintenance activities that are carried out while the machine or equipment is running and they represent those activities that are performed before the actual preventive maintenance activities take place. Preventive Maintenance (PM)

Opportunity maintenance: which is a set of maintenance activities that are performed on a machine or a facility when an unplanned opportunity exists during the period of performing planned maintenance activities to other machines or facilities.

Window maintenance: which is a set of activities that are carried out when a machine or equipment is not required for a definite period of time.

Shutdown preventive maintenance: which is a set of preventive maintenance activities that are carried out when the production line is in total stoppage situation.[15]

II.2.3.2.2. Preventive Maintenance (PM) Disadvantages

- More money upfront- When initially starting a preventative maintenance plan, it will cost you more to regularly maintain equipment and the building, than it would be if you waited for things to simply break down.
- Over maintenance- Because there is a regular plan, sometimes items may not need to be checked as often as planned. If this is the case, you can change your maintenance plan to checking the specific equipment or areas less often, while still maintaining a schedule.
- More workers- Preventative maintenance require more workers because regular checks are a must. When compared to reactive maintenance, you simply need to call someone in for a onetime fix. Instead, this method requires workers to always be on site and perform daily works.

II.2.3.2.3. Preventive Maintenance Advantages

- Less risk factor- Because the equipment and your building are being regularly checked, they are at less risk to breaking down without notice. Therefore, creating a safer working environment for employees.
- Follows a schedule- By following a schedule, you are able to keep to a budget while maintaining your building.
- Longer equipment/building life- When equipment is being checked and maintained, it will be kept in its best shape, therefore extending its lifetime.
- Money saving-Over time, you will see that less money is being spend because you will not have to replace equipment as much, as well as dealing with last minute break downs.

- Less energy wasting- In general when equipment is not kept in the best conditions possible, it will drain more energy
- Less disruptions- With regular checks, you won't be surprised when something goes wrong

The advantage of applying preventive maintenance activities is to satisfy most of maintenance objectives.[16]

II.2.3.3. Corrective Maintenance (CM)

II.2.3.3.1. Definition

In this type, actions such as repair, replacement, or restore will be carried out after the occurrence of a failure in order to eliminate the source of this failure or reduce the frequency of its occurrence.

In the British Standard 3811:1993 Glossary of terms, corrective maintenance is defined as: ''the maintenance carried out after recognition and intended to put an item into a state in which it can perform a required function''.

This type of maintenance is subdivided into three types:

Remedial maintenance: which is a set of activities that are performed to eliminate the source of failure without interrupting the continuity of the production process. The way to carry out this type of corrective maintenance is by taking the item to be corrected out of the production line and replacing it with reconditioned item or transferring its workload to its redundancy. **Deferred maintenance:** which is a set of corrective maintenance activities that are not immediately initiated after the occurrence of a failure but are delayed in such a way that will not affect the production process.

Shutdown corrective maintenance: which is a set of corrective maintenance activities that are performed when the production line is in total stoppage situation.

The main objectives of corrective maintenance are the maximization of the effectiveness of all critical plant systems, the elimination of breakdowns, the elimination of unnecessary repair and the reduction of the deviations from optimum operating conditions. [15]

II.2.3.3.2. Corrective Maintenance Disadvantages

- Unpredictability: Equipment is not monitored after purchase, so flaws are highly unpredictable;
- Stopping operations: Unexpected faults can result in unavailable materials and therefore delay the time required for a repair, increasing equipment downtime;
- Non-maximized equipment: This approach does not protect or care for the equipment, which reduces the useful life of the assets;
- Higher Long-Term Costs: Corrective Maintenance is applied when it is believed that shutdown and repair costs in the event of a breakdown will be less than the investment required for planned maintenance. But this does not always happen. When a "catastrophic" failure occurs, it can be extremely costly, causing negative effects on reputation, customer satisfaction, security, and ability to run a business efficiently and productively.

II.2.3.3.3. Corrective Maintenance Advantages

- Lower short-term costs: Since this is a reactive activity, there is very little to do after purchase and before a problem occurs;
- Minimum Planning Required: Corrective Maintenance consists of correcting a fault identified in a specific component of an equipment or facility currently marked, so there is no need for complex and timely planning;
- Simpler process: The process is easy to understand, since it is only necessary to act when some type of problem occurs;
- Better solution in some cases: When it is believed that shutdown and repair costs in case of breakdown will be less than the investment required for Preventive Maintenance Corrective Maintenance is the best solution.[17]

The main objectives of corrective maintenance: Are the maximization of the effectiveness of all critical plant systems, the elimination of breakdowns, the elimination of unnecessary repair and the reduction of the deviations from optimum operating conditions.

The difference between corrective maintenance and preventive maintenance**:** Is that for the corrective maintenance, the failure should occur before any corrective action is taken.

Corrective maintenance is different from run to failure maintenance: In that its activities are planned and regularly taken out to keep plant's machines and equipment in optimum operating condition.

II.2.3.4. Improvement Maintenance (IM)

II.2.3.4.1. Definition

It aims at reducing or eliminating entirely the need for maintenance. This type of maintenance is subdivided into three types as follows:

Design-out maintenance: which is a set of activities that are used to eliminate the cause of maintenance, simplify maintenance tasks, or raise machine performance from the maintenance point of view by redesigning those machines and facilities which are vulnerable to frequent occurrence of failure and their long-term repair or replacement cost is very expensive.

Engineering services: which include construction and construction modification, removal and installation, and rearrangement of facilities.

Shutdown improvement maintenance: which is a set of improvement maintenance activities that are performed while the production line is in a complete stoppage situation.

II.2.3.5. Predictive Maintenance (PDM)

II.2.3.5.1. Definition

Predictive maintenance is a set of activities that detect changes in the physical condition of equipment (signs of failure) in order to carry out the appropriate maintenance work for maximizing the service life of equipment without increasing the risk of failure. It is classified into two kinds according to the methods of detecting the signs of failure:

Condition-based predictive maintenance: depends on continuous or periodic condition monitoring equipment to detect the signs of failure.

Statistical-based predictive maintenance: depends on statistical data from the meticulous recording of the stoppages of the in-plant items and components in order to develop models for predicting failures.

The drawback of predictive maintenance is that it depends heavily on information and the correct interpretation of the information. Some researchers classified predictive maintenance as a type of preventive maintenance. [15]

II.2.3.5.2. Predictive maintenance disadvantages

- Requires skilled personnel.
- Requires costly monitoring equipment's.

II.2.3.5.3. Predictive Maintenance Advantages

- Prevents the breakdown/catastrophic/premature failure.
- Safety, reliability and availability increases.
- Cost of maintenance is less.
- Proper planning to avoid failure.
- Less down time. [18]

<u>The main difference between preventive maintenance and predictive maintenance</u>: is that predictive maintenance uses monitoring the condition of machines or equipment to determine the actual mean time to failure whereas preventive maintenance depends on industrial average life statistics.

II.2.4. Maintenance Objectives

Maintenance objectives should be consistent with and subordinate to production goals. The relation between maintenance objectives and production goals is reflected in the action of keeping production machines and facilities in the best possible condition.

• Maximizing production or increasing facilities availability at the lowest cost and at the highest quality and safety standards.

• Reducing breakdowns and emergency shutdowns.

• Optimizing resources utilization.

• Reducing downtime.

• Improving spares stock control.

• Improving equipment efficiency and reducing scrap rate.

• Minimizing energy usage.

• Optimizing the useful life of equipment. [15]

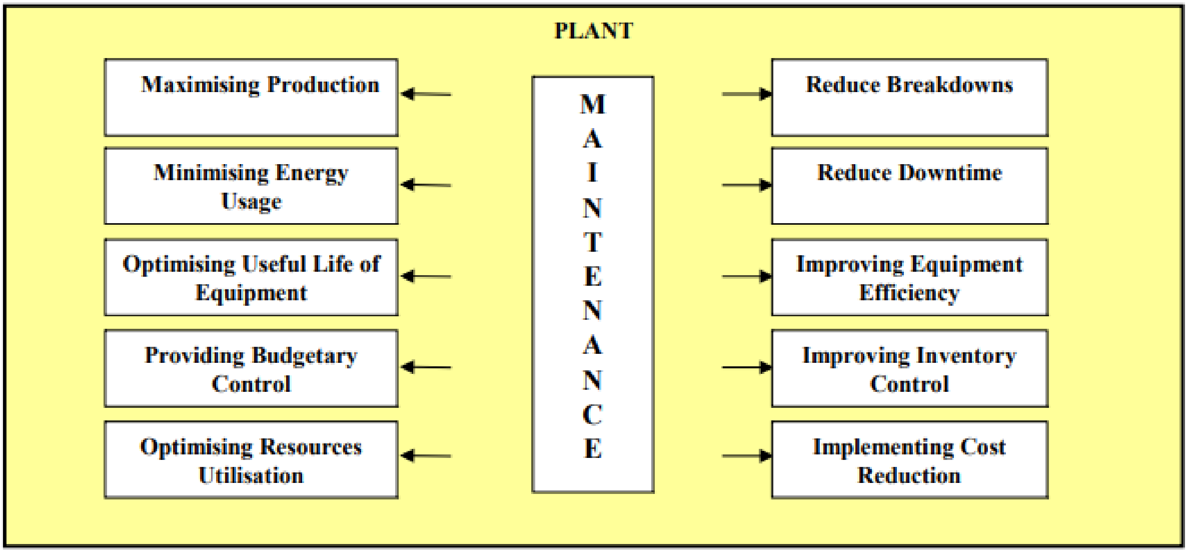


Figure II.2: Maintenance Objectives

II.3. Functional Analysis

II.3.1. The Horned Beast

The horned beast is a graphic tool for analyzing the need that answers three questions:

1/ To whom or what does the product do it serve?

2/ On whom or what does it act?

3/ For what purpose?

The goal is always formulated in the same way: the product allows the user to act on the work material. The answers to these questions are grouped in the benefit graph also known as "horned beast." [20]

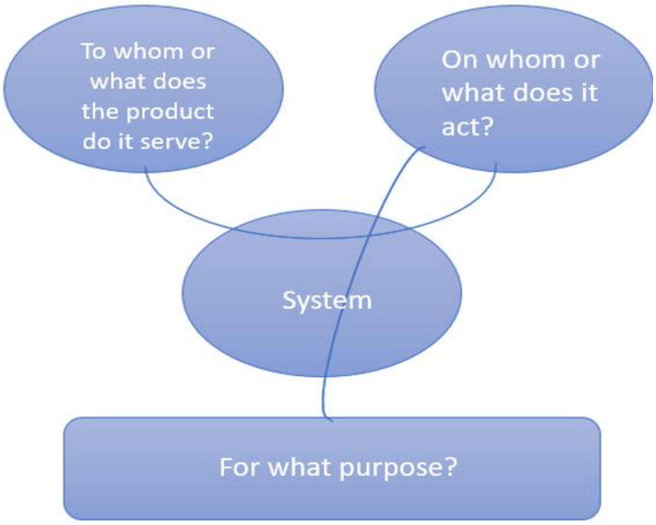


Figure II.3: The Horned Beast

II.3.2. Octopus diagram

The Octopus Diagram is a need analysis tool that graphically represents a product/service's interactions with its environment. The Octopus Diagram highlights the relationships between the different Elements of the External Environments (EEE) and the product/service through functions:

- Main Function (MF): connects 2 EEE through product/service.
- Constraint function (FC): translates an adaptation of the product to an EEE.

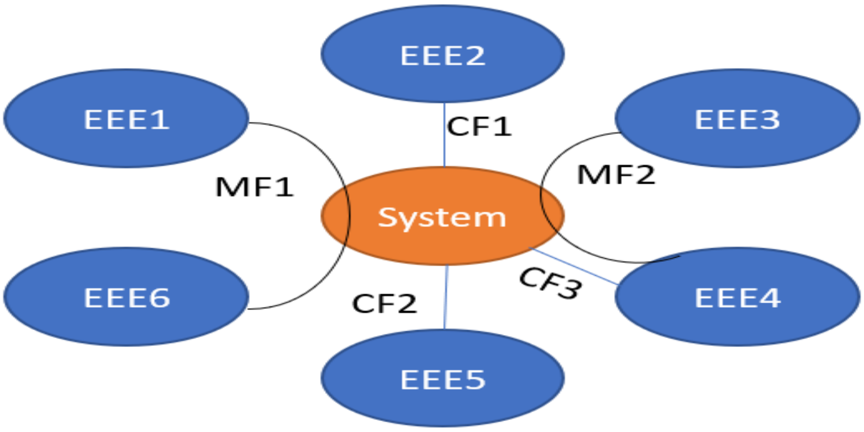


Figure II.4: Octopus diagram

II.3.3. THE S.A.D.T: (Structured Analysis Design Technic)

A function is represented by a SADT "box" or "module." A SADT box is located in context with other boxes or modules, via relationship arrows. These arrows symbolize the constraints of bindings between boxes. They do not act as a command or sequencing in the strict sense. [21]

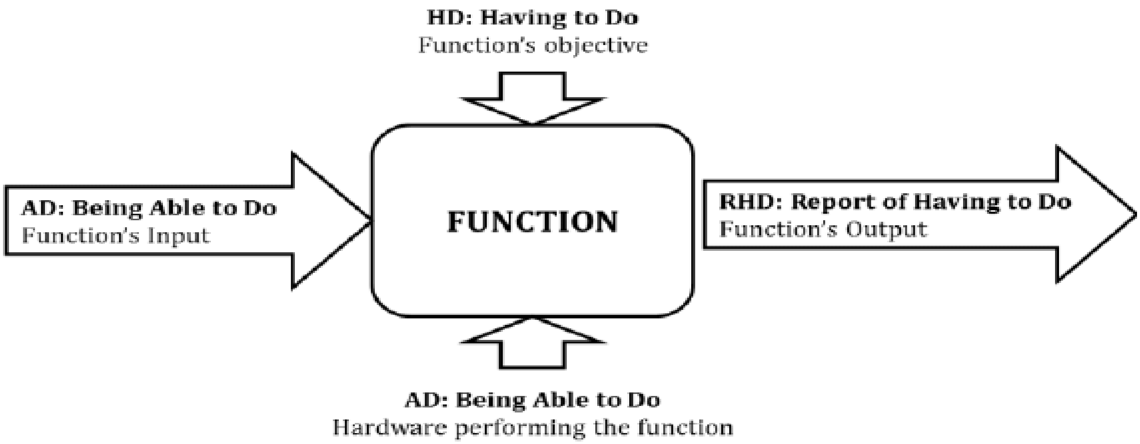


Figure II.5: The S.A.D.T

II.4. Reliability

II.4.1. Definition

According to the Standard (NORME X60—5OO). Reliability is an entity's ability (probability) to perform a required function over a given time interval under specific conditions.

II.4.2. Reliability objectives

Reliability aims to:

- Measure a guarantee over time
- Rigorously assess a degree of trust
- Decipher a lifespan
- Accurately assess operating time
- Determine the interview strategy
- Choose the stock

II.4.3. The Main Probability Laws Used in Reliability

In Reliability Studies of Different Equipment's, a continuous or discrete random variable can be distributed according to various laws that are mainly:

- The exponential law
- Weibull Law
- Normal Law
- The Log-Normal Law (or GALTON Law)
- Binomial Law
- POISSON Law or Low Probability Law [19]

II.4.4. The Weibull Model

Weibull Law is a model commonly used to model the lifespan of a material. This allows, for example, to determine the periodicities in the case of systematic preventive maintenance. Weibull's law is very flexible to use, allowing it to adjust to a large number of samples taken over the life of equipment. It covers cases of variable, decreasing (youthful) or increasing (old age) failure rates. It allows, on the basis of the results obtained, to determine in what period of his life the system studied is located.

II.4.4.1. Methods for approximation of cumulative function values

A number of experimental or actual UT data are available for our reliability studies; UT whose Cumulative function we want to study. This data represents a "n" sample of the population we want to apprehend. They must be ranked in increasing order of duration (hours, days, etc.), according to the most suitable unit. The estimate of density function for a duration (ti) is given by: $f(ti) = \frac{ni}{N+1}$ (II.1)

However, it's not the density function that interests us but the cumulative function F (ti). This cumulative function can be estimated according to several methods, two of which are particularly applicable for reliability laws (exponential and Weibull): these are the methods of the mid- and middle ranks. The choice between either method depends on the "N" size of the sample.

- If $N \leq 20$, the mid-row method is used: $F(ti) = \frac{\Sigma\, ni - 0{,}3}{N+0{,}4}$ (II.2)
- If $N > 20$, the middle row method is used: $F(ti) = \frac{\Sigma\, ni}{N+1}$ (II.3)

II.4.4.2. Weibull's Law

Proposed by Swedish engineer and mathematician Ernst Hjalmar Waloddi Weibull (1887-1979), Weibull's Law is a 3-parameter probability law that is widely used to model the lifespan of products because of its great flexibility.

❖ Parameter Meaning:

➢ β Beta Shape Setting (β) >0 without dimension: This setting provides guidance on the mode of failures and how the failure rate has changed over time.

- If β>1, the failure rate is increasing, characteristic of the old age zone
  - ✓ 1.5 < β< 2.5: fatigue
  - ✓ 3 < β< 4: wear, corrosion
- If β=1, the failure rate is constant, characteristic of the maturity zone
- If β <1, the failure rate is decreasing, characteristic of the youth zone.

Note: for γ =0 and β = 1, we find the exponential distribution, a special case of the Weibull law:

$$\lambda = \frac{1}{\eta} = \frac{1}{MUT} \qquad \text{(II.4)}$$

➢ η Scale Setting (Neta (η) > 0) that expresses itself in the time unit: This setting allows the use of Allan Plait's paper regardless of the order of magnitude of t. It therefore does not have to be interpreted

- γ position setting, -∞< γ < +∞,which is expressed in the time unit
  - $\gamma > 0$: Total survival over the time interval [0, γ].
  - $\gamma = 0$: Failures start at the origin of times
  - $\gamma < 0$ failures started before the times began

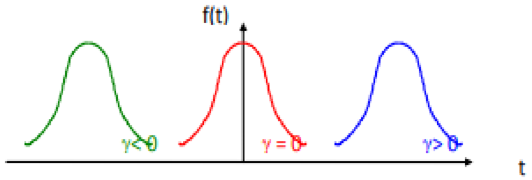


Figure II.6: Density of probability

II.4.4.3. Graphic determination of the parameters of Weibull's law

The curve is drawn on a special paper called Weibull or Allen Plait paper, which allows for a straight line and simplified calculations.

II.4.4.3.1. Appearance of Weibull's paper

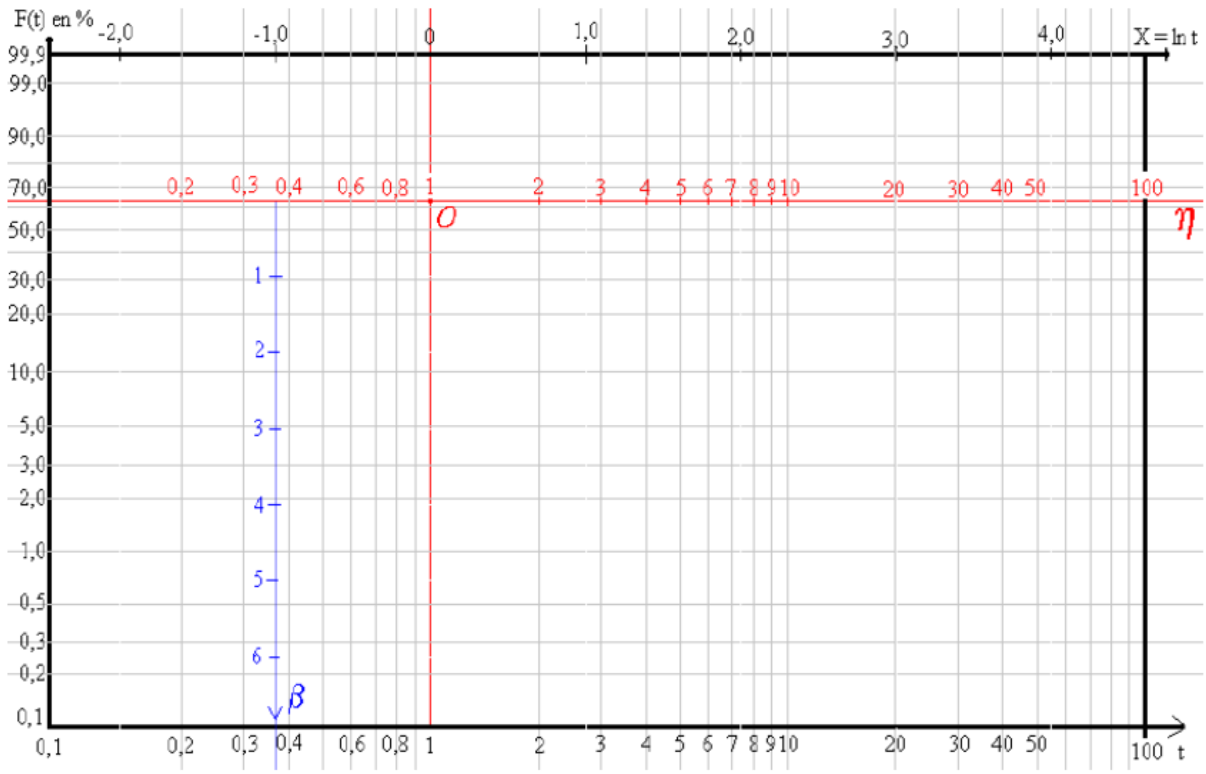


Figure II.7: Weibull's paper

II.4.4.3.2. Failure Rate

Its instant failure rate is a reliability estimator. It is expressed by:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\eta}{\beta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1} \quad \text{(II.5)}$$

II.4.4.3.3. Probability density f(t)

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} . e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{(II.6)}$$

II.4.4.3.4. Cumulative function F (t)

The probability that the device is down at the moment (t) It is expressed by:

$$F(t) = 1 - e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}} \quad \text{(II.7)}$$

II.4.4.3.5. The MUT :

MUT=A. η + γ (II.8)

A : WEIBULL Parameter

II.4.4.3.6. Reliability Function R (t)

The general shape of the reliability function is referred to as R (t) representing the probability of proper operation at the moment t. [20]

$$R(t) = 1 - F(t) \quad \text{(II.9)}$$

$$R(t) = e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}} \quad \text{(II.10)}$$

II.5. Maintainability

Maintainability is "the ability of a device to be maintained or restored to a state in which it can perform its required function, when maintenance is performed under conditions, with specific procedures and means." Maintainability is the ability to restore or maintain a well-functioning property.

$$\mathbf{M(t) = 1 - e^{-\mu t}} \quad \text{(II.11)}$$

Maintainability is characterized by average MTTR technical repair times:

$$MTTR = \frac{\text{Total maintenance time}}{\text{Number of repairs}} \quad \text{(II.12)}$$

Repair rate: $\mu = \frac{1}{MTTR}$ (II.13)

II.6. Availability

II.6.1. Definition

Is the ability of a property in the combined aspects of reliability, maintainability and maintenance organization to be able to perform a required function under specified time conditions. For equipment to be well available, it must:

- Have as few production stops as possible
- Be quickly restored if it fails.

Availability therefore links the notions of reliability and maintainability

II.6.2. The types of availability

II.6.2.1. Intrinsic Availability

This availability is assessed by taking into account operating averages and repair averages, resulting in:

$$Di = \frac{MUT}{MUT+MTTR} \tag{II.14}$$

II.6.2.2. Instant Availability

For a system with the assumption of a constant failure rate and a constant μ repair rate, instant availability is: [19]

$$D(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{II.15}$$

II.7. ABC Method

II.7.1. Definition of the ABC method

The ABC method is an objective means of analysis, it allows to classify the elements that represent the most important fraction of the trait studied, indicating the percentages for a given character.

II.7.2. Purpose of the ABC method

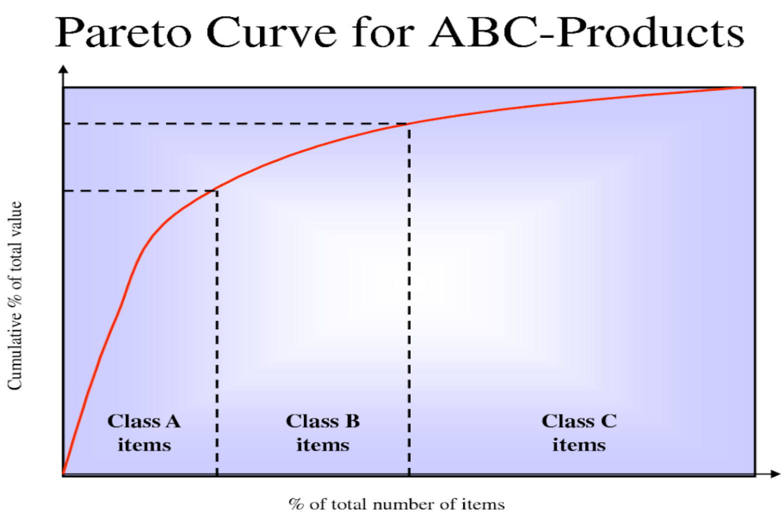


Figure II.8: Pareto curve for ABC product

The A.B.C diagram (PARETO) allows you to visualize the relative importance of the different parts or categories of a set previously analyzed and quantified in the form of a ranking and a hierarchy.

- Zone A: Losses to lead to priority actions
- Zone B: Losses to consider if solutions are inexpensive
- Zone C: Losses that do not warrant action [20]

II.8. Ishikawa diagram

II.8.1. Definition

A tool that identifies the possible causes of an observed effect and thus determines the means to remedy it.

This tool comes in the form of fish bones classifying the categories of cases inventoried according to the law of 5 M (matter, manpower, equipment, Method, Middle)

II.8.2. Construction of the Chart

1) Place an arrow horizontally pointed at the identified problem or purpose. Take, for example, a non-sale or improvement of a service

2) Grouping potential causes into families, commonly referred to as the five M.

- Matter: M1. Identify the causes of the technical media and the products used.
- Labor: M2. Problem of competence, organization, management.
- Material: M3. Causes relating to the Machines, Equipment and Means concerned.
- Method: M4. Procedures or modus operandi used.
- Middle: M5. Physical environment: light, noise, dust, location, signage, etc.

3) Draw secondary arrows corresponding to the number of families of potential causes identified, and connect them to the main arrow.

Each secondary arrow identifies one of the families of potential causes.

4) Write on mini arrows, the causes related to each family. We must ensure that all potential causes appear.

5) Look for the real causes of the identified problem among the potential causes exposed. This will be the most likely cause that will remain to be verified in reality and corrected.

The Ishikawa diagram thus makes the search phase for the primary causes of the work accident livelier and more efficient. [22]

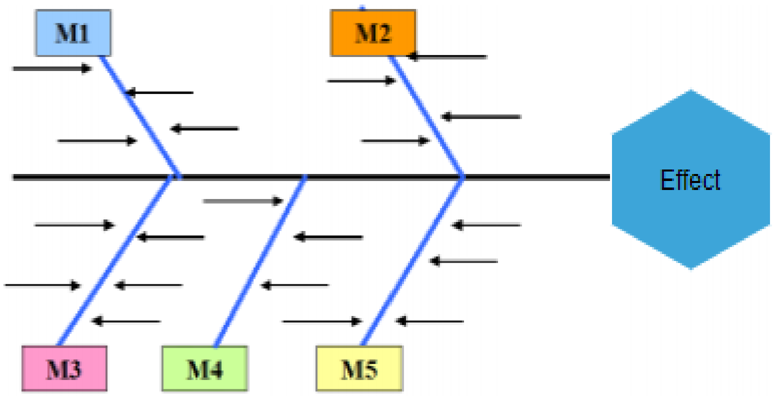


Figure II.9: Ishikawa diagram

II.9. Fault tree Analysis

II.9.1. Definition

Fault tree analysis (FTA) is a graphical tool to explore the causes of system level failures. It uses Boolean logic to combine a series of lower-level events and it is basically a top-down approach to identify the component level failures (basic event) that cause the system level failure (top event) to occur. Fault tree analysis consists of two elements "events" and "logic gates" which connect the events to identify the cause of the top undesired event.

Fault tree analysis is an easier method than the Failure Mode and Effects Analysis (FMEA) as it focuses on all possible system failures of an undesired top event. Whereas FMEA conducts analysis to find all possible system failure modes irrespective of their severity.

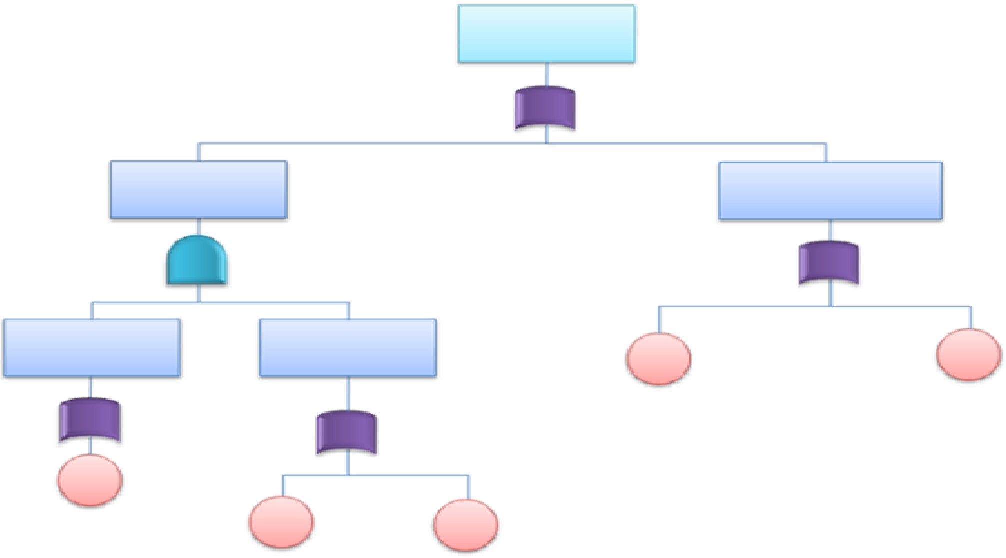


Figure II.10: FTA diagram

II.9.2. History of Fault Tree Analysis

Fault tree analysis is a top-down approach that was originally developed in Bell laboratories by H Watson and A Mearns for the air force in the year 1962. This concept later adopted by Boeing and today it is widely used in aerospace, automobile, chemical, nuclear and software industries especially reliability and safety related events.

II.9.3. FTA symbols

Fault tree uses logical gates to perform the analysis. There are numerous FTA symbols exists, but these are broadly divided in to two categories, Event symbols and Gate symbols.

II.9.3.1. Event Symbols in FTA

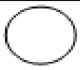
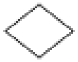
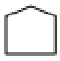
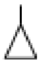
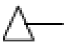
S.No	Event Symbol	Description
1		Primary or basic failure event. It is a random event and sufficient data is available
2		State of system, subsystem or component event
3		Secondary failure or under developed event, can be explored further
4		Conditional event and is associated with the occurrence of some other event
5		House event representing either occurrence or non-occurrence of an event
6	 In  Out	Transfer in and transfer out symbols used to replicate a branch or sub-tree of the FTA

Table II.1: Event Symbols in FTA

II.9.3.2. Gate Symbols in FTA

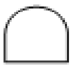
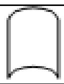
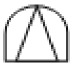
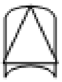
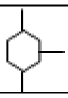
S.No	Gate Symbol	Description
1	 AND Gate	The output event occurs when all the input events occur
2	 OR Gate	The output event occurs when at least one of the input events occur
3	Priority AND Gate 	The output event occurs when all the input events occur in the order from left to right
4	 Exclusive OR gate	The output event occurs if either of the two input events occur but not both
5	 Inhibit gate	The output event occurs when the input event occurs and the attached condition is satisfied

Table II.2: Gate Symbols in FTA

II.9.4. Advantages of Fault tree analysis

- Fault tree visually depict the analysis that will help team to work on cause of event in logical way that leads to failure
- Highlights the critical components related to system failure
- Provides an efficient method to analyze the system
- Unlike other analysis methods, human errors are also including in the analysis
- It helps to prioritize the action items to solve the problem
- Provides qualitative and quantitative analysis

II.9.5. Disadvantages of Fault tree analysis

- Too many gates and events to be consider for large system analysis
- The basic disadvantage is that it examines only one top event
- Common cause failures are not always obvious
- Difficult to capture time related and other delay factors
- Needs experienced individuals to understand the logical gates [23]

II.10. Conclusion

In this chapter, we presented a fundamental of maintenance (definition, classification, advantages and inconvenient), these basics concept: reliability, maintainability and availability, as well as the method of ‘‘PARETO’’, ‘‘ISHIKAWA’’, ‘‘Fault tree analysis’’ in order to exploit them in the next chapter.

CHAPTER III: Analytic Study and Application

III.1. Introduction

Maintenance is content to intervene on a faulty system to restart production and perform the recommended routine operations by the manufacturer.

The objective of this chapter is to exploit the failure history of the DR990 gas turbine and to experimentally study RMA indicators and draw their curves, thus applying the Pareto, Ishikawa and FTA methods.

III.2. Functional Analysis

III.2.1. The Horned Beast

Q1: To whom or what does the product do it serve?

Answer 1: To the user.

Q2: On whom or what does it act?

Answer 2: On a kinetic energy of a combustion gas.

Q3: For what purpose?

Answer 3: Obtain Mechanical energy to drive a generator.

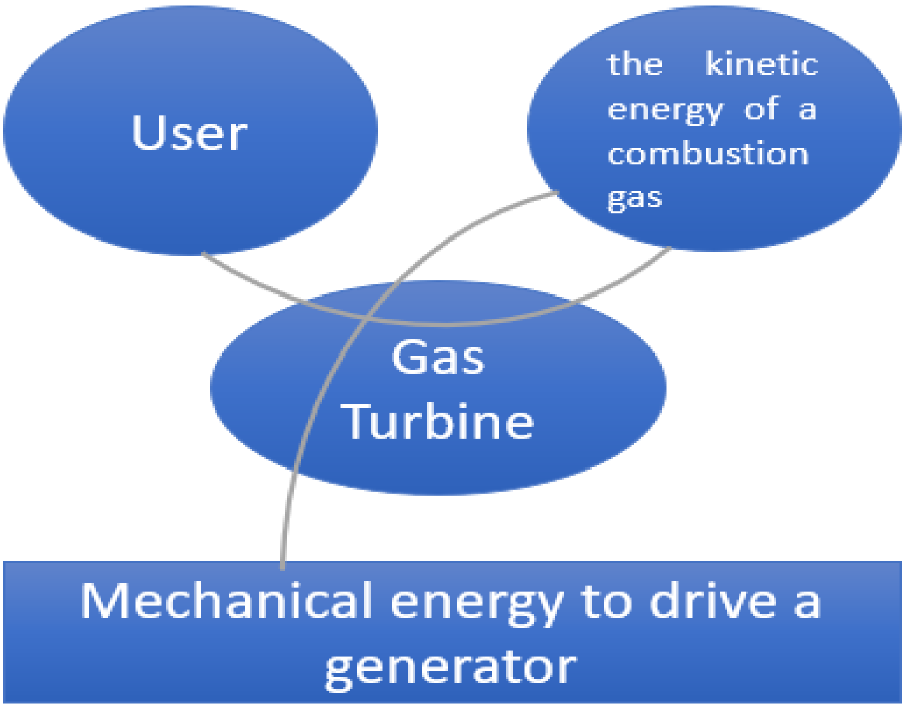


Figure III.1: The horned beast diagram

III.2.2. Octopus diagram

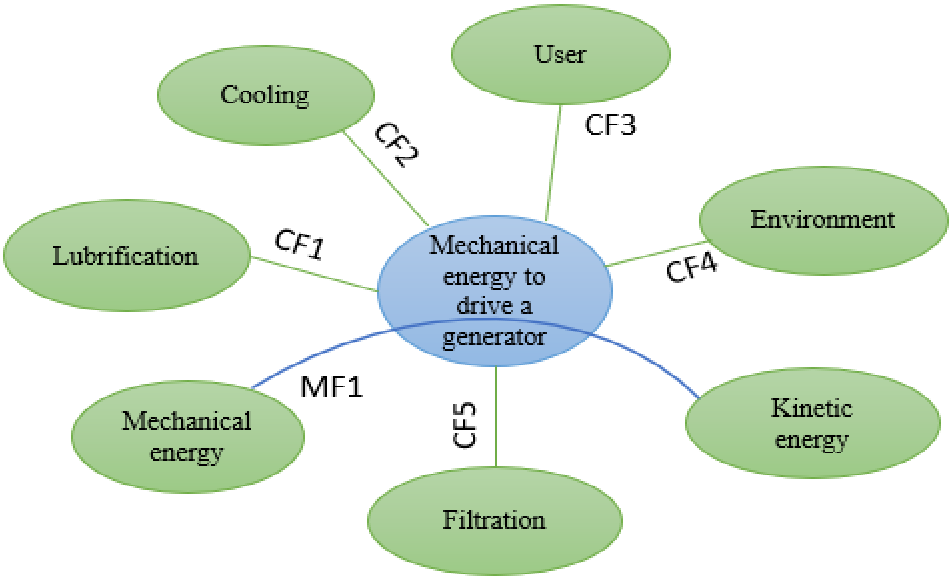


Figure III.2: Octopus diagram

Function	Signification
MF1	Converting the kinetic energy of combustion gas into Mechanical Energy
CF1	Lubricate the mechanical part of the turbine
CF2	Cool the turbine to an optimal operating temperature
CF3	Control and maintain of the turbine
CF4	Protecting the environment from exhaust gases
CF5	Filtering the intake air and oil

Table -III.1: The diagram functions and their meaning

III.2.3. THE S.A.D.T: (Structured Analysis Design Technic)

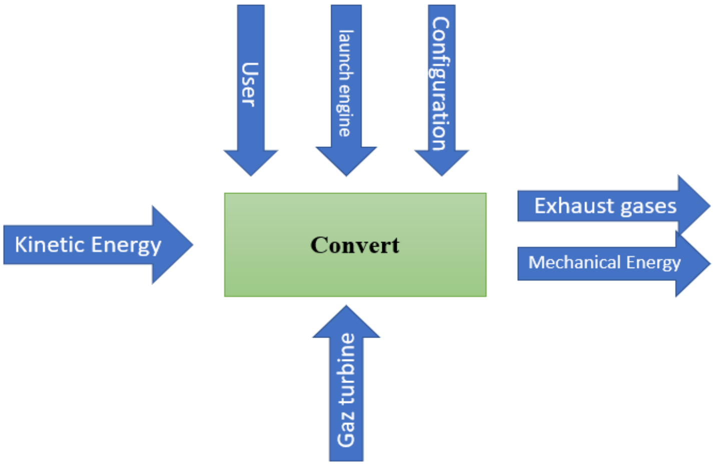


Figure III.3: The S.A.D.T. Diagram

III.3. The Practical Application of Analysis Methods

Exploitation of history

- The processing of the raw historical data (Table III.2) involves:
- Calculating downtime due to outages (DT) resulting from differences between stop and start dates.
- The calculation of the hours of operation (UT), which result from the differences between two successive failures.
- The calculation of technical repair times. (TTR is resulted from the downtime minus the rest time)

N°	Start date	Stop date	TTR (h)	UT (h)	DT (h)	Cause
1	13/02/2010	18/10/2010	24	5952	240	Baroscopic inspection of hot parts. changes of the joints of thermo couples and gas injector.
2	28/10/2010	05/06/2011	06	5304	72	Oil supplement for KT501.
3	08/06/2011	31/10/2011	08	3408	120	Turbine air filter changes
4	04/11/2011	05/05/2012	10	5064	20	sealing oil filter Change.
5	10/05/2012	20/06/2012	12	960	24	Intervention on the greasing circuit.
6	21/06/2012	21/06/2012	03	192	24	Emptying the case's lubrication oil and changing the filter.
7	22/06/2012	12/07/2013	48	912	336	Intervention on the GTG-ME-205-KT501 electric motor.
8	26/07/2013	03/08/2014	15	9840	168	Intervention on the greasing circuit.
9	10/08/2014	26/09/2014	170	1104	1180	overhaul of the k501 gas turbine.

Table III.2: Dr990 turbine history record

III.3.1. Reliability, Maintainability, Availability Study (RMA)

III.3.1.1. Calculate Weibull parameters using Minitab 16

The following table shows the UTs ranked in ascending order as well as the F (ti) calculated by the method of the median ranges by the following law:

$$(N=9) < 20 \longrightarrow F(ti): \frac{\Sigma\, ni-0{,}3}{N+0{,}4} \quad (3.1)$$

n	UT	ni	Σ ni	F(ti)	% F(ti)
1	192	1	1	0,0745	07,45%
2	912	1	2	0,1809	18,09%
3	960	1	3	0,2872	28,72%
4	1104	1	4	0,3936	39,36%
5	3408	1	5	0,5	50%
6	5064	1	6	0,6064	60,64%
7	5304	1	7	0,7128	71,28%
8	5952	1	8	0,8191	81,91%
9	9840	1	9	0,9256	92,56%

Table III.3: The calculation of the distribution function F(ti)

- ***Step 1:*** Filling one column in the worksheet1

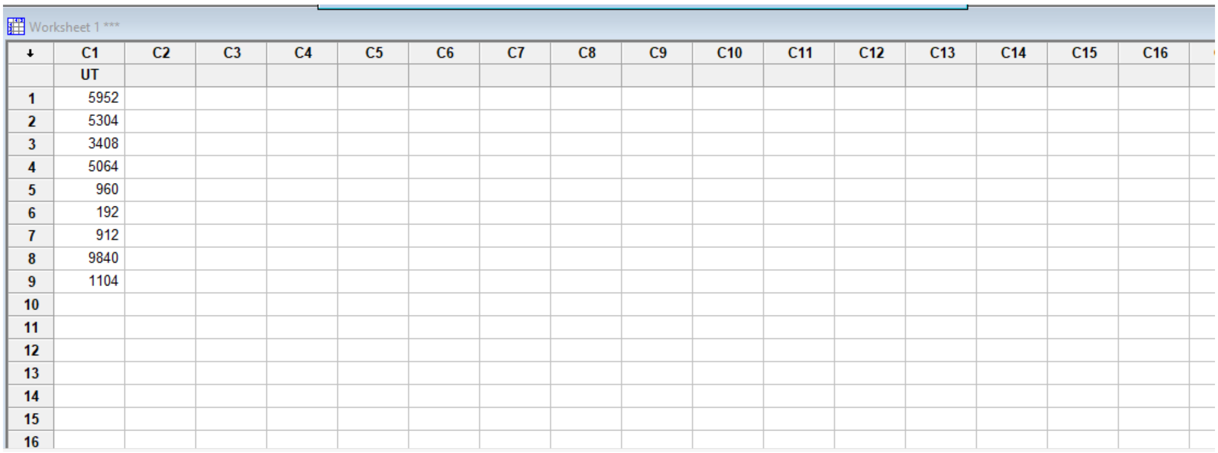


Figure III.4: Step 1 tutorial (Minitab 16 software)

- ***Step 2:*** Go to Stat >> Reliability/Survival >> Distribution analysis (Right Concerning)>>Parametric Distribution Analysis.

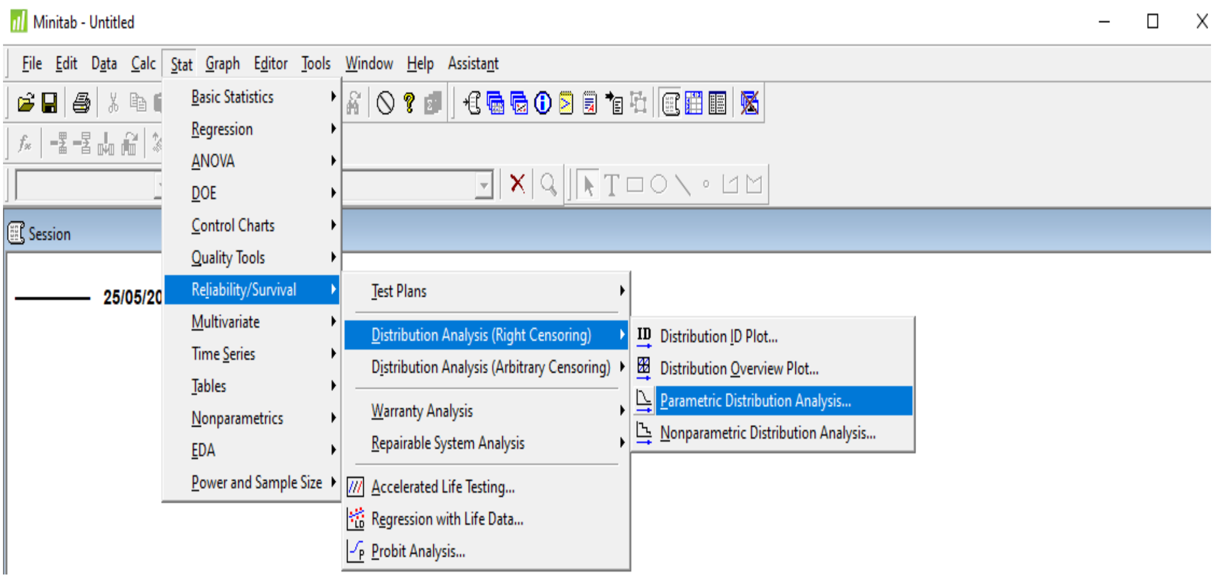


Figure III.5: Step 2 tutorial (Minitab 16 software)

- ***Step 3:*** Go to Variables >> Select C1, then go to Assumed distribution >> 3-parameter Weibull >> Click OK

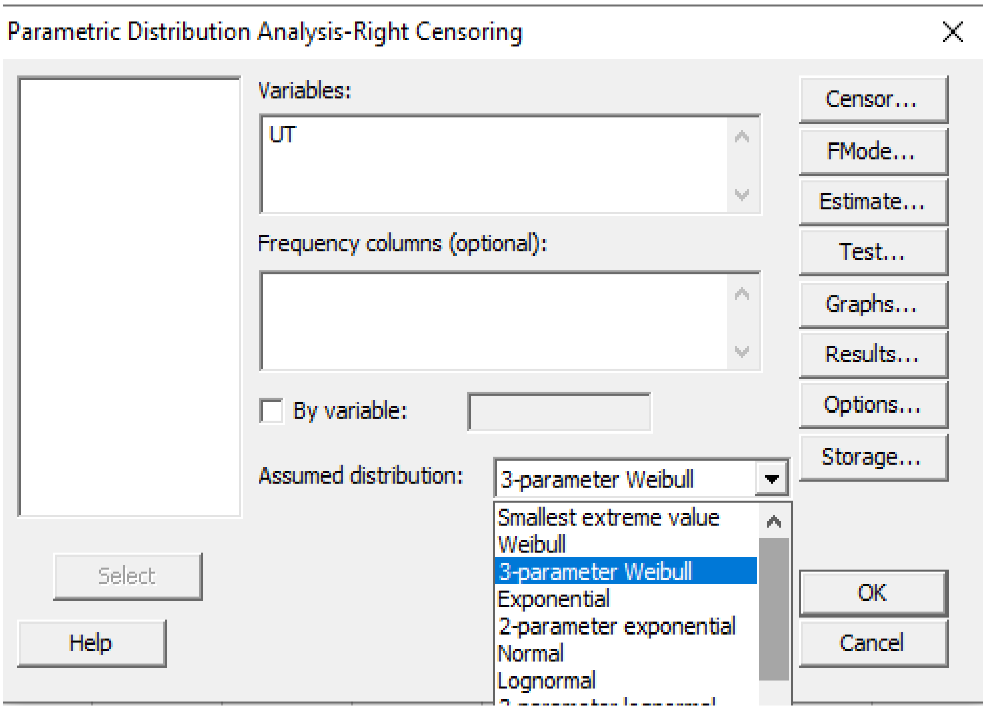


Figure III.6: Parametric Distribution Analysis-Right Censoring (Minitab 16 software)

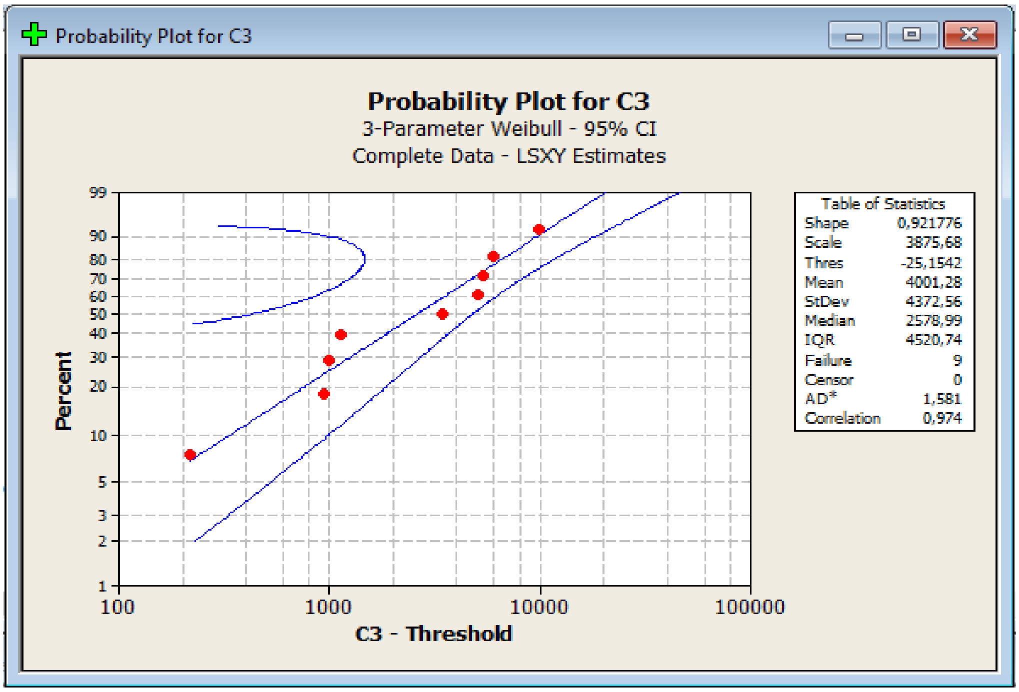


Figure III.7: Weibull's curve (Minitab 16 software)

After drawing the Wei Bull curve, we can determine the parameters β, η et γ , using MINITAB 16 software:

- β = 0,921
- η= 3875,68
- γ= -25,15

III.3.1.2. KOLMOGOROV SMIRNOV Test

Before the validation of all reliability laws, it is necessary to test the hypothesis to find out whether we will have to accept or reject the model proposed by the K-S test with a confidence threshold of α= 20%. This test consists of calculating the difference between the f(ti) theoretical function and the actual function F(t) and taking the maximum in absolute DN.max.

This value is compared with DN. α ,Who is given by Kolmogorov Smirnov's table (see appendix1). If DN.max. > DN. α We refuse the hypothesis.

Where F(t) is obtained by: $F(t) = 1 - e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$ (3.2)

n	UT	F (ti)	F (t)	DN_{max} = |F(ti) – F(t)|
01	192	0,0745	0.068	0,0065
02	912	0,1809	0.237	0,0561
03	960	0,2872	0.2467	0,0405
04	1104	0,3936	0.2747	0,1189
05	3408	0,5	0.5911	0,0911
06	5064	0,6064	0.7234	0,117
07	5304	0,7128	0.7384	0,0256
08	5952	0,8191	0.7747	0,0444
09	9840	0,9256	0.9060	0,0196

Table III.4: KOLMOGOROV SMIRNOV Test

- DN. α = D 9.20 = 0,339 (see Appendix tab.1).
- DN max= 0,1189

0.1189 < 0.339, ''DN max< DN.α'', Which means Weibull's model is accepted.

III.3.1.3 Exploiting Weibull parameters

III.3.1.3.1 The MUT

To calculate the MUT, the A coefficient value must first be determined from Appendix (2)

MUT = A. η + γ (3.3)

A= 1,0522; η= 3875,68; γ= -25,15

MUT = (1,0522 x 3875,68) – 25,15

MUT = 4052,84 H.

III.3.1.3.2 The function of probability density f(t) according to MUT

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} . e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad (3.4)$$

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

$$f(4052{,}84) = \frac{0{,}921}{3875{,}68}\left(\frac{4052{,}84 + 25{,}15}{3875{,}68}\right)^{0{,}921-1} . e^{-\left(\frac{4052{,}84+25{,}15}{3875{,}68}\right)^{0{,}921}}$$

$f(4052{,}84)$ =0,000083 =00,0083%

III.3.1.3.3 The Distribution function according to MUT

For (t = MUT) => $F(t) = 1 - e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$

$$F(MUT) = 1 - e^{-\left[\frac{MUT-\gamma}{\eta}\right]^{\beta}} \Rightarrow F(4052{,}84) = 1 - e^{-\left[\frac{4052{,}84+25{,}15}{3875{,}68}\right]^{0{,}921}}$$

F (4052,84) = 0,6494 = 64,94%

III.3.1.3.4. Reliability according to MUT

$$R(t) = 1 - F(t) \qquad (3.5)$$

For (t = MUT) => $R(MUT) = 1 - F(MUT)$ => $R(MUT) = 1 - 0{,}6494$

R(MUT)=0,3506 = 35,06%

It is noted that the reliability of the turbine is too low.

III.3.1.3.5 Failure rate according to the MUT

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1} \Rightarrow \text{For } (t = MUT) \Rightarrow \lambda(MUT) = \frac{f(MUT)}{R(MUT)} = \frac{\beta}{\eta}\left[\frac{MUT-\gamma}{\eta}\right]^{\beta-1} \qquad (3.6)$$

$$\lambda(4052{,}84) = \frac{0{,}921}{3875{,}68}\left[\frac{4052{,}84 + 25{,}15}{3875{,}68}\right]^{0{,}921-1}$$

$\lambda(\mathbf{4052{,}84})$ = 0,00023 (Failure / Hour)

III.3.1.3.6. Calculating the desirable time to maintain a reliability of 80%

To maintain a reliability of 80% = > R(t) = 80%, must calculate the desirable time for a systematic intervention (ts=?):

$$R(t) = e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}} \qquad (3.7)$$

$\ln R(t) = ln . e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$ => for: R(t) = 0,8

Ln R(t)= $-\left(\frac{t-\gamma}{\eta}\right)^{\beta}$ => $[-\ln R(t)]^{\frac{1}{\beta}} = \frac{t-\gamma}{\eta}$ => $ts = [\eta * [\ln(\frac{1}{R(t)})]^{\frac{1}{\beta}}] + \gamma$

ts= [3875,68 * (ln $(\frac{1}{0.8}))^{\frac{1}{0,921}}$] - 25,15

ts= [3875,68 * 0,1962] – 25,15

ts= 735,27 Hour

So, to keep a reliability of 80% of the turbine it must intervene systematically every 735.27 hours.

III.3.1.4. Weibull model application

In this stage, we will calculate the following functions:

a) The function of probability density f(t): $f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} . e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$

b) Distribution function F (t): $F(t) = 1 - e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$

c) Reliability Function R (t): $R(t) = e^{-\left[\frac{t-\gamma}{\eta}\right]^{\beta}}$

d) Failure Rate function λ(t) : $\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left[\frac{t-\gamma}{\eta}\right]^{\beta-1}$

The following table (Table III.5) represents the calculations of those functions, after that we will draw the curves of each function and we're going to analyze and comment each curve.

UT / Functions	192	912	960	1104	3408	5064	5304	5952	9840
$f(t) * 10^{-3}$	0.278	0.203	0.2	0.190	0.098	0.065	0.061	0.052	0.021
F(t)	0.068	0.237	0.2467	0.2747	0.5911	0.7234	0.7384	0.7747	0.9060
R(t)	0.932	0.7630	0.7533	0.7253	0.4089	0.2766	0.2616	0.2253	0.094
$\lambda(t) * 10^{-3}$	0.2983	0.2661	0.2655	0.262	0.2397	0.2349	0.2331	0.2308	0.2234

Table III.5: Calculation of functions f(t), F(t), R(t) And $\lambda(t)$

III.3.1.4.1. Probability density function f(t) curve and interpretation

Interpretation: From the following curve (Figure III.8), we can see that the function f(t) (density of probability) decreases according to time.

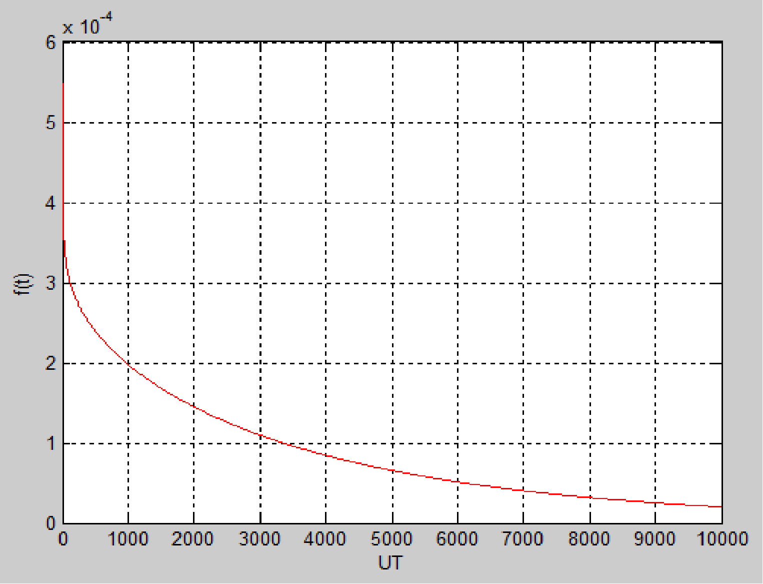


Figure III.8: f(t) curve (MATLAB Software)

III.3.1.4.2. Cumulative function F (t) curve and interpretation

Interpretation: From the following curve (Figure III.9), we can see that the distribution function F(t) is increasing according to time. This translates into Degradation of the turbine with a function of time.

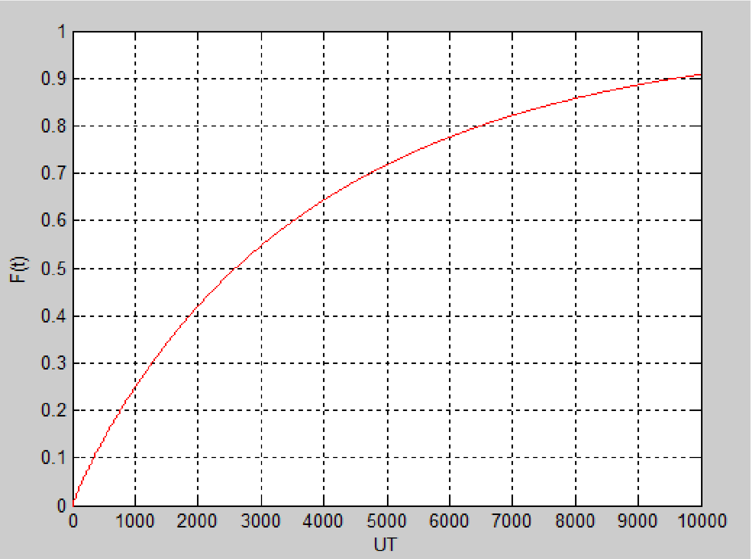


Figure III.9: F(t) curve (MATLAB Software)

III.3.1.4.3. Reliability Function R (t) curve and interpretation

Interpretation: From the following curve (Figure III.10), we notice that the reliability is decreasing according to time, which makes the phenomenon of degradation explain the improvement of the reliability of the turbine necessarily requires an analysis of failures with a study of their causes and consequences.

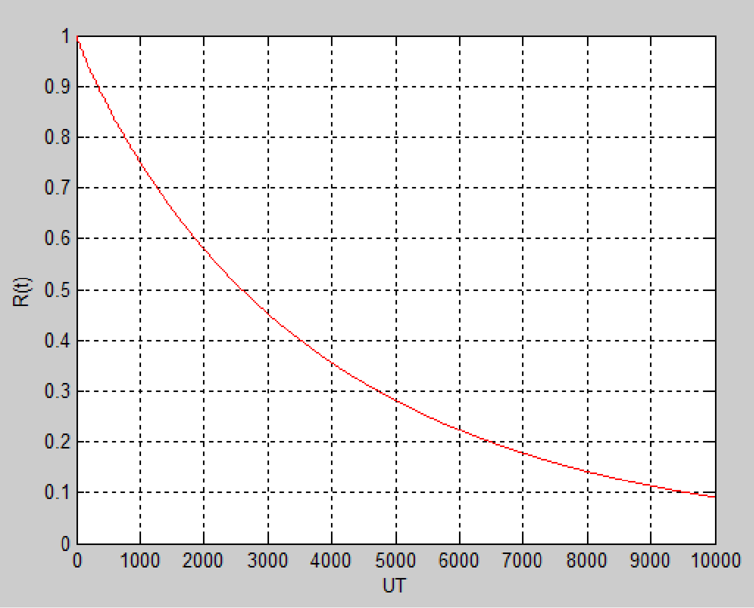


Figure III.10: R(t) Curve (MATLAB Software)

III.3.1.4.4. Failure Rate $\lambda(t)$ curve and interpretation

<u>Interpretation:</u> From the following curve (Figure III.11), we can see that the failure rate decreases overtime. This decrease is considered normal, that is, not Quick**.**

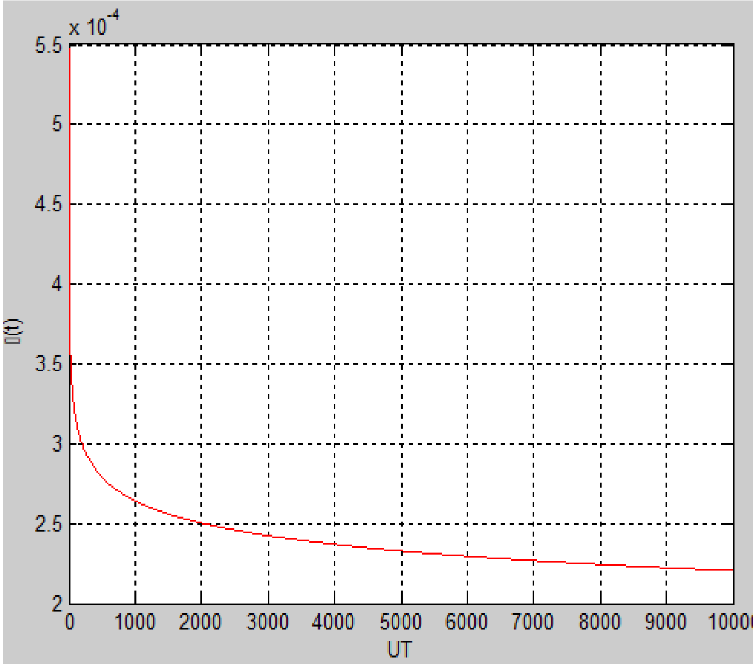


Figure III.11: $\lambda(t)$ curve (MATLAB Software)

III.3.1.5 Maintainability Calculation

Based on the turbine's failure history:

MTTR=ΣTTR/N (3.8)

TTR: Technical Time to repair => N: Number of repairs.

MTTR= $\frac{296}{9}$ = 32,89Hour

$\mu = \frac{1}{MTTR} = \frac{1}{32,89}$ = 0,03040 Intervention / Hour.

M(t)= $1 - e^{-\mu . t}$ (3.9)

The following table (Table III.6) represents the calculations of the maintainability M(t):

t(h)	20	40	60	80	100	120	140	160	180
M(t)%	45.56	70.36	83.86	91.21	95.22	97.40	98.58	99.22	99.57

Table III.6: Calculation of the Maintainability M(t)

III.3.1.5.1 Maintainability curve interpretation

Based on the resulting curve of table III.6 calculations in figure (III.12) above, it is noted that maintainability is increasing over time .Maintainability Increases so that the technical repair time TTR increases, which is a bad sign of degradation of our System. .

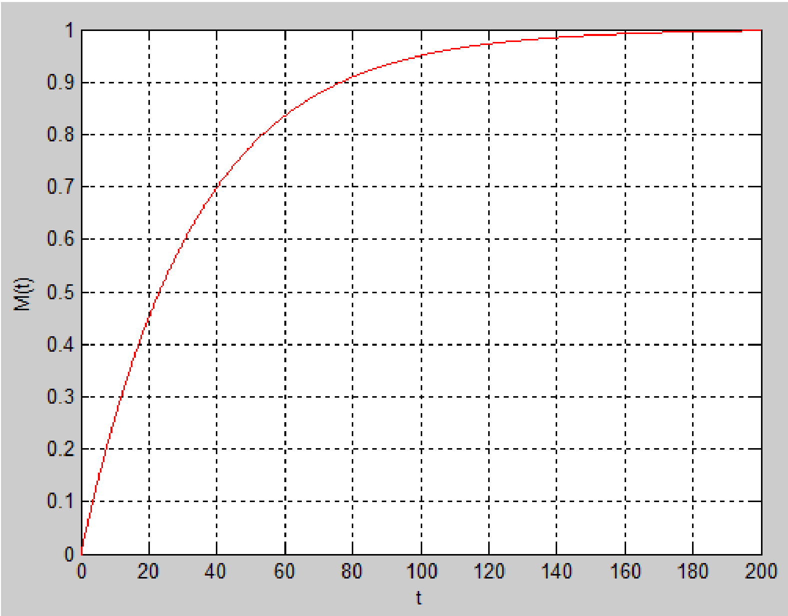


Figure III.12 Maintainability M(t) Curve (MATLAB Software)

III.3.1.6. Availability Calculation

III.3.1.6.1. Intrinsic Availability

$$Di = \frac{MUT}{MUT+MTTR} \quad (3.10)$$

$$Di = \frac{4052,84}{4052,84+32,89} = 0,9920$$

III.3.1.6.2. Instant Availability

$$\boldsymbol{D(t)} = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\boldsymbol{e}^{-(\lambda+\mu)\mathbf{t}} \quad (3.11)$$

$$\lambda = \frac{1}{\boldsymbol{MUT}} = \frac{1}{\mathbf{4052{,}84}} = 0{,}000247 \quad (3.12)$$

μ=0,0304

$\lambda+\mu$ = 0,000247+0,0304 = 0,03065

$$\boldsymbol{D(t)} = \frac{\mathbf{0,0304}}{\mathbf{0,03065}} + \frac{\mathbf{0,000247}}{\mathbf{0,03065}}\boldsymbol{e}^{-(\mathbf{0{,}03065})\boldsymbol{t}}$$

t(h)	20	40	60	80	100	120	140	160	180
D(t)%	99,62	99,42	99,31	99,25	99,22	99,21	99,20	99,19	99,18

Table III.7: Calculation of the availability D(t)

III.3.1.6.3. Availability curve and interpretation

Availability is decreasing over time, to increase the availability of a turbine consists of reducing the number of its stops (increased its reliability) and reducing the time needed to resolve the causes of these (increased its maintainability).

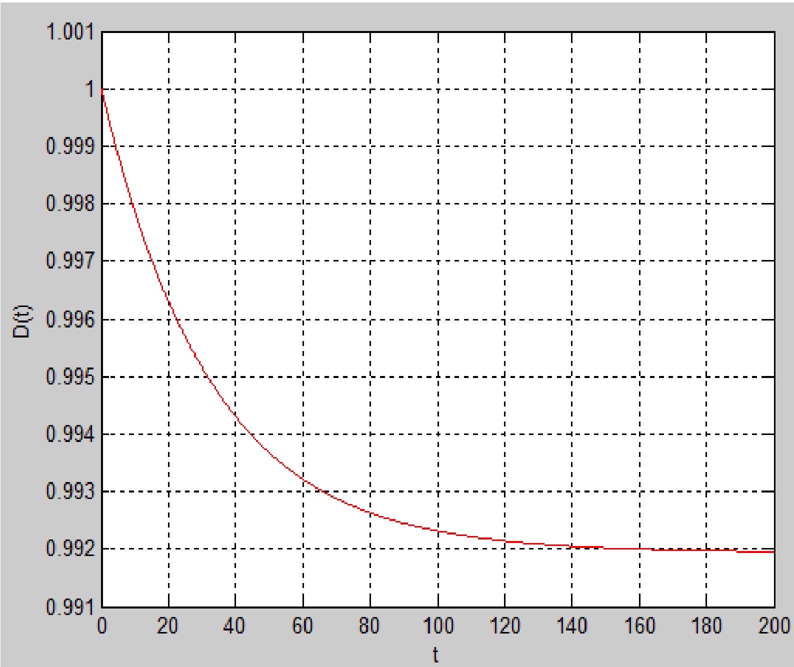


Figure III.13: Availability D(t) Curve (MATLAB Software)

III.3.2. ABC (Pareto) Predictive Analysis Methods

N	Intervention	TTR	Cumulative TTR	TTR%	Number of failures	Cumulative failures	Cumulative failures %
1	Overhaul of the k501 gas turbine.	170	170	57,43%	1	1	**11,11%**
2	Intervention on the GTG-ME-205-KT501 electric motor.	48	218	73,65%	1	2	**22,22%**
3	Intervention on the greasing circuit.	27	245	82,77%	2	4	**44,44%**
4	-Baroscopic inspection of hot parts. -Changes of the joints of thermo couples and gas injector.	24	269	90,88%	1	5	**55,56%**
5	sealing oil filter Change	10	279	94,26%	1	6	**66,67%**
6	Turbine air filter changes	8	287	96,96%	1	7	**77,78%**
7	Oil supplement for KT501	6	293	98,99%	1	8	**88,89%**
8	Emptying the case's lubrication oil and changing the filter	3	296	100%	1	9	**100%**

Table III.8: ABC Analysis

III.3.2.1. ABC analysis curve

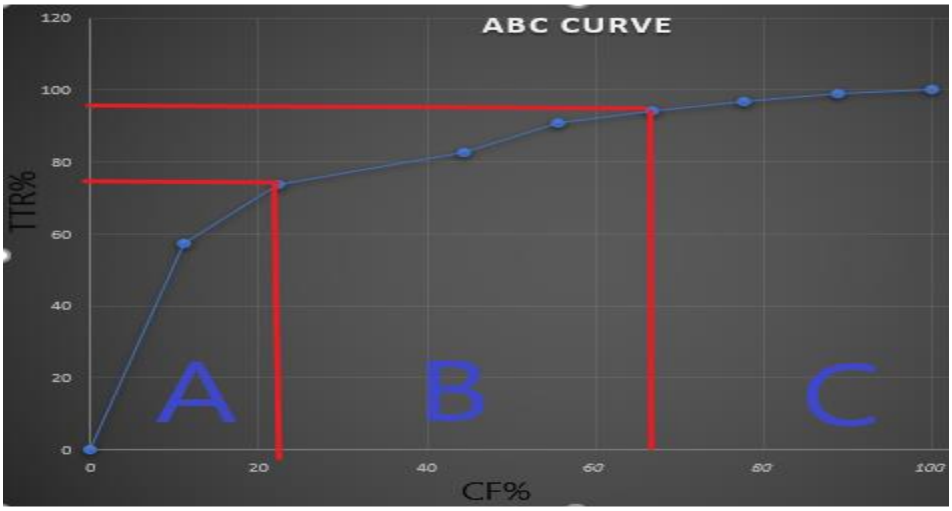


Figure III.14: ABC Curve

II.3.2.2. Interpretation of results

Zone "A": In this zone, we find that about 22.22% of the causes represent 73.65% of the repair time, this constitutes zone A, (Overhaul of the gas turbine, Intervention on the electric motor.)

Zone "B": In this zone, the 44.45% of cases represent 20.61% of the repair time (Intervention on the greasing circuit, Baroscopic inspection of hot parts, Changes in the joints of thermo couples and gas injector, sealing oil filter Change).

Zone "C": In this zone the 33.33% of the remaining causes represent only 5.74% of the repair time (Turbine air filter changes, Oil supplement, Emptying the case's lubrication oil and changing the filter).

III.3.3. ISHIKAWA Diagram

III.3.3.1. GTG-ME-205-KT501 electric motor intervention analysis : An in-depth and detailed Diagnosis of the Different Causes of Failures in an Electric Motor is represented according to the following diagram from ISHIKAWA

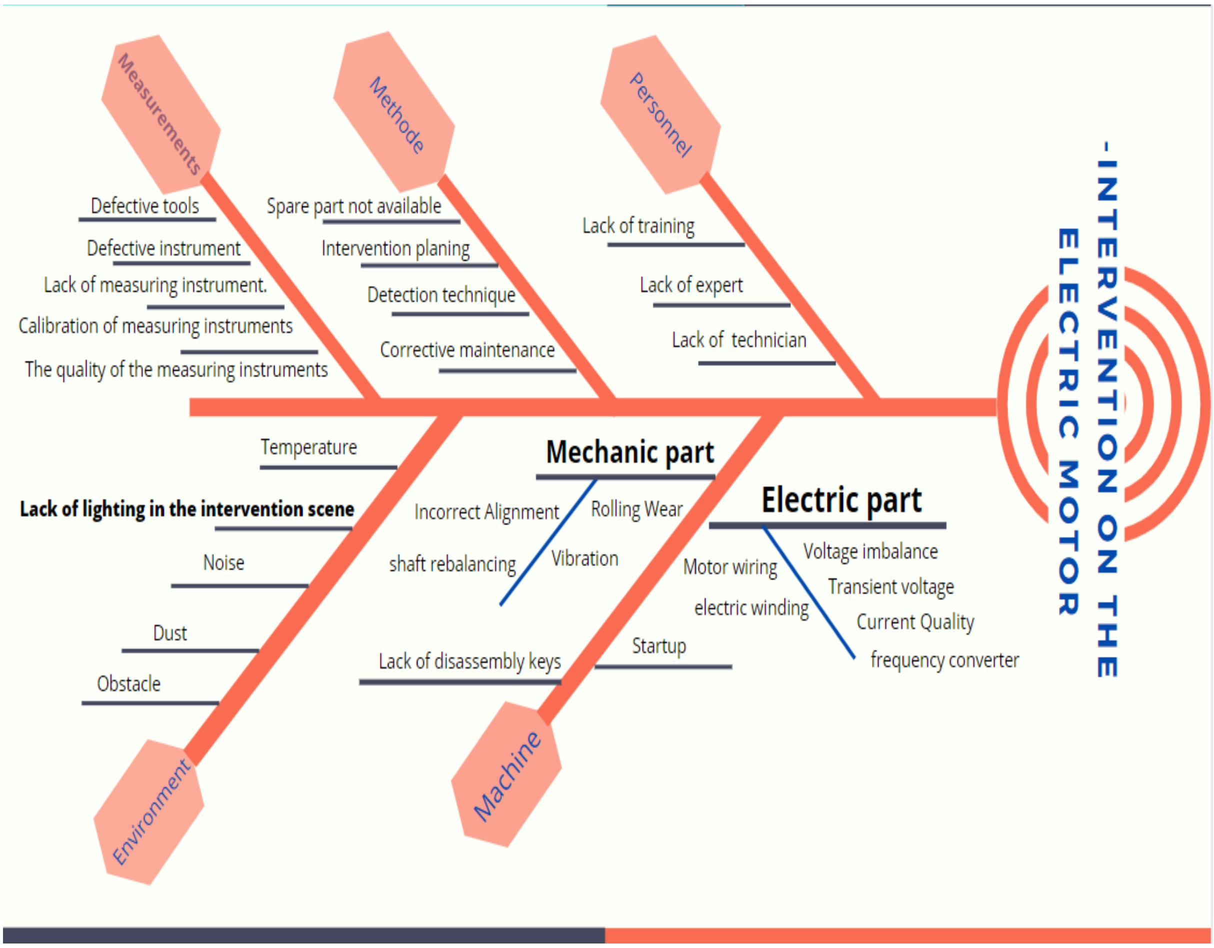


Figure III.15: GTG-ME-205-KT501 electric motor intervention analysis

III.3.3.2. Overhaul intervention analysis on K501 gas turbine

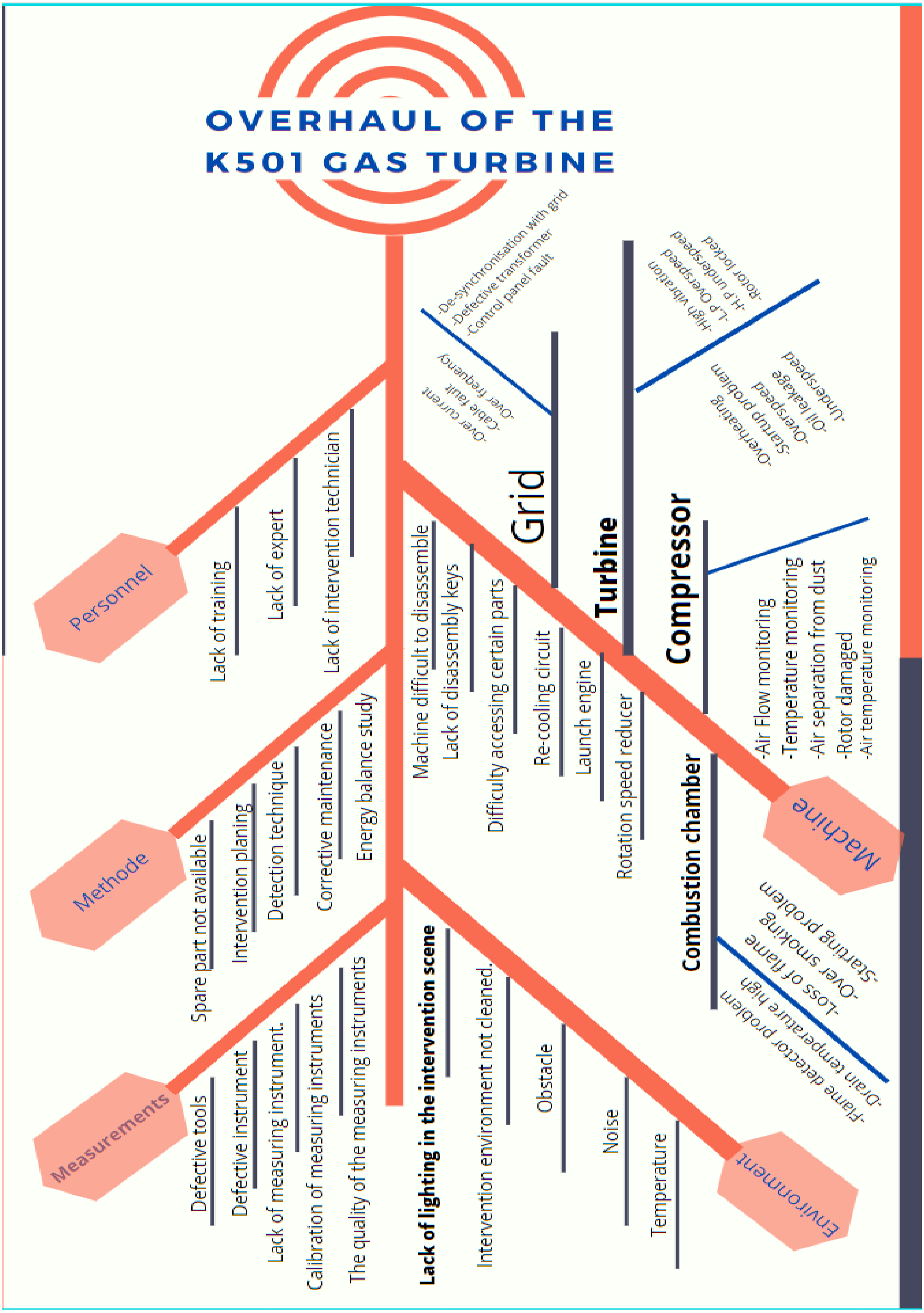


Figure III.16: Overhaul intervention analysis on K501 gas turbine

III.3.4. Fault tree analysis

III.3.4.1. Gas turbine fault tree

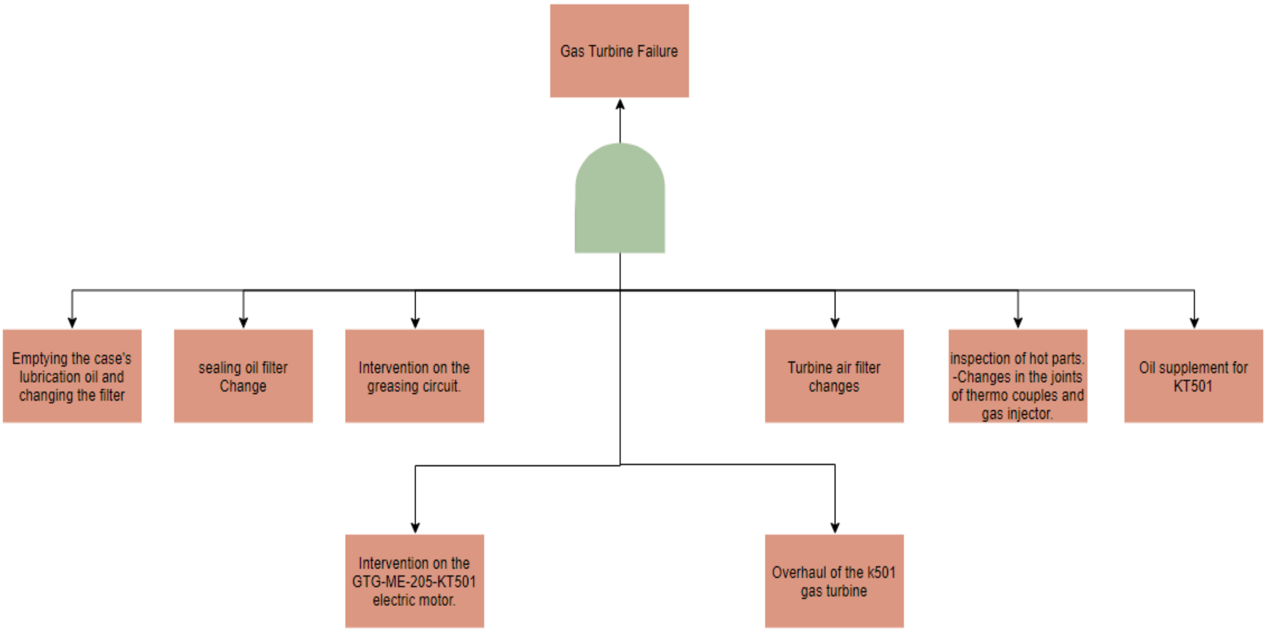


Figure III.17: Gas turbine fault tree

III.3.4.2. GTG-ME-205-KT501 electric motor fault tree

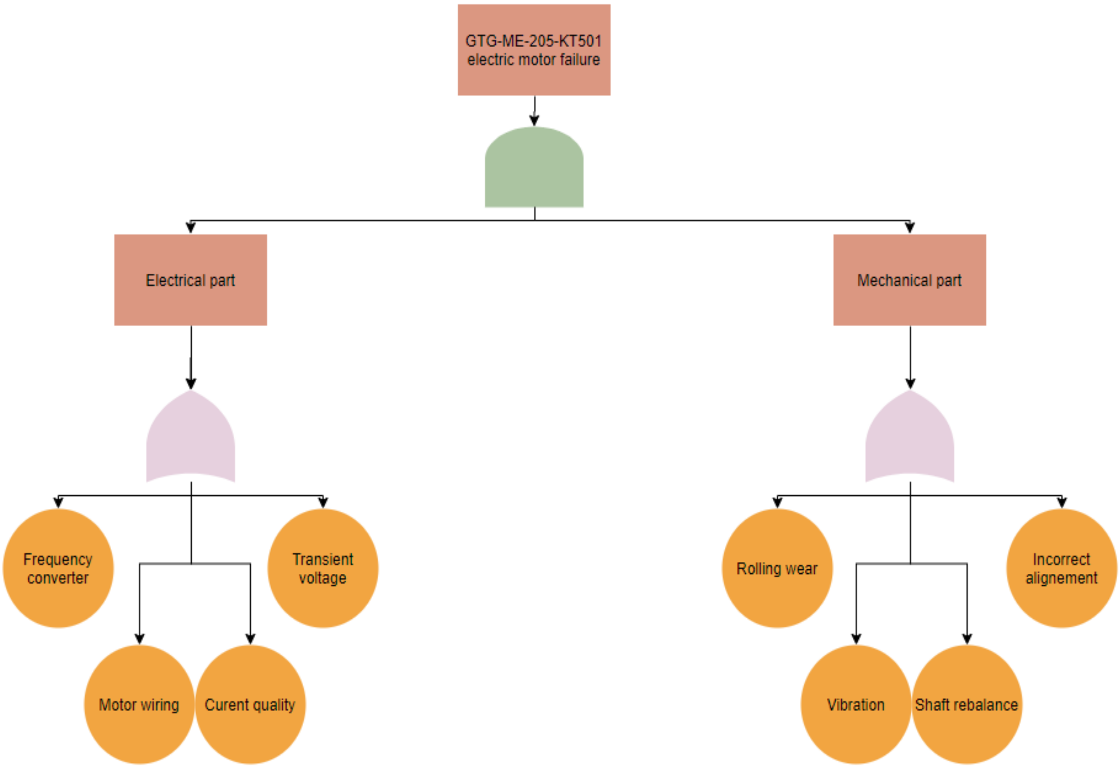


Figure III.18: GTG-ME-205-KT501 electric motor fault tree

III. 3.4.3. Overhaul of the k501 gas turbine fault tree

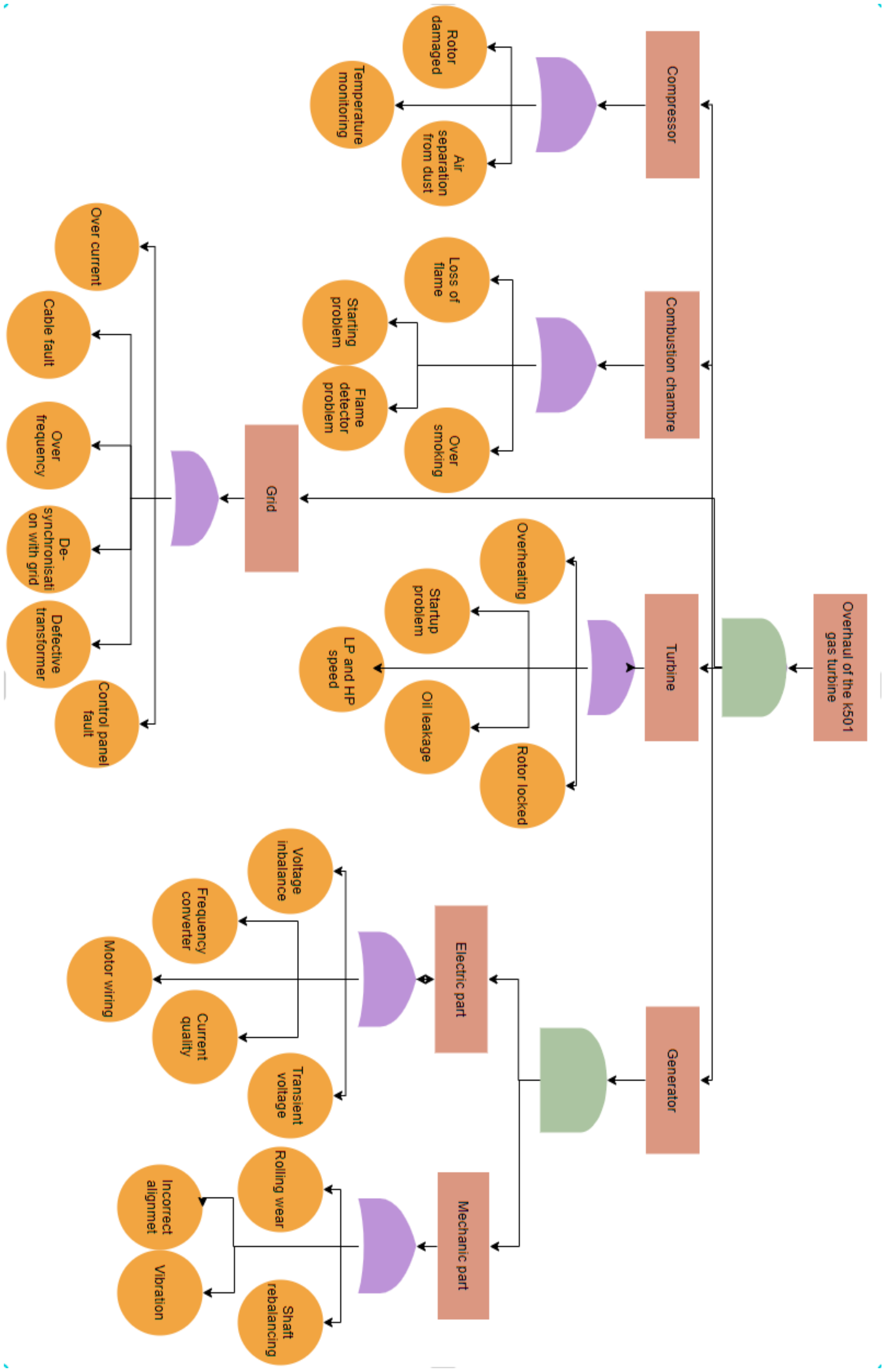


Figure III.19: Overhaul of the k501 gas turbine fault tree

III.3.5. « Causes-Remedies » Table

N°	Causes	Remedies
1	Spare part unavailable	Organize spare parts stocks
2	Lack of disassembly keys	Provide keys
3	Noise	Transfer the repair to the workshop
4	Lack of measuring instruments	Provide measuring instruments
5	Obstacle	Transfer the repair to the workshop
6	Lack of intervention technician	Recruit intervention technicians
7	Accuracy of measurement instruments	Adjust the calibration of measuring instruments
8	Defective tools	Provide new tools
9	Intervention environment not clean	Clean intervention environment
10	Lack of expert	Assist experts

Table III.9: « Causes-Remedies » Table

III.4. Conclusion

In this chapter, functional analysis was applied to the gas turbine, to identify the main objective of this turbine, which is to obtain the mechanical energy from the kinetic energy of the combustion gas to train a receiving machine.

Then, the failure history of the DR990 turbine was exploited. This history has been used to study the reliability, maintainability, and availability of this turbine, and the results obtained are as follows:

- β=0.921, so the failure rate is decreasing, characteristic of the youth zone
- γ=-25.15, failures started before the times began
- The MUT= 4052,84 Hour
- The reliability of the turbine is too low (35,06 %), So, to keep the reliability of 80% of the turbine it must intervene systematically every 735.27 hours

In the end, Pareto (ABC) method was applied and we found that about 22.22% of the causes (Overhaul of the gas turbine, Intervention on the electric motor) represent 73.65% of the repair time, ‘‘Ishikawa diagram’’ was applied to this 22.22% of causes, and according to the two ‘Ishikawa’ diagrams, the majority of the causes are in the category of machines. ending the chapter using the fault tree analysis method, which organizes the possible element failures and combination of failures that lead to the top-level fault being studied in a graphical diagram.

General conclusion

Industrial maintenance aims to ensure the proper functioning of industrial equipment. In turn, it reduces production costs by avoiding, for example, the stoppage of the machining line and the resulting losses. In addition to direct costs, the issue of industrial maintenance also has an impact on the quality of production. Thus, it also makes it possible to contribute to the recovery of certain materials.

The maintenance man needs to know which failures to deal with first, some of which are of little importance in terms of effects and cost, the operation of the history has allowed us to make the choice. After using Pareto's diagram, which allows us to choose between several problems which need to be dealt with as a priority, we noticed that: The times of major repairs of the turbine and which require interventions to be carried out primarily of those who are less so, are the electric motor and the overhaul of the gas turbine.

The analysis of causes-effects by the ISHIKAWA method, allowed us to identify the possible causes of breakdowns according to the law of 5 M, after the realization of the failure tree analysis, we proposed some remedies for the causes identified by the Ishikawa method in a table called ‘‘causes-remedie

APPENDIX 1

n\α	0.001	0.01	0.02	0.05	0.1	0.15	0.2
1		0.99500	0.99000	0.97500	0.95000	0.92500	0.90000
2	0.97764	0.92930	0.90000	0.84189	0.77639	0.72614	0.68377
3	0.92063	0.82900	0.78456	0.70760	0.63604	0.59582	0.56481
4	0.85046	0.73421	0.68887	0.62394	0.56522	0.52476	0.49265
5	0.78137	0.66855	0.62718	0.56327	0.50945	0.47439	0.44697
6	0.72479	0.61660	0.57741	0.51926	0.46799	0.43526	0.41035
7	0.67930	0.57580	0.53844	0.48343	0.43607	0.40497	0.38145
8	0.64098	0.54180	0.50654	0.45427	0.40962	0.38062	0.35828
9	0.60846	0.51330	0.47960	0.43001	0.38746	0.36006	0.33907
10	0.58042	0.48895	0.45662	0.40925	0.36866	0.34250	0.32257
11	0.55588	0.46770	0.43670	0.39122	0.35242	0.32734	0.30826
12	0.53422	0.44905	0.41918	0.37543	0.33815	0.31408	0.29573
13	0.51490	0.43246	0.40362	0.36143	0.32548	0.30233	0.28466
14	0.49753	0.41760	0.38970	0.34890	0.31417	0.29181	0.27477
15	0.48182	0.40420	0.37713	0.33760	0.30397	0.28233	0.26585
16	0.46750	0.39200	0.36571	0.32733	0.29471	0.27372	0.25774
17	0.45440	0.38085	0.35528	0.31796	0.28627	0.26587	0.25035
18	0.44234	0.37063	0.34569	0.30936	0.27851	0.25867	0.24356
19	0.43119	0.36116	0.33685	0.30142	0.27135	0.25202	0.23731
20	0.42085	0.35240	0.32866	0.29407	0.26473	0.24587	0.23152
25	0.37843	0.31656	0.30349	0.26404	0.23767	0.22074	0.20786
30	0.34672	0.28988	0.27704	0.24170	0.21756	0.20207	0.19029
35	0.32187	0.26898	0.25649	0.22424	0.20184	0.18748	0.17655
40	0.30169	0.25188	0.23993	0.21017	0.18939	0.17610	0.16601
45	0.28482	0.23780	0.22621	0.19842	0.17881	0.16626	0.15673
50	0.27051	0.22585	0.21460	0.18845	0.16982	0.15790	0.14886
OVER 50	$\frac{1.94947}{\sqrt{n}}$	$\frac{1.62762}{\sqrt{n}}$	$\frac{1.51743}{\sqrt{n}}$	$\frac{1.35810}{\sqrt{n}}$	$\frac{1.22385}{\sqrt{n}}$	$\frac{1.13795}{\sqrt{n}}$	$\frac{1.07275}{\sqrt{n}}$

Kolmogorov-Smirnov Table

APPENDIX 2

β	A	B	β	A	B	β	A	B	β	A	B
0,05	2,43290E+18	9,03280E+23	1,75	0,89062	0,52523	3,45	0,89907	0,28822	5,15	0,91974	0,20505
0,1	3,62880E+06	1,55977E+09	1,8	0,88929	0,51123	3,5	0,89975	0,28473	5,2	0,92025	0,20336
0,15	2,59357E+03	1,21993E+05	1,85	0,88821	0,49811	3,55	0,90043	0,28133	5,25	0,92075	0,20170
0,2	1,20000E+02	1,90116E+03	1,9	0,88736	0,48579	3,6	0,90111	0,27802	5,3	0,92125	0,20006
0,25	2,40000E+01	1,99359E+02	1,95	0,88671	0,47419	3,65	0,90178	0,27479	5,35	0,92175	0,19846
0,3	9,26053E+00	5,00780E+01	2	0,88623	0,46325	3,7	0,90245	0,27164	5,4	0,92224	0,19688
0,35	5,02914E+00	1,99761E+01	2,05	0,88589	0,45291	3,75	0,90312	0,26857	5,45	0,92272	0,19532
0,4	3,32335E+00	1,04382E+01	2,1	0,88569	0,44310	3,8	0,90379	0,26558	5,5	0,92320	0,19379
0,45	2,47859E+00	6,46009E+00	2,15	0,88561	0,43380	3,85	0,90445	0,26266	5,55	0,92368	0,19229
0,5	2,00000E+00	4,47214E+00	2,2	0,88562	0,42495	3,9	0,90510	0,25980	5,6	0,92414	0,19081
0,55	1,70243E+00	3,34530E+00	2,25	0,88573	0,41652	3,95	0,90576	0,25701	5,65	0,92461	0,18935
0,6	1,50458E+00	2,64514E+00	2,3	0,88591	0,40848	4	0,90640	0,25429	5,7	0,92507	0,18792
0,65	1,36627E+00	2,17887E+00	2,35	0,88617	0,40080	4,05	0,90704	0,25162	5,75	0,92552	0,18651
0,7	1,26582E+00	1,85117E+00	2,4	0,88648	0,39345	4,1	0,90768	0,24902	5,8	0,92597	0,18512
0,75	1,19064	1,61077	2,45	0,88685	0,38642	4,15	0,90831	0,24647	5,85	0,92641	0,18375
0,8	1,13300	1,42816	2,5	0,88726	0,37967	4,2	0,90894	0,24398	5,9	0,92685	0,18240
0,85	1,08796	1,28542	2,55	0,88772	0,37319	4,25	0,90956	0,24154	5,95	0,92729	0,18107
0,9	1,05218	1,17111	2,6	0,88821	0,36696	4,3	0,91017	0,23915	6	0,92772	0,17977
0,95	1,02341	1,07769	2,65	0,88873	0,36097	4,35	0,91078	0,23682	6,05	0,92815	0,17848
1	1,00000	1,00000	2,7	0,88928	0,35520	4,4	0,91138	0,23453	6,1	0,92857	0,17721
1,05	0,98079	0,93440	2,75	0,88986	0,34963	4,45	0,91198	0,23229	6,15	0,92898	0,17596
1,1	0,96491	0,87828	2,8	0,89045	0,34427	4,5	0,91257	0,23009	6,2	0,92940	0,17473
1,15	0,95170	0,82971	2,85	0,89106	0,33909	4,55	0,91316	0,22793	6,25	0,92980	0,17351
1,2	0,94066	0,78724	2,9	0,89169	0,33408	4,6	0,91374	0,22582	6,3	0,93021	0,17232
1,25	0,93138	0,74977	2,95	0,89233	0,32924	4,65	0,91431	0,22375	6,35	0,93061	0,17113
1,3	0,92358	0,71644	3	0,89298	0,32455	4,7	0,91488	0,22172	6,4	0,93100	0,16997
1,35	0,91699	0,68657	3,05	0,89364	0,32001	4,75	0,91544	0,21973	6,45	0,93139	0,16882
1,4	0,91142	0,65964	3,1	0,89431	0,31561	4,8	0,91600	0,21778	6,5	0,93178	0,16769
1,45	0,90672	0,63522	3,15	0,89498	0,31135	4,85	0,91655	0,21586	6,55	0,93216	0,16657
1,5	0,90275	0,61294	3,2	0,89565	0,30721	4,9	0,91710	0,21397	6,6	0,93254	0,16547
1,55	0,89939	0,59252	3,25	0,89633	0,30319	4,95	0,91764	0,21212	6,65	0,93292	0,16439
1,6	0,89657	0,57372	3,3	0,89702	0,29929	5	0,91817	0,21031	6,7	0,93329	0,16332
1,65	0,89421	0,55635	3,35	0,89770	0,29550	5,05	0,91870	0,20853	6,75	0,93366	0,16226
1,7	0,89224	0,54024	3,4	0,89838	0,29181	5,1	0,91922	0,20677	6,8	0,93402	0,16121

The Weibull parameter table: reading the parameters A and B

MATLAB commands:

A) The Distribution function f(t)

1. clc
2. clear
3. B=0.921
4. n=3875.68
5. t=0 :0.1 :10000;
6. f= (exp (-(t/n). ^B)). *((B/n) *(t/n). ^(B-1))
7. plot (t, f,'r')
8. grid

B) The Distribution function F(t)

1. clc
2. clear
3. B=0.921
4. n=3875,68
5. t=0:0.1:10000;
6. F=1-exp(-(t/n). ^B)
7. plot (t, F,'r')
8. grid

C) Reliability function R(t)

1. clc
2. clear
3. B=0.921
4. n=3875.68
5. t=0:0.1:10000;
6. R=exp(-(t/n). ^B)
7. plot (t, R,'r')
8. grid

D) Failure Rate □(t)

1. clc
2. clear
3. B=0.921
4. n=3875,68

5. t=0:0.1:10000;
6. L=(B/n) *(t/n). ^(B-1)
7. plot (t, L,'r')
8. grid

E) Maintainability M(t)

1. clc
2. clear
3. u=0,03040
4. t=0:0.1:200;
5. M=1-exp(-u*t)
6. plot (t, M,'r')
7. grid

F) Availability D(t)

1. clc
2. clear
3. u=0.03040
4. h=0.000247
5. t=0:0.1:200;
6. Dis=u/ (h+u) + ((h/(h+u)). *exp (-(h+u) *t))
7. plot (t, Dis,'r')
8. grid

[1] Fred Landis ,Professor of Mechanical Engineering, University of Wisconsin, Milwaukee; Dean, College of Engineering and Applied Science, 1974–83.

[2] Munson, Bruce Roy, T. H. Okiishi, and Wade W. Huebsch. "Turbomachines." Fundamentals of Fluid Mechanics. 6th ed. Hoboken, NJ: J. Wiley & Sons, 2009

[3] IS: 12800 (Part 3) – 1991, Guidelines for selection of hydraulic turbine, preliminary dimensioning and layout of surface hydroelectric powerhouses.

[4] 'A brief history of hydropower' article available on https://www.hydropower.org/discover/history-of-hydropower

[5] Dr. M.N. Shesha Prakash, Hydraulics and Hydraulic Machines, PAGE 4

[6] BOSTON UNIVERSITY, MECHANICLE ENGINEERING, COHERENT APPLICATION THREADS ARTICLE PAGE 1

[7] Kharsan Al Makhalas Faisal Aleshia, thesis is presented as part of Degree of Bachelor of Science in Electrical Engineering, 2014

[8] Cyrus B. Meher-Homji, THE HISTORICAL EVOLUTION OF TURBOMACHINERY Monrovia, California

[9] Japan International Cooperation Agency, Final Draft, « Steam Turbine », June 2013

[10] Arslane Mustapha, Thesis submitted for obtaining Academic Master's degree ''Conception et Réalisation d'un Montage d'usinage à la base du Principe de Six-Points''

[11] Japan International Cooperation Agency, Final Draft, « Gaz Turbine », June 2013

[12] Renaud Gicquel, « Turbines à gaz » [archive], sur École nationale supérieure des mines de Paris

[13] HATHAT Abdelkader et DEBLAOUI Hicham, Mémoire MASTER PROFESSIONNEL, Etude analytique FMD d'une turbine DR990, UKM OUARGLA, 2015

[14] "European Federation of National Maintenance Societies". EFNMS.org. Retrieved 5 August 2016

[15] Semester 6, CB602 -Maintenance Management, Topic 1 -Introduction to Maintenance Management, Published Jul 27, 2013.

[16] Protech property solution, advantages and disadvantages of preventive maintenance, November 30,2015 in building Maintenance.

[17] The Realtime report, Advantages and Disadvantages of Corrective Maintenance, May 20, 2019.

[18] Sanjay Mundra, preserve article, Advantages and disadvantages of predictive/condition-based Maintenance article.

[19] DOUABA NADJI, BEROUBA SLIMANE, Mémoire MASTER PROFESSIONNEL, Analyse analytique FMD et AMDEC d'un compresseur à vis- ATLAS COPCO ZE3- , UKM OUARGLA ,2017

[20] TOUMI Ouail, AKERMI Saïd, Mémoire MASTER ACADEMIQUE, Etude Analytique De La maintenance Préventive D'une Turbine à Gaz GE10/2, UKM OUARGLA, 2019

[21] Khabbar Hocine, Hamdaoui Lakhdar. Thème (Etude Analytique De La Maintenance Préventive D'un Compresseur à Vis- ATLAS COPCO GA15) Université Ouargla 2017- 2018.

[22] karek rabie, Module Stratégie de maintenance, Master 1 maintenance industrielle, université de Kasdi-Merbah 2020/2021

[23] Article Posted by RAMANA PV, Fault tree analysis https://sixsigmastudyguide.com/fault-tree-analysis/