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Analytical Analysis and Maintenance of a Centrifugal Pump

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All our parents for their contribution, their availability, and their constant support.

All our relatives and friends, who have always encouraged us during the realization

DEDICATION

First of all, I want to thank the almighty for giving me the courage and patience to get to this point to carry out this work that I dedicate: To my dear parents: my dear mother and respectful father.

To the whole Bouabboune family. To all my friends everywhere and in particular and no doubt to my dearest friends at the University of Ouargla

Bouabboune Aissa

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Acronyms

CHAPTER I: FUNDAMENTALS OF PUMPS

RPM: Revolutions Per Minute.

Psig: Pound Per Square Inch.

TDH: Total Differential Head**.**

NPSHR: Net Positive Suction Head Required.

NPSHA: Net Positive Suction Head Available.

Q: Flow.

CHAPTER II: GENERAL DEFINITION OF MAINTENANCE

t: Time.

TTR: Temps To Repair.

UT: Up Time.

MUT: Mean Up Time.

MDT: Mean Down Time.

MTBF: Mean Time Between Failure.

MTTF: Mean Time To Failure.

MTTR: Mean time to Repair.

PDF: Probability Distribution Function.

CDF: Cumulative Distribution Function

R(t): Reliability Function

F(t): Failure Function (CDF)

f (t): Probability Density Function (PDF).

λ (t): Failure Rate (Hazard Rate)**.**

M(t): Maintainability Function

A(t): Availability Function.

µ: Repair Rate.

R: Reliability.

M: Maintainability.

A: Availability**.**

β: Shape Parameter.

γ: Location Parameter.

η: Scale Parameter.

APTE: APplication to business Techniques.

SADT: (Structure Analyses Design Technique).

IDEF0: Integration Definition for Function Modeling.

FMECA: Failure mode, effects, and Criticality Analysis.

FMEA: Failure mode and effects analysis

CA: Criticality Analysis.

RPN: Risk Priority Number

Abstract

In Algeria, most of the companies & corporations don't organize their maintenance which leads to the unavailability and unreliability of their most equipment, and also risk impacts. This study aims to determine how to use some of the maintenance methods in a centrifugal pump to increase the reliability, availability and to reduce risk of the dangerous failures.

Some of these methods are RMA analysis and Pareto chart & Ishikawa diagram used to increase reliability and availability, and FMECA used for decreasing failure risks, the results show that the pump required a maintenance plan to achieve high availability and a secure environment without great economic losses.

Keywords: Centrifugal Pump, Reliability, Availability, Maintainability, Pareto, FMCEA.

ملخص

في الجزائر ، لا تنظم معظم الشركات والمؤسسات صيانتها مما يؤدي إلى عدم توفر وعدم موثوقية معظم معداتها ، وكذلك آثار المخاطر. تهدف هذه الدراسة إلى تحديد كيفية استخدام بعض طرق الصيانة في مضخة الطرد المركزي لزيادة الموثوقية والتوافر وتقليل مخاطر الأعطال الخطيرة.

بعض هذه الطرق هي تحليل RMA ومخطط باريتو ومخطط إيشيكاوا الذي يستخدم لزيادة الموثوقية والتوافر ، و FMECA المستخدمة لتقليل مخاطر الفشل ، تظهر النتائج أن المضخة تتطلب خطة صيانة لتحقيق التوافر العالي وبيئة آمنة دون خسائر اقتصادية كبيرة.

الكلمات المفتاحية: مضخة الطرد المركزي، الموثوقية، التوفر ،قابلية الصيانة، باريتو, FMCEA.

Résumé

En Algérie, la plupart des entreprises n'organisent pas leur maintenance ce qui entraîne l'indisponibilité et le manque de fiabilité de la plupart de leurs équipements, ainsi que des risques d'impacts. Cette étude vise à déterminer comment utiliser certaines des méthodes de maintenance dans une pompe centrifuge pour augmenter la fiabilité, la disponibilité et réduire le risque de défaillances dangereuses.

Certaines de ces méthodes sont l'analyse RMA et le diagramme de Pareto et le diagramme d'Ishikawa utilisés pour augmenter la fiabilité et la disponibilité, et l'AMDEC utilisée pour réduire les risques de défaillance, les résultats montrent que la pompe nécessitait un plan de maintenance pour obtenir une haute disponibilité et un environnement sécurisé sans grandes pertes économiques.

Mots clés : Pompe centrifuge, Fiabilité, Disponibilité, Maintenabilité, Pareto, AMDEC

General introduction

Most of the companies rely upon their equipment for profitable benefits and to achieve their own objective. Its quite clear the importance of retaining those systems in the operating state and avoid all high risks that are dangerous for either humans, the economy, or both.

This study seeks to increase the availability of the pump FLOWSERVE ME 300/450 "T07" by realizing high reliability and maintainability using RMA analysis and Pareto chart with Ishikawa diagram, also provide a safe workplace and eliminate resources losses by using FMECA.

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

-In the first chapter we'll present the concepts of the pump in general.

-The second chapter is reserved for the theoretical study on functional analysis and RMA concepts in maintenance after having recalled some notions and generalities on maintenance, also some diagrams (Pareto, Ishikawa), and finally FMECA.

- Finally, the third chapter presents the analytical application of the theoretical methods and analyses that we have introduced in the previous chapter on this particular pump.

CHAPTER I

FUNDAMENTALS OF PUMPS

I.1 Introduction

Only the sail can contend with the pump for the title of the earliest invention for the conversion of natural energy to useful work, the pump stands essentially unchallenged as the earliest form of the machine for substituting natural energy for human physical effort.[1]

Because pumps have existed for so long and are so widely used, it is hardly surprising that they are produced in a seemingly endless variety of sizes and types and are applied to an equally endless variety of services. Pumps are the second most common machine in use today, they are exceeded in numbers only by the electric motor.[1]

In this chapter, we will present the different types of pumps, their operating principle, their advantages, and their disadvantages. The pump studied in this thesis will be presented later, we will focus on its operation, on the various components that constitute it.

I.2 Definition of the pumps

Simply stated, a pump is a machine used to move liquid through a piping system and to raise the pressure of the liquid. A pump can be further defined as a machine that uses several energy transformations to increase the pressure of a liquid. The energy input into the pump is typically the energy source used to power the driver. Most commonly, this is electricity used to power an electric motor. Alternative forms of energy used to power the driver include high-pressure steam to drive a steam turbine, fuel oil to power a diesel engine, high-pressure hydraulic fluid to power a hydraulic motor, and compressed air to drive an air motor.[2]

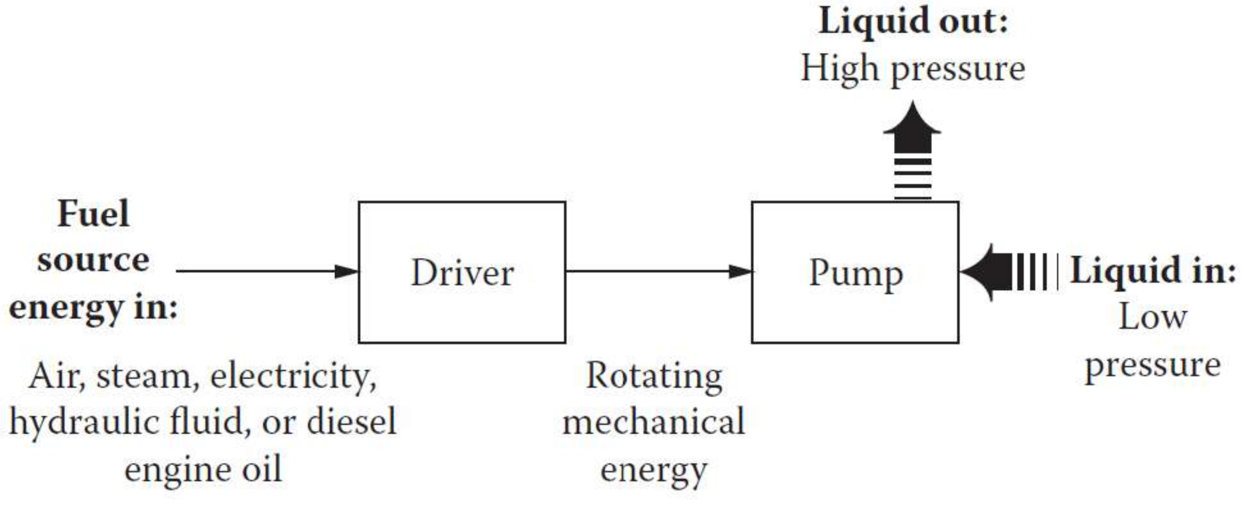


Figure I.1: Pump working principle

I.3 Pump parameters

I.3.1 Flow

This term refers to the liquid that enters the pump's suction nozzle. Flow (Q) measurements are cubic meters per second (m^3s−1, m^3/s), The pump's flow capacity varies with impeller width, impeller diameter, and pump revolutions per minute (rpm).[4]

I.3.2 Discharge pressure

This is the pressure measured at the pump's discharge nozzle. Measurements may be stated in Psig, kg/cm^2, Bars, Kilopascals.[4]

I.3.3 Discharge head

Measured in feet or meters, the discharge head is the same as the discharge pressure converted into the height of a liquid column.[4]

I.3.4 Total differential head

The difference between the discharge head and the suction head is the total differential head (TDH), expressed in feet or meters.[4]

I.3.5 Net positive suction head

The net positive suction head available (NPSHA) is the suction head present at the pump suction over and above the vapor pressure of the liquid.[2] The NPSH required (NPSHR) refers to the NPSH specified by a pump manufacturer for proper pump operation.[4]

I.3.6 Static suction head

The height of a column of liquid upstream from the pump's suction nozzle's centerline is known as the static suction head. It may also be the suction pressure, in Pascal, converted to suction head. Meters measure suction head.[4]

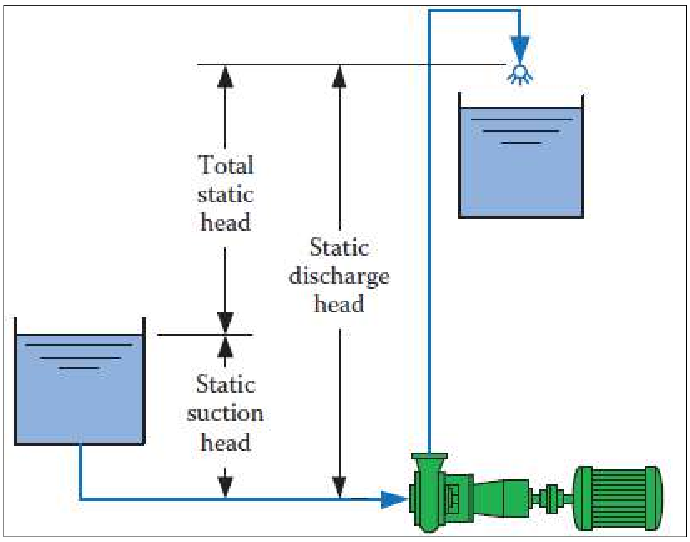


Figure I.2: Static suction head

I.3.7 Static suction lift

The maximum distance of a liquid level below the impeller eye is known as “static suction lift”. Because a liquid is not cohesive, it cannot be pulled. Instead, the pump impeller, pistons, plungers, or rotors form a partial vacuum in the pump. The atmospheric pressure pushes the liquid into this partial vacuum. Because of mechanical losses in the pump, suction lifts are always less than 10 meters. [4]

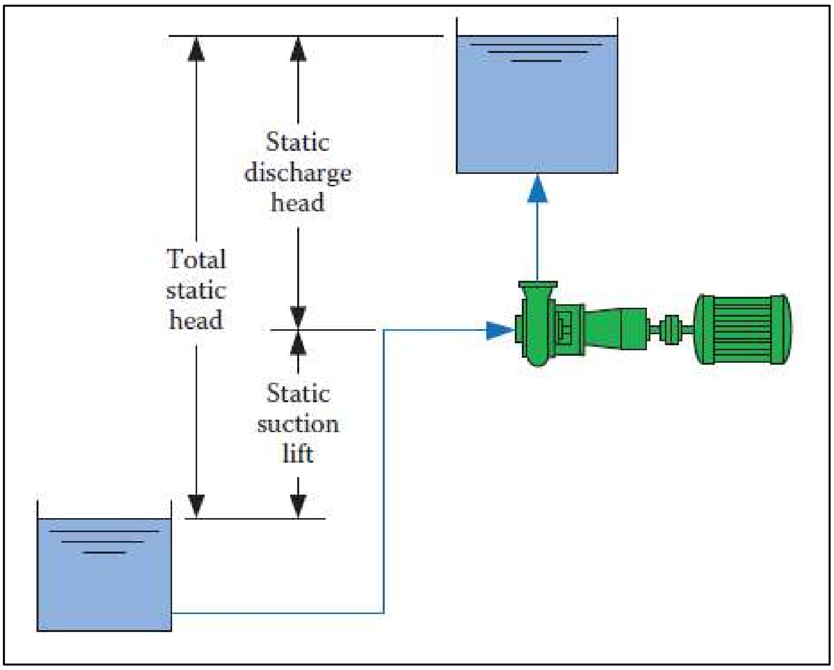


Figure I.3: Static suction lift

I.3.8 Vapor pressure

Vapor pressure is the pressure caused by the evaporation of liquids. The vapor pressure will vary with changes in either temperature or pressure.[4]

I.3.9 Horsepower

The work a pump performs while moving a determined amount of liquid at a given pressure is horsepower (hp).[4]

I.3.10 Cavitation

If the pressure drop between the pump suction and the eye of the impeller is large enough, the pressure drop may be sufficient to cause the liquid to flash to vapor when the local pressure falls below the saturation pressure for the fluid being pumped. When the bubbles enter a region where the local pressure is greater than saturation pressure farther out the impeller vane, the vapor bubbles suddenly collapse.[3] Cavitation may produce noises that sound like pebbles rattling inside the pump casing, continued serious cavitation may destroy even the hardest surfaces.[4]

For a pump to operate free of cavitation, NPSHA must be greater than NPSHR.[2]

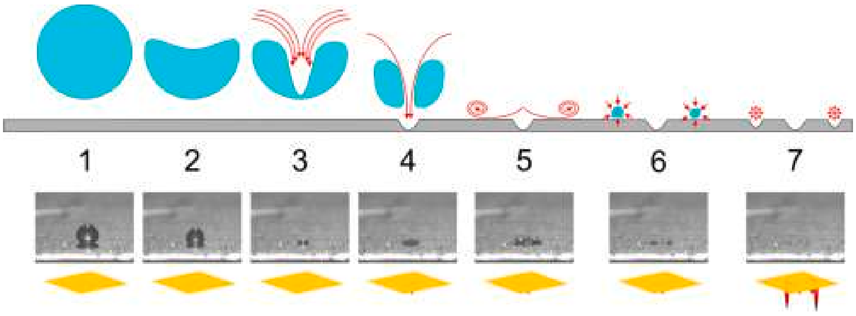


Figure I.4: Cavitation steps

I.3.11 Minimum flow

The lowest continuous flow at which a manufacturer will guarantee a pump's performance is the pump's minimum flow.[4]

I.3.12 Minimum flow bypass

This pipe leads from the pump discharge piping back into the pump suction system. A pressure control, or flow control, valve opens this line when the pump discharge flow approaches the pump's minimum flow value. The purpose is to protect the pump from damage.[4]

I.3.13 Critical speed

At this speed, a pump may vibrate enough to cause damage. Pump manufacturers try to design pumps with the first critical speed at least 20 percent higher or lower than the rated speed.[4]

I.3.14 Priming

If the pipeline leading to the pump inlet contains no condensable gas such as air, then the pressure reduction at the impeller inlet merely causes the gas to expand, and suction pressure does not force liquid into the impeller inlet. Consequently, no pumping action can occur unless this incondensable gas is first eliminated, a process known as priming the pump.[2]

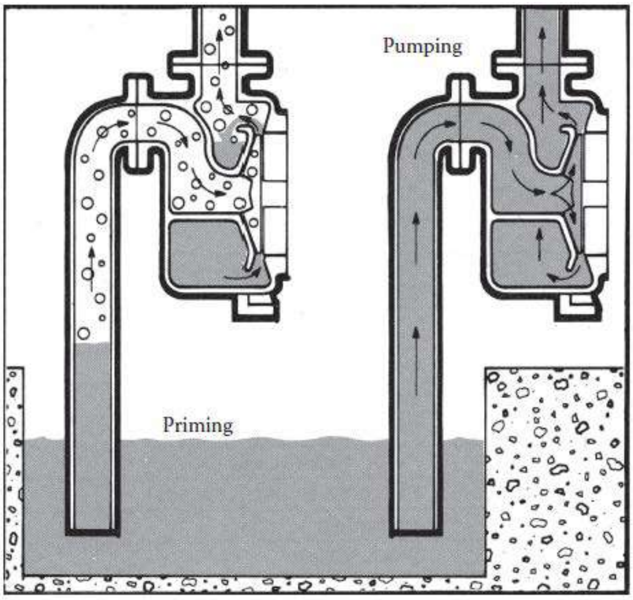


Figure I.5: Illustration of how the self-priming centrifugal pump works

I.4 Pump classification

Fig.I.6 shows a pump classification chart that breaks the classification down into two main categories; positive displacement and kinetic (or dynamic or rotodynamic).[6]

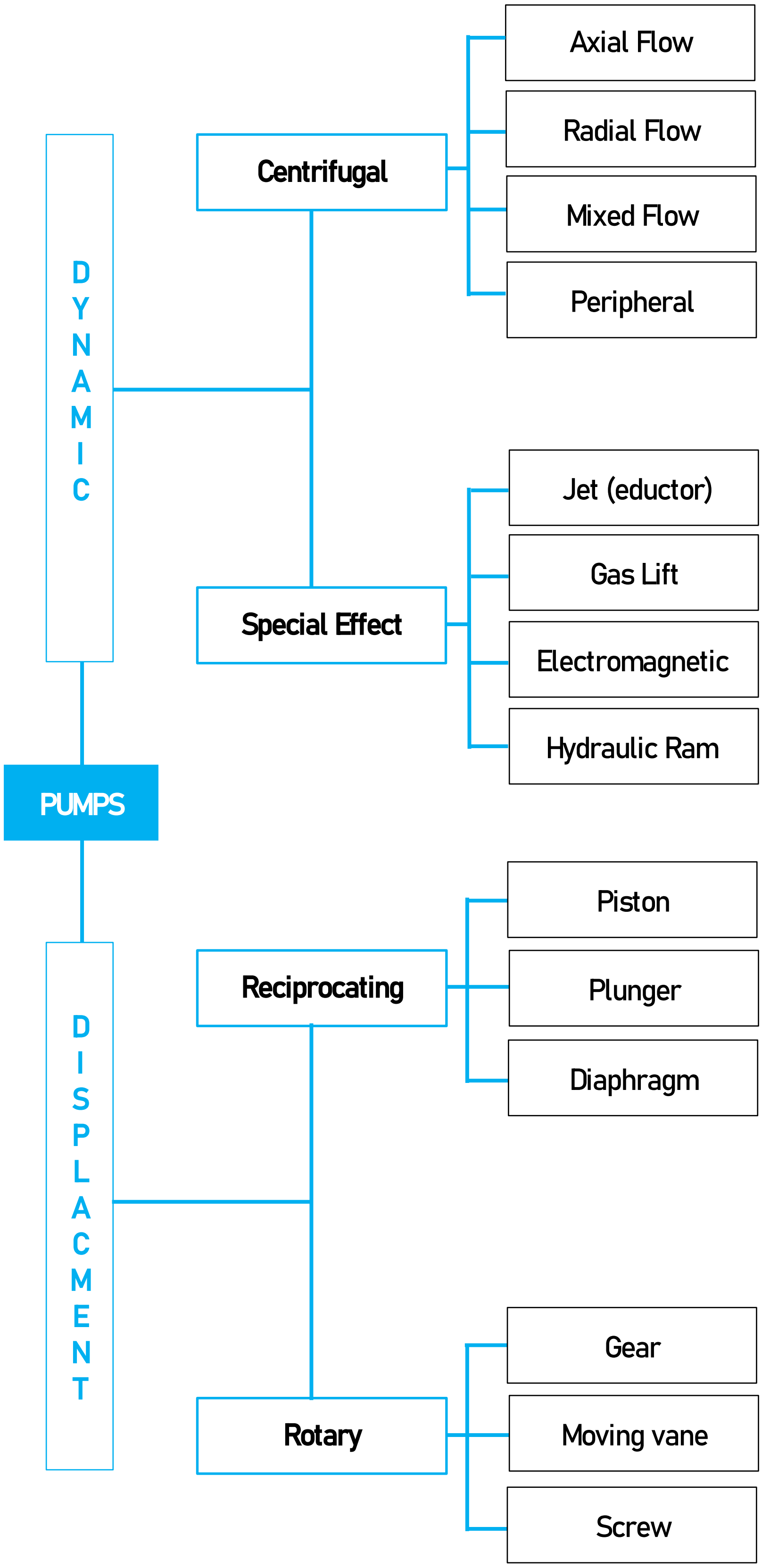


Figure I.6: Pump classification tree

I.4.1 Displacement (Positive-displacement)

Positive displacement pumps are batch delivery, periodic energy addition devices whose fluid displacement volume (or volumes) is set in motion and positively delivers that batch of fluid from a lower to higher pressure regardless of the value of that higher pressure.[6]

I.4.1.1 Reciprocating pump

A Reciprocating pump is a positive displacement pump consisting of a liquid end and a drive end. The liquid end consists of a device to displace a fixed volume of fluid for each stroke of the drive end. Suction and discharge flow is usually determined by the position of check valves.

Reciprocating pumps are divided into three general types: **Plunger**, **Diaphragm**, and **Piston type**.[7]

Figure I.7: Reciprocating pump

I.4.1.1.1 Working principle

Reciprocating positive displacement pump consisting of a piston, plunger, or diaphragm in a cylinder with a single suction port and a single discharge port (as shown in Fig.I.8). Check valves in the suction and discharge ports allow flow in only one direction.[3]

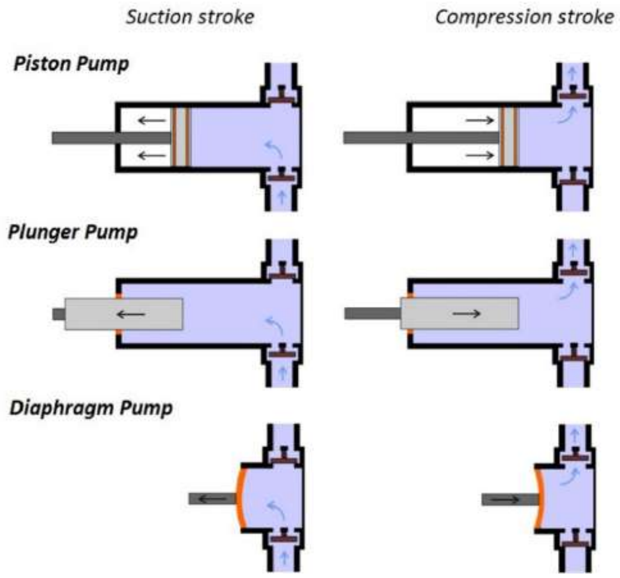


Figure I.8: Typical reciprocating pump design

I.4.1.1.2 Advantages of reciprocating pump

- No priming is needed in the Reciprocating pump compared to the Centrifugal pump.
- It can deliver liquid at high pressure from the sump to the desired height.
- It offers a continuous rate of discharge.
- High efficiency.

I.4.1.1.3 Disadvantages of reciprocating pump

- The maintenance cost is very high due to the presence of a large number of parts.
- The initial cost of this pump is high.
- Flow rate is less
- Viscous fluids are difficult to pump.

I.4.1.1.4 Applications of reciprocating pump

- Gas industries
- Petrochemical industries
- Oil refineries
- Vehicle water servicing centers etc.

I.4.1.2 Rotary pump

Rotary pumps trap the liquid in the suction side of the pump casing and force it to the discharge side of the casing.

Rotary pumps make up the second-largest group of pumps in terms of numbers. They also represent the second most economical selection, next to centrifugal.[6]

There are many types of positive displacement rotary pumps, and they are grouped into three basic categories that include **gear** pumps, **screw** pumps, **moving vane** pumps.[3]

Figure I.9: Oil pump

I.4.1.2.1 Working principle

In all these types of pumps, except the screw pump, the liquid is forced to travel circumferentially when displaced by the movement of vane or gear. The only difference between the screw pump and other rotary pumps is that the liquid displaced in the screw pump moves axially, whereas in other rotary pumps it moves in a circumferential pattern.[1]

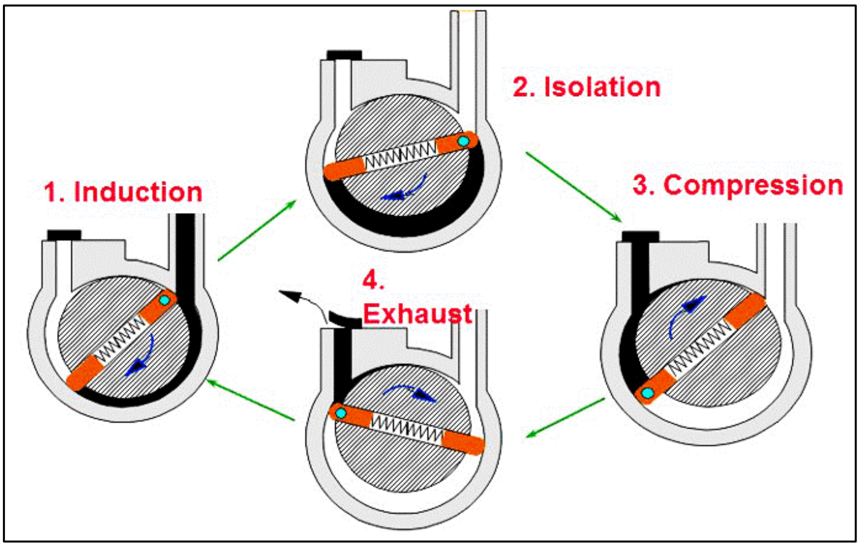


Figure I.10: Four stages rotary vane pump

I.4.1.2.2 Advantages of rotary pump

- They can deliver liquid to high pressures.
- Self-priming.
- Give a relatively smooth output, (especially at high speed).
- Can pump viscous liquids.
- Their efficiency ranges from low to medium head (up to discharge of 2000 liters/minute).[1]

I.4.1.2.3 Disadvantages of rotary pump

- More expensive than centrifugal pumps.
- Should not be used for fluids containing suspended solids.
- Excessive wear if not pumping viscous material.
- Must never be used with the discharge closed.
- Due to the abrasion of cams and gears, the maintenance cost increases.[1]

I.4.1.2.4 Applications of rotary pump

- Lubricating oil.
- Chemical transfer and metering.
- Sewage treatment plants.
- Water supply and carbon slurry pumps.

I.4.2 Dynamic (Kinetic)

Kinetic pumps are continuous delivery, continuous energy addition devices that build up kinetic energy in the rotating element or impeller and convert most of that energy into static energy to a point where the fluid delivery to the higher-pressure level commences.[6]

I.4.2.1 Special effect pump

Special effect pumps are for the most part used for specific applications and in small quantities. The eductor or jet pump is probably the exception and sees the most usage of the group.

Some of these pumps have been applied to their specific applications for over a century, the electromagnetic being the most recent addition.[6]

I.4.2.1.1 Hydraulic ram pump

The hydraulic ram pump has been used for over a century for raising water when it was the only power available is from a waterfall of 2 meters or more. A portion of the water entering the suction can be raised to a height several times that of the waterfall. Or a smaller portion can be raised to an inversely proportioned higher height. This pump also is rarely used today.[6]

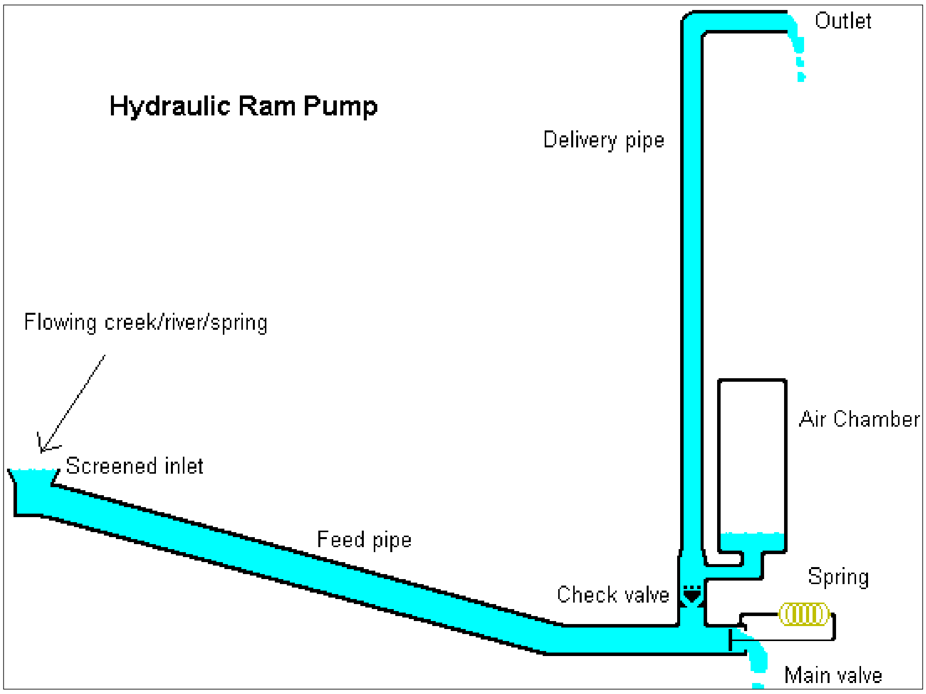


Figure I.11: Hydraulic ram pump

I.4.2.1.2 Gaz lift pump

The airlift pump has been used for lifting water or oil from wells. It consists of an air pipe inside of a discharge pipe. Air or other gas is discharged from the bottom of the air pipe.

The result is a flow motivated by the reduction of specific gravity of the water or oil and the floatability of the air bubbles.[6]

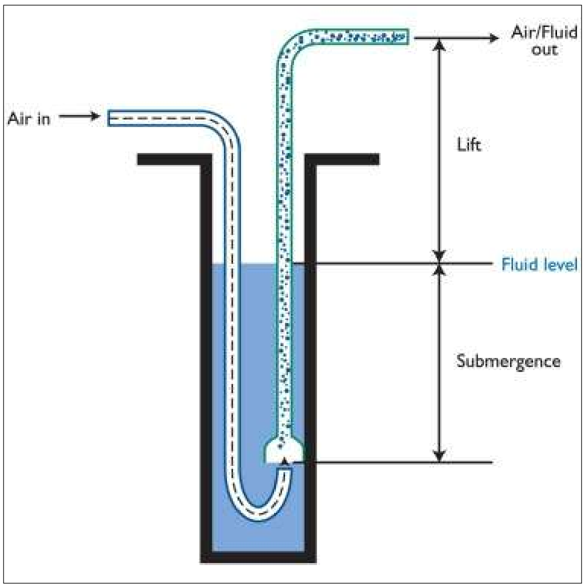


Figure I.12: Hydraulic ram pump

I.4.2.1.3 Water eductor (jet pump)

The water eductor or jet pump has also been around for a long time and it is commonly used today in series with a centrifugal pump on home wells. [6]

The jet pump transfers energy from a liquid or gas primary fluid to a secondary fluid. The latter may be a liquid, a gas, a two-phase gas-in-liquid mixture, or solid particles transported in a gas or a liquid.[1]

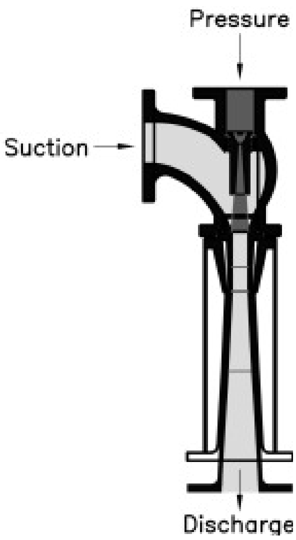


Figure I.13: Jet pump

I.4.2.1.4 Electromagnetic pump

The electromagnetic pump was founded in the nuclear and aerospace fields. It is used for the circulation of liquid metals and other media of high conductance. They are expensive and large. A non-magnetic pipe has a magnet placed on it such that the lines of force are radial to the pipe. When energized this creates a force in the conducting fluid, causing it to flow.[6]

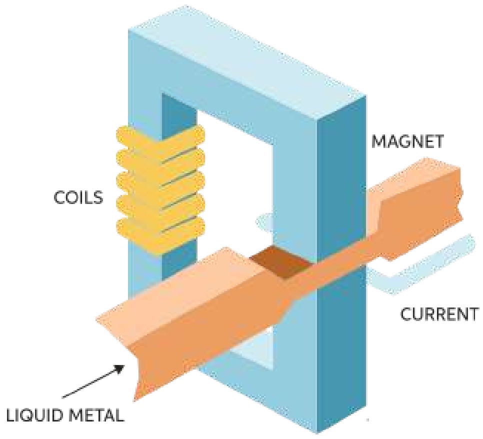


Figure I.14: Electromagnetic pump

I.4.2.2 Centrifugal pump

The centrifugal is by far the most common and has been estimated to make up 90% of all pumps sold.[6]

This type of pump is a machine that uses the dynamic principle of accelerating fluid, through centrifugal activity, and converting the kinetic energy into pressure.

Centrifugal pumps will only pump, or build pressure, to a designed level. When this level is reached, the fluid no longer moves and all the kinetic energy is converted to heat.[7]

Figure I.15: Centrifugal pump suction end

I.4.2.2.1 Working principle

In these pumps, the rotation of a series of vanes in an impeller creates pressure. The motion of the impeller forms a partial vacuum at the suction end of the impeller. Outside forces, such as the atmospheric pressure or the weight of a column of liquids, push fluid into the impeller's eye and out to the periphery of the impeller. From there, the rotation of the high-speed impeller throws the liquid into the pump casing. Through the volute configuration of the pump casing or diffuser vanes, the velocity head generated by the centrifugal motion of the impeller converts into a static head.[4]

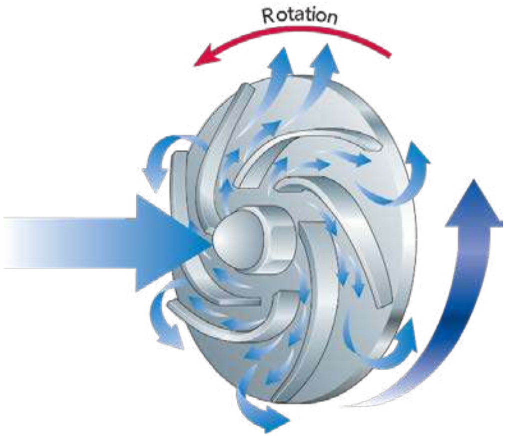


Figure I.16: Flow principle in a centrifugal pump

I.4.2.2.2 Centrifugal pump configuration

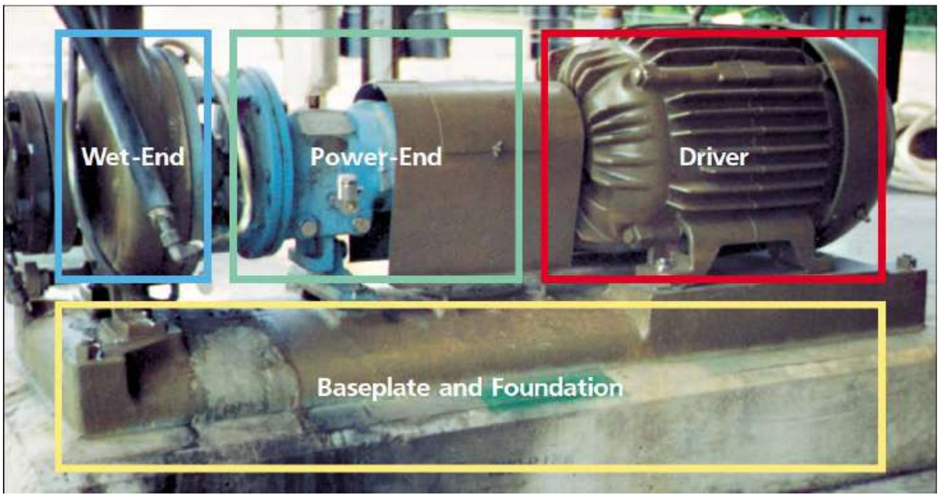


Figure I.17: Centrifugal pump configuration

I.4.2.2.3 Centrifugal pump components

I.4.2.2.3.1 Wet end parts

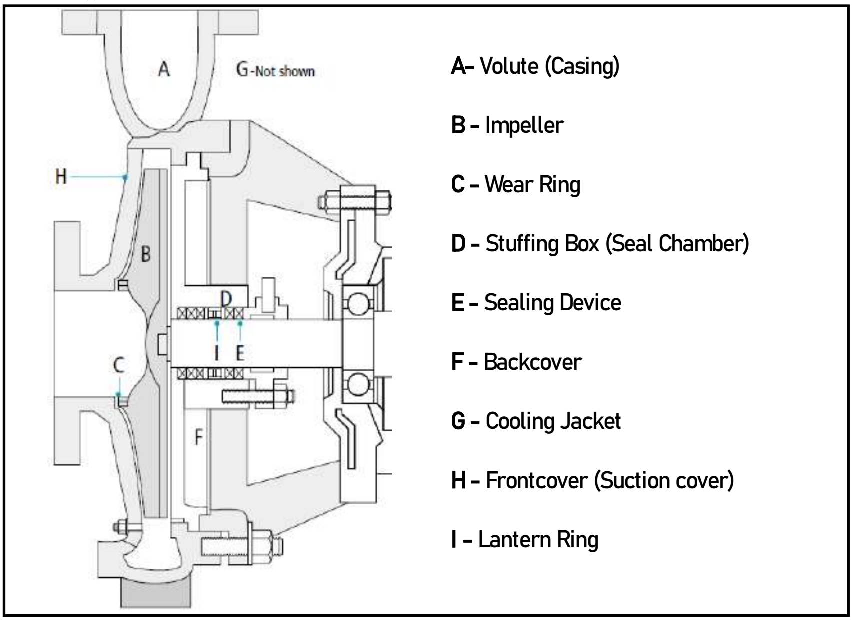


Figure I.18: Wet end components

I.4.2.2.3.2 Power end parts

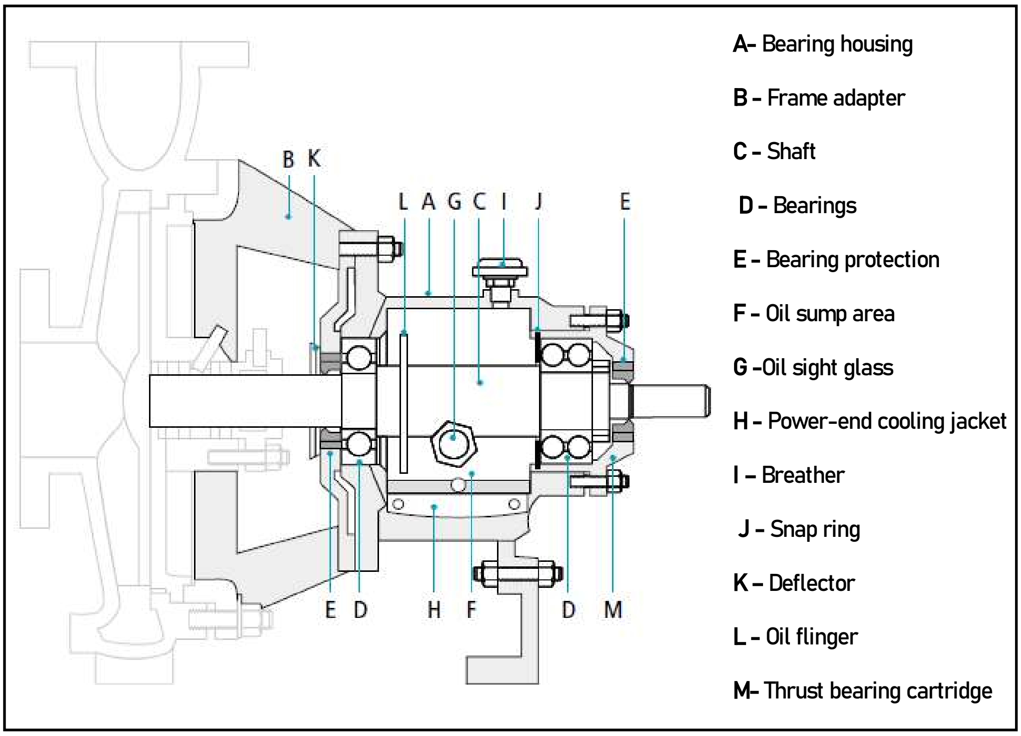


Figure I.19: Power end parts

I.4.2.2.3.3 Driver parts

- Motor (Driver)
- Coupling
- Motor adapter
- Belts
- Gears

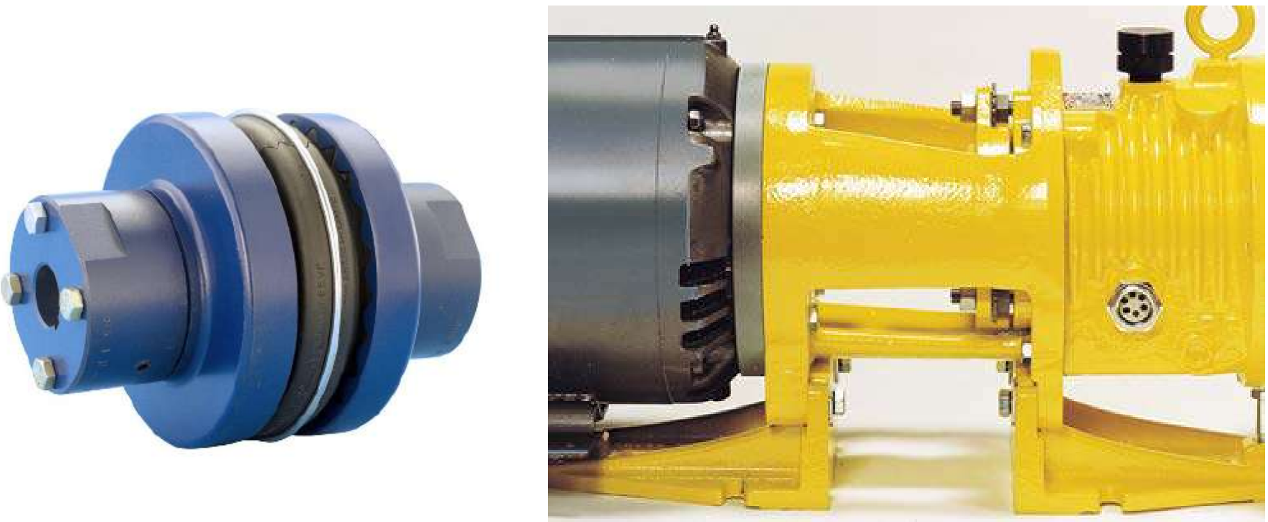


Figure I.20: Coupling left, and motor adapter right

I.4.2.2.3.4 Support Structure Parts

- Baseplate (Bedplate)
- Foundation
- Grouting
- Jack-bolts
- Shims

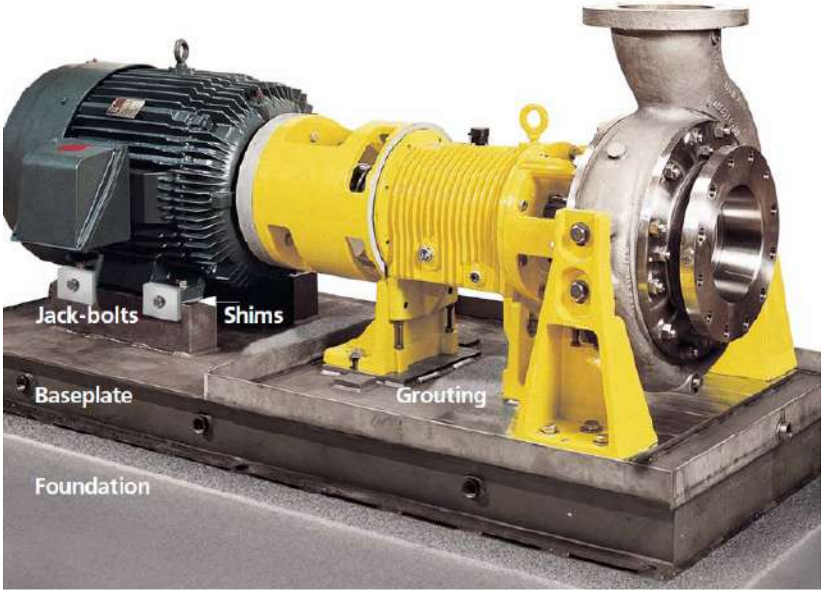


Figure I.21: Support structure components

I.4.2.2.4 Centrifugal pump classification

I.4.2.2.4.1 Impeller type

a) Single-suction: impeller allows liquid to enter the center of the blades from only one direction.[3]

b) Double-suction: impeller allows liquid to enter the center of the impeller blades from both sides simultaneously.[3]

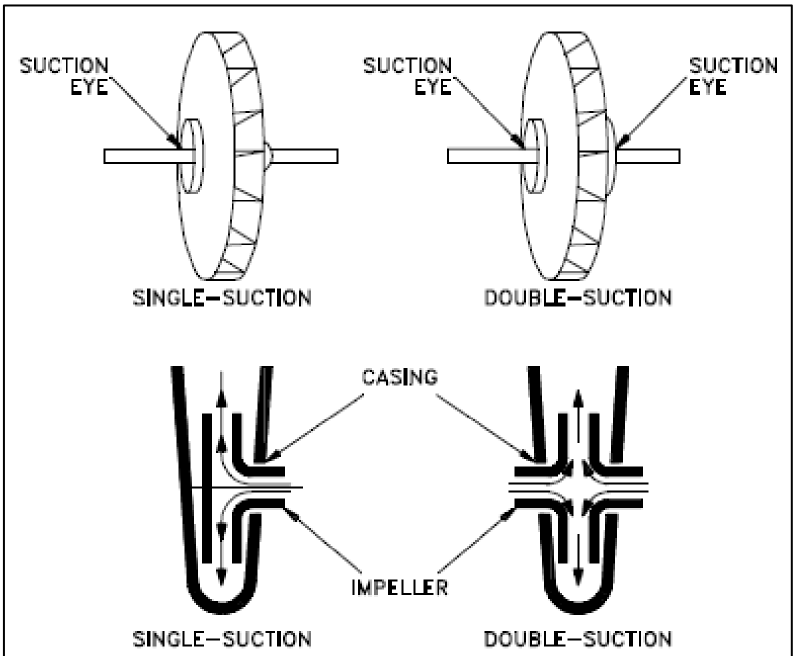


Figure I.22: Single & double-suction impeller

c) Open: consists only of blades attached to a hub.[3]

d) Semi-open: constructed with a circular plate (the web) attached to one side of the blades.[3]

e) Closed: impeller has circular plates attached to both sides of the blades. Enclosed impellers are also referred to as shrouded impellers.[3]

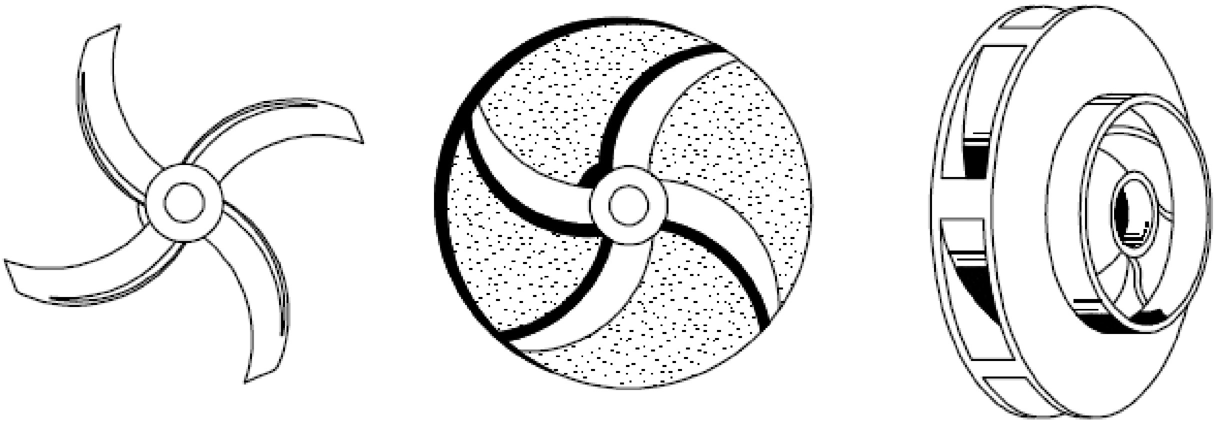


Figure I.23: Open, semi-open, and enclosed impellers

I.4.2.2.4.2 Number of stages

a) Single-stage: It is one in which the total head is developed by a single impeller.[5]

b) Multistage: If the total head required is too high for a single impeller to produce, two or more impellers (or pumps) may be used in series, the second impeller taking its suction from the discharge of the first impeller. If all impellers acting in series are in a single casing, the pump is a multistage design.[5]

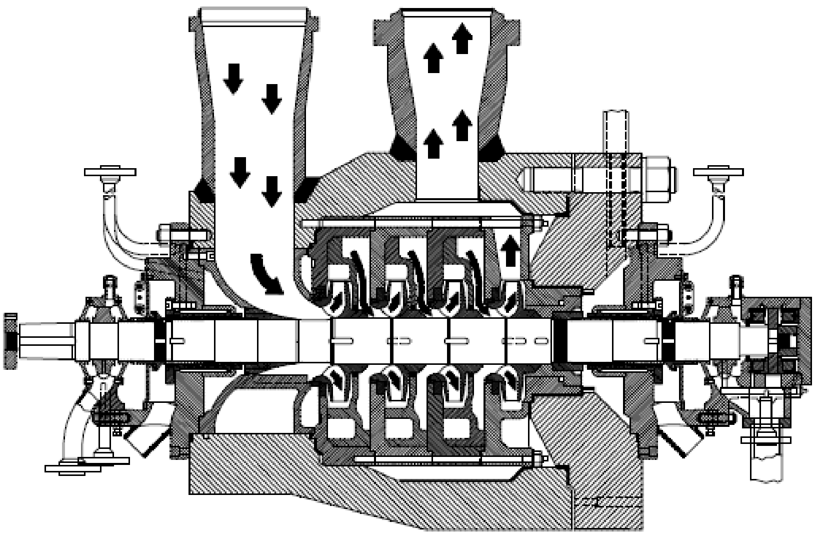


Figure I.24: Multistage centrifugal pump

I.4.2.2.4.3 Flow

a) Radial flow (straight-vane) impeller: On a radial flow impeller, the vane surfaces are generated by straight lines parallel to the axis of rotation.

On most pumps, the axis of rotation is the pump shaft. Flow strictly follows a line perpendicular to this axis of rotation. The liquid enters the impeller at the hub and flows radially to the periphery. In other words, the liquid enters the impeller and makes a 90° turn, and runs parallel to the vanes until it exits the Impeller at the vane tips.[7]

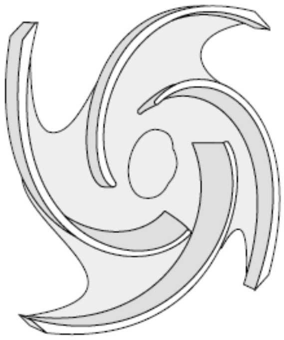


Figure I.25: Radial flow impeller

b) Axial flow impeller: In an axial flow impeller, the vane surfaces are perpendicular to the axis of rotation.

On most pumps, the axis of rotation is the pump shaft. Flow strictly parallels this axis of rotation. The liquid enters the pump inlet axially and discharges nearly axially. This means the flow enters the impeller and keeps on going straight through, parallel to the shaft.[7]

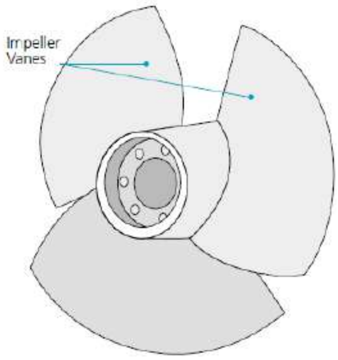


Figure I.26: Axial flow impeller

c) Mixed flow impeller: In a mixed flow impeller, the vane surfaces have both an axial and radial component.

Flow follows this mix of components with axial and radial movement, enters the pump axially, and discharges in an axial and radial direction.[7]

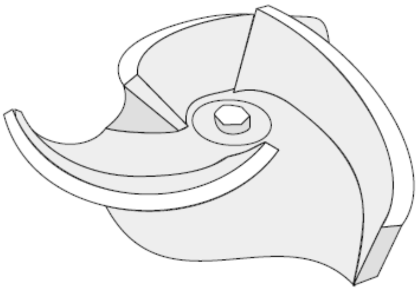


Figure I.27: Mixed flow impeller

I.4.2.2.4.4 Peripheral pump

Also known as a "Regenerative Turbine Pump". Regenerative Turbine Pumps are used for clean non-abrasive fluids with relatively high head and low flow requirements.[6]

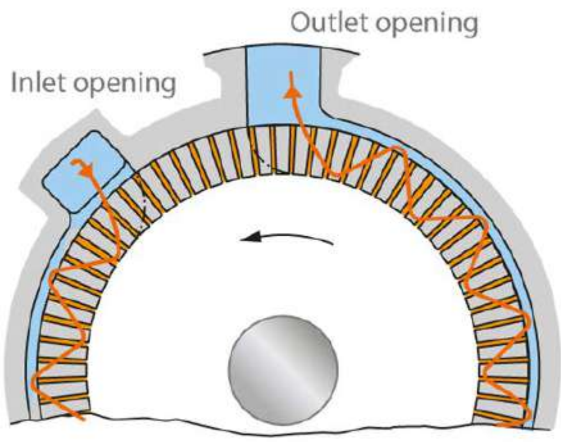


Figure I.28: Peripheral pump

Instead of having the traditional backward-curved impeller vanes, a regenerative turbine impeller has radially oriented teeth or buckets.

The impeller rotates in the casing channel with the liquid flowing between the vanes and casing transmitting large amounts of energy leading to a large increase in pressure within the pump. The pump can handle up to 20% vapor or no condensable gases in the pumped liquid.[2]

I.4.2.2.5 Advantages of centrifugal pump

- Weight, size, initial cost, and the installing cost are lower than PD pumps with the same hydraulic conditions.
- They can be fixed to a high-speed driving mechanism.
- It can handle liquids containing catalysts, and dirt solids.
- The cost of production, therefore the price is low.
- Variable-capacity control over operating range at a constant speed.

I.4.2.2.6 Disadvantages of centrifugal pump

- Additional priming is required.
- Develops limited head over operating range at a constant speed
- Cannot deal with high viscous fluid.
- Low to moderate efficiencies

I.4.2.2.7 Applications of centrifugal pump

- Power Plants
- Refineries, Chemical, and Petrochemical Plants.

- Oil and Gas Industries.
- Chemical and Mining Industry.
- Pharmaceutical Industries.
- Farming
- Water Treatment Plants
- Fire Protection Industries, etc.

I.4.3 Selection of pumps

Economically, the lowest cost in the following order centrifugal, rotary, reciprocating. On the head vs capacity plot, the kinetic pump would have a horizontal constant head characteristic with varying capacity, while the positive displacement pump would have a vertical, constant capacity characteristic with varying heads. These pumps have losses and deviations from the ideal.[6]

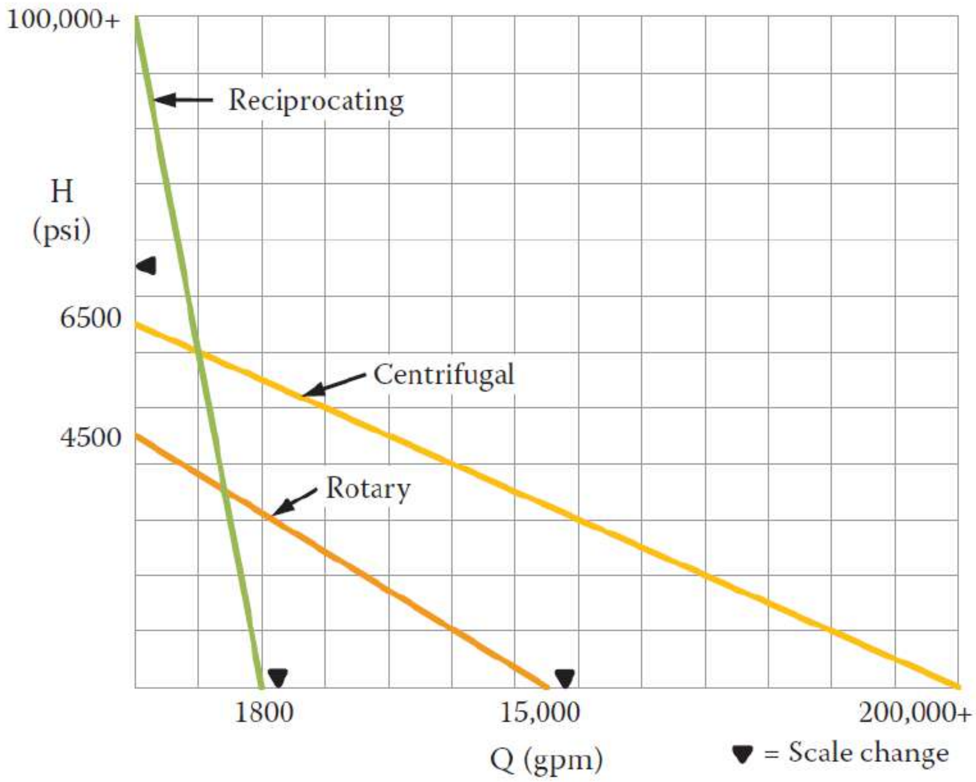


Figure I.29: Head vs. flow for centrifugal, rotary, and reciprocating pumps

I.5 Technical study of the FLOWSERVE ME 300/450 "T07" pump

The FLOWSERVE ME 300/450 "T07" pump is located at The IMITAL SIDER steel complex in El-Hadjar, 15km south of the city of Annaba. It is a centrifugal pump with axial suction and vertical discharge. This pumping operation is used to cool the working rolls which support the slabs inside the furnace to avoid their wear due to the high temperature (wear that stops the operation of the furnace).

Figure I.30: The FLOWSERVE ME 300/450 "T07" pump

I.5.1 Operating principle

The FLOWSERVE pump is installed in a semi-closed circuit, it absorbs water by horizontal suction and delivers it vertically. This pumped water will cool the working rolls and return to the pump to be sucked in and delivered again (Continuous operation).

I.5.2 FLOWSERVE ME 300/450 "T07" characteristics

Table I.1: FLOWSERVE ME 300/450 "T07" characteristics

-Standard	ISO 2372
Pump	
-Flow	1080 m^3/h
-Pressure	5 Bar
Motor	
-Motor puissance	185 KW
-Speed	1479 RPM

I.6 Conclusion

Pumps are among the oldest machines still in use, and they are probably the most widely used machines today in commercial and industrial activities.

Even the most precisely sized pump will not perform properly if its installation and maintenance are not performed carefully, or its operating condition doesn't meet. A better understanding of how these issues are managed will help to solve problems or to prevent them from occurring in the first place.

This leads us to devote Chapter II to the study of the maintenance function.

CHAPTER II

GENERAL DEFINITION OF MAINTENANCE

II.1 Introduction

The history of the reliability field may be traced back to the early years of the 1930s when probability concepts were applied to electric power generation-associated problems. During World War II, Germans applied the basic reliability concepts to improve the reliability of their V1 and V2 rockets. Between 1945 and 1950, the U.S. Department of Defense formed an ad hoc committee on reliability, and in 1952, the committee was transformed to a permanent body: The Advisory Group on the Reliability of Electronic Equipment.[9]

Industrial plants, factories, and vessels rely heavily on the reliability of their equipment and machinery; pumps being a core part of this. The downtime of a pump can costly in terms of loss of output and the cost of repairs.

Exercising pump maintenance procedures is essential to extend the life of these pumps. The latter can experience several issues over time if not properly maintained.

In this chapter, we will first recall some notions and generalities about maintenance; definition, and type of maintenance, with some functional analysis concepts. We'll then present a theoretical study on the **RMA** concept, **Pareto** chart **Ishikawa** diagram, and finally **FMECA** study.

II.2 Maintenance

Maintenance is defined as: "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function".[11]

Figure II.1: Benefits of planned maintenance

II.2.1 Maintenance classification

In the European Standard of EN 13306, (as shown in Fig.II.2) the preventive maintenance has been sorted into two categories, condition-based and pre-determined maintenance (CEN, 2001).[12] The corrective maintenance has been sorted into two categories, Deferred and immediate.

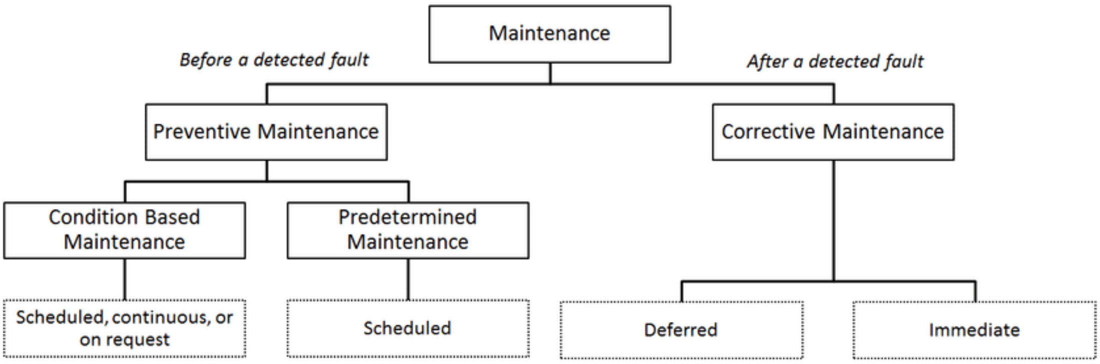


Figure II.2: Maintenance types by CEN (2001)

II.2.1.1 Corrective maintenance

defined as “maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function”.[11]

II.2.1.1.1 Deferred

defined as “corrective maintenance which is not immediately carried out after a fault detection but is delayed in accordance with given rules”.[11]

II.2.1.2.2 Immediate

Defined as “corrective maintenance that is carried out without delay after a fault has been detected to avoid unacceptable consequences”.[11]

II.2.1.2 Preventive maintenance

Defined as “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 of an item”.[11]

II.2.1.2.1 Condition-based maintenance

Is defined as “preventive maintenance which include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions”.[11]

II.2.1.2.2 Predetermined maintenance

Defined as “preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation”.[11]

II.2.2 Maintenance level

Maintenance task categorization by complexity:

- **Level 1** is characterized by simple actions carried out with minimal training.
- **Level 2** is characterized by basic actions which should be carried out by qualified personnel using detailed procedures.
- **Level 3** is characterized by complex actions carried out by qualified technical personnel using detailed procedures.
- **Level 4** is characterized by actions which imply the know-how of a technique or a technology and carried out by specialized technical personnel.
- **Level 5** is characterized by actions which imply a knowledge held by the manufacturer or a specialized company with industrial logistic support equipment.[11]

II.3 Functional analysis

Functional analysis is a tool to enhance creativity and innovation in design which help the designer from the very early stage of design, it’s a structured approach for describing how a system might be used**,** it defines a functional architecture for which system products and services can be designed and performed to a depth needed, it also identifies and arranges lower-level functions needed to accomplish parent requirements**.** There are three main methods of functional analysis including **APTE** and **IDEF0** (**SADT**).[17]

II.3.1 APTE (APplication to business Techniques) method

APTE means (APplication to business Techniques, or in French “Application aux Techniques d‟Enterprise”). APTE has been created by Gilbert Barbey in 1964 and is focused on functional analysis at the early stages of design. Currently, this method is deposed by APTE company and represents a functional analysis method and registered under NF X50150 standards to drive innovation and project optimization. APTE consists of six different algorithms to analyze different aspects of a product in this chapter we focused on and used two from six algorithms.[17]

II.3.1.1 Horned beast

(“La bête à cornes” in French) It is a diagram (see Fig.II.3) that is used for defining the requirements and needs of a product. To draw a horned beast, we should answer the following questions:

- Who is the product useful for?
- What does it affect?
- What is the goal?[17]

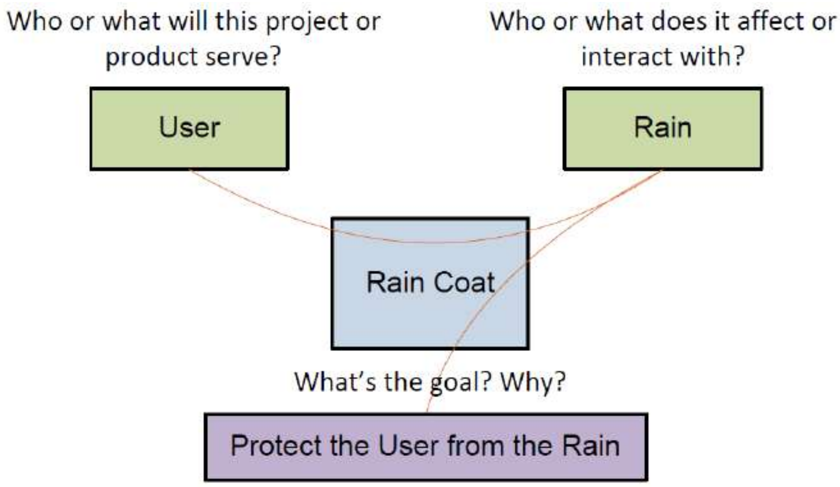


Figure II.3: Horned beast example of "the raincoat"

II.3.1.2 Octopus diagram

Octopus diagram ("Diagramme de pieuvre" in French) is applied after analyzing the customer need where functional analysis determines the functional requirements. by investigating the connections between the product and the external environment. These connections are divided into two lists.[17]

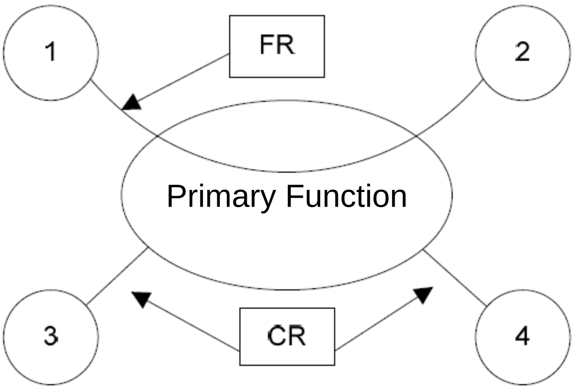


Figure II.4: Octopus diagram

- **Constraint Requirements (CR):** Refers to present adoption or action of the product, in means of either the product has to be adopted with an element or it acts on an element.
- **Functional Requirements (FR):** Interaction of the product with surroundings elements.

This method defines the main functions in addition to the constraint functions to have an overview or a global view of the product.[18]

II.3.2 SADT Structured Analysis and Design Technique (IDEF0)

Structured analysis and design technique (SADT) is a diagrammatic notation designed specifically to help people describe and understand systems. It offers building blocks to represent entities and activities, and a variety of arrows to relate boxes. These boxes and arrows have associated informal semantics. The IDEF0 can analyze a new system or an existing system. For the new systems, it is applied to define the requirements and specify the functions. Applying this methodology helps to improve the design and implementation of a system to fulfill the requirements as well as execution of the functions accurately. In the case of an existing system, the IDEF0 method analysis the content and the mechanism of functions. Afterward, the existing system will be converted into a model with hierarchical series of diagrams, texts, and cross-referenced to each other.[18]

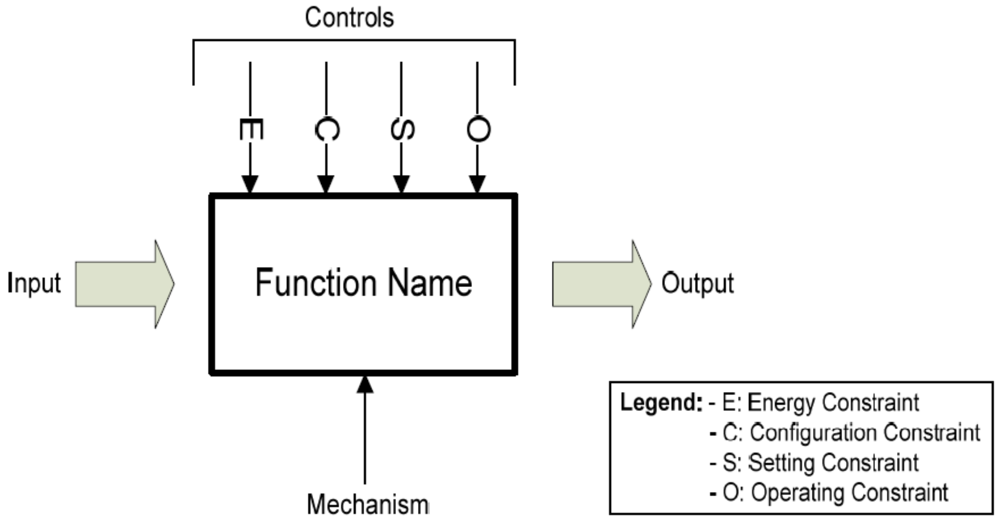


Figure II.5: SADT structure

II.4 RMA analysis

The fundamental understanding of the concepts of reliability, availability, and maintainability, (sometimes it comes with "S" for Supportability) has in the main dealt with statistical techniques for the measure and/or estimation of various parameters related to each of these concepts, based on obtained data. Such data may be obtained from current observations or experiences and may be complete or incomplete. These statistical techniques are mainly couched in probability theory.[8]

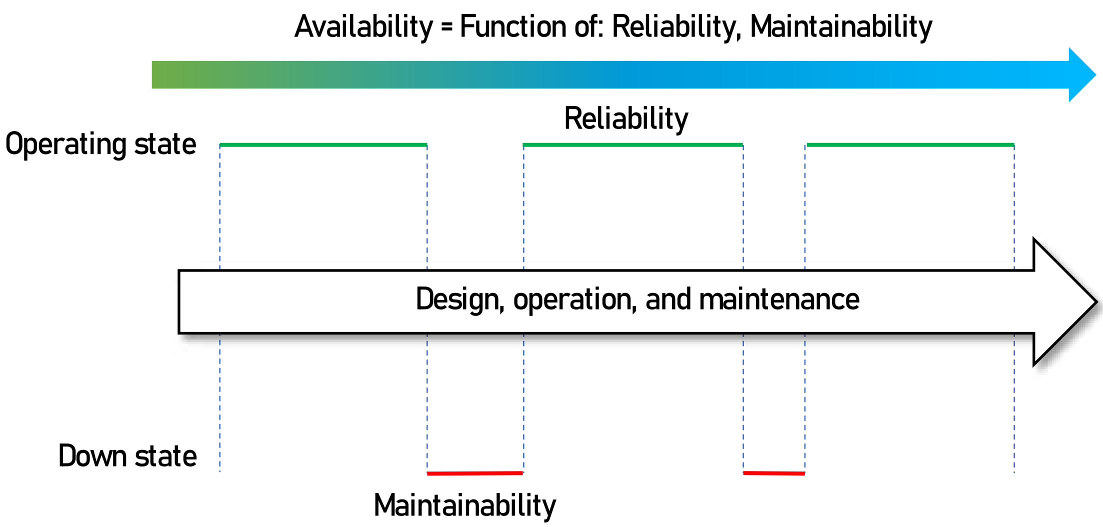


Figure II.6: RMA analysis structure

II.4.1 Benefits of an RMA program

The benefits of an effective RMA program include the following:

- Increase production and profitability
- Lower maintenance costs
- Enhanced customer satisfaction
- Personal life.[10]

II.5 General reliability concepts

Before we jump in RMA attributes, we have to introduce some of reliability general concepts

II.5.1 Failure rate

Failure Rate (λ) represents the number of failures likely to occur over some time.[16] Approximately (during the useful life period) defined as:

$$\lambda(t) = \frac{number\ of\ failures}{usage\ duration} \tag{II.1}$$

II.5.2 Bathtub hazard rate curve

This curve is usually used to describe the failure rate of engineering systems/equipment and is shown in Fig. II.7 The curve is called the bathtub hazard rate curve because it resembles the shape of a bathtub. As shown, the curve is divided into three sections. These sections are:

- During the **burn-in period (Decreasing Failure Region DFR)**, the system/equipment/item hazard rate decreases with time t.
- During the **useful life period (Constant Failure Region CFR)**, the hazard rate remains constant.
- Finally, during the **wear-out period (Increasing Failure Region IFR)**, the hazard rate increases with time.[9]

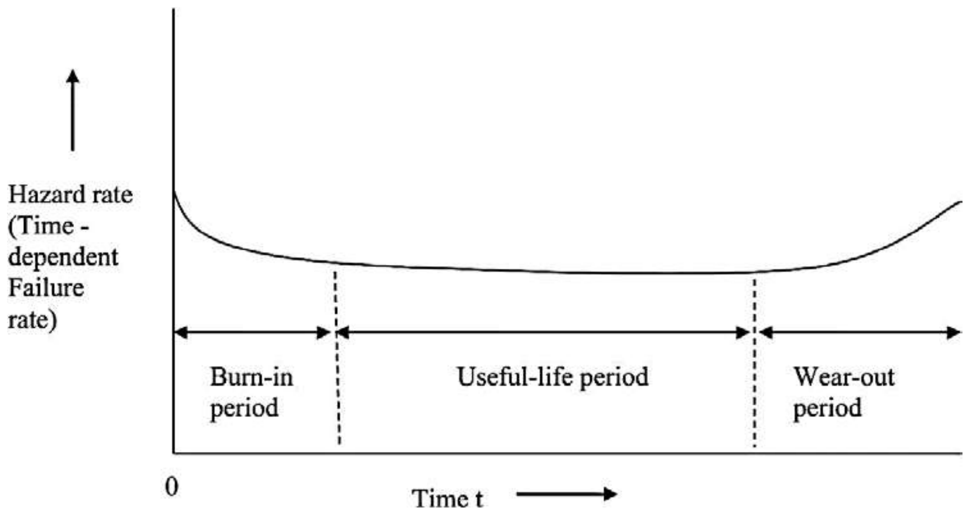


Figure II.7: Bathtub hazard rate curve

Table II.1: Failure characteristic, their causes, and remedial actions

Failure characteristic	Causes	Remedial actions
Decreasing Failure Rate (DFR)	Manufacturing defects: welding flaws, cracks, flawed parts, poor quality control, poor workmanship, contamination	The burn-in operation, screening quality control, acceptance testing
Constant Failure Rate (CFR)	Environment: random loads, human error	Operation within design envelope, strict commitment to operation & maintenance procedures
Increasing Failure Rate (IFR)	Normal/abnormal fatigue, corrosion, aging, cyclical loads	Part replacement (before failure)

II.5.3 Probability density function (PDF)

The probability density f (t) is defined as the probability of failure in any time interval dt.[10]

$$f\ (t) = \lambda(t)e^{-\int_0^{t0}\ \lambda(t)dt} \tag{II.2}$$

II.5.4 Cumulative distribution function (CDF)

The cumulative distribution function, F(t) is the integral of f(t) and is defined as the probability that a particular item will have failed by time t. [10]

$$F(t) = \int_0^{t0} f(t)dt = 1 - e^{-\int_0^{t0}\lambda(t)dt} = P(x \leq t) \tag{II.3}$$

II.5.5 Families of distribution

The data are normally governed by some parametric probability distribution. This means that the data can be explained by one or another mathematical formula representing a specific statistical probability distribution that belongs to a family of distributions differing from one another only in the values of their parameters. Such a family of distributions may be grouped accordingly: ■ Beta distribution ■ Binomial distribution ■ Lognormal distribution ■ Exponential (Poisson) distribution ■ Weibull distribution.[8]

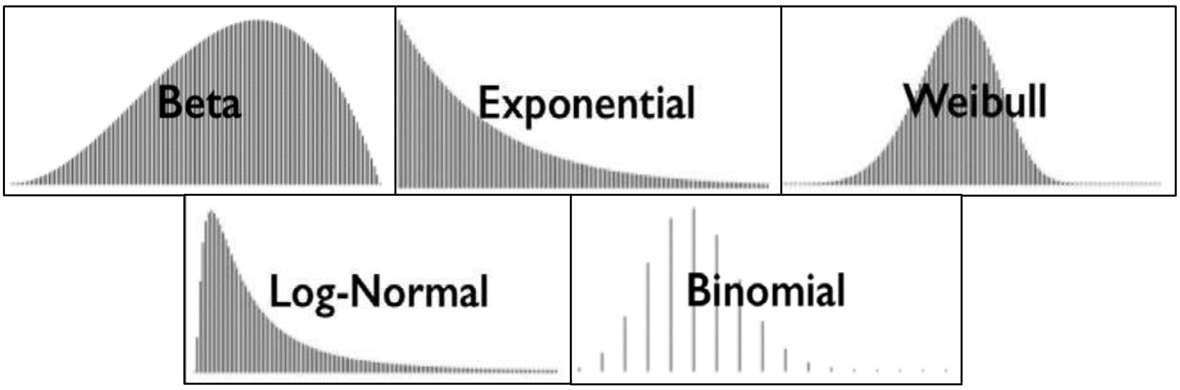


Figure II.8: Basic types of lifetime data analysis distributions

II.5.6 MTBF, MTTR, MTTF, MDT & MUT Explanation of Terms

Performance variables relating availability to reliability and maintainability are concerned with the measures of time that are subject to equipment failure. These measures are:

• Mean Time to Failure (MTTF)

The mean of an equipment item's operating times, i.e., the time from when an item is put into operation to the time when it fails.[10]

• Mean Time to Repair (MTTR)

The mean time to repair an equipment item. It is formally defined as the "total corrective maintenance time divided by the number of corresponding maintenance actions during a given period of time".[10]

• Mean Downtime (MDT)

MDT and MTTR are often treated as being the same. Some analysts distinguish between MTTR, which is just the repair time itself, and MDT is the average time that a system is non-operational, including repair time and scheduled shutdown, and other delays. [10]

• Mean Uptime (MUT)

Mean Up Time is defined as the continuous operating time of the system without any downtime. MUT can be approximated with MTBF when MTTR is in the order of a few hours only and MTTF is in the order of several thousand hours. [16]

• Mean Time between Failures (MTBF)

MTBF is the mean of the time between the failures for any particular item. It includes both operating and repair time. It relates to the other terms as shown in Eq. (II.4) and Fig.II.9. [10]

$$MTBF = MUT + MDT \tag{II.4}$$

MTBF is calculated as the total operating lifetime divided by the number of failures. MTBF is measured in hours or years.[16] The following relationships apply between failure rate and MUT:

$$MUT = \frac{1}{\lambda} \tag{II.5}$$

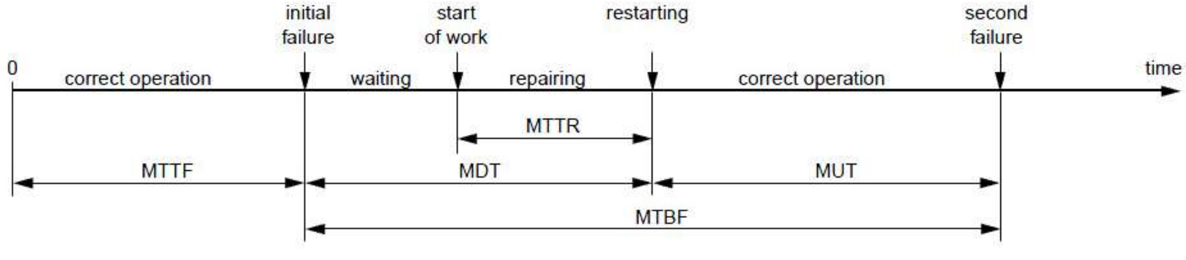


Figure II.9: MTBF, MTTF, MTTR, MDT, and MUT on the time scale

II.6 Reliability

Defined as “ability of an item to perform a required function under given conditions for a given time interval”.[11]

II.6.1 Reliability formula

Eq. (II.6) is the general reliability function. This equation can be used for obtaining the reliability function of a system/item.[9]

$$R(t) = 1 - F(t) = 1 - \int_{t0}^{+\infty} f(t)dt = 1 - \int_{t0}^{+\infty} \lambda(t)e^{-\int_0^{t0} \lambda(t)dt} = P(x \geq t) \qquad \text{(II.6)}$$

II.6.2 The Weibull distribution

One method for shaping the distribution to achieve a best-fit match for the sampled data is the Weibull distribution created by Dr. E. H. Waloddi Weibull, a Swedish engineer, scientist, and mathematician.[13]

The Weibull function can represent exponential, lognormal, or normal shape characteristics.[14]

The three control parameters: a shape parameter (β), a characteristic life parameter (η), and a position parameter (γ). provide a powerful combination and flexibility to recreate most life data distributions. We can express probability density function (PDF) mathematically where $\eta > 0$, and t > γ as:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} . e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad \text{(II.7)}$$

II.6.2.1 Weibull parameters

- **Shape Parameter (Beta, $\boldsymbol{\beta}$):** A unitless quantity that controls the shape of the distribution.
  - For $\beta < 1$, the shape of Weibull distribution models approximates the early failure profiles Bathtub **burn-in** period.
  - For $\beta = 1$, the shape of Weibull distribution models approximates the Exponential PDF Bathtub **useful life** period.
  - For $\beta = 3$, the shape of Weibull distribution models approximates the Gaussian PDF.
  - For $\beta = 10$, the shape of Weibull distribution models approximates the Bathtub **wear-out** period.[13]
- **Scale Parameter (Eta, $\boldsymbol{\eta}$):** A unitless quantity that controls the scale of the Weibull Distribution in terms of its width standard deviation. Fig.II.10 illustrates some of the effects as Eta is assigned different values such as 50, 100, and 200.[13]

- **Location Parameter (Gamma, γ):** A quantity that controls the location of the distribution relative to the origin (t = 0) along the abscissa of the graph. Fig.II.10 illustrates one of the offset effects as Gamma is assigned a different value.[13]

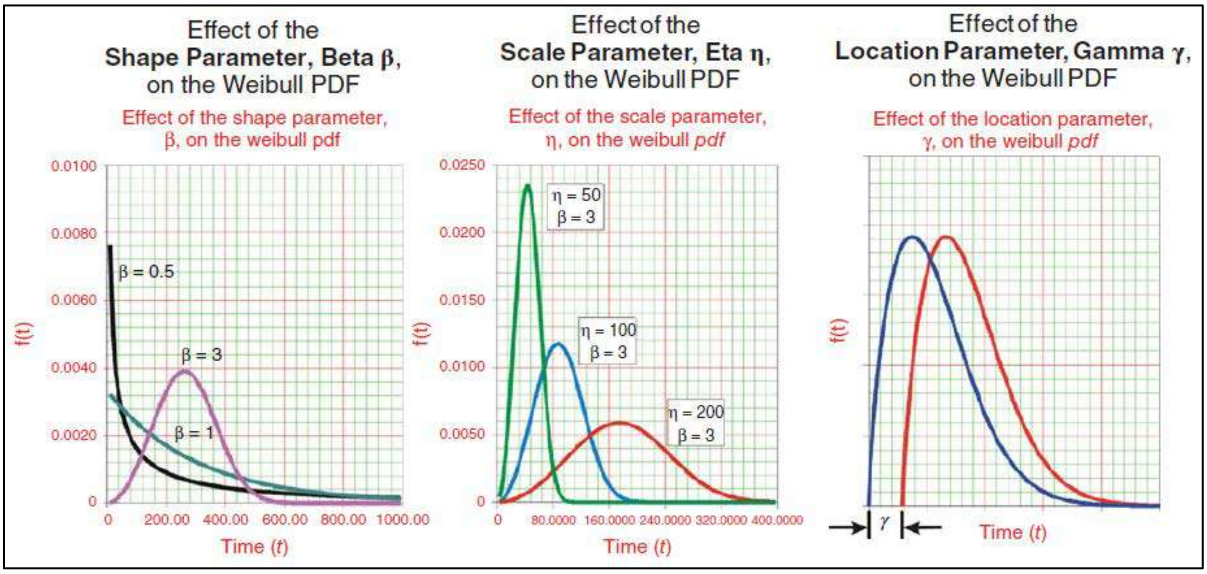


Figure II.10: Weibull distribution examples illustrating the parameter effects

II.6.2.2 Weibull distribution plot method

The first step is to define the rank of the failure. Then it is necessary to define the CDF values for each failure time, and with plotted functions, it is possible to define the CDF parameter values. To define the CDF values for each failure time it is necessary to apply a median rank or mean rank method.[14]

We need to rank the failure times from smallest to largest and calculate the F(ti) by one of the rank approaches.

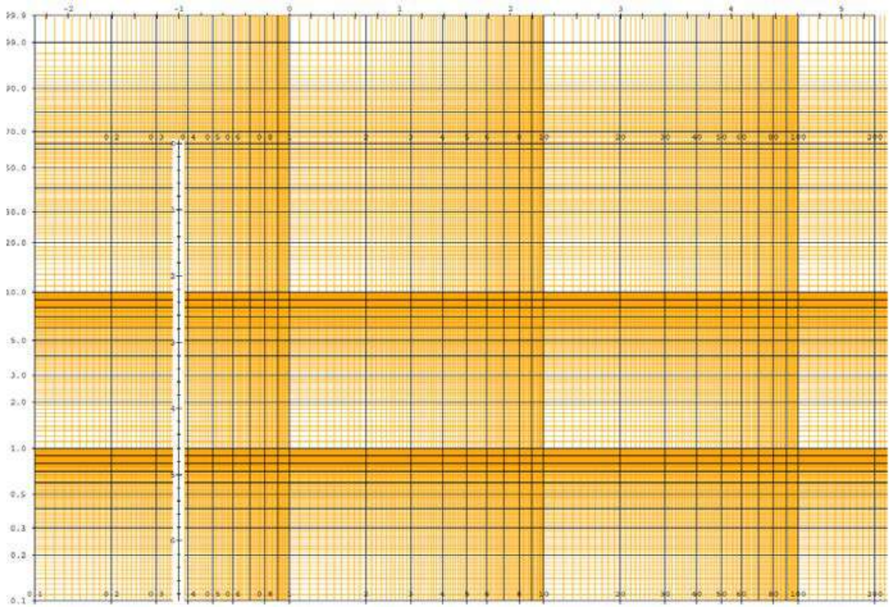


Figure II.11: Weibull probability paper

- If N≤ 20, we use the median rank approach: $F(t_i) = \frac{\sum ni - 0.3}{N+0.4}$ (II.8)
- If N> 20, we use the mean rank approach: $F(t_i) = \frac{\sum ni}{N+1}$ (II.9)

The next step is to plot data on the Weibull probability paper shown in Fig.II.11.[14]

The Weibull plot is formed by:

o **Vertical axis:** Weibull cumulative probability expressed as a percentage.

o **Horizontal axis:** ordered failure times (in a LOG10 scale).

Then obtaining the 3 parameters:

- **The shape parameter (β)** is a slope of the linear function.
- **The scale parameter, or characteristic life (η),** is defined when it goes to 63% of failure and graphically is when the Y-axis meets the function with a direct line from 63% in Y axes and then meets value in X-axis, that is characteristic life characteristic parameter value (η).
- **The position parameter (γ)** is defined by the difference of the first X value from the first curve (X1) and the first X value from the adjusted curve (X2), as shown in Fig.II.12.

  If the adjusted line is on the right, the position value is negative, and if it is on the left, the position parameter value is positive.[14]

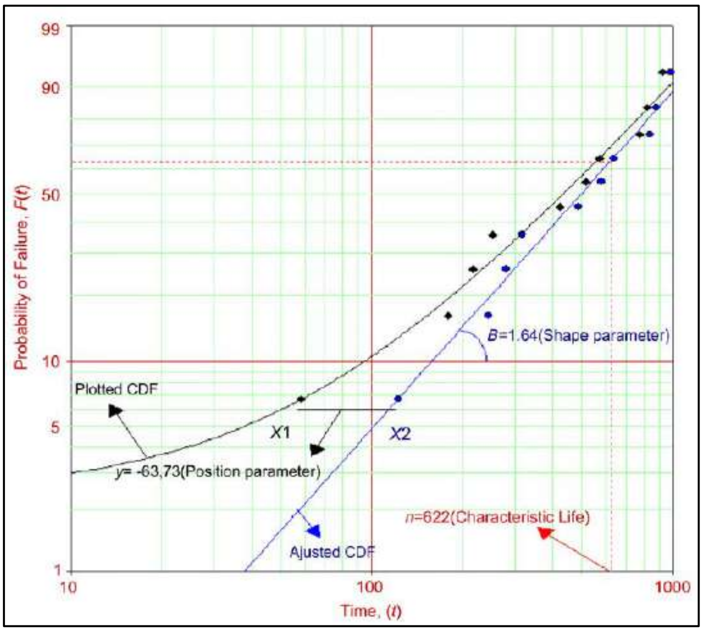


Figure II.12: Plotted Weibull 3P CFD and parameters

If the points correspond to a Weibull distribution Fig.II.13, the linearity condition is:

$$\left[\frac{(Y_3 - Y_2)}{(\ln(t_3 - \gamma) - \ln(t_2 - \gamma))}\right] = \left[\frac{(Y_2 - Y_1)}{(\ln(t_2 - \gamma) - \ln(t_1 - \gamma))}\right] \quad \text{(II.10)}$$

From Eq. (II.10) we can obtain the position parameter (γ) by using Eq. (II.11):

$$\gamma = \frac{t_2^2 - (t_1 t_3)}{2t_2 - (t_1 + t_3)} \quad \text{(II.11)}$$

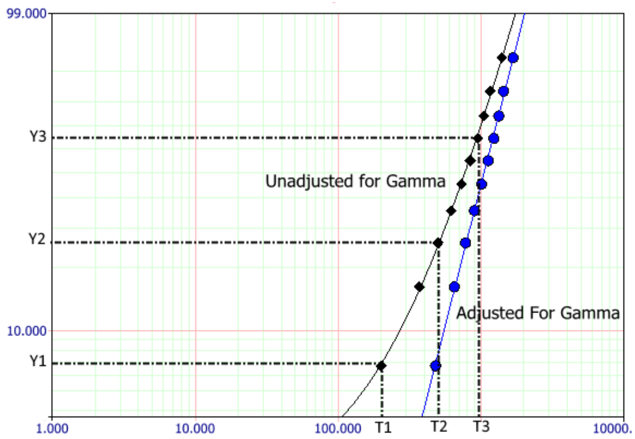


Figure II.13: The position parameter (γ) obtainment

II.6.2.3 Kolmogorov–Smirnov test

The test is concerned with the agreement between the distribution of a set of sample values and a theoretical distribution we call it "test of goodness of fit".[19]

II.6.2.3.1 The test

If F0(x) is the population cumulative distribution, and SN(x) the observed cumulative step function of a sample then the sampling distribution of d=maximum |F0(x)-F(x)| is known.[19]

Kolmogorov–Smirnov table gives certain critical points of the distribution of d for various sample sizes.[19]

II.6.2.3.2 Application

Our procedure is to draw the hypothetical cumulative distribution function on a graph and to draw curves a distance dα(N) above and be-low the hypothetical curve (see Fig.II.14). If F(x) passes outside of this band at any point we will reject, at the α level of significance, the hypothesis that the true distribution is F0(x).

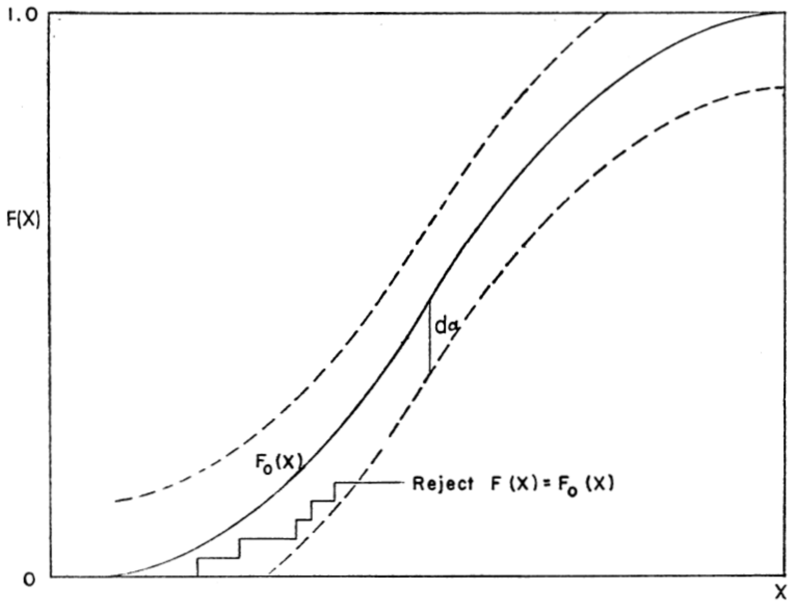


Figure II.14: Graphical method of applying the d test

II.6.2.4 Weibull failure rate

The Weibull failure rate function *λ(t)* is given by:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \quad \text{(II.12)}$$

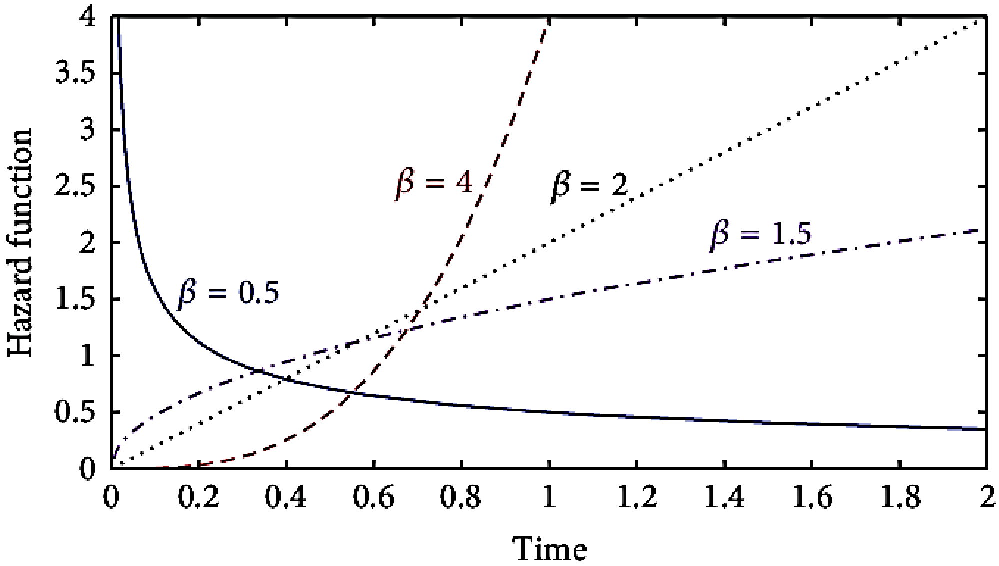


Figure II.15: Theoretical Weibull failure rate plot

II.6.2.5 Weibull cumulative distribution function (CDF)

The Weibull cumulative distribution function, *F(t)*, is defined as:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{(II.13)}$$

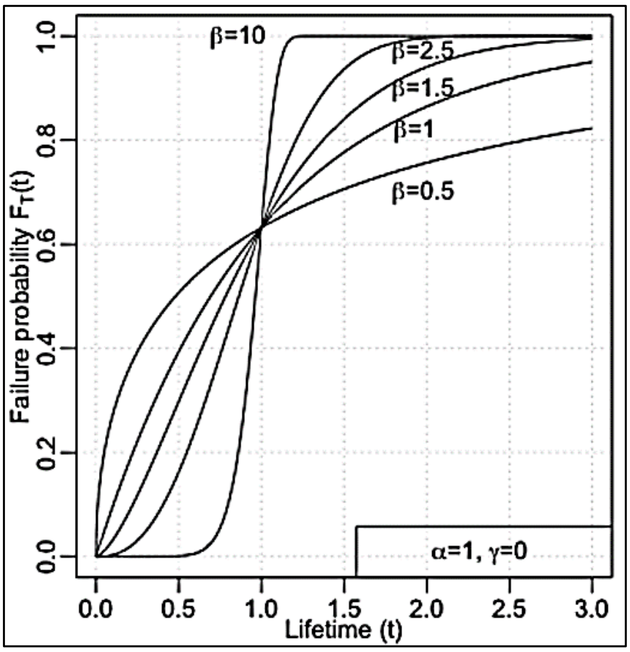


Figure II.16: Theoretical Weibull cumulative distribution function plot

II.6.2.6 Weibull reliability function

The Weibull reliability function R(t), is represented by:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{(II.14)}$$

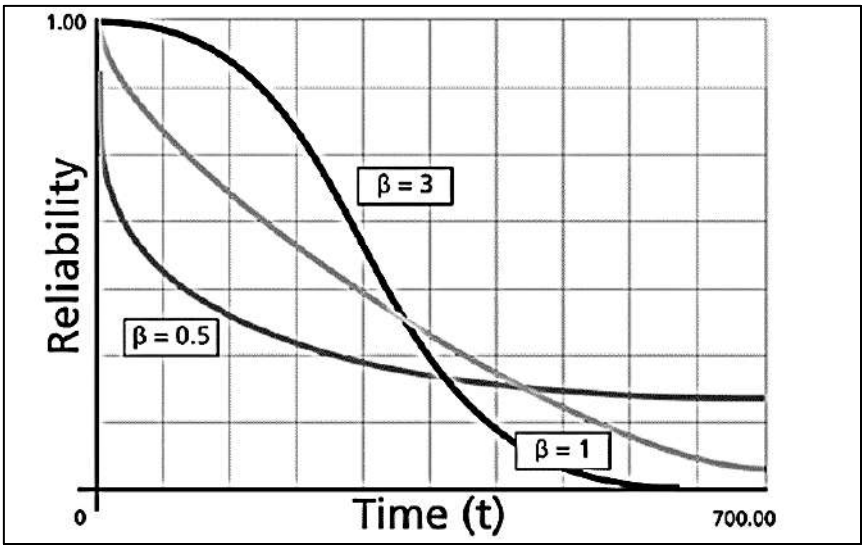


Figure II.17: Theoretical Weibull reliability function plot

II.7 Maintainability

Maintainability is defined as “ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources”.[11]

II.7.1 Maintainability formula

Just like in other areas of engineering, probability distributions play an important role in maintainability engineering. In this case, after the identification of the repair time distribution, the corresponding maintainability function may be obtained. This function is concerned with predicting the probability that a repair, beginning at time t = 0, will be accomplished in a time t. [9] Mathematically, the maintainability function is expressed by:

$$M(t) = \int_0^t m(t)dt \quad \text{(II.15)}$$

II.7.1.1 Exponential distribution maintainability function

This distribution is simple and straightforward to handle and is quite useful for representing repair times. Its probability density function concerning repair times.[9] is expressed by:

$$m(t) = \mu e^{-\mu t} \quad \text{(II.16)}$$

Where $$\mu = \frac{1}{MTTR} \quad \text{(II.17)}$$

By substituting Eq. (II.16) into Eq. (II.15), we obtain

$$M(t) = \int_0^t \mu e^{-\mu t}dt = 1 - e^{-\mu t} \quad \text{(II.18)}$$

II.8 Availability

Availability is defined as “ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided”.[11]

The difference between reliability and availability is illustrated in Fig.II.18. Over a long period, the value of availability levels out at (usually) quite a high number. The reliability values for individual equipment items, however, tend asymptotically to zero. If an item is in service long enough, and if it is not either repaired or replaced, it will eventually fail.[10]

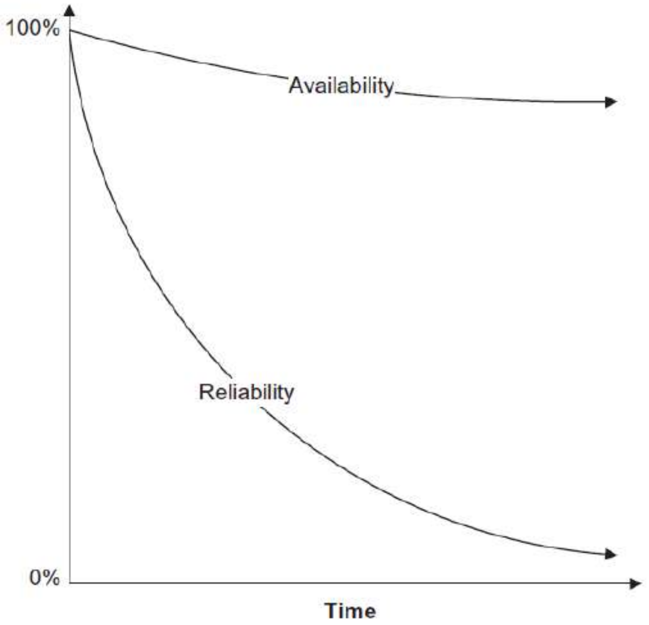


Figure II.18: Availability and reliability

II.8.1 Nines

Availability expectations are described in terms of nines. The following table shows the anticipated downtime for different availabilities for a mission time of one year. This is the typical period used with commercial systems.

Table II.2: The 9s of availability

Availability %	Downtime/year	Downtime/month	Downtime/week
90% (1 nine)	36.5 days	72 hours	16.8 hours
99% (2 nine)	3.65 days	7.2 hours	1.68 hours
99.9% (3 nine)	8.76 hours	43.8 minutes	10.1 minutes
99.99% (4 nine)	52.56 minutes	4.32 minutes	1.01 minutes
99.999% (5 nine)	5.26 minutes	25.9 seconds	6.05 seconds
99.9999% (6 nine)	31.5 seconds	2.59 seconds	0.605 seconds
99.99999% (7 nine)	3.15 seconds	0.259 seconds	0.0605 seconds

II.8.2 Availability types

The types of availability include inherent availability, achieved availability, and operational availability, and Instantaneous availability, we'll focus on two types: **Inherent availability** and **Instantaneous availability**.

II.8.2.1 Inherent availability

Inherent availability is a measure of the variables inherent in the design that affect availability. In the calculation of downtime, it usually includes only repair time.[15] The inherent availability of a system or product is expressed by:

$$A_I = \frac{MUT}{MTTR+MUT} = \frac{\mu}{\lambda+\mu} \tag{II.19}$$

II.8.2.2 Instantaneous or point availability

Instantaneous (or point) availability is the probability that a system (or component) will be operational (up and running) at a specific time, t.

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \tag{II.20}$$

II.9 ABC analysis (Pareto chart)

A Pareto chart is a tool that enables factors influencing a particular phenomenon to be organized. Employing this graphic picture, it is possible to present both relative and absolute distribution of the types of errors, problems, and their causes (Fig.II.19).[20]

The field under the Pareto chart has been divided into three areas:

- Area A – in the case of 20% of populations containing 80% of cumulative feature values.
- Area B – in case of another 30% of populations containing 10% of cumulative feature values
- Area C –the remaining 50% of populations that contain 10% of cumulative feature values.

In practice, a Pareto chart is used to group particular problems and their causes to solve crucial problems in a given enterprise.[20]

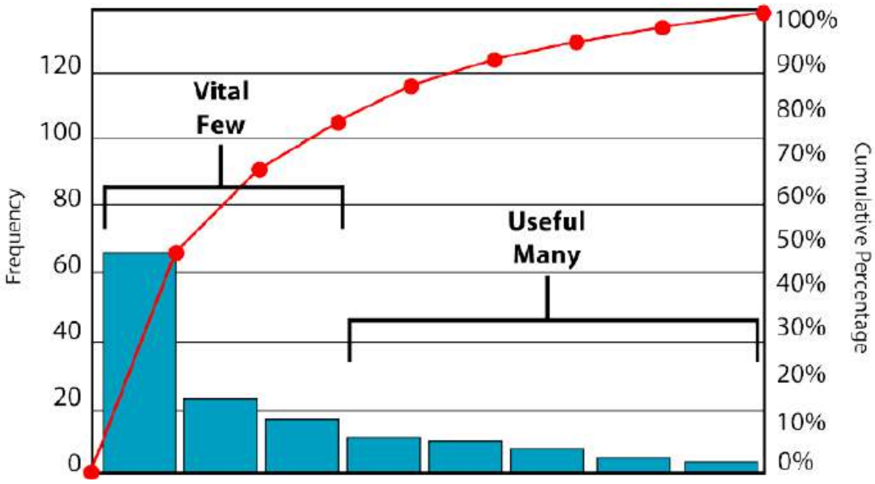


Figure II.19: Pareto chart

II.9.1 ABC analysis steps

The construction of a Pareto chart is divided into the following stages:

1- Information collection

2- Putting the collected data in order

3- Calculation of cumulative percentage values (establishing the cumulative percentage values for particular failures),

4- Preparing a Pareto chart,

5- Review of the Pareto chart.[20]

II.9.2 Benefit of ABC analysis

- Eliminating the most frequent phenomena.
- Eliminating the biggest cost sources.
- Analysis of problem importance and frequency.

II.10 Cause-and-effect diagram

This is a deductive analysis approach that can be quite useful in reliability, maintainability, and availability areas. It is to be noted that in the published written works, this method is also known as a fishbone diagram because it resembles the skeleton of a fish, or an Ishikawa diagram, after its originator, K. Ishikawa of Japan.

A cause of effect diagram makes use of a graphic fishbone to illustrate the cause-and-effect relationship between an undesired event and its all associated contributing causes.

The right side (i.e., the fish head or the box) of the diagram denotes the effect (i.e., the problem or the undesired event), and left of this, all possible causes of the problem are connected to the central fish spine.[9]

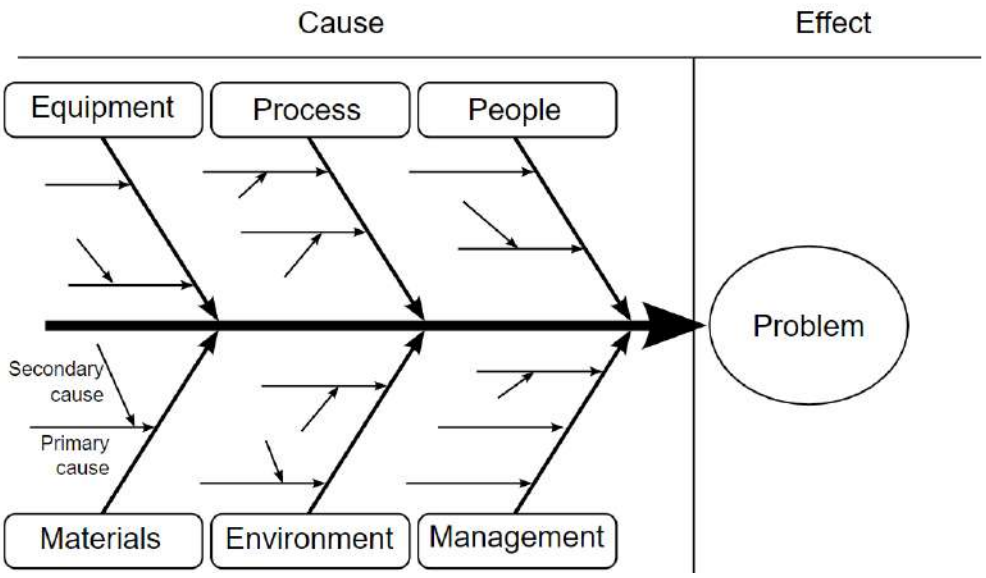


Figure II.20: Ishikawa diagram

II.10.1 Benefits of the cause-and-effect diagram

Some of the important benefits of the cause-and-effect diagram are

- Useful to generate ideas.
- Useful in guiding further investigation.
- Useful to identify root causes.
- Useful to present an orderly arrangement of theories.

Finally, it is added that a well-developed cause and effect diagram can be a very effective tool for identifying possible reliability, maintainability, and availability problems.[9]

II.10.2 Steps for constructing the cause-and-effect diagram

The basic five steps involved in developing a cause-and-effect diagram are as follows:

- Step 1: Establish a problem statement or identify the effect to be investigated.
- Step 2: Brainstorm for identifying all possible causes for the problem under study.
- Step 3: Group all major causes into categories and align them.
- Step 4: Develop the diagram by linking the causes under appropriate process steps and write down the effect or problem in the diagram box (i.e., the fish head) on the right side.
- Step 5: Refine all-cause categories by asking questions such as ‘What causes this?’ and ‘What is the reason for the existence of this condition?’.[9]

Generally, the categories used in manufacturing are:

- Man/mind power (physical or knowledge work, includes: kaizens, suggestions)
- Machine (equipment, technology)
- Material (includes raw material, consumables, and information)
- Method (process)
- Measurement / medium (inspection, environment)

II.11 Failure mode, effects, and criticality analysis (FMECA)

The FMECA is composed of two separate analyses, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA).

The FMEA analyzes different failure modes and their effects on the system while the CA classifies or prioritizes their level of importance based on failure rate and severity of the effect of failure.

The ranking process of the CA can be accomplished by utilizing existing failure data or by a subjective ranking procedure conducted by a team of people with an understanding of the system.[16]

II.11.1 FMECA purpose

When reliability professionals do not know much about equipment, FMECA is a good first step because it provides information about the kinds of failures likely found in historical data and the ones impacting system availability.[14]

II.11.2 FMECA benefits

- Proves useful for making design comparisons.
- Is easy to understand.
- Generates input data for use in test planning.
- Serves as a visibility tool for managers.
- Provides a systematic approach to classifying hardware failures.
- Identifies all possible failure modes and their effects on mission, personnel, and system.
- Generates useful data for use in system safety and maintainability analyses.
- Effectively analyzes small, large, and complex systems.
- Starts from the level of greatest detail and works upward.[14]

II.11.3 FMECA types

- **The system-level FMECA:** Of these three, the highest level of analysis is the system-level FMECA, which usually consists of a collection of subsystem FMECAs. Performed in the initial design concept phase, the system level FMECA highlights potential system or subsystem failures so that they can be prevented.[15]
- **The design level FMECA:** Helps identify and prevent failures stemming from the product design. It analyzes the design that has been developed and examines how failures of individual items would affect the system's functioning or operation.[15]
- **The process level FMECA:** The purpose of the process level FMECA is to analyze the process by which the product or system is to be built and assess how potential failures in the manufacturing or service process would affect the product/system functioning or operation.[15]

II.11.4 Criticality assessment

This assessment ranks potential failures identified during the system analysis based on the severity of their effects and the likelihood of their occurrence. The method most often used for making criticality assessments are the risk priority number (RPN) method.[15]

II.11.4.1 Risk priority number method

This technique, commonly used in the industry, bases the risk priority number for an item failure mode on three factors:

- **The probability of occurrence (O):** is the likelihood of failure, or relative number of failures, expected during the item's useful life [15]
- **The severity of the failure (S):** The severity of the effect of an item's failure is the consequences it will have for the next highest level of the system, the system as a whole, and/or the user.[15]
- **The probability of failure detection (D)**: is an assessment of the proposed design verification program's ability to detect a potential problem before the item involved goes into production.[15] The risk priority number is expressed by:

$$RPN = (O)\,(S)\,(D) \tag{II.21}$$

II.11.5 FMECA methodology steps

To perform an FMECA the analysts must perform an FMEA first then the CA. The FMEA will then be used as the foundation of the criticality analysis, (see Fig.II.21).[16]

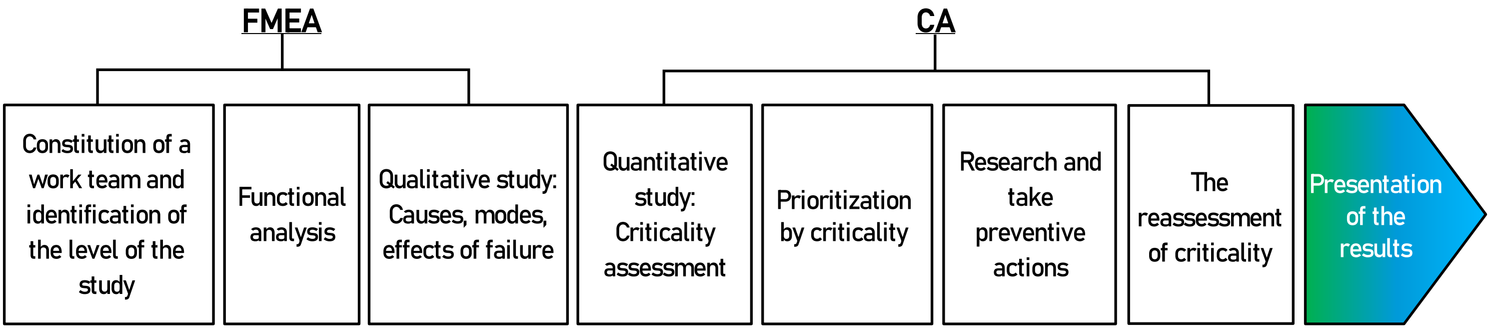


Figure II.21: Typical FMECA flow

II.12 Conclusion

In this chapter, we have presented generalities on basic concepts of maintenance, effective analyses like reliability, maintainability, availability analysis, and FMECA, also using visual presentation methods like Pareto chart, and method of Ishikawa, to eliminating faults caused by these pumps because of their importance in most companies and manufacturers.

CHAPTER III

STUDY AND MAINTENANCE IMPROVEMENT OF A PUMP

III.1 Introduction

Maintenance is an important factor in quality assurance and some cases determines the long-term success of a company. Poorly maintained resources can cause instability and partially or completely pause production. Malfunctioning machines or complete breakdowns can become a costly process for most companies.

In this final chapter, by exploiting the failure history of the FLOWSERVE ME300/450 «T07» pump, dealing with experimental study of functional analysis, RMA analysis, Ishikawa, Pareto chart, eventually FMCEA study of the mentioned pump.

III.2 Functional analysis

III.2.1 APTE method

III.2.1.1 Horned beast

The purpose of the FLOWSERVE ME300/450 «T07» is to circulate the water to cool the working rolls with a pressure of 4 to 18 bars to avoid any risk of damaging the surfaces of the rolls.

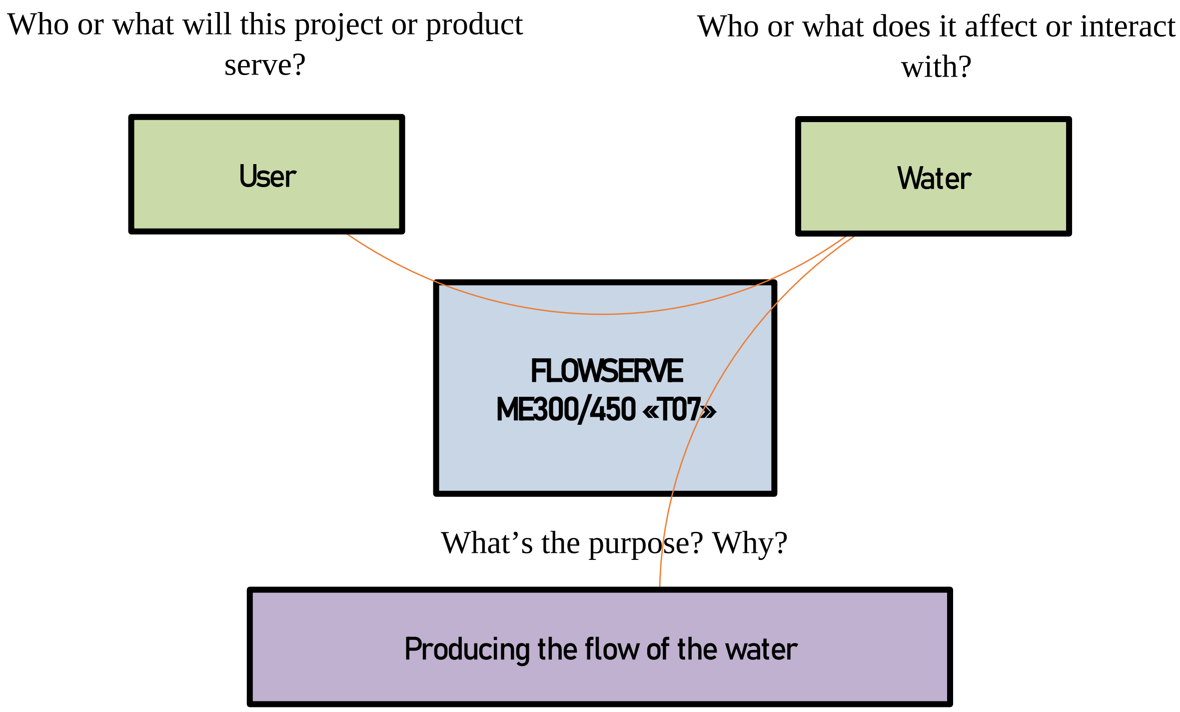


Figure III.1: FLOWSERVE ME300/450 «T07» horned beast diagram

III.2.1.2 Octopus diagram

The octopus diagram makes it possible to see the interactions linked to the system with the exterior. This diagram is shown below (Fig.III.2).

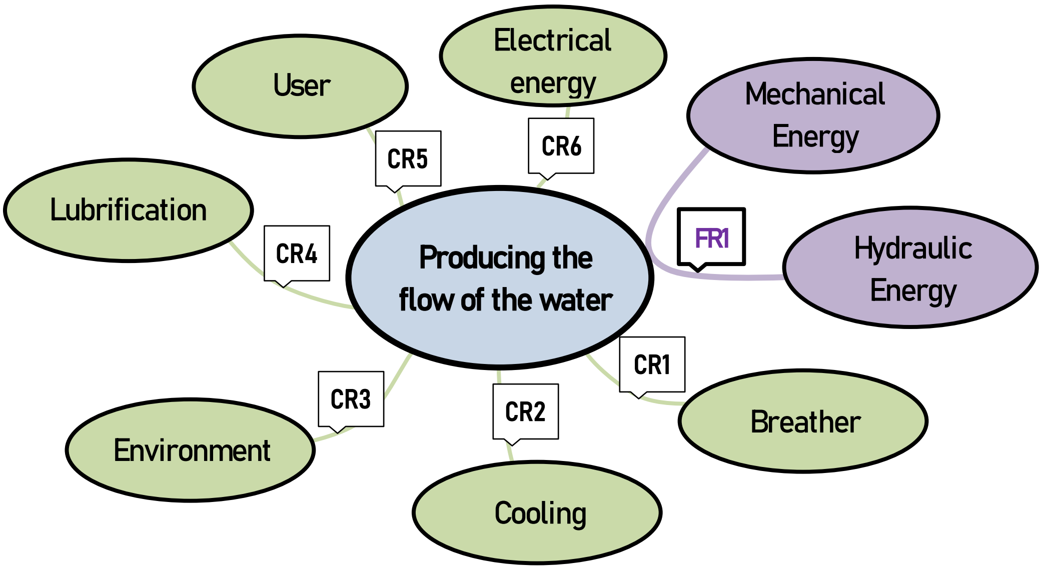


Figure III.2: FLOWSERVE ME300/450 «T07» octopus's diagram

Table III.1: Octopus functions and their significations

Function	Signification
FR 1	Transfer mechanical energy to hydraulic energy.
CR 1	Expel expanded air while temperature rises and the opposite.
CR 2	Ensure operation at optimum temperature.
CR 3	Prevent water and oil from leaking into the environment.
CR 4	Provide lubrication and cooling for the bearings.
CR 5	Control the pump.
CR 6	Supply the motor with electrical energy.

III.2.2 SADT

To better represent the pump and define its interactions with the exterior and these components, and SADT was made as shown in Fig.III.3.

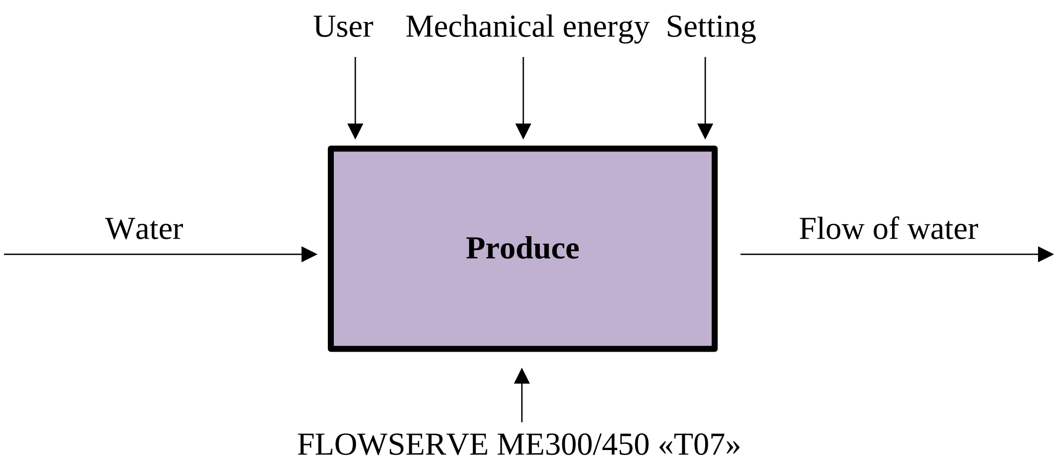


Figure III.3: FLOWSERVE ME300/450 «T07» SADT level 0

III.3 History data exploitation

The history data file of the FLOWSERVE ME300/450 «T07».

We treat them as well and obtained as the following:

- Time to repair (TTR): represent the technical repair hours.
- Uptime (UT): hours of functioning.

Table III.2: FLOWSERVE ME300/450 «T07» history data

Date	Cause of shutdown	UT(h)	TTR(h)
28/05/2013	Pump fixing.	179.45	01
04/06/2013	Lubrication of the pump bearing (abnormal noise. heating).	30.85	0.5
05/06/2013	Overhaul and assembly of the pump.	222.95	1.5
15/06/2013	Switching the pump.	177.15	0.5
22/06/2013	Overhaul and assembly of the pump.	94.55	3.25
26/06/2013	Overhaul and assembly of the pump.	12	0.75
27/06/2013	Switching the pump.	15.3	0.5
28/06/2013	Lubrication of the pump bearing (abnormal noise. heating).	71.55	0.5
01/07/2013	Crankcase change.	74.45	1
07/06/2014	Overhaul and assembly of the pump.	238	2
17/06/2014	Pump fixing.	28.7	0.75
18/06/2014	Lubrication of the pump bearing (abnormal noise. heating).	262.65	2
29/06/2014	Crankcase change.	30.45	0.75
01/07/2014	Pump fixing.	40	1.25
02/07/2014	Crankcase change.	19.9	0.5
03/07/2014	Cleaning, priming hose and ball valve	9.8	0.75
04/07/2014	Check valve control	73.3	0.5
07/07/2014	Braid change (Insufficient pressure).	50.7	0.5
09/07/2014	Alignment control (vibration. noise).	185.75	1.75
16/03/2015	Pump fixing.	571.7	0.75
30/05/2016	Lubrication of the pump bearing (abnormal noise. heating).	215.15	2.25
08/06/2016	Welding crack on the pump body.	459.45	0.5
20/06/2016	Changing the bridle.	301.6	0.75

III.4 RMA analysis

III.4.1 Weibull parameters estimation using Mnitab19

- **Preparing step:** Go to File>Option>Individual>Probability Plots and check “Method for Calculating Plot Points” to select the desired method.

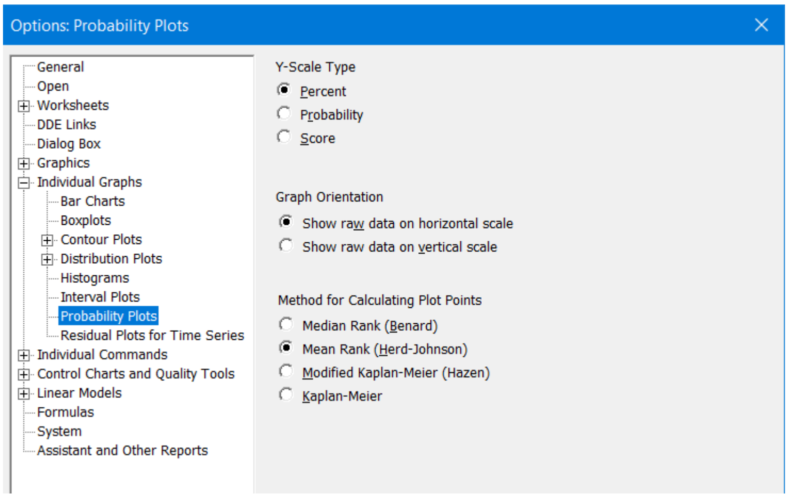
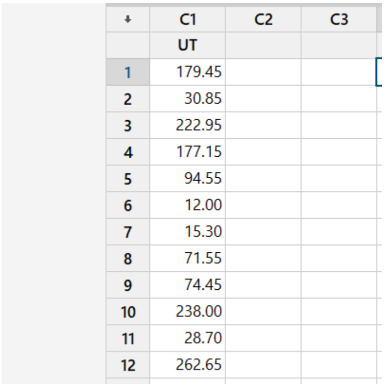


Figure III.4: Minitab19 Options: Probability Plots

- **Step 1:** Filling one column with UTs in the worksheet.



↓	C1	C2	C3
	UT		
1	179.45		
2	30.85		
3	222.95		
4	177.15		
5	94.55		
6	12.00		
7	15.30		
8	71.55		
9	74.45		
10	238.00		
11	28.70		
12	262.65		

Figure III.5: Minitab19 worksheet

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

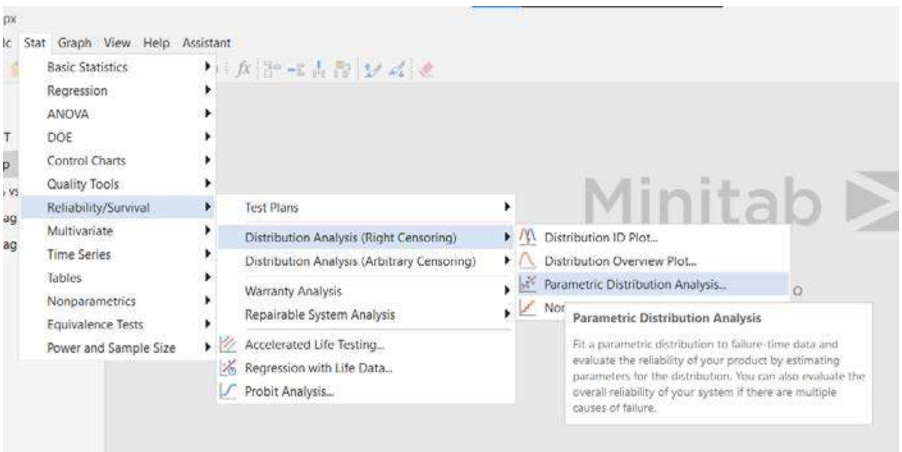


Figure III.6: Minitab19 “Parametric Distribution Analysis” tool location

- **Step 3:** Select the right column in the "Variable" textbox, then click on "Graphs".

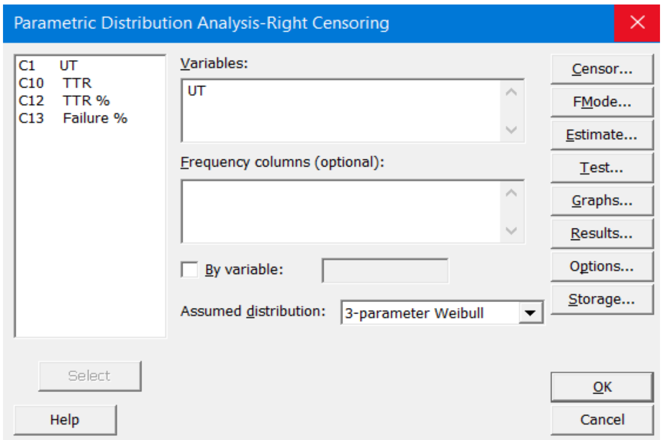


Figure III.7: Minitab19 "Parametric Distribution Analysis: Right Censoring" dialog box

- **Step 4:** Check the following checkbox: "Survival plot", "Cumulative failure plot", "Hazard plot" to obtain these plots, then click "ok", and "ok" again.

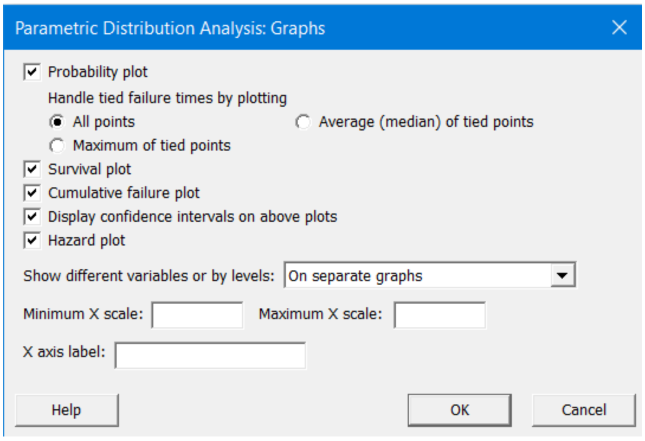


Figure III.8: Minitab19 "Parametric Distribution Analysis: Graphs" dialog box

- **Weibull parameters:** $\boxed{\beta=0.8927,\ \eta=133.211,\ \gamma=5.60}$

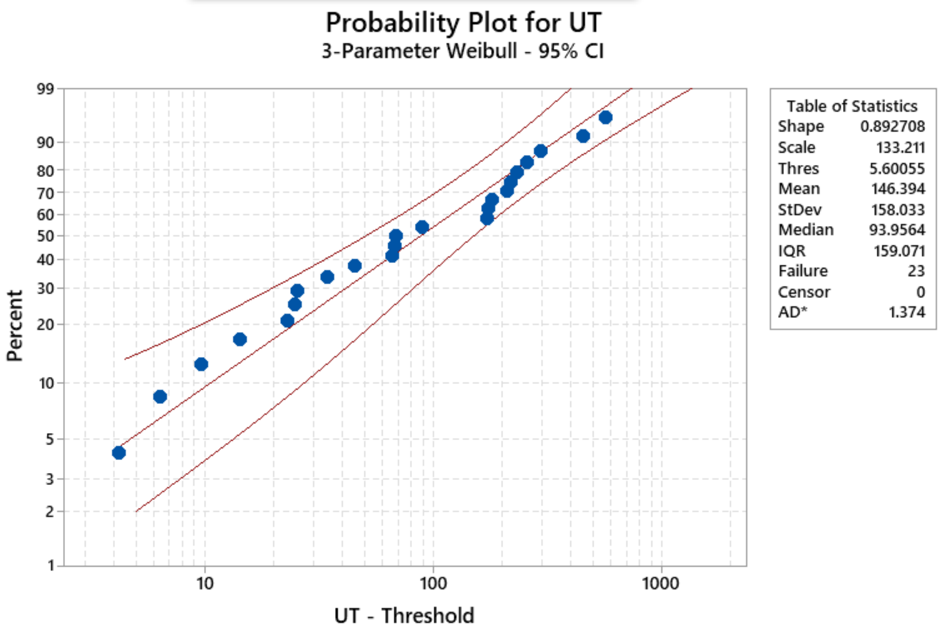


Figure III.9: Weibull probability plot for Uptime

III.4.2 Kolmogorov Smirnov test

We've got the number of population (UT) N=23 which is more than 20 (N>20), so the F(ti) calculated by the mean rank approach: $F(ti) = \frac{\sum ni}{N+1}$ (III.1)

Where F(t) is obtained by: $F(t) = 1 - e^{-\left(\frac{t-5.6}{133.211}\right)^{0.8927}}$ (III.2)

Table III.3: Maximum $D_{n.max}$ determination

N°	UT(h)	F(ti)	F(t)	$D_{n.max} = \lvert F(ti) - F(t) \rvert$
1	9.8	0.041667	0.044660	0.002993
2	12	0.083333	0.064377	0.018956
3	15.3	0.125000	0.091947	0.033053
4	19.9	0.166667	0.127500	0.039166
5	28.7	0.208333	0.188829	0.019505
6	30.45	0.250000	0.200184	0.049816
7	30.85	0.291667	0.202745	0.088922
8	40	0.333333	0.258154	0.075180
9	50.7	0.375000	0.316332	0.058668
10	71.55	0.416667	0.413669	0.002998
11	73.3	0.458333	0.421027	0.037306
12	74.45	0.500000	0.425801	0.074199
13	94.55	0.541667	0.502077	0.039590
14	177.15	0.583333	0.714446	**0.131113**
15	179.45	0.625000	0.718695	0.093695
16	185.75	0.666667	0.729982	0.063315
17	215.15	0.708333	0.776519	0.068186
18	222.95	0.750000	0.787353	0.037353
19	238	0.791667	0.806692	0.015025
20	262.65	0.833333	0.834409	0.001075
21	301.60	0.875000	0.869919	0.005081
22	459.45	0.916667	0.949566	0.032899
23	571.70	0.958333	0.973710	0.015377

-From the K-S table, we've obtained the maximum $\boldsymbol{D_{n.max} = 0.131113}$

-And from K-S Annex (Annex tab 1) $\boldsymbol{D_{N.\alpha} = D_{23\ 20} = 0.210}$

$-\mathbf{0.131113} < \mathbf{0.210}$ which means that the FLOWSERVE ME300/450 «T07» sample data (history file) fits the Weibull distribution.

III.4.3 Mean Up Time (MUT)

From Weibull Annex (Annex tab 2), A=1.05218.

$$MUT = A.\eta + \gamma = 1.05218 * 133.211 + 5.60 \qquad \text{(III.3)}$$

MUT=145.762 Hour

III.4.4 Probability density function PDF

Using the previously obtained parameters, probability density function can be described as:

$$f(t) = 0.0067014\left(\frac{t-5.6}{133.211}\right)^{-0.1073} e^{-\left(\frac{t-5.6}{133.211}\right)^{0.8927}} \qquad \text{(III.4)}$$

Probability density functions at mean up time: $\boldsymbol{f(145.762)}$ **=0.002341=0.2341%**

Table III.4: PDF values in terms of UT

UT(h)	9.8	12	15.30	19.9	28.7	30.45	30.85	40	50.7	71.55	73.3
$\boldsymbol{f(t).10^{-3}}$	9.277	8.684	8.060	7.429	6.560	6.418	6.387	5.749	5.146	4.237	4.172

74.45	94.55	177.15	179.45	185.75	215.15	222.95	238	262.65	301.6	459.45	571.7
4.130	3.485	1.862	1.832	1.752	1.427	1.352	1.220	1.034	0.800	0.296	0.151

III.4.4.1 PDF graph plot and analysis

Plotting PDF curve using Minitab19 software.

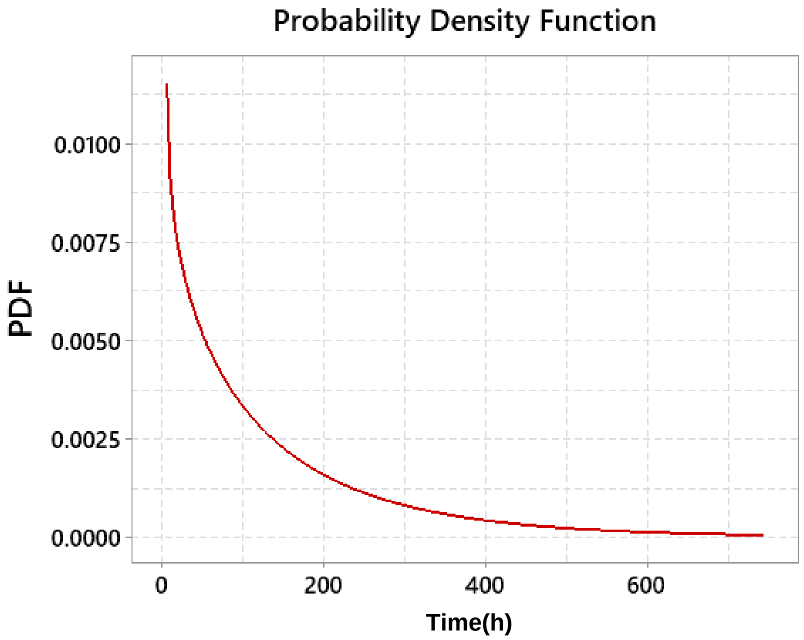


Figure III.10: PDF plot in terms of UT

From this curve, we notice that the PDF (probability density function) f (t) decreases with time.

III.4.5 Cumulative distribution function (CDF)

Using the previously obtained parameters, the cumulative distribution function can be described as we've seen before:

$$F(t) = 1 - e^{-\left(\frac{t-5.6}{133.211}\right)^{0.8927}} \tag{III.2}$$

Cumulative density functions at mean up time: $\boxed{\boldsymbol{F(145.762) = 0.64881 = 64.88\%}}$

Table III.5: CDF values in terms of UT

UT(h)	**9.8**	**12**	**15.30**	**19.9**	**28.7**	**30.45**	**30.85**	**40**	**50.7**	**71.55**	**73.3**
$\boldsymbol{F(t)}$	0.045	0.064	0.092	0.128	0.189	0.200	0.203	0.258	0.316	0.414	0.421

74.45	**94.55**	**177.15**	**179.45**	**185.75**	**215.15**	**222.95**	**238**	**262.65**	**301.6**	**459.45**	**571.7**
0.426	0.502	0.714	0.719	0.730	0.777	0.787	0.807	0.834	0.870	0.950	0.974

III.4.5.1 CDF graph plot and analysis

Plotting CDF curve using Minitab19 software.

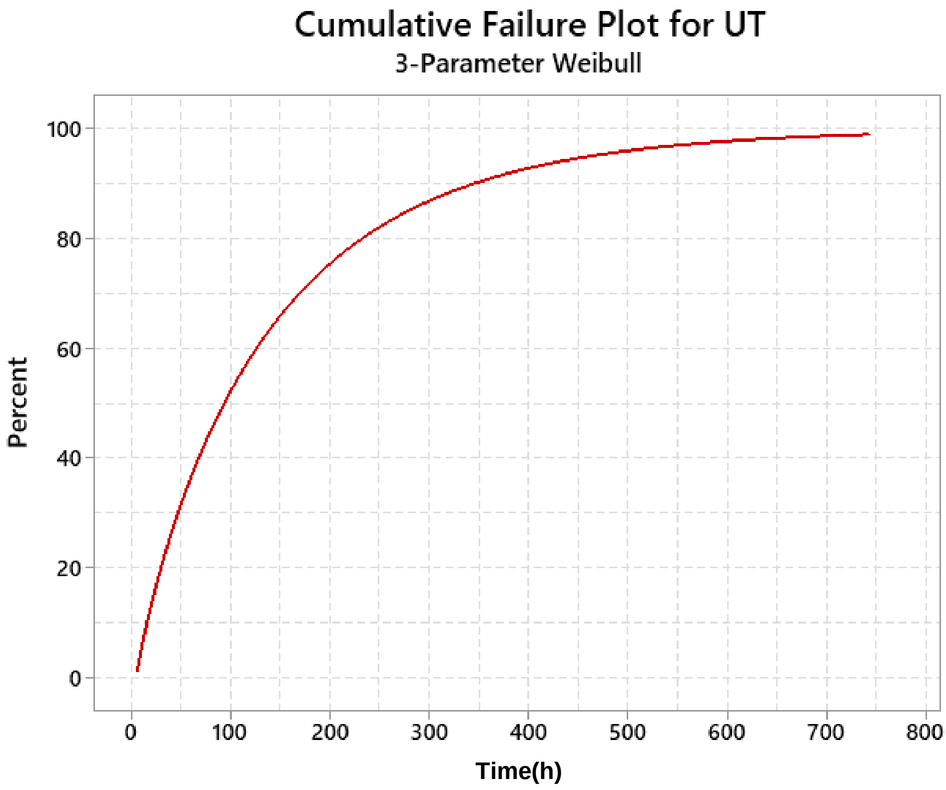


Figure III.11: CDF plot in terms of UT

The failure function (cumulative distribution function) increases in the term of time, and for t= MUT, F (MUT) = **64.88%**

III.4.6 Hazard rate (failure rate)

Using the previously obtained parameters, the hazard rate function can be described as:

$$\lambda(t) = 0.0067014\left(\frac{t-5.6}{133.211}\right)^{-0.1073} \tag{III.5}$$

Table III.6: Hazard rate values in terms of UT

UT(h)	**9.8**	**12**	**15.30**	**19.9**	**28.7**	**30.45**	**30.85**	**40**	**50.7**	**71.55**	**73.3**
$\boldsymbol{\lambda(t).10^{-3}}$	9.711	9.282	8.877	8.515	8.087	8.024	8.011	7.749	7.527	7.226	7.206
74.45	**94.55**	**177.15**	**179.45**	**185.75**	**215.15**	**222.95**	**238**	**262.65**	**301.6**	**459.45**	**571.7**
7.193	6.998	6.522	6.513	6.488	6.383	6.358	6.313	6.245	6.151	5.875	5.738

III.4.6.1 Hazard rate graph plot and analysis

Plotting Hazard rate curve using Minitab19 software.

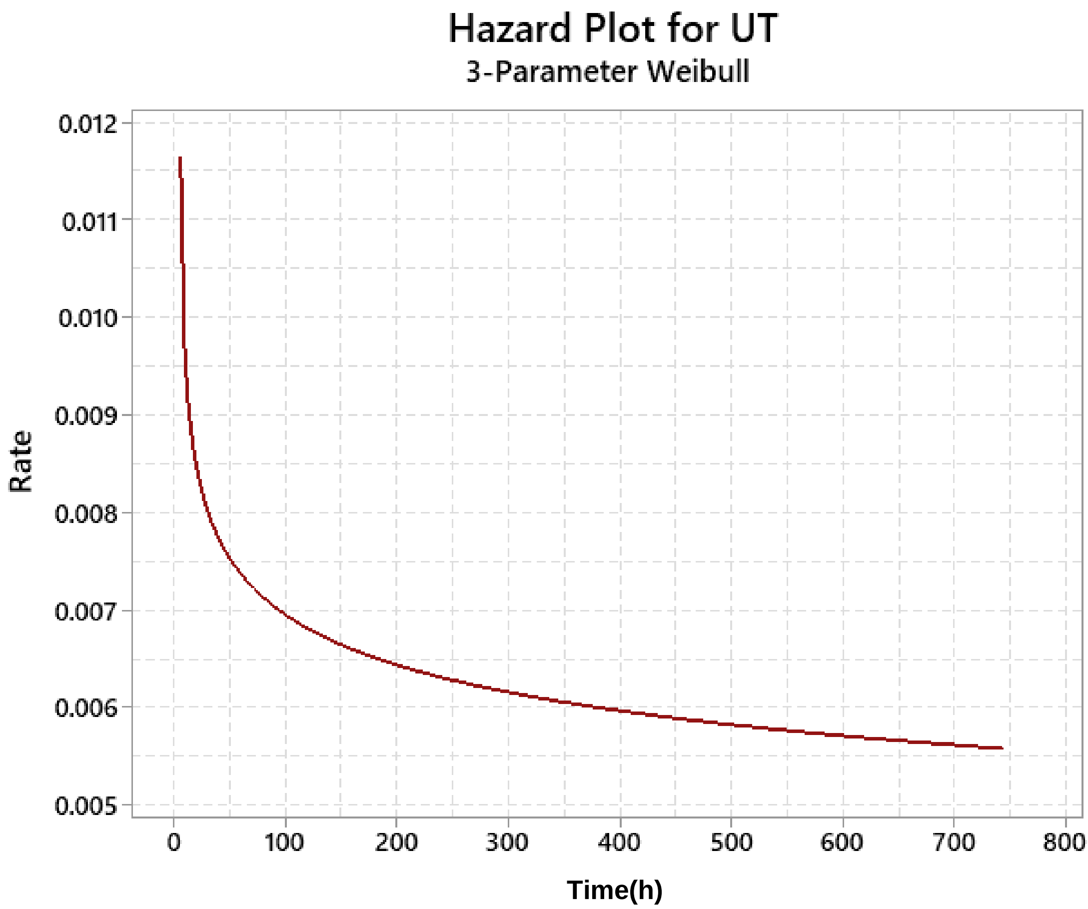


Figure III.12: Hazard rate plot in terms of UT

The hazard rate decreases with time t, which means that the pump going through the **burn-in period (Decreasing Failure Region DFR).**

III.4.7 Reliability

Using the previously obtained parameters, the reliability function can be described as:

$$R(t) = e^{-\left(\frac{t-5.6}{133.211}\right)^{0.8927}} \tag{III.6}$$

Reliability functions at Mean Up Time: $\boxed{\boldsymbol{R(145.762)} = \mathbf{0.3512=35.12\%}}$

After calculating the reliability of the pump at t = MUT, it appears that the value is not satisfying so we can say that the pump is unreliable at t = MUT.

Table III.7: Reliability values in terms of UT

UT(h)	9.8	12	15.30	19.9	28.7	30.45	30.85	40	50.7	71.55	73.3
$R(t)$	0.955	0.936	0.908	0.872	0.811	0.8	0.797	0.742	0.684	0.586	0.579

74.45	94.55	177.15	179.45	185.75	215.15	222.95	238	262.65	301.6	459.45	571.7
0.574	0.498	0.286	0.281	0.27	0.223	0.213	0.193	0.166	0.13	0.050	0.026

III.4.7.1 Reliability graph plot and analysis

Plotting reliability (survival) curve using Minitab19 software.

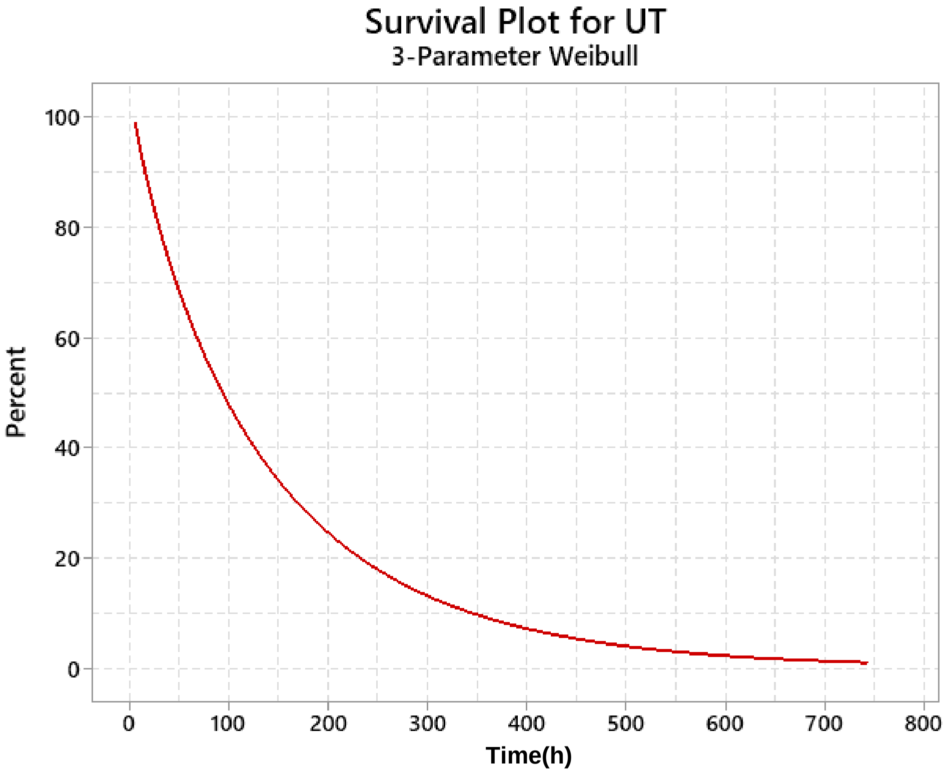


Figure III.13: Reliability plot in terms of UT

The decreasing graph as a function of time which explains the phenomenon of degradation, improving the reliability of the pump necessarily involves an analysis of the failures with a detailed study of their causes, their modes, and their consequences.

III.4.7.2 Calculation of the desirable time for a systematic intervention

We suppose that the minimum reliability of the pump to proceed with periodic maintenance is 80% so:

$$R(t) = e^{-\left(\frac{t-5.6}{133.211}\right)^{0.8927}} = 0.8 \quad \text{(III.7)}$$

$$t_p = \left[133.211 * \left(\ln\left(\frac{1}{0.8}\right)^{\frac{1}{0.8927}}\right)\right] + 5.2 = \boxed{\textbf{30.42h}} \quad \text{(III.8)}$$

To retain the reliability of the pump above 80%, it is necessary to intervene every period of 30.42 hours.

III.4.8 Maintainability

The first thing before introducing maintainability function is to calculate μ:

$$\mu = \frac{1}{MTTR} = \frac{N}{\sum TTR} = \boxed{\textbf{0.9388 intervention / hour}} \quad \text{(III.9)}$$

Where MTTR=1.06522.

Using the previously obtained parameters, the maintainability function can be described as:

$$M(t) = 1 - e^{-0.9388t} \quad \text{(III.10)}$$

Table III.8: Maintainability values in terms of UT

TTR(h)	0	1	2	3	4	5	6	7	8
$M(t)$	0	0.609	0.847	0.94	0.977	0.991	0.996	0.999	0.999

III.4.8.1 Maintainability graph plot and analysis

Plotting Maintainability curve using MATLAB software.

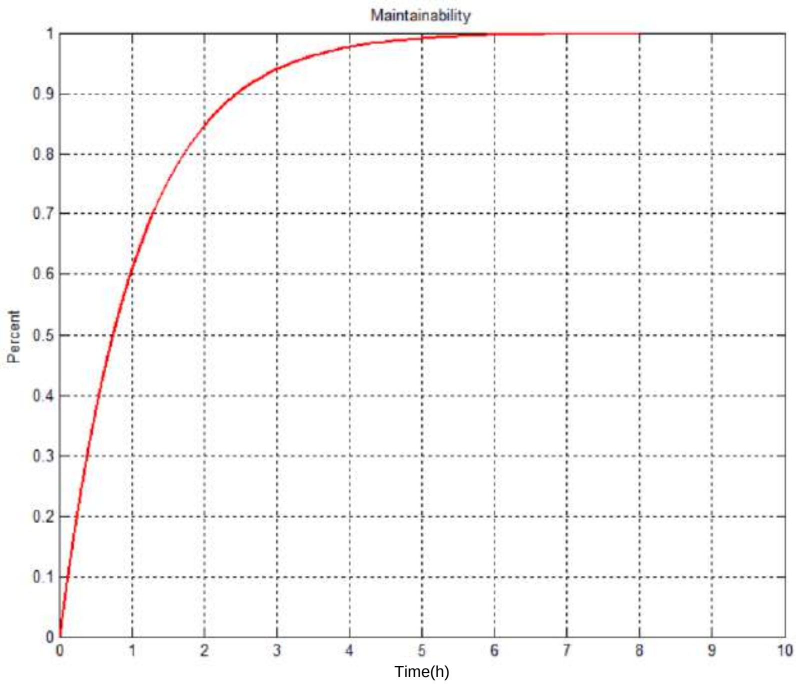


Figure III.14: Maintainability plot in terms of TTR

Maintainability increases with time at instant t = 7 hours, where it comes maintainable 99.9%.

III.4.9 Availability

III.4.9.1 Inherent availability

$$\lambda = \frac{1}{MUT} = \boxed{0.006886} \qquad \text{(III.11)}$$

$$A_I = \frac{MUT}{MTTR+MUT} = \frac{\mu}{\lambda+\mu} = \boxed{0.9927=99.27\approx 99\%\ \text{(Two nines)}} \qquad \text{(III.12)}$$

III.4.9.2 Instantaneous availability

$$A(t) = 0.9927 + 0.00728e^{-(0.9457t)} \qquad \text{(III.13)}$$

Table III.9: Availability values in terms of UT

t(h)	0	1	2	3	4	5	6	7	8
$A(t)$	1	0.9955	0.9938	0.9931	0.9929	0.9928	0.9927	0.9927	0.9927

III.4.9.3 Availability graph plot and analysis

Plotting Availability curve using MATLAB software.

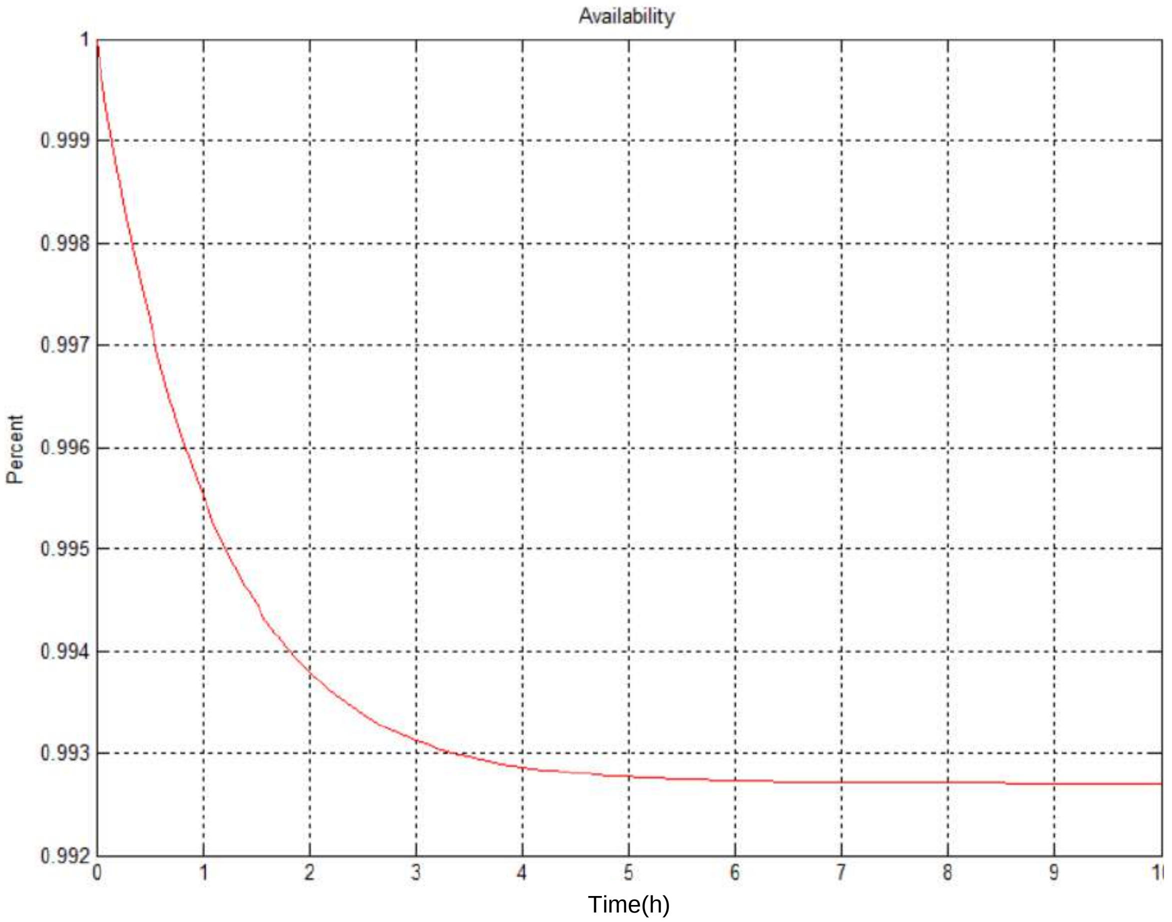


Figure III.15: Availability plot in terms of hour

The availability of the pump keeps decreasing until 6 hours, the availability remains at **99.27**%.

III.5 Pareto method analysis

Table III.10: Pareto method calculation

N	Interventions	TTR (h)	Cumulative TTR	TTR%	ni	∑ni	Failures %
1	Overhaul and assembly of the pump.	7.50	7.5	30.61	4	4	17.39
2	Lubrication of the pump bearing.	5.25	12.25	50	4	8	34.78
3	Pump fixing.	3.75	16.5	67.34	4	12	52.17
4	Crankcase change.	2.25	18.75	76.53	3	15	65.22
5	Alignment control.	1.75	20.5	83.67	1	16	69.57
6	Switching the pump.	1.00	21.5	87.76	2	18	78.26
7	Cleaning, priming hose, and ball valve.	0.75	22.25	90.82	1	19	82.61
8	Changing the bridle.	0.75	23	93.88	1	20	86.96
9	Check valve control	0.50	23.5	95.92	1	21	91.3
10	Braid change.	0.50	24	97.96	1	22	95.65
11	Welding crack on the pump body.	0.50	24.5	100	1	23	100

II.5.1 Pareto chart analysis

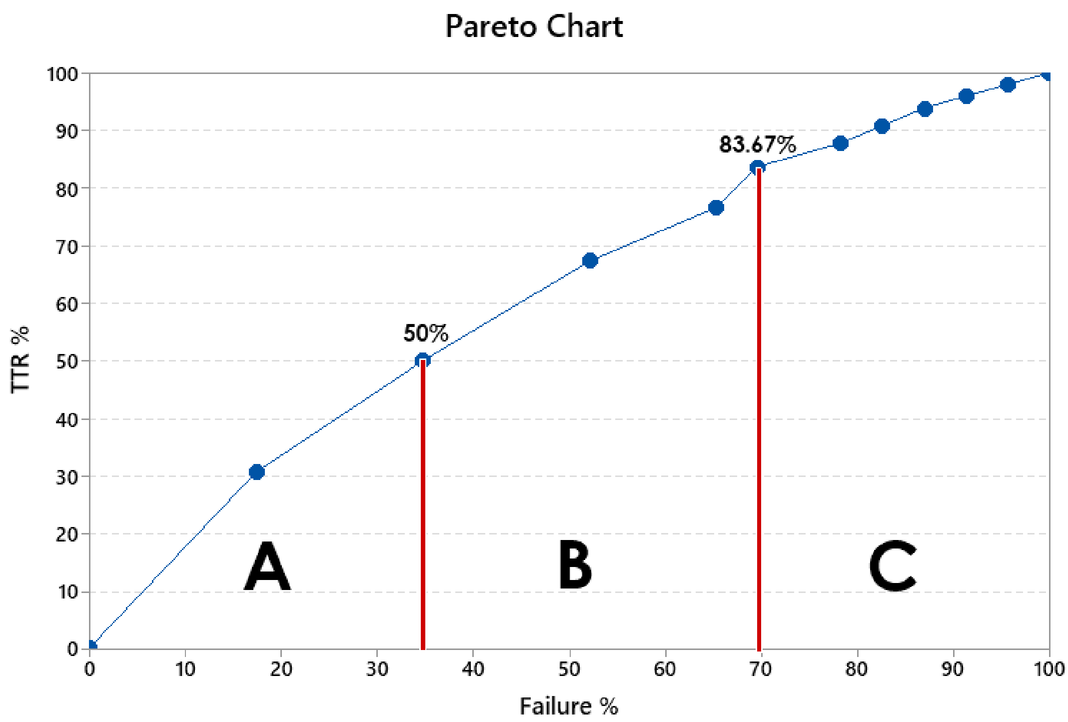


Figure III.16: Pareto chart for FLOWSERVE ME300/450 «T07» interventions

❖ **"A" Zone:** In this zone, we find that approximately 34.78% of the interventions represent 50% of the repair hours, this constitutes zone A, (overhaul and assembly of the pump, lubrication of the pump bearing).

❖ **"B" Zone:** In this slice, 34.79% of interventions represent an additional 33.67% (pump fixing, crankcase change, alignment control).

❖ **"C" Zone:** In this zone, 30.43% of the remaining interventions only represent 16.33% of the repair hours (switching the pump, cleaning, priming hose, and ball valve, changing the bridle, check valve control, braid change, welding crack on the pump body).

III.6 Cause-effect (Ishikawa) diagram

Establishing Ishikawa diagram of the causes that increase downtime, using Minitab19

- **Step 1:** Fill some column with the causes

C14-T	C15-T	C16-T	C17-T	C18-T
Man	Machines	Measurement	Methods	Medium
Lack of skills	Old pump	Some measurement tools are not available	Poor Standards	High Temperature
Lack of knowledge	Bearing failure	Uncalibrated measurement tools	Corrective maintenance	High Pressure
Ignorance	Worn O-rings	Current, voltage and speed not measured	Some parameters are miscalculated	Vibration
Fail to follow instructions	Worn packing			Dust
Human errors				Unstable voltage

Figure III.17: Worksheet filled with causes

- **Step 2:** Go to Stat>Quantity Tools>Cause-and-Effect

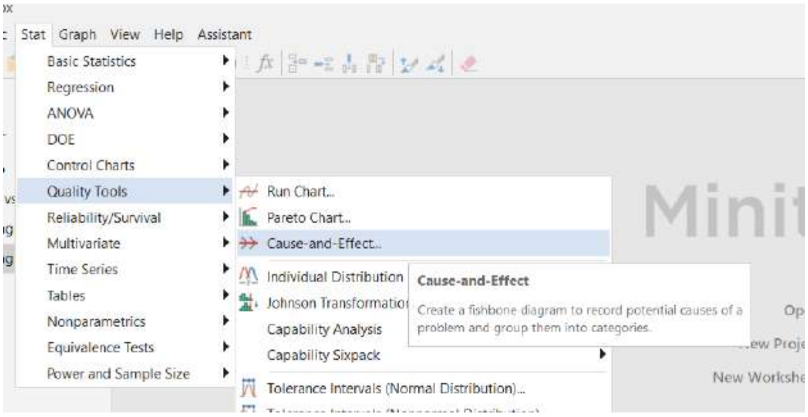


Figure III.18: Cause-and-Effect location on Minitab19

- **Step 3:** Fill the dialog box with the cause columns, the labels, and the effect textbox then click "OK".

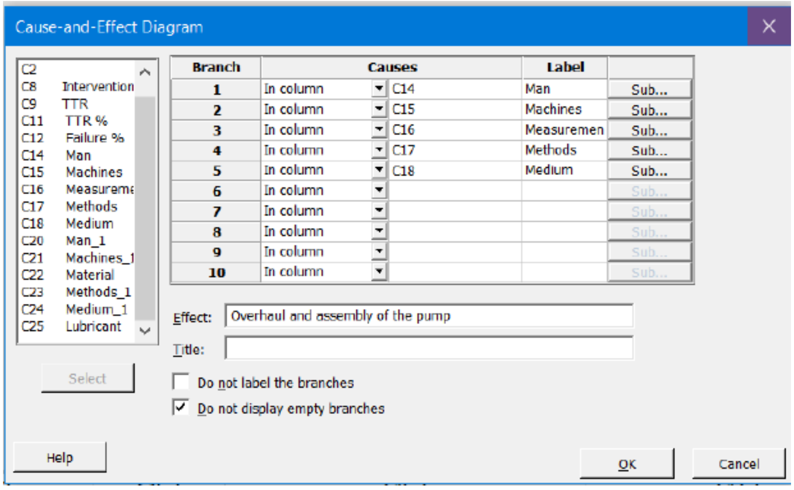


Figure III.19: Cause-and-Effect location dialog box

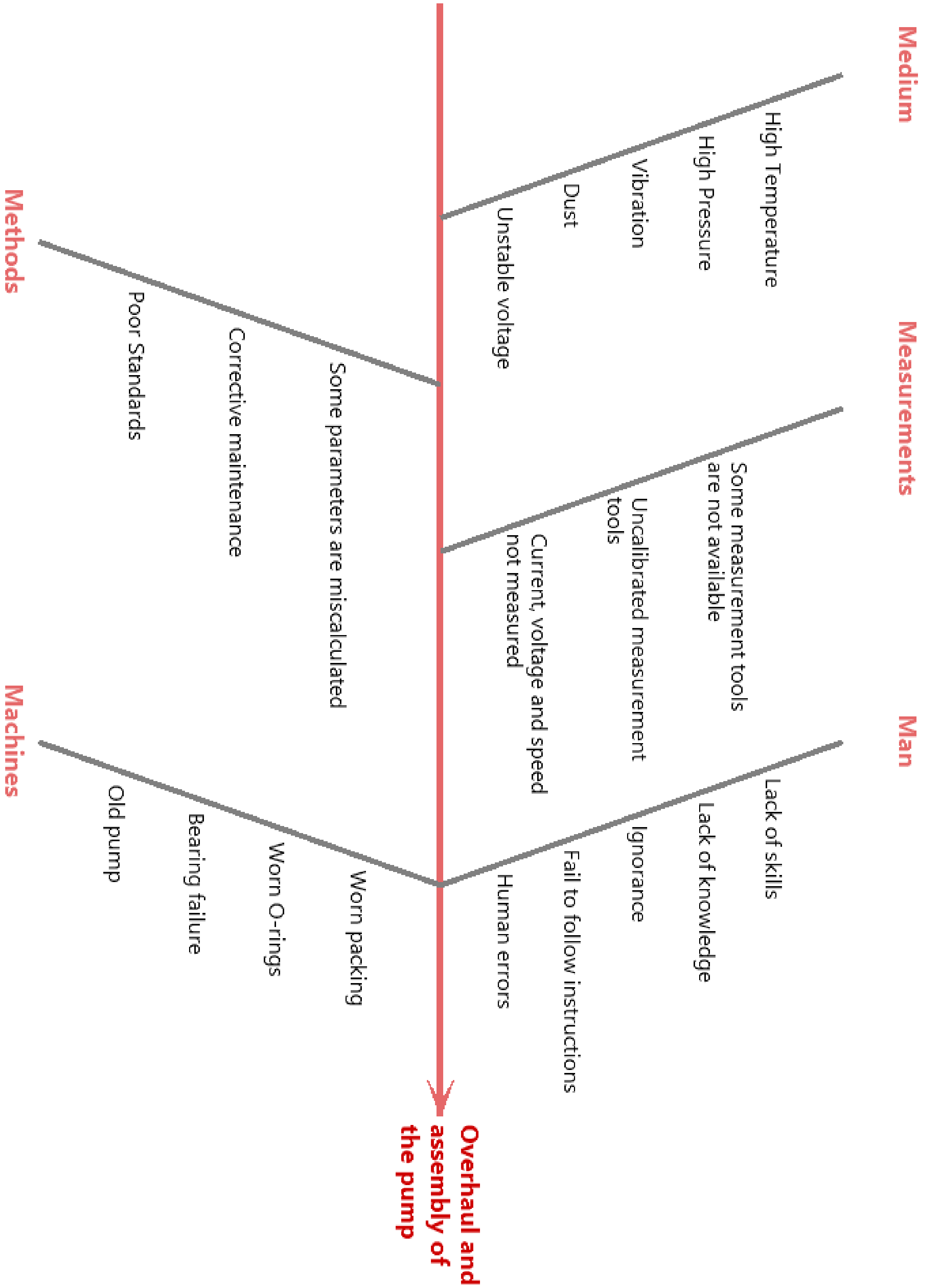


Figure III.20: Analysis of intervention: overhaul and assembly of the pump

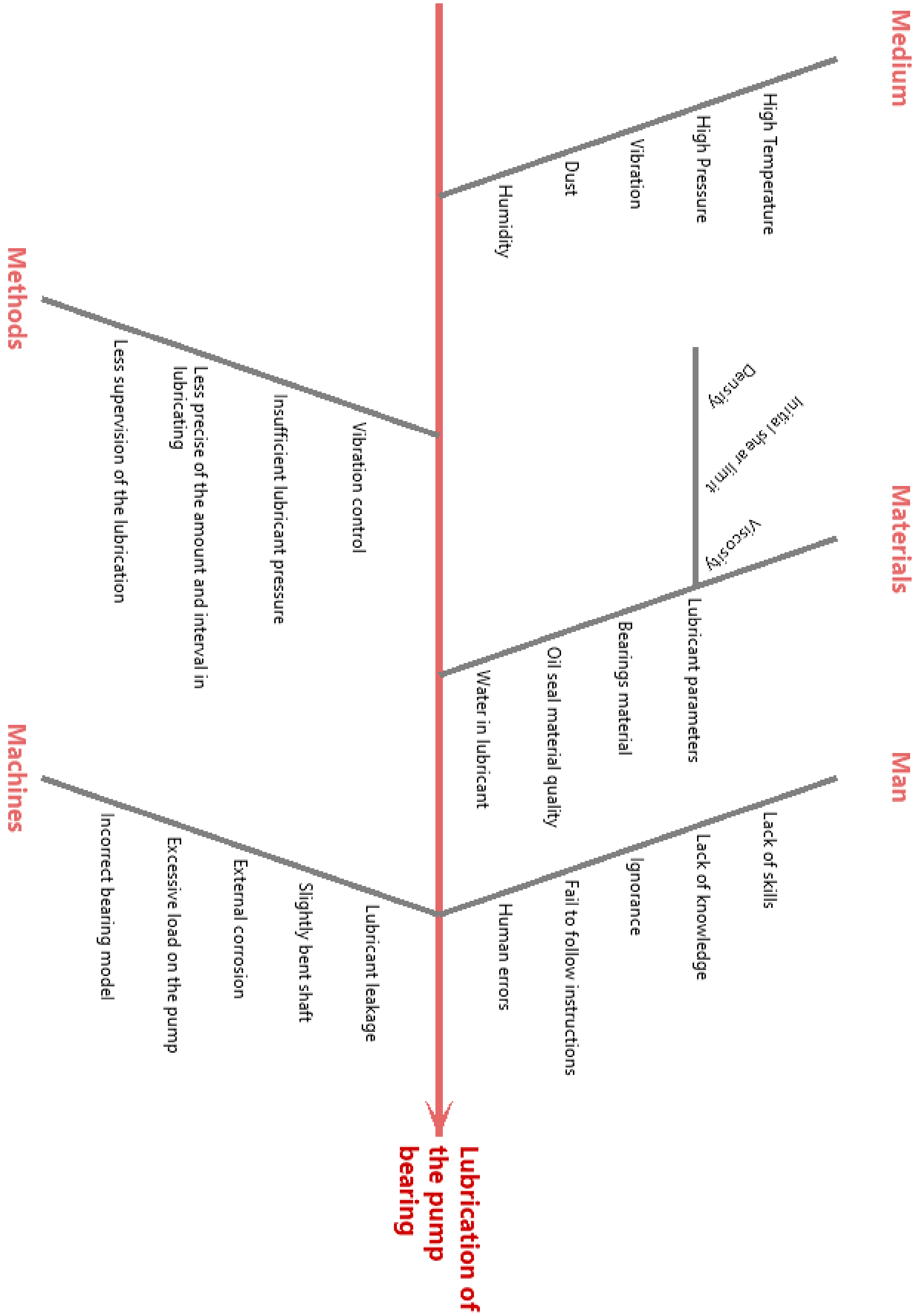


Figure III.21: Analysis of intervention: lubrication of the pump bearing

III.7 Troubleshooting (cause-remedy table)

For minimizing intervention times, we have proposed some solutions according to each cause in the following table:

Table III.11: Troubleshooting

N°	Causes	Remedy
1	Lubricant parameters	Change the lubricant used
2	Oil seal material quality	Switch oil seal supplier
3	Incorrect bearing model, material	Change bearing model
4	Lubricant leakage	-Breather should be open and clean. -Check that all oil drain locations are clean and permit free flow. -Check oil seals and replace them if worn. -Adjust or replace the packing. Tighten packing gradually to break in. - Reduce the flow of lubricant to bearing by adjusting orifices.
5	Slightly bent shaft	Straightening the shaft
6	Insufficient lubricant pressure	Increase lubricant pressure
7	Corrective maintenance	Preventive maintenance
8	High Temperature	Improve workshop adaptation
9	Vibration	Adjustments to the pump support structure
10	Dust	Install dust collection/cleaning system
11	Worn packing	Change packing
12	Worn O-rings	Change O-rings
13	Some parameters are miscalculated	Recalculate the parameters
14	Some measurements tools not available	Provide the missing tools
15	Uncalibrated measurement tools	Calibrate the measurement tools
16	Current, voltage, and speed not measured	Install current, volt meter, and speed gauges
17	Fail to follow instructions	Provide instructions checklist
18	Lack of knowledge	Engaging the operators on training program
19	Lack of skills	Assist with Seniors
20	Poor Standards	Switch to advanced standards
21	Less precise of the amount and interval in lubricating	Use the tools of lubricating measurement

III.8 FMECA

III.8.1 FMECA RPN calculation

Table III.12: Rankings of probability of occurrence and associated descriptions

Description of ranking	Probability of occurrence	Rank
Very high (the failure is very likely to occur)	1 in 2	10
Very high	1 in 8	9
High (the failure will occur often)	1 in 20	8
High	1 in 40	7
Moderate (the failure will occur occasionally)	1 in 80	6
Moderate	1 in 400	5
Moderate	1 in 1000	4
Low (the failure will rarely occur)	1 in 4000	3
Low	1 in 20000	2
Remote (the failure is unlikely to occur)	Less than 1 in 1,000,000	1

Table III.13: Rankings of severity of failure effect and associated descriptions

Level of severity	Severity Description	Rank
Hazardous without warning	Very high severity ranking when a potential failure mode affects safe system operation without warning	10
Hazardous with warning	Very high severity ranking when a potential failure mode affects safe system operation with warning	9
Very high	System inoperable with destructive failure without compromising safety	8
High	System inoperable with equipment damage	7
Moderate	System inoperable with minor damage	6
Low	System inoperable without damage	5
Very low	System operable with significant degradation of performance	4
Minor	System operable with some degradation of performance	3
Very minor	System operable with minimal interference	2
None	No effect	1

Table III.14: Rankings of likelihood of detection and associated descriptions

Detection	Likelihood of Detection	Rank
Absolute uncertainty	Cannot detect potential cause/ mechanism and subsequent failure mode	10
Very remote	Very remote chance to detect potential cause/mechanism and subsequent failure mode	9
Remote	Remote chance to detect potential cause/mechanism and subsequent failure mode	8
Very low	Very low chance to detect potential cause/mechanism and subsequent failure mode	7
Low	Low chance to detect potential cause/mechanism and subsequent failure mode	6
Moderate	Moderate chance to detect potential cause/mechanism and subsequent failure mode	5
Moderate high	Moderate high chance to detect potential cause/mechanism and subsequent failure mode	4
High	High chance to detect potential cause/mechanism and subsequent failure mode	3
Very high	Very high chance to detect potential cause/mechanism and subsequent failure mode	2
Almost certain	Detection of potential cause/mechanism and subsequent failure mode	1

Table III.15: RPN calculation

The element	O	S	D	RPN
Mechanical seal	3 (1 in 4000)	3 (Minor)	1 (Almost certain)	3*3*1=9
Bearing	4 (1 in 1000)	6 (Moderate)	2 (Very high)	4*6*2=48
Shaft	3 (1 in 4000)	6 (Moderate)	3 (High)	3*6*3=54
Impeller	3 (1 in 4000)	7 (High)	6 (Low)	3*7*6=126
Casing	2 (1 in 20000)	9 (Hazardous with warning)	3 (High)	2*9*3=54

III.8.2 FMECA table

Table III.16: Failure Mode, Effects & Criticality Analysis worksheet

FMECA										
System: FLOWSERVE ME300/450 «T07»										
The element	**Function**	**Failure modes**	**Cause**	**Effect**	**Detection**	**Risk Priority Number**				**Action**
						O	S	D	RPN	
Mechanical seal	Reduce or eliminate leaks	Leakage, surface erosion, crack	Incorrect installation	Fluid spills into the environment	Leak	3	3	1	9	Study the troubleshooting book properly and apply it
Bearing	Guide and support the shaft	Defect bearings	Misalignment	Excess vibration, eroded	-Vibration -Noise	4	6	2	48	Evaluate shaft and bearing position
Shaft	Provides rotation	Deformation on shaft	Lack of lubrification	Shaft scratches, size change, and excessive vibration	Vibration analysis	3	6	3	54	-Check the brittle parts -Monitor the state of corrosion -Clean the shaft. -Check that the shaft run-outs are within acceptable ranges. -Check the shaft seal
Impeller	Transmit energy from the shaft to the fluid	Deformation on impeller	Erosion and contamination fluid	Cracked, perforated, unbalanced, high vibration impeller	-Vibration -Noise -Low flow	3	7	6	**126**	Evacuate the chemical content in the fluid that is flowed
Casing	Translate the fluid flow into a controlled discharge at a pressure	Crack formation	The pressure is too high and the fluid is dirty	Casing perforated, gaps, pressure drop, erosion	-Low flow -Leak	2	9	3	54	Evaluate pressure rise and fluid content

III.8.3 FMECA results

Classification of the elements by their criticality into four groups like following:

Table III.17: Elements criticality classification

Group	*Element*	*Corrective action*
I	Mechanical seal	-No modification. -Corrective maintenance.
II	Bearing	-Element performance improvement. -Systematic preventive maintenance.
III	-Shaft -Casing	-Individual monitoring. -Conditional preventive maintenance.
IV	Impeller	-Full reconstruction of conditional preventive design.

III.9 Conclusion

In the **first** part of this chapter, we used the functional analysis of the pump, we identified the main purpose of the pump, which is producing the water flow, and the other functions of the pump.

In the **second** part, using the pump failure history data, we studied RMA indicators, then the **third** part for certain charts (Pareto, Ishikawa), and the **final** part where we used FMECA for obtaining the following results:

- We find that **β=0.8927** which is less than 1, meaning that our pump is in the **burn-in** period (Decreasing Failure Rate **DFR**).
- Also**, γ=5.6** which is more than 0, meaning that our pump fully survived (100% reliability) over the time interval [0,5.6]
- **MUT**=145.762 hour
- The reliability of the pump is unreliable: **35.12%.**
- To keep the reliability of the pump 80%, it is necessary to intervene every systematic time **30.42h**.
- Availability of the pump is approximately two nines **99%** (downtime: **3.65 days/year**).
- We find that approximately **34.78%** of the interventions (overhaul and assembly of the pump, lubrication of the pump bearing) represent **50%** of the repair hours.
- Extracting possible causes that play a part in increasing the downtime, in both of the two diagrams, the **Machine** category was the major of the cause categories.
- Extract the criticality groups from the risk priority number, where we find that the **impeller** has the highest RPN **(126)**, which requires a full reconstruction of conditional preventive design.

General conclusion

At the end of our study, we can see and conclude that it is very important to exploit the advanced maintenance methods. This will allow with accuracy the knowledge and understanding of the behavior of reliability, and the availability of the equipment studied, without neglecting the advantage of risk control.

The results show that the pump was unreliable with a long repair time, also finding the high risk of the specified failure mode of the impeller.

A maintenance plan was created for the sake of reducing the time to repair and increasing the uptime as a consequence of increasing the reliability and availability of the particular pump by applying the preventive maintenance every systematic time and some remedy of the problems that cause the repair time, this plan also consists a cure for critical failures like redesigning the conditional maintenance for the impeller's failure mode.

Annex 1

n	α 0.01	α 0.05	α 0.1	α 0.15	α 0.2
1	0.995	0.975	0.950	0.925	0.900
2	0.929	0.842	0.776	0.726	0.684
3	0.828	0.708	0.642	0.597	0.565
4	0.733	0.624	0.564	0.525	0.494
5	0.669	0.565	0.510	0.474	0.446
6	0.618	0.521	0.470	0.436	0.410
7	0.577	0.486	0.438	0.405	0.381
8	0.543	0.457	0.411	0.381	0.358
9	0.514	0.432	0.388	0.360	0.339
10	0.490	0.410	0.368	0.342	0.322
11	0.468	0.391	0.352	0.326	0.307
12	0.450	0.375	0.338	0.313	0.295
13	0.433	0.361	0.325	0.302	0.284
14	0.418	0.349	0.314	0.292	0.274
15	0.404	0.338	0.304	0.283	0.266
16	0.392	0.328	0.295	0.274	0.258
17	0.381	0.318	0.286	0.266	0.250
18	0.371	0.309	0.278	0.259	0.244
19	0.363	0.301	0.272	0.252	0.237
20	0.356	0.294	0.264	0.246	0.231
25	0.320	0.270	0.240	0.220	0.210
30	0.290	0.240	0.220	0.200	0.190
35	0.270	0.230	0.210	0.190	0.180
40	0.250	0.210	0.190	0.180	0.170
45	0.240	0.200	0.180	0.170	0.160
50	0.230	0.190	0.170	0.160	0.150
OVER 50	$\frac{1.63}{\sqrt{n}}$	$\frac{1.36}{\sqrt{n}}$	$\frac{1.22}{\sqrt{n}}$	$\frac{1.14}{\sqrt{n}}$	$\frac{1.07}{\sqrt{n}}$

Kolmogorov-Smirnov Table

Annex 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

Weibull law table: reading of parameters A and B

MATLAB commands for obtaining:

Maintainability	Availability
1) clc 2) clear 3) u=0.9388 4) t=0:0.5:8; 5) M=1-exp(-u*t); 6) plot(t,M,'r') 7) grid	1) clc 2) clear 3) u=0.9388 4) h=0.006886 5)t=0:1:10; 6) A=(u/(h+u))+((h/(h+u))*exp(-(h+u)*t)); 7) plot(t,A,'r') 8) grid

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