RELIABILITY ANALYSIS OF A STEAM TURBINE WITH APLICATION OF CONCEPTS OF RELIABILTY CENTERED MAINTENANCE AND LIFE CYCLE COST

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ANÁLISE FIABILÍSTICA DE UMA TURBINA A VAPOR COM APLICAÇÃO DOS CONCEITOS DE *RELIABILITY CENTERED MAINTENANCE* E *LIFE CYCLE COST*

Thesis submitted with the purpose of achieving the Master's degree in Mechanical Engineer, option of Project and Mechanical Construction.

Thesis realized with the orientation and support of the Professor Luís Andrade Ferreira and in partnership with the petrochemical refinery of Matosinhos.

Abstract

This thesis, "Reliability analysis of a steam turbine with the application of the concepts of Reliability Centered Maintenance and Life Cycle Cost", arises as the final part of the Integrated Master's degree in Mechanical Engineering (MIEM) - option of Project and Mechanical Construction (PCM), as final work and it was carried out in partnership with the Petrogal refinery of Matosinhos.

A steam turbine of the manufacturer KUNGNLE, KOPP & KAUSCH Company (currently part of the Siemens group) - model AF 3.5G - TP2302 A / B, that is used to drive a axial pump, is the case study of this thesis.

The ultimate objectives of this work are to obtain the Failure, Mode, Effects, and Criticality Analysis (FMECA), with application of the Reliability Centered Maintenance (RCM), for the components that make up the equipment, and the study of the Life Cycle Cost (LCC), in order to judge if the equipment is still viable or if its replacement is the path to follow.

Resumo

Esta tese, "Reliability analysis of a steam turbine with the application of concepts of Reliability Centered Maintenance and Life Cycle Cost", surge no âmbito do Mestrado Integrado em Engenharia Mecânica (MIEM) - opção de Projecto e Construção Mecânica (PCM), como trabalho final de conclusão de ciclo de estudos e foi realizada em parceria com a refinaria da Petrogal de Matosinhos.

Dos muitos equipamentos em funcionamento na refinaria, foi destinado a objecto de estudo desta tese uma turbina a vapor do fabricante KUNGNLE, KOPP & KAUSCH Company (actualmente parte do grupo Siemens), modelo AF 3.5G – TP2302 A/B e que serve para acionamento de uma bomba axial.

Constituem objectivos últimos deste trabalho a obtenção dos Failure, Mode, Effects, and Criticality Analysis (FMECA), com aplicação do conceito de Reliability Centered Maintenance (RCM), para os componentes que constituem o equipamento, e o estudo do Life Cycle Cost (LCC) para ajuizar se o equipamento é ainda viável ou se a sua substituição é o caminho a seguir.

Abstract

Cette thèse, “Reliability analysis of a steam turbine with the application of the concepts of Reliability Centered Maintenance and Life Cycle Cost” se situe dans le cadre de la Maîtrise Intégrée en Génie Mécanique (MIEM) - option de Projet et Construction Mécanique (PCM), le travail final a été réalisé en partenariat avec la raffinerie Petrogal de Matosinhos.

Une turbine à vapeur du fabricant KUNGNLE, KOPP & KAUSCH Company (actuellement membre du groupe Siemens), modèle AF 3.5G - TP2302 A / B, est utilisée pour l'étude de cette thèse.

Les objectifs finaux de ce travail sont d'obtenir l'analyse des échecs, des modes, des effets et de la critique (FMECA), des composants qui composent l'équipement et de l'étude du coût du cycle de vie (LCC) afin de juger si l'équipement est toujours viable ou si son remplacement est le chemin le plus viable.

Acknowledgments

Primarily, I would like to thank to Professor Luís Andrade Ferreira, my principal supervisor in this thesis, for altruistically devoted is time and gave me the help I needed in the different stages of this work and for is sensibility in our meetings to speak and to treat me as an engineer.

I want to thank to Petrogal, the engineers Carlos Fagundes and Manuel Melo, my co-supervisors, for their experience and the availability in our meetings.

I do not want to forget the enormous patience and kindness of the engineer Hugo Araújo, part of the Petrogal maintenance team as well. Without him it would not be possible to understand in detail the functioning principles of the equipment.

I have to thank to my cousins Fábio Pereira and Ricardo Pereira for giving me the support and friendship that I needed.

I want to thank in a very special way to my girlfriend, Ana Teresa Silva, for helping me in the different stages of this work and for her attention and affect.

Last but not least, I want to thank to my parents, my brother, my sister-in-law and my nephew-in-law, for all the love they give me.

“Yesterday’s home runs don’t win today’s games”,

Babe Ruth.

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List of abbreviations

AMSAA	Army Material Systems Analysis Activity
CBM	Condition Based Maintenance
CFT	Cross Functional Team
CIP	Capital Improvement Program
DFMA	Design For Manufacturing and Assembly
DFMECA	Design FMECA
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
HP	Homogeneous Poisson
LCC	Life Cycle Cost
LCCP	Life Cycle Cost Projection
MLE	Maximum Likelihood Estimation
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MSG	Maintenance Steering Group
NHP	Non Homogeneous Poisson
OLS	Ordinary Least Squares
PD	Product Development
PdM	Predictive Maintenance
PFMECA	Process FMECA
PM	Preventive Maintenance
RCM	Reliability centered maintenance
ROCOF	Rate of Occurrence Failure
RPN	Risk Priority Number
RTF	Run To Failure
RTM	Real Time Monitoring
TBF	Time Between Failure

I Part: theoretical framework

1. Introduction

At least in the past twenty years, maintenance has suffered a great evolution. Due to the exponential increase in the diversity of the industrial equipment, new techniques and methodologies have been developed to manage the assets and at the same time improve the existing ones.

Nowadays, the survival of the companies does not only depend on the economic demands, but also in the manner on they do not affect the environment and the society. There are several legislations to punish the companies that do not attend these expectations.

Along the economic and environment aspects, the necessity to maintain the equipment in normal conditions of operation and to maximize its performance and efficiency, makes today's companies to be more concerned with developing maintenance plans to prevent or to fix some failures. To do that, some techniques are used and in this work it will be followed the Failure, Mode, Effects and Criticality Analysis (FMECA) technique with application of the concepts of Reliability Centered Maintenance (RCM) and Life Cycle Cost (LCC), as well.

It is possible to perform a FMECA attending to two approaches: the reliability approach and the maintenance approach. While the reliability approach concerns with the prevention of failure and the knowhow to make equipment more reliable, the maintenance approach is pointed to fix a failure whenever it occurs. The one adopted here is the maintenance approach (Tahara, 2008).

Key-words: reliability, maintenance, RCM, FMECA, LCC

1.1. Refinery overview

The Petrogal is a petrochemical refinery that is divided in two main factories in Portugal: the refineries of Sines and Matosinhos.

From the Galp data book of 2015, the following image gives a general overview of the refinery:

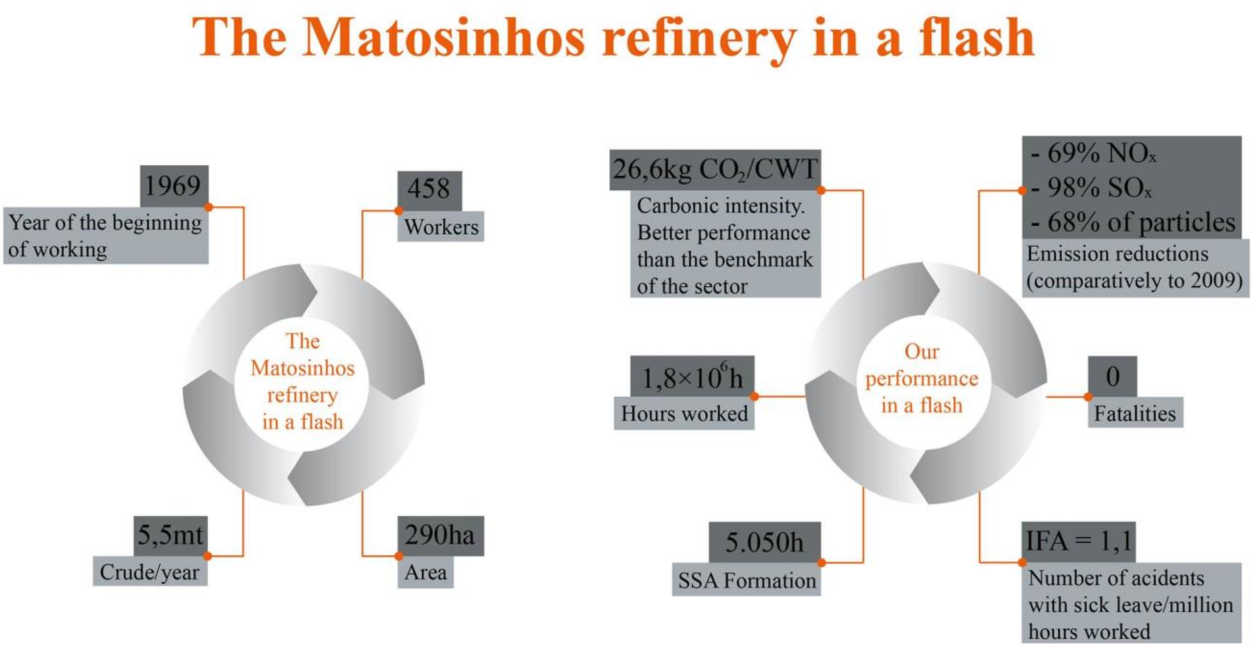

Figure 1 – Overview of the Matosinhos Refinery (Galp data book, 2015)

The Petrogal, or only Galp, is one of the pioneers in the fields of the reliability and maintenance. In fact, they have a department, the Reliability department that is divided in two teams: the reliability and the maintenance teams that work in partnership to prevent failures (reliability team) and to fix them whenever they occur (maintenance team). This department is the one that supported this work in the different levels needed.

1.2. Project goals

The goal of this master thesis is to create a maintenance plan to the equipment, based on the RCM and FMECA methodologies and, ultimately, to judge if the equipment is still viable or became obsolete, by application of concepts of the LCC, as well.

1.3. Structure

This text is divided, basically, in two main parts:

- Part I – theoretical framing

In this part are introduced the concepts of steam turbine and the use of steam to convert thermal in mechanical energy, the RCM, the FMECA and LCC.

- Part II – application of the methodology

The concepts presented in part I are applied to a case study. Also, the results are discussed and some conclusions and future works are presented.

2. Steam turbines

2.1. STEAM AS A POWER SOURCE

"If you must deal with water, first consult the experience and then the reason", Leonardo *Da Vinci*

Throughout history, the use of steam as a power source has boosted industrial advances. Its first use goes back to 200 B.C by a Greek named *Hero* in a simple machine called *aeolipile*. This was the first known machine that used steam as a power source.

It was in the early seventeen century that an Italian inventor named *Giovanni Branca* produced a fluid machine that by channeling the steam to a wheel in rotation caused the wheel to turn due to steam pressure. It was the first thing similar to a steam turbine ever created. Since then, the turbines evolved into mechanisms very sophisticated and even today, with the numerous options available to perform this type of functions, (the electrical equipment as an example) they are used and they are vital for performing some functions in certain fields of the industrial world (Latcovich, 2005).

Figure 2 - Schematic of an Aelolipile (Encyclopaedia Britannica, 2000)

2.2. FLUID MACHINES

Before further considerations, it is important to situate the steam turbines in the main group that they are part of: the fluid machines. So, a steam turbine is a fluid machine, more specifically a thermic machine.

The figure 3 represents the main types of fluid machines and the distinction of colors, blue or orange, it is not random: it represents the processes that are made with no variation of pressure - in the case of the blue ones, and with variation of pressure - in the case of the orange ones.

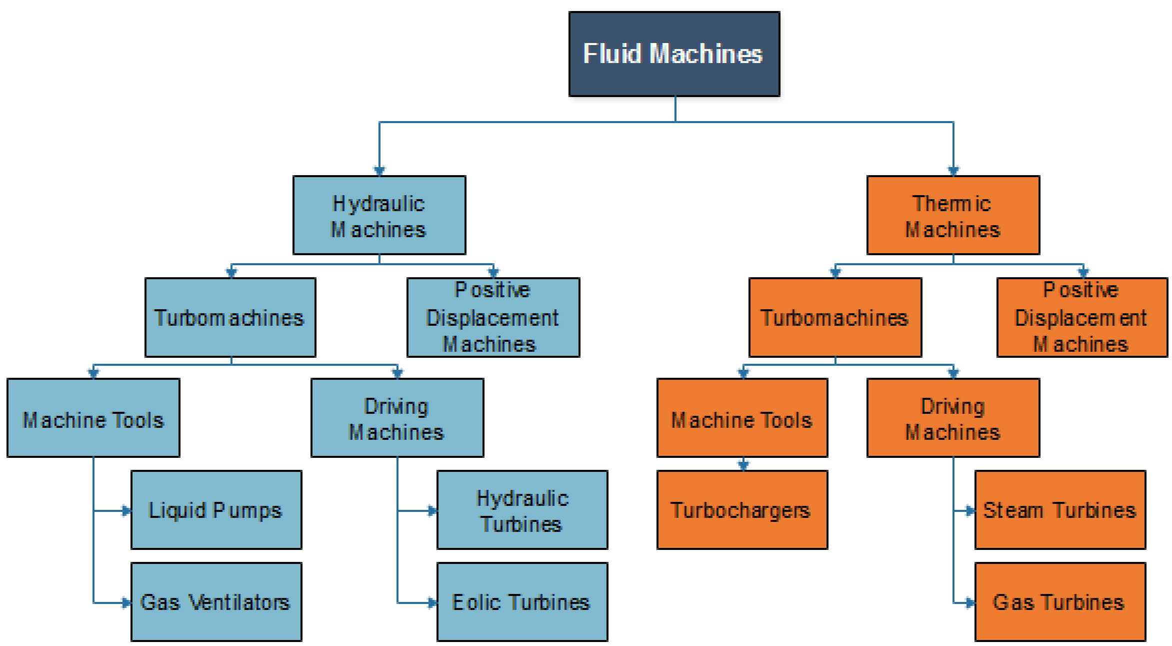

Figure 3 - Fluid Machines.

2.3. STEAM TURBINE DEFINITION

A steam turbine is a mechanical device that extracts thermal energy from pressurized steam and transforms it into mechanical work, which may subsequently be converted into electrical energy.

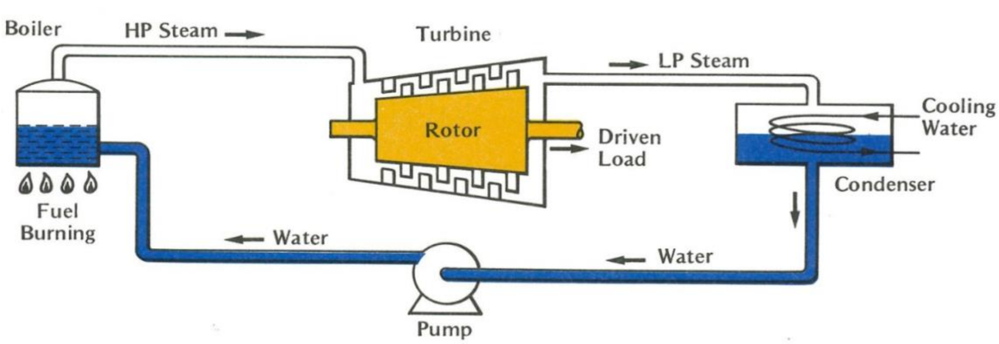

Figure 4 - Schematic of steam turbine system (Student Energy, 2010).

There are two main types of steam turbines:

- **Impulse:** the rotating blades are like deep buckets. High-velocity jets of incoming steam from carefully shaped nozzles kick into the blades, pushing them around with a series of impulses, and bouncing off to the other side with a similar pressure but much-reduced velocity.

- **Reaction:** there are two sets of blades; the additional one here is stationary and it is attached to the inside of the casing. This leads to a speed increase and helps to direct the steam onto the rotating blades at just the right angle, before the steam dissipates with reduced temperature and pressure (Fukui Seisakusho CO., LTD, 2004), (Babcock and Wilcox Company, 2005).

2.3.1. APPLICATIONS

The main applications of these steam turbines are:

- Power generation;
- Petrochemical refineries;
- Pharmaceuticals;
- Food processing;
- Petroleum/gas processing;
- Paper mills;
- Sugar industry;
- Waste-to-energy.

2.3.2. TYPES OF STEAM TURBINES

According to the norm ISO_14224_2006 (E), the steam turbines can be divided in two classes relatively to how many stages the steam circuit has:

Table 1 - Type classification - Steam turbines ISO_14224_2006 (E).

Equipment class – Level 6		**Equipment type**	
Description	Code	Description	Code
Steam turbines	ST	Multi-stage	MS
		Single-stage	SS

These turbines can be divided also in two other classes that differ in the expander that the turbine activates:

Table 2 - Type classification – Turboexpanders.

Equipment class – Level 6		**Equipment type**	
Description	Code	Description	Code
Turboexpander	TE	Centrifugal	CE
		Axial	AX

The two most widely used steam turbine types are the reaction turbine and the pressure-compounded or the so called Rateau turbine. The high pressure part for both types consists of a simple or two-stage velocity-wheel, depending on the live steam conditions at the turbine entry. The impulse stage, known as the governing stage, is generally applicable since it alone permits partial steam admission to the moving wheel.

There is no better steam turbine than the other; both types have their own vantages and limitations (Termuehlen, H., and Emsperger, W. (2003)).

2.3.3. Turbine failures

The causes of failure divide into two groups: those inherent in the design or in the material used in the construction of the turbine, and those which are related to the operating conditions. Some of the former are inter-related to some of the latter; for instance, blade erosion might be due to unsuitable material or to bad steam conditions.

The causes of failure inherent in design and materials of construction may be classified as follows:

- shaft vibration;
- disc vibration;
- blade vibration;
- faults in machining;
- incorrect design of casing;
- faulty arrangement of steam pipes, causing distortion of the casing;
- materials of construction (Termuehlen, H., and Emsperger, W. (2003)).

2.3.4. TYPICAL COMPONENTS OF A STEAM TURBINE

The typical components of a steam turbine and a generic way to divide the system are shown in the figure bellow:

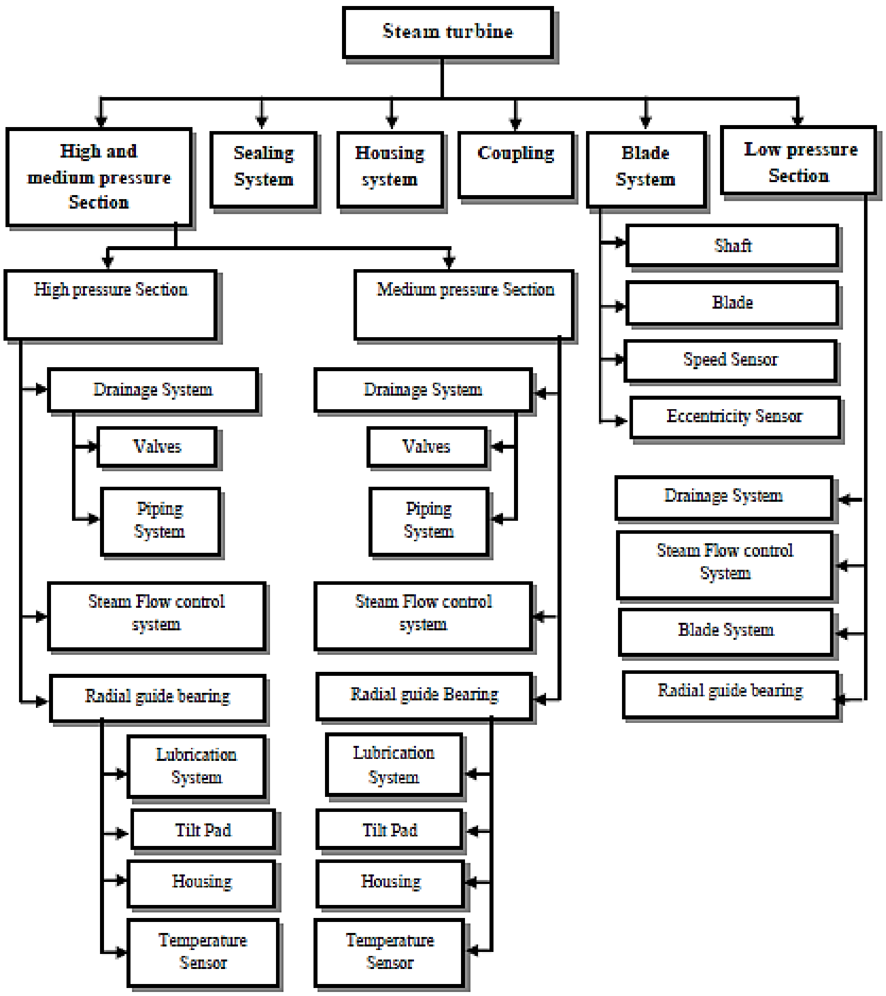

Figure 5 – Typical Components of a Steam Turbine (TERMUEHLEN, H., AND EMSPERGER, W. (2003)).

3. Reliability and maintenance

According with the norm EN 13306:2010 (ed.2), maintenance can be defined as the combination of all the techniques, administrative and management, during a life cycle of a material asset, with the purpose of maintain or replace it in a state that it can perform the desired function.

The world of industrial maintenance has been suffering several changes in the past twenty years as the industries begin to value the importance of maintenance and how their lack can affect the normal performance of the equipment.

These changes are due to a big increase in the number and variety of physical assets; which must be maintained in normal operation and to do so new maintenance techniques and changing views have been applied, leading to push to the limits the skills and attitudes of the maintenance workers who must adopt new ways of thinking and acting.

Facing this entire avalanche of change, a new approach to maintenance has been developed. This modern approach seeks a "*strategic framework which synthesizes the new developments into a coherent pattern, so that they can evaluate them sensibly and apply those likely to be of most value to them and their companies*" (Moubray, 1997).

There are various methodologies to provide such a framework. In this work, it will be approached three different, but complement views: the Failure Mode and Effects Analysis (FMEA), the Failure Modes, Effects and Criticality Analysis (FMECA), which is an extension of FMEA, and the Reliability Centered Maintenance (RCM).

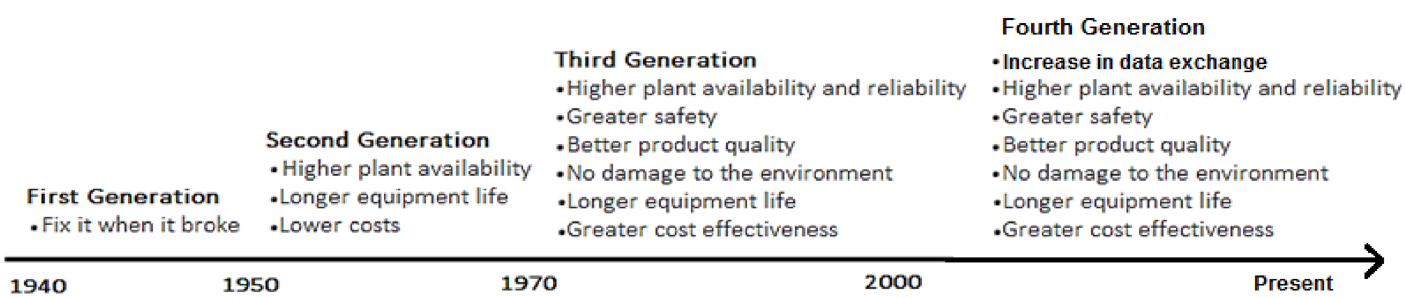

Figure 6 - Increasing Expectations of Maintenance (Moubray, 1997).

3.1. FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

3.1.1. INTRODUCTION TO FMECA

Failure Mode, Effects, and Criticality Analysis (FMECA) consists in a disciplined method of product or process analysis to identify potential failures that could affect the expectations of customers for a product quality or process performance. It is an extension of Failure Mode Effects Analysis (FMEA), performed to study the criticality of the equipment. When correctly applied, FMECA permits to anticipate failure during the design stage by identifying all of the possible failure modes in a design or manufacturing process.

Is first use goes back to early 1950s in the aerospace industries, when it was required more complex and sophisticated flight control systems. Today, it is still a highly effective and very used method of lowering the possibility of failure.

Although this methodology is inherently simple, its application is frequently misunderstood and consequently the organizations and companies using it do not profit the enormous benefits that can result from this type of analysis. The problem here is that many companies and organizations see this tool as a secondary and normally delegate this task to a small group of engineers (in many occasions only one) and forget the importance of keep in contact the people that applies this technique and the people who understand the product or process being studied (Mills, 2012).

3.1.2. FMECA AND HOW IT WORKS

As already introduced in the previous section, Failure Mode, Effects and Criticality Analysis (FMECA) is a structured approach to discovering potential failures that may exist within the design of a product or process.

But what are the so called failure modes? And effects?

- The failure modes are the ways in which a process can fail.
- Effects are the ways that these failures can lead to waste, defects or harmful outcomes for the customer. Failure Mode and Effects Analysis is designed to identify, prioritize and limit these failure modes.

It is important to perceive that FMECA is not a substitute for good engineering. Rather, it boosts good engineering by applying the knowledge and experience of a Cross Functional Team (CFT) – team specialized in equipment's reliable- to review the design progress of a product or process by assessing its risk of failure (He, C. and Gu, Y.,2011).

There are two main types of FMECA: the **design FMECA (DFMECA)** and the **process FMECA (PFMECA)**. They will be both described in the following section.

3.1.2.1. DESIGN FMECA

Design FMECA (DFMECA) explores the possibility of product malfunctions, reduced product life, and safety and regulatory concerns derived from:

- material properties;
- geometry;
- tolerances;
- interfaces with other components and/or systems;
- engineering noise derived from environments, user profile, degradation and systems interactions.

3.1.2.2. PROCESS FMECA

Process FMECA (PFMECA) discovers failure that impacts product quality, reduced reliability of the process, customer dissatisfaction, and safety or environmental hazards derived from:

- human factors;
- methods followed while processing;
- materials used;
- machines utilized;
- measurement systems impact on acceptance;
- environment factors on process performance.

3.1.3. WHY TO PERFORM FMECA

Generally, the sooner a failure is discovered, the less it will be the costs associated. If a failure is discovered late in product development or launch, the impact is exponentially more devastating.

FMECA is one of many tools used to discover failure at its earliest possible point in product or process design. Discovering a failure early in **Product Development (PD)** using FMECA provides the benefits of:

- Multiple choices for Mitigating the Risk.
- Higher capability of Verification and Validation of changes.
- Collaboration between design of the product and process.
- Lower cost solutions.

Ultimately, this methodology is effective at identifying and correcting process failures at early stages, so that companies and organizations can avoid the drastic possible consequences of poor performance.

3.1.4. When to Perform FMECA

FMECA normally is performed when:

- designing a new product, process or service;
- planning on performing an existing process in a different way;
- a quality improvement goal for a specific process;
- need to understand the failures and improve the process.

In addition, it is advisable to perform a FMECA occasionally throughout the lifetime of a process or equipment in order to verify the performance and the levels of reliability.

3.1.5. How to Perform a FMECA

According to Brumbach, M.E. and Clade, J.A. (2013), the conduct of FMECA is a step-wise, well organized, iterative process which is defined in the following sections.

- **Learn about the design**

Independently of the knowledge of the people who make the FMECA, it is important to first understand the product or process and his key characteristics, avoiding the normal temptation to rush into analysis without knowing well the case in study.

- **Set the level of the analysis**

Normally, the application of FMECA is started at higher levels of product. This means that if the case in study is a system that can be divided in sub-systems and these sub-systems can be ramified too, it is better to commence the process at higher levels and then to lower to the levels below. By this way, the people that are applying the FMECA can understand better not only the equipment, but also how he can fail.

To do this type of analysis is convenient to draw a diagram similar to the one that is show in the Figure 7 and as the analysis proceed, it is possible to found at which sub-system the failure occurred and then continue only on that ramification of the diagram to find the origin of the failure. If in the analysis it is found that the majority of the serious problems occurred in one of the sub-systems, the priority of further analysis can be placed in that sub-system.

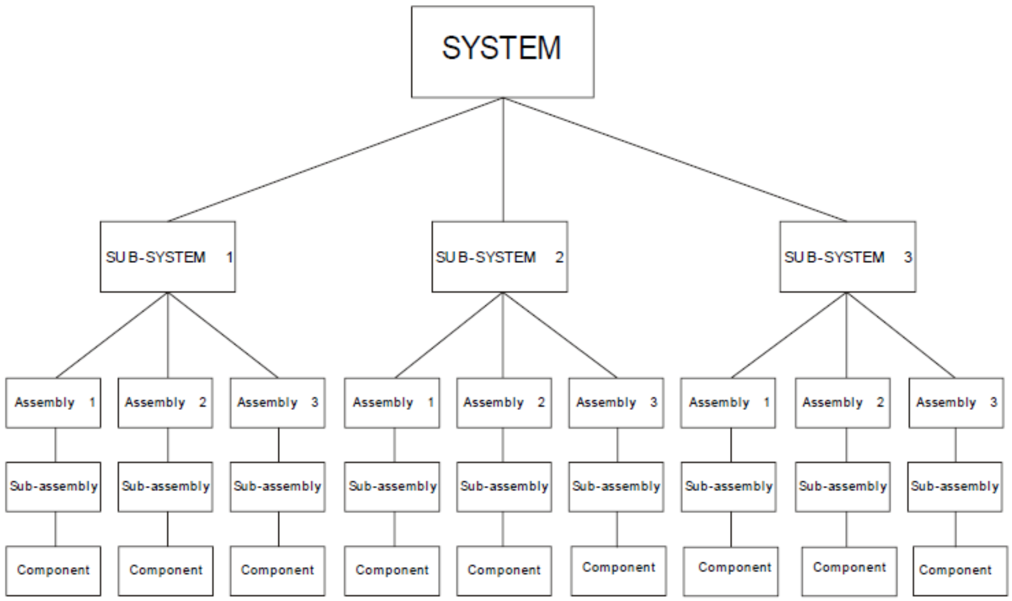

Figure 7 - System Break Down (Mills, 2012)

- **Describe the desired functions**

The goal is to find how the product can fail, but before considering that it is important to fully understand its functions. This can be done with brainstorming. If there is a team involved in the application of a FMECA, the exchange of impressions by the members of different areas is vital.

- **Review and rationalize the functions**

At this point, it is the opportunity to review the possible duplications and to ensure that the ideas of functions and features are well separated, because is distinction is not always clear. In consequence, it is important to state the difference and perhaps the easiest way is saying that a function employs the active verb, like “to cool the turbine”, and a feature the passive, like “to be clean”. If this step is controversial, it can be postponed in favor of the continuity of the process.

- **List all potential failure modes**

In contraire of simply put the potential failure modes as the function is not reached or the component is working defect, it is wise to brainstorming the case in study to list all the potential failures and in the end to verify that the inverse of the functions are included in the list of the potential failure modes.

- **Describe the potential effects of each failure**

Once the potential failure modes are listed, it must be described how they can affect the system. The task it is not simply to describe the potential effects on the level that is analyzed, but the potential effects in the whole system. For example, in a steam turbine if the cooler is not working correctly the immediate potential failure it will be that the oil is at a temperature different from the normal conditions, but if the oil is at a different temperature from it is required it cannot lubricate like it is pretended and the components will be suffering more detrition.

- **Describe the potential causes of each failure**

It is not enough to detect the failure and even to describe its potential effects; it should be identified all the potential causes of the failure modes too in order to eliminate or minimize the probability of occurrence.

- **Describe the current controls (if they exist)**

Describe the controls that at present exist which will prevent or at least detect the causes of failure. It is not a task to describe the wanted or future expected controls, but the current and existence controls.

- **Assess criticality**

Using literature guidelines that are suitable for the case in study score the severity, occurrence and detection ratings and multiply these together to give the index severity, (Moubray, 1997), or the normally called Risk Priority Number (RPN). Then it is possible to draw a pareto plot for the causes of failure and the priority for corrective actions.

- **Take corrective action**

The knowledge gained in the process analysis of how the system can fail is the value gained from the application of the FMECA. In the worksheet, the columns allocated for the corrective actions have to describe the agreed corrective actions, its responsibility and the date when the action was finished. Parallel to the completion details that enter in the corrective actions it is wise and advisable to re-score the RPN to reflect the improvements made.

- **Standardize the actions taken**

It is important to assess how the information gained by the application of this technique can be applied elsewhere in the organization. The cost/benefit of any analysis is significantly increased if it can be used multiple times. Furthermore, the FMECA is an active document for any company or organization that once is done it remains for the subject product/process that had been studied and even to another similar products/process.

3.1.6. FMECA APPLICATIONS

The conduct of FMECA requires an investment of time and human resources, but the analysis can be used to solve many issues that concern the today's companies and organizations. Its key application is to:

- identify failures that have unwanted or significant effects; to determine the failure modes that may seriously affect the expected or required quality of a product/process;
- identify safety danger and liability problem areas, or non-compliance with regulations;
- identify key areas in which to control the process and, where appropriate, place inspection and manufacturing controls;
- focus development testing on areas of greatest need;
- maintenance planning;

- provide a systematic and rigorous study of the process and its environment that will almost always improve our understanding of how the process might fail;
- the design of built-in-test and failure indications;
- preparation of diagnostic flowcharts or faultfinding tables;
- identify lacks in operator and supervisor training and practices.

3.1.7. Benefits of FMECA

According with the norm ISO 9001:1997, among the various benefits of FMECA, it is important to mention the following:

- It helps communication between the different participants during the concept and design stages of a product/process. By bring closer engineers, designers, workers and all the people involved at the analysis, assists to accomplish a good environment at work.
- It is a live document that improves knowledge and understanding of how a process or equipment works and it will serve to future possible analysis since it remains to provide corporate memory.
- When the analysis is conducted rigorously, it will reduce the total time required to design and develop a product/process and help to ensure that requirements are met at first entry to service.
- It provides proof of the extent of care that has been taken to ensure that the product will meet the needs and expectations of the customer in service.
- It assists the company or organization to act attending like it is oriented by the analysis conducted and to take the correspondent corrective action when and where they were appropriate.

3.2. RELIABILITY CENTERED MAINTENANCE (RCM)

3.2.1. INTRODUCTION TO RCM

Reliability Centered Maintenance (RCM) is the process that determines the most effective maintenance approach. Originated in the Airline industry in late 1960's, the first application of this technique was made by the 747 Maintenance Steering Group (MSG) and the purpose was to answer to the high costs spend in the maintenance tasks.

The analysis provides a structured framework for analyzing the functions and potential failures for a physical asset (such as an airplane, a manufacturing production line, turbines, etc.) with a focus on protecting system functions, rather than protecting equipment. The RCM philosophy employs Preventive Maintenance (PM), Predictive Maintenance (PdM), Real-time Monitoring (RTM), Run-to-failure or Reactive Maintenance (RTF) and Proactive Maintenance techniques that are used to increase the probability that reducing to a minimum of maintenance, the machine or component keeps functioning like it is required over its life cycle in an efficient and cost-effective manner, with an acceptable level of risk (Moubray, 2012).

3.2.2. WHAT RCM PURSUES

As have been said previously, the today's expectations for maintenance are very ambitious. As stated by Nowlan and Heap (1978), the RCM objectives are:

- ✓ Ensure the accomplishment of safety and reliability levels of the equipment.
- ✓ Whenever deterioration occurs at the equipment, restore these levels.
- ✓ Give feedback for design improvement of the components that have inadequate and/or insufficient levels of reliability.
- ✓ Fulfill these goals at a minimum total cost, when total cost englobes maintenance costs, assistance costs and the costs associated with loses by operational failures or production stops.

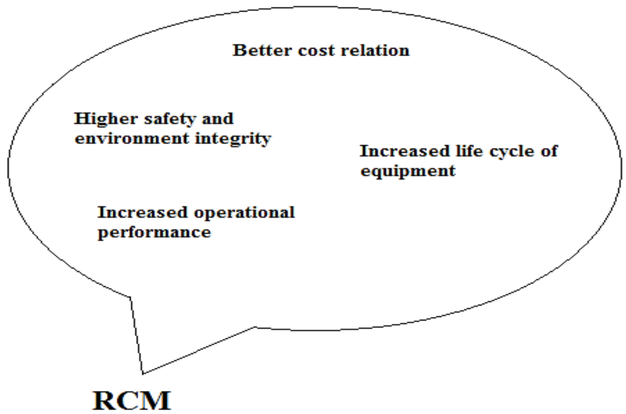

Figure 8 - RCM Goals.

3.2.3. RCM PRINCIPLES

According to the High Technology for the Producers, Distributors and Users of Electric Power (2009), the RCM principles are:

- **Functioned Oriented**

Beyond the operability, it pursues to preserve the equipment or system and its functions. It is considered the balance between the redundancy of equipment, which increases the reliability, and the life cycle costs.

- **System focused**

The goal is to maintain the whole system performing like it is required and not the individual components.

- **Reliability centered**

Have concerns in the relationship between operating age and the failures. It is not a statistic tool, overly concerned with failure rate; it goes beyond and seeks to find the probability of failure in the different ages of the life cycle.

- **Acknowledges design limitations**

RCM have the objective to maintain the reliability of the equipment design. This methodology recognizes that maintenance can, at best, achieve and maintain the level of reliability for the equipment, which is provided by design.

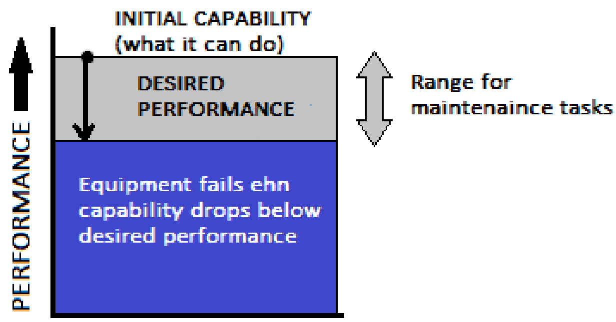

Figure 9 – Desired Performance For An Asset (Moubray, 1997).

- **Driven by safety and economics**

First the priority is to safeguard people and only after the cost-effectiveness.

- **Defines failure as any unsatisfactory condition**

Failure may be either a loss of function and the operation stops, or a loss of required capability and the operation continues at a lower level of performance.

- **Uses a logic tree to guide for maintenance tasks**

This is the guideline to any consistent approach to the maintenance of all kinds of equipment.

As Moubray (1997) stated, the logic tree may be posted like the figure 10.

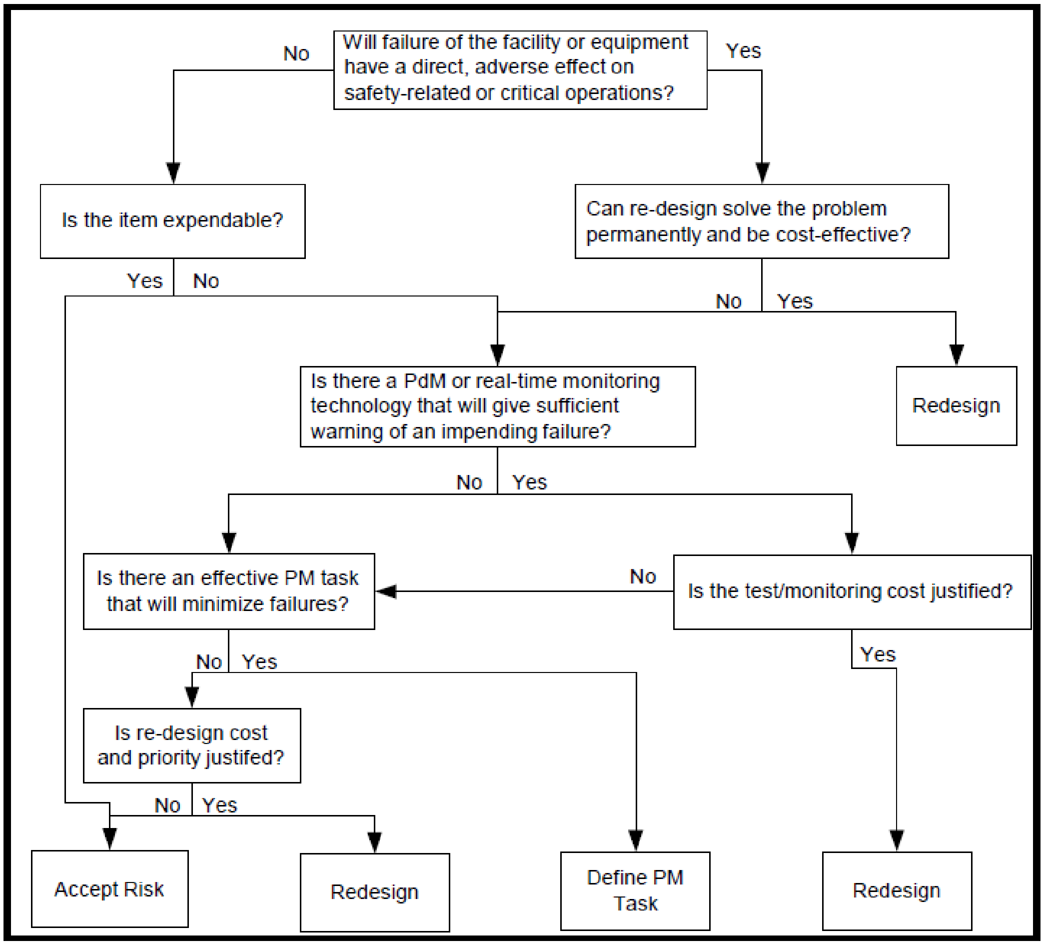

Figure 10 - RCM Logic Tree (BABCOCK AND WILCOX COMPANY, 2005).

- **Tasks must be applicable**

The tasks must correspond and be applicable to the different failure modes.

- **Tasks must be effective**

The tasks must be effective and serve to reduce the probability of occurrence of failure attending to the costs as well.

- **Acknowledges three type of maintenance tasks**

✓ Scheduled and programmed maintenance – Time-directed (PM)

✓ Maintenance performed when it is required by means of real-time monitoring – Condition-directed (PdM)

- ✓ Let the equipment run until failure. It may be convenient in certain occasions, depending on the type of equipment or the specific situation – Failure Finding (Proactive Maintenance)

- **Living system**

It engages data from the results obtained in the analysis and feed it back to permit redesign and future maintenance. This feedback is responsible for improving performance of equipment and processes.

3.2.4. Questions of RCM

According with what have been proposed by Moubray (1997) and the posted in the standard norm SAE JA1011, which describes the minimum criteria that a process must comply with to be called "RCM," a Reliability Centered Maintenance Process answers the following questions:

1. What are the functions and associated desired standards of performance of the asset in its present operating context **(functions)**?
2. In what ways can it fail to fulfil its functions **(functional failures)**?
3. What causes each functional failure **(failure modes)**?
4. What happens when each failure occurs **(failure effects)**?
5. In what way does each failure matter **(failure consequences)**?
6. What should be done to predict or prevent each failure **(proactive tasks and task intervals)**?
7. What should be done if a suitable proactive task cannot be found **(default actions)**?
8. What is the function of risk associated with each failure **(function of risk)**?

Although there is a great deal of variation in the application of RCM, most procedures include some or all of the following steps.

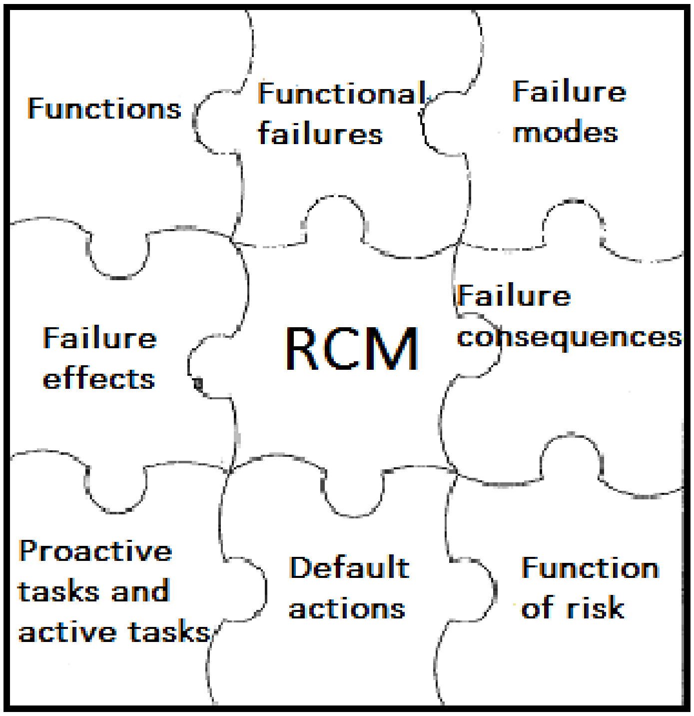

Figure 11 - The RCM Puzzle (Nuno Silva, 2000).

3.2.5. THE EQUIPMENT AND THE ANALYSIS

To perform a RCM analysis it is required the investment of time and resources and the company or organization may wish to focus the analysis resources on determined components of the equipment. To do that, safety and economic concerns emerge as two main methods help to analyze as follows:

- **Selection Questions:** consist of a set of Yes/No questions that are designed to identify whether RCM analysis is indicated for a particular piece of equipment or not.

- **Criticality Factors**: consists of a set of factors designed to evaluate the criticality of the equipment in terms of safety, maintenance, operations, environmental impact, and other operational concerns. To each factor is attributed a value according to a pre-defined scale where higher rating values correspond to higher criticality.

There are other methods, such as Pareto analysis of equipment based on downtime, and many others. Whichever method (or multiple methods) is selected, the goal is to focus RCM analysis resources on the equipment that will provide the maximum benefit to the organization in terms of safety, legal, operational, economic and related priorities.

3.2.6. Select Maintenance Tasks

Once the functions that are required from equipment have been identified, the ways that it might fail to perform those intended functions and evaluated the consequences of these failures; the next step is to define the appropriate maintenance strategy for the equipment. The RCM analysis team's decision of which strategy (s) to employ for each potential failure may be based on judgment/experience, a pre-defined logic diagram (connected to the failure effect categorization), cost comparisons or some combination of factors (Silva, N.M.F.O., 2000).

Many RCM guidelines include task selection logic diagrams based on the Failure Effect Categorization. When safety is not an issue, another is to compare normalized cost values for the available maintenance strategies and select the maintenance task that provides the desired level of availability for the minimum cost. For example, if the cost per uptime of performing corrective maintenance only (run to failure) is less than the cost per uptime of performing a scheduled repair/replacement, and the run to failure approach provides an acceptable level of equipment availability (uptime), then the team may recommend no scheduled maintenance tasks for the equipment.

3.2.7. Maintenance Packaging

Once the appropriate schedule maintenance tasks have been identified, the final step is to package them into a workable maintenance plan. This may involve choosing time intervals at which groups of tasks can be carried out most effectively and efficiently (Brumbach, M.E. and Clade, J.A., 2013).

3.2.8. RCM outcomes

According to what have been stated by Nuno Silva (2000), at the end of a RCM analysis there are four possible outcomes:

- **Perform no Maintenance (RTF)**

This is denoted as Reactive Maintenance and it is letting the equipment Run-Ro-Fail (RTF) and repair, fix-on-fail. This approach assumes equal probability of occurrence of failure for any part of the equipment and that when a failure exists it is not detrimental to the normal operation. Associated with this type of maintenance are normally high failure rates, excessive amounts of overtime and large parts inventories and high costs.

- **Perform Preventive Maintenance (PM)**

This type of maintenance consists of regularly scheduled inspections and it is a based on programed intervals for doing some operations at the equipment like adjustments, verification of tolerances in gaps, cleanings, lubrication and regulation, and even replacement of components. It is performed independently of the equipment condition as it may be good or bad. Although the apparently lot of advantages of this type of maintenance, recent studies proved that a PM program can result in a significant increase in time and costs dispensed without any increase in reliability.

- **Perform Condition Based Maintenance (CBM)**

Contrary to the PM, CBM consists of Predictive Maintenance and real-time monitoring and uses non-intrusive tests to evaluate the performance of the equipment. Maintenance only is performed if the result of the test indicates that the performance of the equipment is suffering a breaking. Real-Time-Monitoring (RTM) uses current performance data to measure machinery condition. This continuing analysis of equipment condition permits to save time and monetary resources and prioritize and scheduling maintenance or repairs to the components that are more susceptible to failure.

- **Redesign**

This is the ultimate action and only it is performed when the failure of a system or piece of equipment is an unacceptable risk and none of the above maintenance tasks can help mitigates the failure. It consists in a redesign of the component to improve is reliability. One way to go when this is the conclusion taken from the analysis is to add redundancy by adding another equipment or piece of equipment, reducing this mode the risk and adding little costs to the overall maintenance costs.

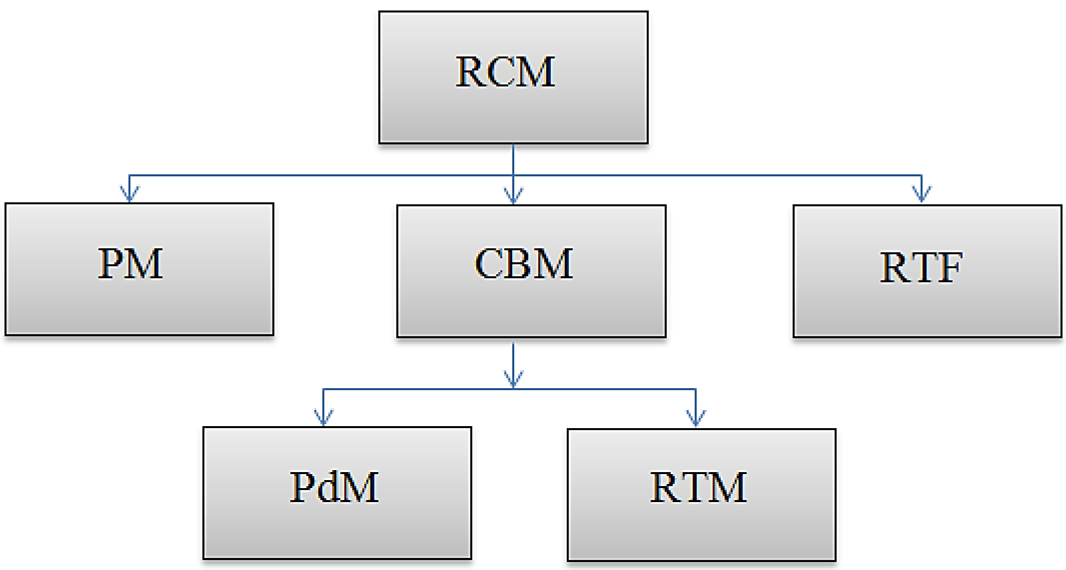

Figure 12 - Elements of RCM.

3.3. Life Cycle Cost (LCC)

3.3.1. INTRODUCTION

It is vital for today's companies to know, precisely, how much they expend and how can they save more money, maintaining their processes and activities in order to compete in the industrial world. So, owners, users and managers need to make decisions on the acquisition and ongoing use of the different assets including items of equipment and the facilities to house them.

The initial capital outlay cost is usually clearly defined and is often a key factor influencing the choice of asset when given a number of alternatives from which to select.

The initial capital outlay cost is, however, only a portion of the costs over an asset's life cycle that needs to be considered in making the right choice for asset investment. The process of identifying and documenting all the costs involved over the life of an asset is known as Life Cycle Costing (LCC).

According with the norm ISO 55000:2014 and the PAS 55-1:2008/PAS 55-2:2008 (Publicly Available Specification), British norms about Asset Management, Rui Assis (2012) stated that it is important to the organizations to develop,

"systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and assets systems, their associated performance, risks and expenditures "over their life cycles for the purpose of achieving its organizational strategic plan, understood as "overall long-term plan for the organization that is derived from, and embodies, its vision, mission, values, business policies, stakeholder requirements, objectives and the management of its risk""

The total cost of ownership of an asset is often far greater than the initial capital outlay cost and can vary significantly between different alternative solutions to a given operational need. Consideration of the costs over the whole life of an asset provides a sound basis for decision-making. With this information, it is possible to:

- Assess future resource requirements (through projection of projected itemized line item costs for relevant assets);
- Assess comparative costs of potential acquisitions (investment evaluation or appraisal);
- Decide between sources of supply (source selection);
- Account for resources used now or in the past (reporting and auditing);
- Improve system design (through improved understanding of input trends such as manpower and utilities over the expected life cycle);
- Optimize operational and maintenance support; through more detailed understanding of input requirements over the expected life cycle)
- Assess when assets reach the end of their economic life and if renewal is required (through understanding of changes in input requirements such as manpower, chemicals, and utilities as the asset ages).

The Life Cycle Costing process can be as simple as a table of expected annual costs or it can be a complex (computerized) model that allows for the creation of scenarios based on assumptions about future cost drivers. The scope and complexity of the life cycle cost analysis should generally reflect the complexity of the assets under investigation, the ability to predict future costs and the significance of the future costs to the decision being made by the organization.

3.3.2. PHYSICAL ASSETS AND LIFE CYCLE

Before further considerations it is important to define some concepts crucial to understanding a life cycle cost analysis:

- **Physical asset** – is anything that as real value or potential to an organization (plants, installations, equipment's, assets, buildings, vehicles, etc.).
- **Life of the asset** – is the period between the identification that an asset is necessary until the deactivation of the asset or any posterior responsibilities with it. The life cycle of an asset not necessarily end when it is retired from its function or even discarded.

- **Life cycle** – englobes all the stages in the management of an asset. It is not absolutely in a manner that the analysis of the life cycle is susceptible and can vary from organization to organization.
- **Useful life** – it is the life of equipment and the limit beyond its operability it is not reasonable since the wear and tear is too much to do any repair (Water Research Foundation, 2011).
- **Technologic life (obsoletely)** – even if, theoretical, it is possible to perform reparation on an equipment in order to maintain it work, it become obsolete and keeping it turned impracticable.
- **Economical life (operability cost)** – a system may be yet functional, but had become much expensive its continuity (high cost of reparation or maintenance).
- **Politics –** intentions and the direction of a company or organization as formally expressed and dictated by its board administration.
- **Process** – group of activities inter-related or interactive that transforms the products.
- **Strategic –** goals of a company or an organization, programs that are chosen to get there and the pattern to allocate the resources (Water Research Foundation, 2011)).

Figure 13 – LCC overview.

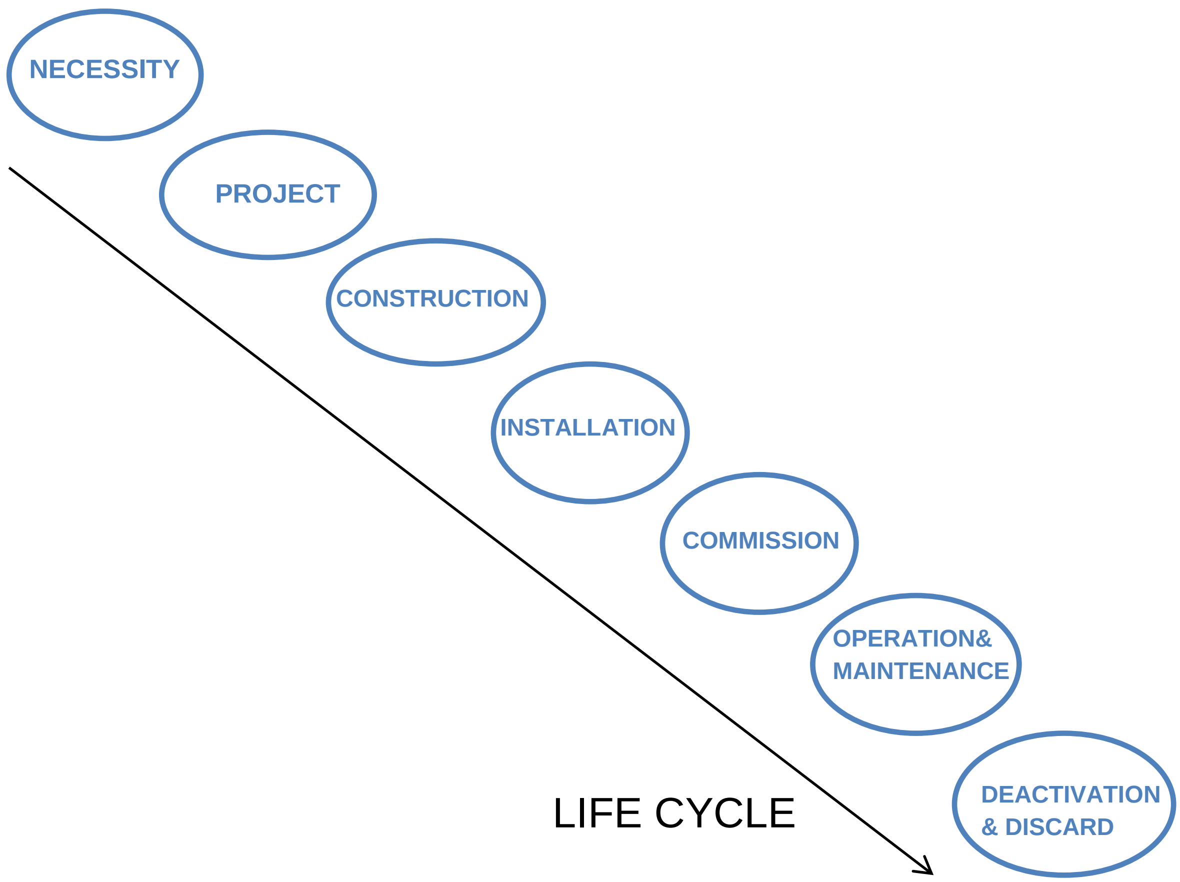

Figure 14 – The Life Cycle of an asset.

3.3.3. Life cycle cost analysis

A life cycle cost analysis involves the balance of every costs that are inherent of a component or a system over is entire life cycle. Typically the total costs are evaluated in the so called Life Cycle Cost Projection (LCCP) and may include:

- **Acquisition costs** (or design and development costs).

- **Operating costs:**
  - Cost of failures
  - Cost of repairs
  - Cost for spares
  - Downtime costs
  - Loss of production

- **Maintenance costs:**
  - Cost of corrective maintenance
  - Cost of preventive maintenance
  - Cost for predictive maintenance

- **Disposal costs**.

- **Other costs** (such as depreciation or present value of money, etc.).

For the purpose of LCCP if all costs are known, then the analysis is as simple as summation the different costs for several options computing the discount rates. With respect to the cost inputs for such an analysis, the costs involved are either deterministic (such as acquisition costs, disposal costs, etc.) or probabilistic (such as cost of failures, repairs, spares, downtime, etc.). Most of the probabilistic costs are directly related to the reliability and maintainability characteristics of the system.

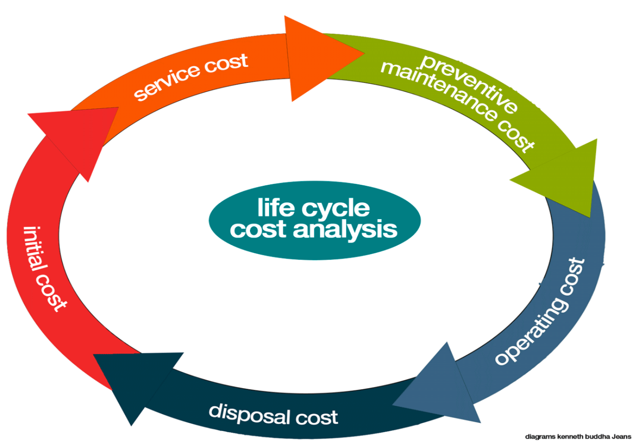

Figure 15 – Life Cycle Cost analysis, (Kenneth Jeans, 2008).

3.3.4. LCC METHODOLOGY

According to Water Research Foundation (2011), the life cycle of an asset is described as the time interval between the initial planning for the creation of an asset and its final disposal and it can be defined by the following steps:

- definition of the initial concept;
- delineation of the design requirements, specifications and documentation;
- construction, manufacture or purchase;
- certificated period and early stages of usage or occupation;
- period of usage and functional support, with operational and maintenance costs, along the associated series of upgrades and renewal;
- the disposal and cleanup at the end of the useful life of the asset.

As demonstrated in Figure 14 and in the Figure 15, there are constantly, periodic and strategic activities that may occur for any asset. The asset life cycle begins with strategic planning, creation of the asset, operations, maintenance, rehabilitation, and on through decommissioning and disposal at the end of the assets life. An asset's life will be influenced by its ability to continue to offer a required level of service. Before they become non-functional (regulations change, the asset becomes non-economic, the expected level of service increases, and capacity requirements exceed design capability), many assets reach the end of their effective life.

The key factors that affect the effective life of an asset are the technological developments and the changes in requirements of the user.

Objectives of the Methodology

The analysis of the Life cycle cost can be accomplished during any phase of an asset's life cycle.

The life cycle costing objectives are:

- To minimize the total cost of possession of the utility's infrastructure to its customers giving them an uninterrupted performance;

- Support management considerations that affect decisions during any life-cycle phase;
- Identify the attributes of the asset which significantly influence the Life Cycle Cost drivers so that the assets can be effectively managed;
- Classify the cash flow requirements for projects.

Minimizing Life Cycle Costs with the Impact of Analysis Timing

An extensive portion of projected life cycle costs arises from the consequences of decisions made during the early phases of asset planning and conceptual design.

The definition of operations and maintenance requirements, and setting of the operating context of the asset are the early decisions made during the design of an asset that commit a large fraction of the life cycle costs for that asset.

The level of cost reduction can be reached at various stages of the project. As a project moves from strategic planning that the lager part of decisions have been made that deliver the majority of the cost to the project.

During the early concept development and design phase of any project occur the best opportunities to achieve significant cost reductions in life cycle costs. At this time, significant changes can be made for the least cost. At later stages of the project many costs have become “closed” and are not easily changed. To accomplish the maximum benefit available during this stage of the project it is important to analyze the following:

- A range of alternative solutions;
- The cost drivers for each alternative;
- The time for which the asset will be required;
- The level and frequency of usage;
- The maintenance and/or operating arrangements and costs;
- Quantification of future cash flows;
- Quantification of risk.

A framework to document and compare alternatives can be realized by the concept of the life cycle of an asset that is provided.

Potential outcomes from the analysis

From a LCC analysis it is possible to considerate the following situations as a way to proceed relatively to the asset:

- **Do-nothing** - The Do-Nothing option is not investing any money on any form of maintenance or renewal.

- **Status Quo** - The Status Quo option is defined as maintaining the current operations and maintenance behavior – typically that defined by the manufacturer or the design engineer. It is the realistic baseline case against which other alternatives are compared.

- **Renewal (Major Repair, Rehabilitation or Replacement)** - Assessment of different rehabilitation or replacement strategies requires an understanding of the costs and longevity of different asset intervention strategies. Each strategy is costed for the expected life of that strategy, converted to an equivalent present worth, adjusted for varying alternative life lengths, and compared to find the least overall cost.

- **Non-Asset Solutions** - In certain circumstances the non-asset solution (providing the same level of service without a major additional investment) can be a viable alternative.

- **Change Levels of Service** - Most life cycles costing assumes a constant Level of Service across options being compared. When such is not the case (which is not infrequent in reality), comparisons across alternatives with different levels of service (that is, different levels of benefit) must introduce a projected benefits section for each alternative in addition to the cost projections.

- **Dispose** - Disposal of the asset is retiring the asset at the end of its useful life. Perhaps the function or level of service originally desired from the asset is no longer relevant.

The Effect of Intervention

A single intervention option for the entire life cycle is not likely to be the best approach to maximizing the life extension for an asset. Multiple strategies and options will need to be studied to determine the optimal strategy or combination of strategies for maximum life extension.

Optimal Renewal Decision Making uses life cycle cost analysis as a core Tool for determining the optimum intervention strategy and intervention timing. See the “End of Asset Life” Reinvestment Tool or the Remaining Effective Life Tool for further discussion of concepts and practices in estimating the optimal time in the life cycle for reinvestment.

Estimating Future Costs

Knowing with certainty the exact costs for the entire life cycle of an asset is, of course, not possible; future costs can only be estimated with varying degrees of confidence. Future costs are usually subject to a level of uncertainty that arises from a variety of factors, including:

- The prediction of the utilization pattern of the asset over time;
- The nature, scale, and trend of operating costs;
- The need for and cost of maintenance activities;
- The impact of inflation;
- The opportunity cost of alternative investments;
- The prediction of the length of the asset's useful life.

The main goal in assessing life cycle costs is to generate a reasonable approximation of the costs (consistently derived over all feasible alternatives), not to try and achieve a perfect answer.

As rehabilitations and or replacement of assets occur during the life cycle, adjust both operations and maintenance costs appropriately. Both maintenance and operations costs are likely to materially increase as the asset ages. The pattern of increase will vary by asset type and operational environment [on many assets, as the asset ages, it requires an increasing number of visits per year by the maintenance team, longer time while at the asset to execute the work order, and often a higher level of maintenance staff to be deployed; these costs are both real and material and can be simply “modeled” in a spreadsheet.

II Part: methodology application

1. Case study

1.1. TURBO-PUMP DESCRIPTION

The system is a turbo-pump aggregate. It works by entering steam in the turbine that is utilized to move a rotor in rotation connected with a solidary shaft which drives the pump, producing mechanical work. It can be represented by the following block diagram:

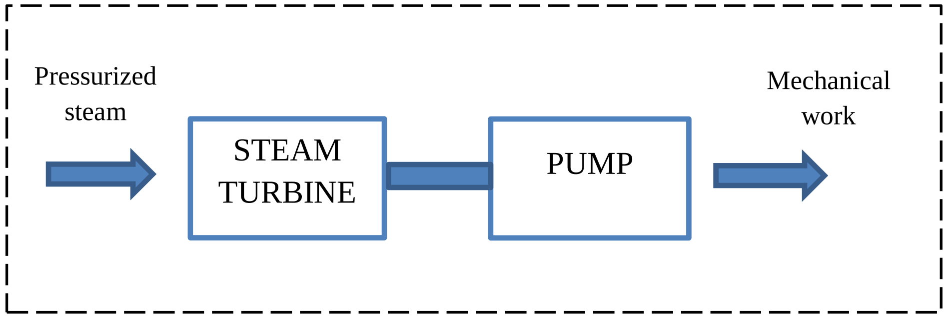

Figure 16 - System Block Diagram.

It is not object of study of this thesis the whole system but only the turbine that drives the pump. The steam turbine is one of the impulse and single-stage (SS) types and drives a pump of the axial type (AX). The main characteristics are summarized below:

Technical designation: Steam turbine KKK, type AF 3, 5 G

Manufacturer: KUNGNLE, KOPP & KAUSCH Company

Year of construction: 1967

Regulation: Cantilever-spring speed regulation

Direction of rotation: clockwise (as seen from the turbine towards the coupling of the driven machine)

1.2. CHARACTERISTICS OF THE TURBINE KKK

The main characteristics of the steam turbine KKK are summarized below:

Table 3 – Characteristics of the Turbine KKK.

Output	Normal Maximum	82 BHP 102 BHP
Speed of the turbine	Normal	8584 RPM
Secondary speed of the turbine	Normal	2900 RPM
Speed of the overspeed trip		3200 RPM
Live-steam pressure	Normal Maximum	185 psig -
Live-steam temperature	Normal Maximum	195 ℃ -
Exhaust-steam back pressure	Normal Maximum	- 25 psig
Control-oil pressure		142 psig
Lubricating oil pressure	Normal Minimum	14-28 psig 7 psig
Oil temperature	Normal Maximum	45 ℃ 70 ℃
Oil charge	See the assembly drawing	

Table 4 – Units Used In The Table Above.

BHP	Brake Horse Power
RPM	Revolutions Per Minute
psig	pounds per square inch, gage
℃	Degrees Celsius

1.3. THE TURBO-PUMP SYSTEM AND HOW IT WORKS

1.3.1. IDENTIFICATION OF THE COMPONENTS AND BRIEF DESCRIPTION

Before identifying the components of the system, a schematic of the steam turbine is presented to a better comprehension of how it works.

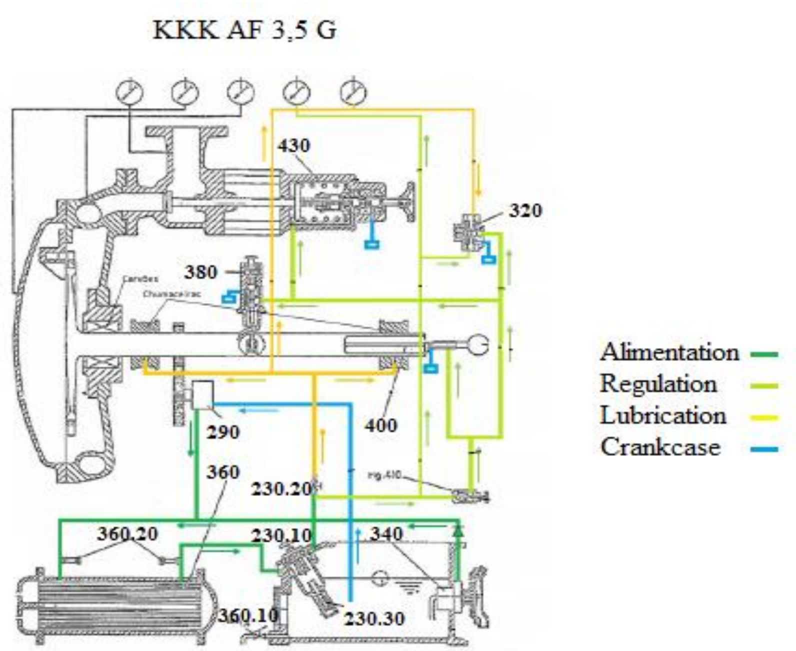

Figure 17-Schematic of The Steam Turbine (Hugo Araújo, 2012).

The main components of the system are briefly described below and the numeration of components follows the one described by the manufacturer.

Number	**Component** (description)
(230.10)	**Oil filter** (filters the impurities of the oil);
(230.20)	**Pressure reducer** (reduces the lubrication pressure to values between 1 $kg/cm^2 < \Delta < 2\ kg/cm^2$);
(230.30)	**Relief valve** (pressure variation by the addition or removal of washers);
(290.00)	**Oil pump** (this is the main oil pump of the system and it is driven by the turbine shaft);
(320)	**Lube-oil trip** (lubrication pressure and the regulating pressure enter in the device where the equilibrium of pressures is done. When lubrication pressure is less than 0,5 kg/cm^2, the regulating pressure dominates and leads to opening the valve, which discharges the oil to the crankcase, forcing the turbine to stop);
(340)	**Turbo pump for starting** (must guarantee 7 kg/cm^2in the pressure regulator and $\pm$ $1kg/cm^2$of lubrication);
(360)	**Oil cooler** (helps to lower the temperature of the oil);
(360.10)	**Purge** (helps to purge the water out of the system);

(360.20) **Temperature indicators** (indicates the temperature of the inlet and outlet feed oil).

(380) **Trigger device** (when it shoots discharges oil to the crankcase);

(400) **Cantilever spring speed governor** (regulates/maintain the oil pressure through the eccentric in the end of the rod. This rod is fixed to the shaft and as the rotation increases, higher is the gap between the eccentric and the fixed base – gap = $0{,}1 \pm 0{,}02$ mm);

(410) **Fine speed adjustment** (if open passes oil, if close doesn't pass and the RPM's of the turbine are reduced);

(430) **Speed regulating valve** (oil admission to help opening the shutter steam).

1.3.2. HOW IT WORKS

The turbo-pump for starting (340) pulls the oil from the crankcase at the pressure of 7 kg/cm^2. Then, the oil goes to the oil cooler (360) as the temperature decreases to the normal temperature that is approximately $45℃$. After that, the oil follows to the oil filter (230.10.35) where the impurities are filtered. Hence the oil is in normal conditions to operate, it bifurcates in two lines: one, that passes in the pressure reducer (230.10.30) where the pressure is reduced to ± 1 kg/cm^2, used to lubricate the shaft bearings and the other one, at the normal pressure of 7 kg/cm^2, that goes to the lube-oil trip (320) and to the cantilever spring governor (400).

In the lube-oil trip, a security mechanism composed with two plates (diaphragms) with auto-compensated springs, is guaranteed that both oil pressures, lubrication and regulation, operate in the pretended conditions (1 kg/cm^2 of lubrication and 7 kg/cm^2 of regulation): if the pressures are okay, the oil flows and the turbine starts, if not, the oil goes to the crankcase and the turbine does not start.

After this, the oil goes to the speed regulating valve (430) where the 7 kg/cm^2 of pressure are used to commutate a piston, solidary with a rod that works like a obturator, that leads the steam to enter in the steam shoot and the rotor is put in rotation. Although the turbine shaft rotates at 8000RPMs and higher, the pump shaft rotates above the 3000 RPMs. This is achieved by a gearing system that works between the two shafts and works like a speed reducer.

1.4. DEFINITION OF THE SYSTEM IN ANALYSIS AND ITS BOUNDARIES

To perform an analysis of this type, it is highly recommended to divide the system in study in sub-systems. The partition of the system allows better comprehension of the parts and even to perceive much better how it works. To do that, it will be followed the posted in the norm ISO 14224:2006 (E).

According to this norm, the following division of a typical steam turbine can be made:

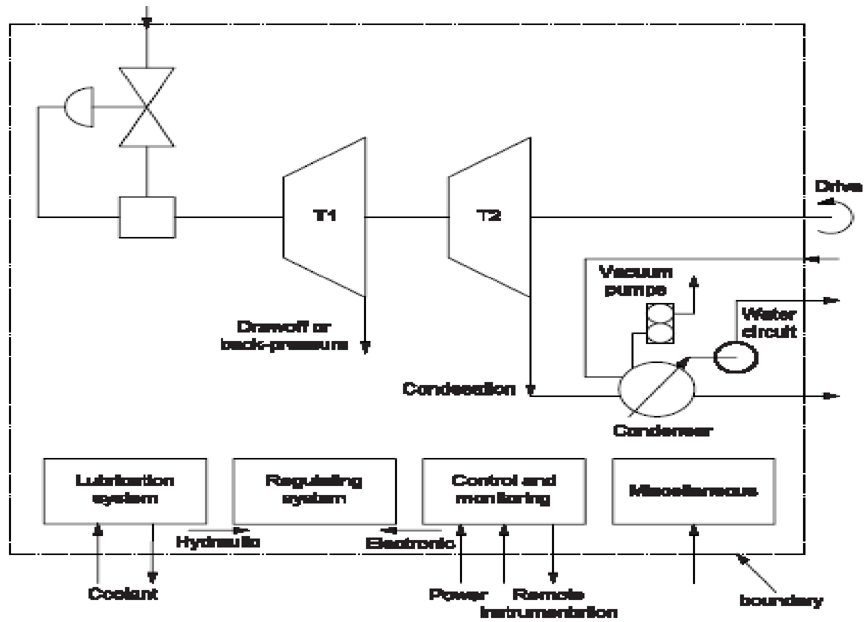

Figure 18- Boundary Definition – Steam Turbines Iso_14224_2006 (E).

However the figure above presents a steam turbine with two stages and the steam turbine in study only has one stage, this division will serve as guideline to the one that is made in the following section.

In an industrial environment, maintenance must be performed efficiently and when a failure occurs, the maintenance team must act quickly and know how to fix things to prevent a possible major cost loss. In this case, if the turbine stops the production line does not stop because the equipment is redundant in the refinery; there is similar electrical equipment.

It is important to prioritize the different components in terms of importance to the equipment vital functions and by that to the production line where he is inserted. So, according with the same norm, ISO 14224:2006 (E), the different units are classified as:

Table 5 – Technical description of the system.

Name	Description	Unit or code list	Priority
Driven unit	Pump	Compressor, crane, generator, pump, winch, etc.	High
Power-design	ISO power rating	Kilowatt	High
Power-operating	61 kW	Kilowatt	Medium
Speed	8584	Revolutions per minute	Medium
Number of shafts	2	Number	Medium
Regulating system	Hydraulic	Electronic, hydraulic	Medium
Backup starting system	Electric	Electric, hydraulic, pneumatic	Low
Fuel	Steam	Gas, oil-light, oil-medium, oil-heavy, dual	Medium
Air inlet filtration type	Type	Free text	Low

According with what have been seen above, the system was divided in the follow five sub-systems:

- Steam circuit;
- Power unit;
- Oil cooling circuit;
- Regulating and lubricating oil circuit;
- Miscellaneous (it is not represented in the figure 19).

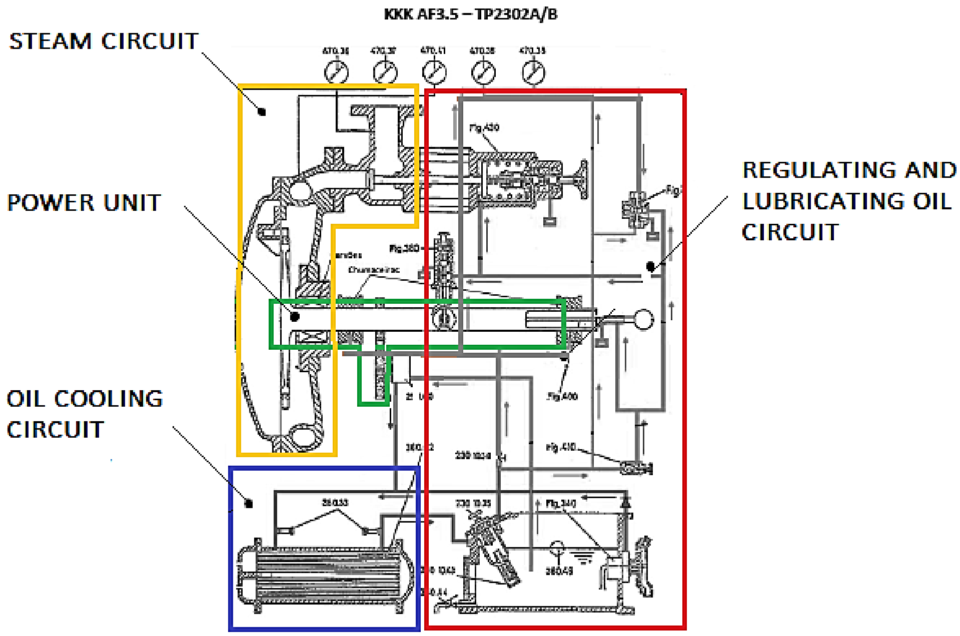

Figure 19 –Division of The System.

Once the division of the system was made, the maintainable items/components organized in its sub-systems are presented in the table 6.

Table 6 - Equipment Subdivision – Steam Turbines.

Equipment unit	**Steam turbine KKK AF 3,5 G**				
Subunit	Power unit	Regulating and lubricating oil circuit	Oil cooling circuit	Steam circuit	Miscellaneous
Maintainable items	Piping Radial bearing Rotor Seals Shaft stuffing box Thrust bearing Gearing system	Emergency governor relay Filter Speed adjusting device Relief valve Retention valve Cantilever spring speed governor Lube-oil trip Speed regulating valve Pressure reducer Bearings Turbo-pump Piping Oil Pump	Cooler Piping	Obturator Nozzle valve Seals	Cranking system Hood

The table above will be the support to perform the FMECA methodology in the next section. The maintainable items that are presented here will be the ones discriminated in the FMECAS worksheets.

2. Methodology application

2.1. FMECAS

Following the division that was made in the last section and attending to the methodology of FMECA that was described in the Part I, in this section it will be answered the different questions of FMECA:

- What are the functions and associated desired standards of performance of the asset in its present operating context?
- In what ways can it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?

Since the FMECA was formally presented in the part one, here only be seen the topics of severity, occurrence and detectability and how to rank them.

2.1.1. RANKING THE SEVERITY

To satisfy the precepts of the RCM methodology, the effect's severity must be divided in three main components, following the next order:

1. Safety of people and material assets.
2. Environment.
3. Operational and economical criterions (direct cost of maintenance intervention and costs associated with loss of production).

Table 7 – Ranking the Severity.

	Effect	**Effect's severity**	**Severity**	**Index**
Security of people and assets	Dangerous to people and assets – capable of inflict serious injuries or even dead	It happens suddenly and has significant impacts at the level of security of the installation and/or the people that works there.	++++++	7
	Dangerous to people and assets – no serious injuries	It has significant impacts at the level of security of the installation and/or the people that works there. It can be predicted, however.	+++++	6
Security of the environment	Dangerous to the environment	Puts in risk the environmental standards. It's more risky when there is not any warning.	++++	5
Operational and economical concerns	Long stoppage time	Production stoppage higher than 24 hours does not put in risk the integrity of people and the equipment and the security of the environment.	+++	4
	Moderate stoppage time	Production stoppage higher than 4 hours and lower than 24 hours, does not put in risk the integrity of people and the equipment and the security of the environment.	++	3
	Short stoppage time	Production stoppage lower than 4 hours, does not put in risk the integrity of people and the equipment and the security of the environment.	+	2
	No consequences	The equipment can perform correctly his function because the failure does not causes appreciable damages. It's not necessary to perform control and maintenance actions.	-	1

2.1.2. RANKING THE OCCURRENCE

In order to evaluate how many times a certain failure mode occurs, it is ranked the Occurrence as follows:

Table 8 – Ranking the Occurrence.

Probability of occurrence	**MTTF**	**Index**
Very high	Intermittent operation that results in a MTTF higher than 170 (≅1week) hours and lower than 750 hours (≅1month).	4
High	Intermittent operation that results in a MTTF higher than 750 (≅1month) hours and lower than 4400 hours (≅half a year).	3
Moderate	Intermittent operation that results in a MTTF higher than 4400 (≅half a year) hours and lower than 8800 hours (≅1 year).	2
Low or remote	Intermittent operation that results in a MTTF higher than 8800 hours (>1 year).	1

2.1.3. RANKING THE DETECTABILITY

Quite similar to the Severity and Occurrence criterions, the level of detectability of a failure mode can be ranked in the following way:

Table 9 – Ranking the Detectability.

Probability of detection	**Detectability by inspection of the turbine**	**Index**
Uncertain	It’s not possible to detect the failure.	4
Low	The probability of detection of the failure is LOW.	3
Moderate	The probability of detection of the failure is MODERATE.	2
High or very high	The probability of detection of the failure is HIGH or VERY HIGH.	1

2.1.4. RPN

In FMECAS worksheets, the Risk Priority Number (RPN) shows how critical a component is and results from the multiplication of the values of severity, occurrence and detectability.

$$RPN = S \times O \times D$$

By analyzing the formula above, it is perceptible that the RPN is influenced by three different variables: Severity (S), Occurrence (O) and Detectability (D).

It is attributed higher values to the Severity criterion [1 to 7] than to the values of Detectability and Occurrence, both between [1 to 4], in order to prioritize the safety of the people and assets and the economic and operational politics of the company, by this order.

To combine these values, it was created a risk ranking table with three entrances that uses a map of colors in order to be easier to identify the risk associated to each situation of failure.

The mapping of colors preconizes that to the green color corresponds the lowest level of dangerous, to the yellow color the medium level of dangerous and to the red color the most dangerous situations.

Green: 1-23

Yellow: 24-63

Red: 64-112

Table 10 – Risk Matrix.

DETECTABILITY	OCCURRENCE	SEVERITY 1	2	3	4	5	6	7
1	1	1	2	3	4	5	6	7
	2	2	4	6	8	10	12	14
	3	3	6	9	12	15	18	21
	4	4	8	12	16	20	24	28
2	1	2	4	6	8	10	12	14
	2	4	8	12	16	20	24	28
	3	6	12	18	24	30	36	42
	4	8	16	24	32	40	48	56
3	1	3	6	9	12	15	18	21
	2	6	12	18	24	30	36	42
	3	9	18	27	36	45	54	63
	4	12	24	36	48	60	72	84
4	1	4	8	12	16	20	24	28
	2	8	16	24	32	40	48	56
	3	12	24	36	48	60	72	84
	4	16	32	48	64	80	96	112

The most risky situation is obtained by the multiplication of the maximum values of the three RPN components: Severity=7, Occurrence=4 and Detectability=4, which results in a maximum value for the RPN of 112.

Performed FMECAS

The following components were the ones that have been subjected to the FMECA analysis:

Table 11 – Performed FMECAS.

Nº	Sub – system	Designation
1	Steam circuit	Sealing elements
3	Steam circuit	Obturator
4	Steam circuit	Nozzle valve
5	Regulating and lubrication oil circuit	Emergency governor and relay
6	Regulating and lubrication oil circuit	Filter
7	Regulating and lubrication oil circuit	Relief valve
8	Regulating and lubrication oil circuit	Speed adjusting device
9	Regulating and lubrication oil circuit	Safety Retention valve
10	Regulating and lubrication oil circuit	Cantilever spring speed governor
11	Regulating and lubrication oil circuit	Lube-oil trip
12	Regulating and lubrication oil circuit	Speed regulating valve
13	Regulating and lubrication oil circuit	Pressure reducer
14	Regulating and lubrication oil circuit	Turbo-pump for starting
15	Regulating and lubrication oil circuit	Piping
16	Regulating and lubrication oil circuit	Oil
17	Regulating and lubrication oil circuit	Oil pump
18	Oil cooling system	Cooler
19	Oil cooling system	Piping
20	Power unit	Shaft coupling
21	Power unit	Gearing
22	Power unit	Rotor
23	Power unit	Shaft stuffing box
24	Miscellaneous	Cranking system
25	Miscellaneous	Hood

Application of the RCM decision diagram

To achieve the purposes of the RCM it is not enough to answer the questions presented to the resolution of the FMECAS.

It will be performed the RCM analysis to the critical component. To do that, it will be follow the methodology preconized by Moubray (1997), represented by the diagram represented in the figure 9.

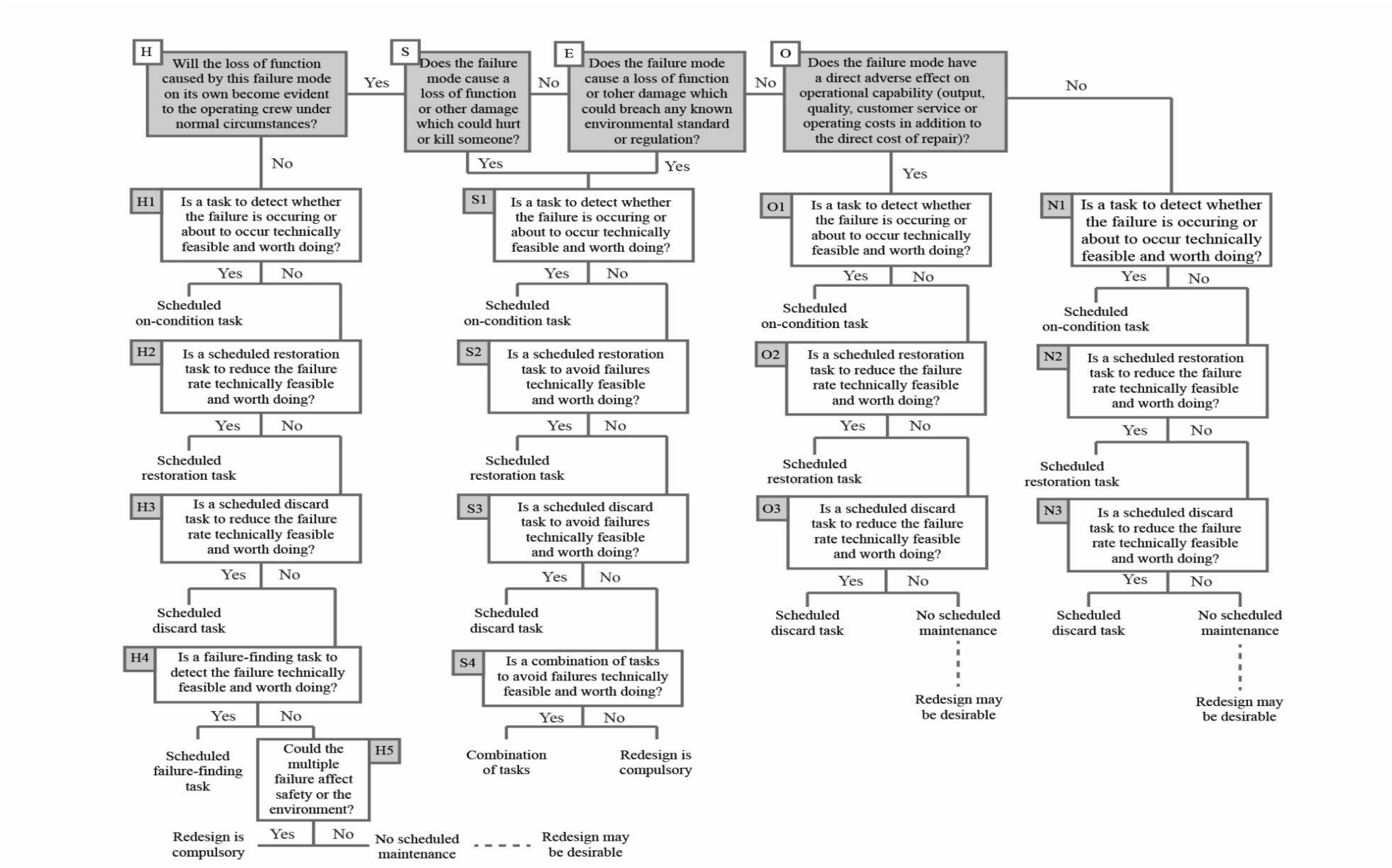

Figure 20 - RCM Decision Diagram.

2.2. LCC

In this section it will be study if the equipment in cause is still benefit for the company or, in the perspective of management of assets and application of the percepts of LCC, it has become obsolete and buying a new one is the more viable way.

To do that, it must be estimated the remaining life of the defender (actual equipment) and the life cycle of the challenger (challenger equipment), as previously have been seen.

The Challenger

The challenger choice was made attending the characteristics of the actual equipment. The challenger is a steam turbine, model SST-040, and is a Siemens product. The price and all the information was obtained directly from the supplier.

According with the information provided by the Siemens company book, the newly developed steam turbine SST-040 is a single-stage impulse turbine. A generator drive specially designed for the 75-300 kW output range. It is a simple, extremely compact turbine, short start-up times and a high degree of operational reliability. The SST-040 steam turbine is delivered as a pre-tested package unit composed with turbine, gear, generator, oil unit, control and protection unit as well as circuit breaker, built on a common base frame.

Typical fields of application for the SST-040 series

The key fields of application for the SST-040 are:

- Waste-heat recovery, behind gas engines and biogas engines;
- Small petrochemical plants;
- Decentralized solar facilities.

Benefits

There are various benefits derived from the use of the SST-040. The most are referred:

- Minimal foundation work thanks to small and compact design;
- Largely maintenance-free due to stalwart, robust construction;
- High availability thanks to resilient and sure technology;
- Quick start without preheating of the turbine due to minimized gyrating masses;
- Favourably priced thanks to proven components;
- Quick development and commissioning due to production orientated design.

Table 12 – Defender vs. Challenger.

	Defender	**Challenger**
Technical designation	Steam turbine KKK AF 3, 5 G	Steam turbine Siemens SST-040
Condition	Condition: Used (year of construction-1967)	Condition: new
Price	3000 € (*)	100 000 € up to 120 000 € (**)
Output	82 BHP 102 BHP	100 BHP
Speed of the turbine	8584 RPM	6000-9000 RPM
Second speed of the turbine	2900 RPM	2900 RPM
Inlet steam pressure	12,8 bar	2 – 40 bar
Live steam temperature	195 ℃	250- 400 ℃
Weight (approx.)	520 kg	3000-4500 kg

- *current estimated price for actual equipment
- **price variable according with additional specifications

3. Results and discussion

Global criticality

The global criticality for the different components is obtained by summation the RPNs attributed to each failure mode and it is shown in the following table, where the most critical component, the one with higher global criticality, is underlined in red.

Table 13 – Global Criticality of the Components.

Nº	Sub – system	Designation	Global Criticality (GC)
1	Steam circuit	Sealing elements	18
3	Steam circuit	Obturator	48
4	Steam circuit	Nozzle valve	48
5	Regulating and lubricating oil circuit	Emergency governor and relay	105
6	Regulating and lubricating oil circuit	Filter	12
7	Regulating and lubricating oil circuit	Relief valve	69
8	Regulating and lubricating oil circuit	Speed adjusting device	18
9	Regulating and lubricating oil circuit	Safety retention valve	32
10	Regulating and lubricating oil circuit	Cantilever spring speed governor	106
11	Regulating and lubricating oil circuit	Lube-oil trip	119
12	Regulating and lubricating oil circuit	Speed regulating valve	112
13	Regulating and lubricating oil circuit	Pressure reducer	72
14	Regulating and lubricating oil circuit	Turbo-pump for starting	102
15	Regulating and lubricating oil circuit	Piping	44

16	Regulating and lubricating oil circuit	Oil	60
17	Regulating and lubricating oil circuit	Oil pump	42
19	Oil cooling system	Cooler	36
20	Oil cooling system	Piping	44
21	Power unit	Shaft coupling	56
22	Power unit	Gearing	110
23	Power unit	Rotor	52
24	Power unit	Shaft stuffing box	72
25	Miscellaneous	Cranking system	37
26	Miscellaneous	Hood	20

Critical FMECA

With the purpose of not overloading the text, only is represented here the FMECA of the most critical component. The FMECAS for the other components are presented in the annexes, section 6.2, at the end of the document.

Accordingly with the analysis made, it was concluded that the most critical component is the *lube-oil trip*, a component that is part of the *regulating and lubricating oil circuit* sub-system.

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Lube-oil trip **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Security device where the regulating and the lubricating pressures are balanced. When the lubricating pressure is lower than $0{,}5 kg/cm^2$, the regulating pressure wins and the oil is discharged to the crankcase.	The pressures are not balanced and therefore the turbine does not start.	Tied/damaged diaphragms	The correct contact between the two diaphragms is no longer possible and the pressures of lubrication and regulation are not compensated leading to the non-start of the turbine.	4	2	-	4	32	119
		Damaged cylindrical helical springs		3	2	-	24	24	
		Deregulated device	The device is not correctly regulated and even if the internal components are fine, the turbine does not start because the equilibrium of lubrication and regulation pressures is not made.	3	3	-	4	27	
		Wear of the gasket	Leak of the oil to the crankcase and subsequently drop of pressure in the system, which may cause the turbine to stop.	3	3	-	4	36	

The components that were subjected to the RCM analysis were the ones with higher RPN values and high occurrence values, since when the value attributed to the occurrence is high, normally, means that some improvements can be done in order to reduce how many times a failure mode occurs.

Table 14 – RCM Maintenance Corrective Plan.

Component	GC	Function	Functional failure	Failure mode	Time span	Proposed task
Lube-Oil Trip	119	Security device where the regulating and the lubricating pressures are balanced. When the lubricating pressure is lower than $0{,}5 kg/cm^2$, the regulating pressure wins and the oil is discharged to the crankcase.	The pressures are not balanced and therefore the turbine does not start.	Tied/damaged diaphragms	1 Month	Monitoring the condition of the springs
Emergency Governor and Relay	105	Security device that prevents the system to go over the maximum RPM.	Does not act when the maximum RPM is reached.	Gap between the device and the shaft out of the tolerance	1 Month	Visual inspection to the mechanical connection
Relief Valve	69	Discharges the oil to the crankcase when the pressure is too high.	Does not open when the pressure of the oil is too high.	Error in the set point (opening pressure)	1 Month	Implementation of electronical sensor to track the set pressure.
Cantilever Spring Speed Governor	106	Device with an eccentric in the end that opens more or less to let the steam pass, as the velocity of the turbine is reduced or increased, respectively.	The device does not work like it is required; either if lets the steam pass or not pass.	Eccentric gap out of the tolerance ($a = 0{,}1 \pm 0{,}02 mm$)	1 Month	Visual inspection to the gap

LCC outcome

Since the actual turbine is relatively reliable and efficient on performing its function and also the investment in a new similar product is very expensive, as have been seen from the quotation giving by the Siemens company, the conduct of this limited LCC analysis (it does not have been performed the calculations to verify the actual price and the total costs of maintenance tasks, because there is no data to support this application) leads to conclude that <u>maintaining the older/actual equipment is more benefit for the company than acquiring a new equipment</u>.

4. Conclusions and future works

In the chapter one, is presented the theoretical framework to serve as support for the defined methodology exposed on chapter two.

Through the first chapter, the characteristics of steam turbines, FMECA, RCM and LCC, were referred and some conclusions could be taken, for example:

- The steam turbines are mechanical devices that have been used since a long time and they are still helpful to perform some functions in the industrial world.
- FMECA is a well-organized technique, which seeks to find how a equipment can fail in its performance and evaluate the criticality of different failure modes.
- The RCM is a methodology that is more extensive than the FMECA. Besides the goals of FMECA, it searches to look for corrective and preventive maintenance actions, in order to reduce the criticality of the components. Among the main characteristics of RCM, the recognition that the consequences of failure are much more important than technical characteristics is a relevant one.
- The LCC is a powerful tool to manage the assets, helping the companies/organizations understanding the current value and importance of their assets. By comparing how a process is performed by their own equipment facing how it would be if they buy new equipment, it permits to judge if the current equipment is still viable or, eventually, it turned obsolete.

On the second chapter, the methodology was implemented. The objectives were to obtain the FMECAS of the different components of the equipment, the application of the RCM decision diagram to the most critical failure modes and the LCC study. Like in the first chapter is possible to conclude the following aspects:

- By analyzing the FMECAS worksheets, it is possible to conclude that the majority of the components are not very critical. Here it was found that the Lube Oil Trip is the most critical component which has the higher value for the RPNs summation.

- After the application of the RCM decision diagram some corrective maintenance tasks were arbitrated, in order to reduce the criticality of the referred failure modes.
- The LCC analysis was limited by the lack of information of maintenance costs and the absence of the number of failures in its historical records.
- Following the LCC application it was concluded that maintaining the older/current equipment is a good strategy to the company. The reasons why, are mainly, due to the reliability of the older equipment in performing its function, the relatively low costs to maintain it and the high investment required to buy a new steam turbine.

As future work, it is proposed the modification of the RCM decision diagram incorporating the percepts of LCC and the economic and management demands of the company.

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6. Annexes

6.1. Non Homogenous Poisson Systems

When reparation is practicable in a system, the repairs, normally, are about substitute or recuperate only part(s) of the whole system. The purpose is to let the system in a state approximately equal to the one before the intervention.

As the system ages, the interventions became more frequently and in this situation is said that the system it is not already a Homogeneous Poisson (HP) system, but a Non Homogeneous Poisson (NHP). The difference between these two designations is the Time Between Failures (TBF), as the TBF in NHP may be not independently and uniformly distributed attending the growing required number of interventions and the new components required. The conclusion to take is that as a system ages, gradually it passes from HP to NHP.

Following the methodology stated by Rui Assis (2012) in his work about management of assets, it will be defined a methodology to, in the section XXX, apply the LCC tool to the case of study of this thesis.

This is a stochastic process, defining the function of intensity $\rho(t)$, also called renovation rate or failure occurrence rate (ROCOF), as the variation rate of the expected number of failures dE[N(t)] in relation to time dt,

$$\rho(t) = \frac{dE[N(t)]}{dt}$$

Or, approximately,

$$\rho(t) \approx \frac{N(t + \Delta t) - N(t)}{\Delta t}$$

According with the AMSAA (Army Material Systems Analysis Activity) the cumulate number of failures *m* all along can be described by,

$$m(t) = a.t^b$$

This expression can be derived in relation to time and results,

$$\rho(t) = a >< . b . t^{b-1}$$

If,

- $b > 1$, it is a PNH process and the ROCOF increases;
- $0 < b < 1$, it is a PNH process and the ROCOF decreases;
- $b = 1$, it is a PH process.

It is possible to calculate the number of failures in a period, knowing how ρ varies with *t*, by integer over the interval $(t_i - t_{i-1})$, results,

$$m(t_i - t_{i-1}) = \int_{t_{i-1}}^{t_i} \rho(t)dt = a.(t_i^b - t_{i-1}^b)$$

The Mean Time To Failure (MTTF) for any component under a test or the Mean Time Between Failure (MTBF) for components under maintenance, that is the case for this work, its variable with time. If an estimate is satisfactory, it is possible to calculate the MTBF only by dividing the number of failures per the days of the year. To calculate a value more accurate, it follows,

$$MTBF(t) = \frac{1}{\rho(t)}$$

To estimate the parameters *a* and *b*, it can be used one of two methods:

- Ordinary Least Squares (OLS);
- Maximum-Likelihood Estimation (MLE).

Using the MLE, it must be considered two different types of data:

1. Type I – analysis limited by time T (life of the equipment at the present of the study)
2. Type II – analysis limited by the time until the last failure, t_n.

Data of the Type I

Defining,

$$\hat{b} = \frac{n}{n.\ln(T) - \sum_1^n \ln(t_i)}$$

$$\hat{a} = \frac{n}{T^{\hat{b}}}$$

$$\hat{\rho}(T) = \hat{a}.\hat{b}.T^{\hat{b}-1}$$

$$MTTF = \frac{1}{\hat{\rho}(T)}$$

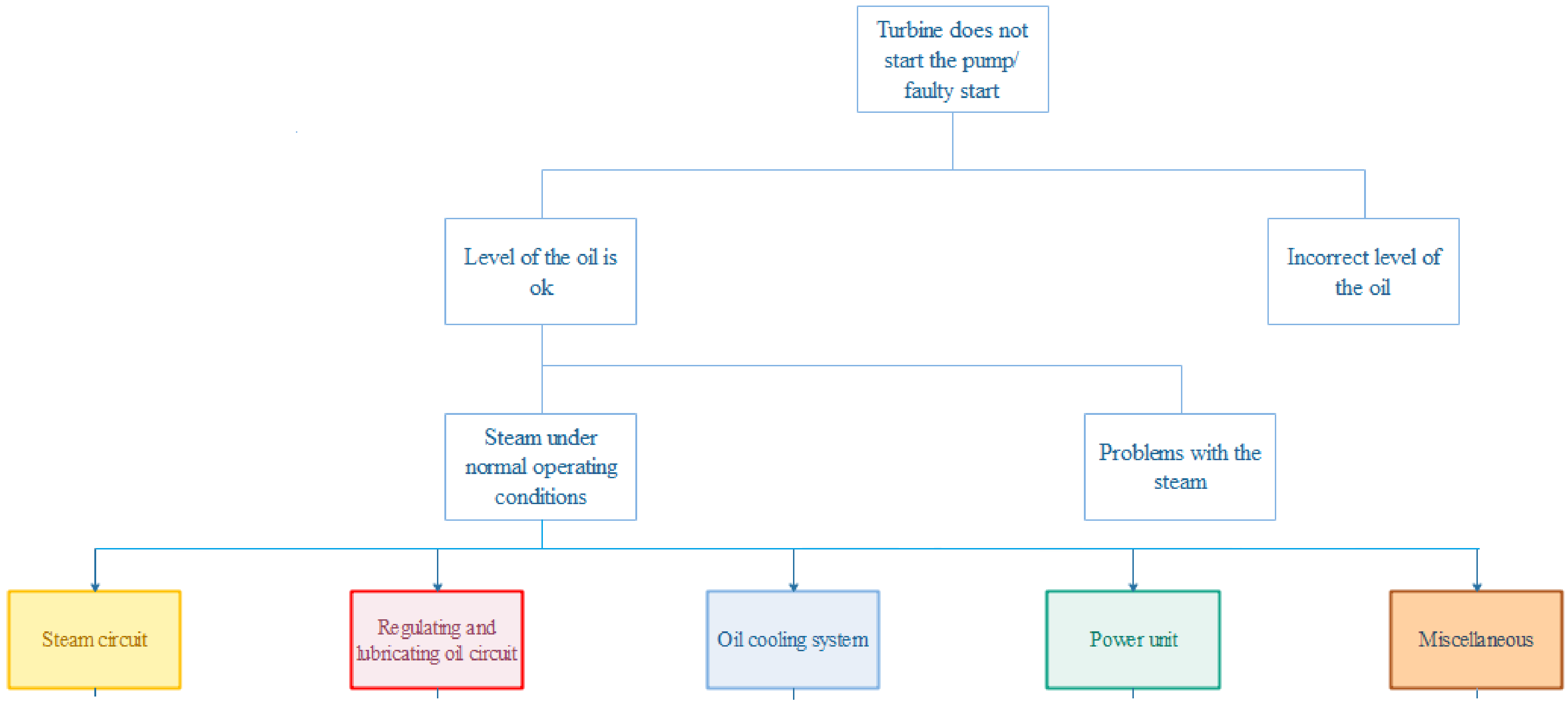
Data of the Type II

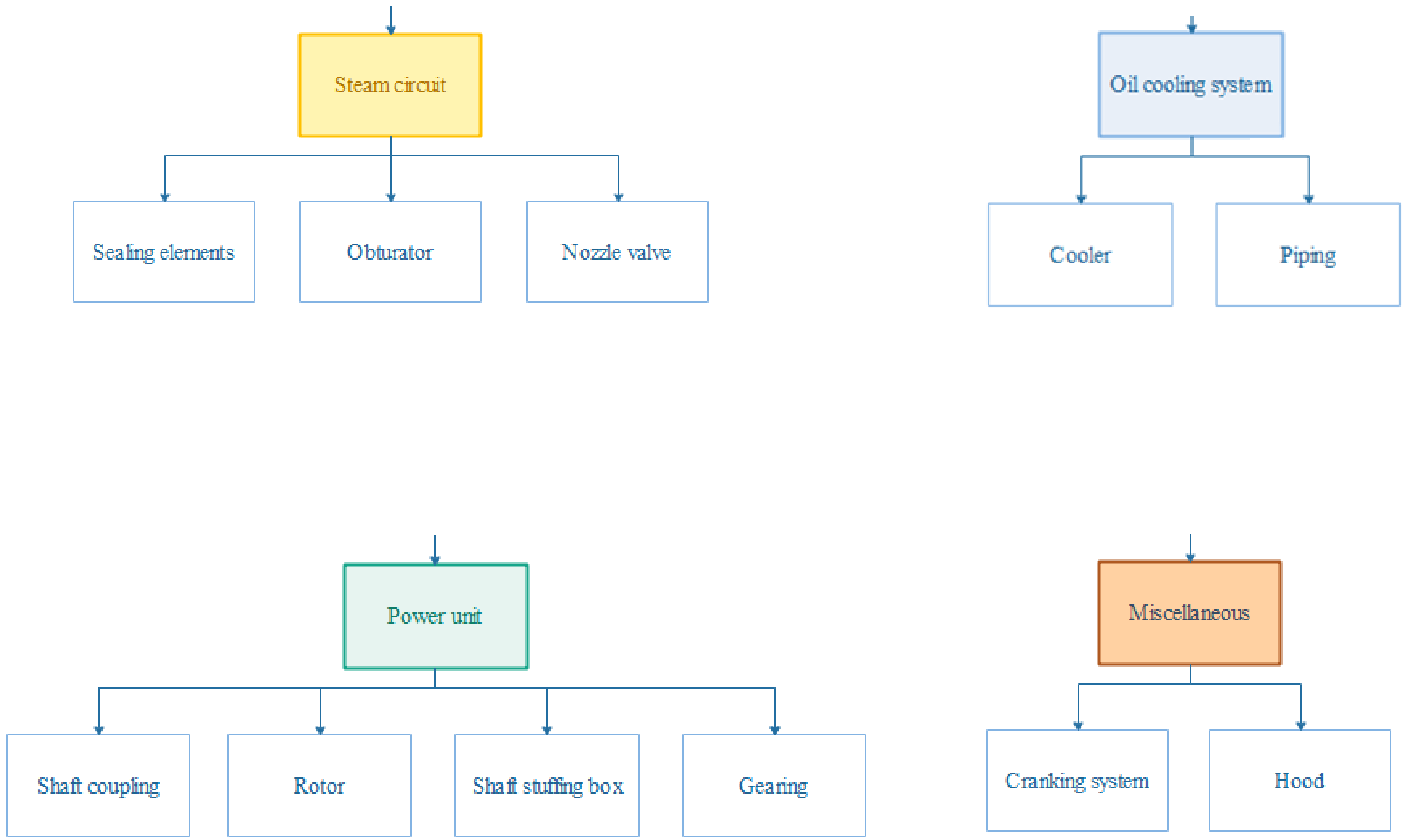
Defining,

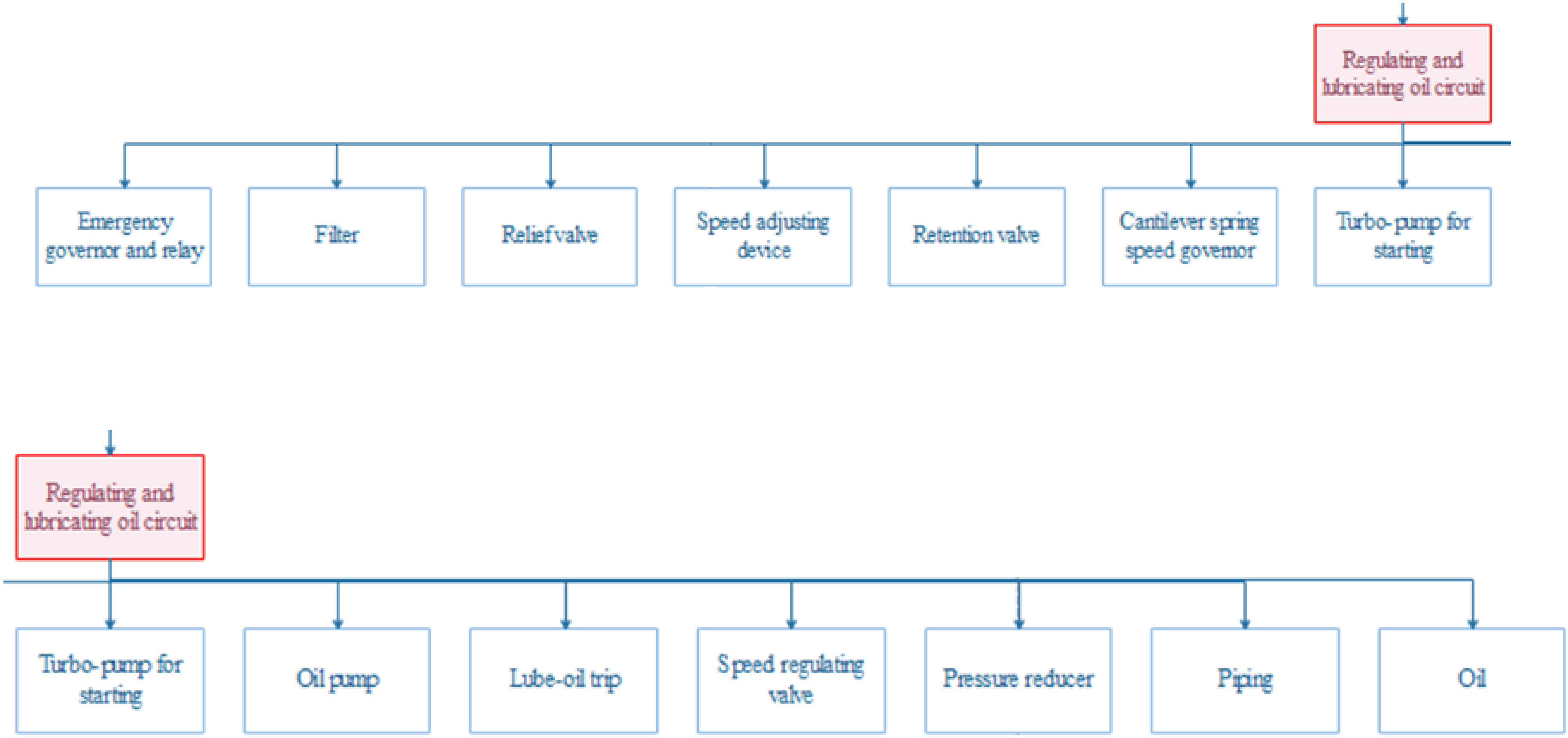
$$\hat{b} = \frac{n}{(n-1).\ln(t_n) - \sum_1^{n-1} \ln(t_i)}$$

$$\hat{a} = \frac{n}{{t_n}^{\hat{b}}}$$

6.2. Failure Tree and FMECAS




Steam circuit
Sealing elements
Obturator
Nozzle valve
Oil cooling system
Cooler
Piping
Power unit
Shaft coupling
Rotor
Shaft stuffing box
Gearing
Miscellaneous
Cranking system
Hood


Regulating and lubricating oil circuit
Emergency governor and relay
Filter
Relief valve
Speed adjusting device
Retention valve
Cantilever spring speed governor
Turbo-pump for starting
Regulating and lubricating oil circuit
Turbo-pump for starting
Oil pump
Lube-oil trip
Speed regulating valve
Pressure reducer
Piping
Oil

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Steam circuit **Made by:** **Made in:** 25-07-2017

Equipment: Sealing elements **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Elements that seal and does not allow the leakage of steam.	The seal elements does not seal correctly.	Wear and tear of the sealing elements	There is leakage of steam affecting the normal performance and consume of the turbine.	3	2	-	3	18	18

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** ____ **Revision nº:** ____

Sub-system: Steam circuit **Made by:** ____ **Made in:** 25-07-2017

Equipment: Obturator **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Controls the passage of steam to the rotor by closing or open more as the velocity of the turbine is lower or higher, respectively.	Does not open nor close like it is required.	Misalignment	The rod of the obturator is misaligned and it leads to an inefficient closing or opening of the steam intake channel	4	1	-	4	16	48
		Bad seal in the shutter seat	A bad seal in the shutter seat will implicate leak of steam.	4	2	-	4	32	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Steam circuit **Made by:** **Made in:** 25-07-2017

Equipment: Nozzle valve **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Control the volumetric caudal of steam that enters in the turbine.	It is not possible to control precisely the caudal.	Valve spindle is stuck	The closing in the spindle valve cone junction is working deficiently.	2	1	-	4	8	48
		Damaged valve cone		2	1	-	4	8	
		Wear and tear of the cap screw		2	2	-	4	16	
		Wear and tear of the steam packing and the gasket	There is steam leakage and the volumetric caudal that enters in the turbine is lower than the pretended.	2	2	-	4	16	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Emergency governor and relay **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Security device that prevents the system to go over the maximum RPM.	Does not act when the maximum RPM is reached.	Gap between the device and the shaft out of the tolerance	The device can not interrupt the functioning when the maximum RPM is reached.	7	3	-	3	63	105
		Internal wear and leakage to the crankcase	The turbine loses power and the pressure condition of the lube-oil trip may no long be verified which leads to the turbine stop.	7	2	-	3	42	

System: Turbine AF 3.5 – TP2302A/B

FMECA nº:

Revision nº:

Sub-system: Regulating and lubricating oil circuit

Made by:

Made in: 25-07-2017

Equipment: Filter

Page: 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Filters the impurities of the oil.	Does not filter correctly.	Filter element obstructed	Puts in risk the quality of the oil and is capacity to lubricate correctly.	2	2	-	3	12	12

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Relief valve **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Discharges the oil to the crankcase when the pressure is too high.	Does not open when the pressure of the oil is too high.	Error in the set point (opening pressure)	The system goes over the maximum admissible pressure.	7	2	-	4	42	69
		Internal wear and leakage to the crankcase	The oil flows into the crankcase and the turbine loses power. If the pressure condition of the lube-oil trip is no longer verified, the turbine stops.	3	3	-	3	27	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Speed adjusting device **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Regulates the speed of the turbine by letting the oil pass to the crankcase.	Does not regulates correctly the RPMs.	Wear between the seat and the rod	It is no longer possible to regulate accurately the speed of the turbine.	1	2	-	3	6	18
		Damaged spring		1	2	-	3	6	
		Damaged needle		1	2	-	3	6	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Safety retention valve **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Permits the oil to flow only in one direction.	Let the oil pass in both directions.	Bad seat seal	Return of the oil in the pipes, leading to a bad functioning of the turbine and even to its stoppage.	4	2	-	4	32	32

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Cantilever spring speed governor **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Device with an eccentric in the end that opens more or less to let the steam pass, as the velocity of the turbine is reduced or increased, respectively.	The device does not work like it is required; either if lets the steam pass or not pass.	Seized thrust bearing	It will implicate additional vibration of the control pivot and difficulties in controlling the velocity of the turbine.	3	2	-	4	24	106
		Wear of the radial gasket ring	There is a leakage of the oil.	3	2	-	3	18	
		Eccentric gap out of the tolerance ($a = 0{,}1 \pm 0{,}02mm$)	The velocity of the turbine cannot be regulated.	4	3	-	4	48	
		Control pivot stuck	The device works deficiently.	4	1	-	4	16	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Lube-oil trip **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Security device where the regulating and the lubricating pressures are balanced. When the lubricating pressure is lower than $0{,}5 kg/cm^2$, the regulating pressure wins and the oil is discharged to the crankcase.	The pressures are not balanced and therefore the turbine does not start.	Tied/damaged diaphragms	The correct contact between the two diaphragms is no longer possible and the pressures of lubrication and regulation are not compensated leading to the non-start of the turbine.	4	2	-	4	32	119
		Damaged cylindrical helical springs		3	2	-	2	24	
		Deregulated device	The device is not correctly regulated and even if the internal components are fine, the turbine does not start because the equilibrium of lubrication and regulation pressures is not made.	3	3	-	4	27	
		Wear of the gasket	Leak of the oil to the crankcase and subsequently drop of pressure in the system, which may cause the turbine to stop.	3	3	-	4	36	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Speed regulating valve **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Regulates the speed of the turbine by entering oil in the cylinder that helps the obturator to open.	The oil does not push the piston and the obturator does not move.	Damaged spring	The piston cannot return nor does it efficiently.	4	2	-	4	32	112
		Wear of the piston, segments and liners	Leaks of oil in the piston chamber that can lead to the oil passing to the steam channel.	5	2	-	4	40	
		Excessive leakage to the crankcase	The turbine loses power and, after some time, stops.	5	2	-	4	40	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Pressure reducer **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Works to reduce the lubricating pressure to values between 1,0 $kg/cm^2 < \Delta <$ 2,0 kg/cm^2	The pressure regulator does not reduce the pressure of the lubricating line.	Deregulation	It is no longer possible to reduce the pressure of lubrication and therefore both pressures, lubrication and regulation, does not equalize in the lube-oil trip and the turbine does not stars.	6	2	-	3	36	72
		Wear in the seat		6	2	-	3	36	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Turbo-pump for starting **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
It must guarantee $7\ kg/cm^2$ in the regulator line and $\pm 1 kg/cm^2$ in the lubricating line.	Does not provide the pressure needed to start the oil system.	Problems in the rotor	The turbine does not start because the turbo-pump cannot provide enough pressure to the oil to flow into the lube-oil trip.	4	1	-	3	12	102
		Seized bearings		3	2	-	3	18	
		Carbon rings wear		3	3	-	3	27	
		Wear of the sealing elements		3	3	-	3	27	
		Reel wear		3	2	-	3	18	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** ______ **Revision nº:** ______

Sub-system: Regulating and lubricating oil circuit **Made by:** ______ **Made in:** 25-07-2017

Equipment: Hydraulic Piping **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Makes the oil connection between the components.	The oil does not flow or it does so with difficulty.	Obstruction	It can lead to an increment in the system pressure that affects the normal performance of the turbine and even puts in risk the involving.	6	1	-	4	24	44
		Rupture/leakage	Results in a drop of pressure of the system that leads to a bad functioning of the turbine and after some time its stoppage.	5	1	-	4	20	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Oil pump **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Converts mechanical energy into hydraulic letting the oil to drain to the different components.	Does not provide enough pressure.	Incapacity to pump	The components of the system are not lubricated and may cause the components to seize.	4	2	-	3	24	42
		Pumping capacity lower than the data specifics	Accelerated wear and tear of the system components.	3	2	-	3	18	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Oil cooling system **Made by:** **Made in:** 25-07-2017

Equipment: Cooler **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Cools the oil to its normal temperature of operation (45°C).	Does not cool the oil or does it so but inefficiently and subsequently the normal temperature of the oil is not reached.	Hole in the pipes	The oil leaks and may cause the components to seize.	3	1	-	4	12	36
		Obstruction in the pipes		3	1	-	4	12	
		Loss of efficiency of the cooler	The cooler is no longer efficient and the oil does not cool to its normal functional temperature leading to a bad function of the system.	4	1		3	12	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Oil cooling system **Made by:** **Made in:** 25-07-2017

Equipment: Hydraulic Piping **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Makes the oil connection between the components.	The oil does not flow or it does so with difficulty.	Obstruction	It can lead to an increment in the system pressure that affects the normal performance of the turbine and even puts in risk the involving.	6	1	-	4	24	44
		Rupture/leakage	Results in a drop of pressure of the system that leads to a bad functioning of the turbine and after some time its stoppage.	5	1	-	4	20	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Hydraulic fluid (Oil) **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Responsible of lubricating, heat dissipation and power transmission.	Viscosity variation: high viscosity	Low environment temperature	Increase in temperature	5	2	-	3	30	60
		Inappropriate oil	Less power in the output						
	Viscosity variation: low viscosity	Failure in the oil cooler	Losing the capable to lubricate	5	2	-	3	30	
		Contamination by water in the oil	Accelerates the wear of the components of the system						
		Lack of cleaning in the reservoir	Accelerates the wear of the components of the system						
		Inappropriate oil	Drop of pressure						

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Power unit **Made by:** **Made in:** 25-07-2017

Equipment: Shaft coupling **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Junction responsible for transmitting the power from the turbine shaft to the pump shaft.	The transmission is not performed correctly.	Misalignment	The connection turbine-pump is not performed correctly, and the pump is not driven like it is required.	4	2	-	4	32	56
		Fracture and decouple	The system stops and there is no longer connection between the turbine and the pump.	6	1	-	4	24	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Power unit **Made by:** **Made in:** 25-07-2017

Equipment: Gearing **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
System responsible to decrease the rotational speed, connecting the turbine to the pump, and to put into work the main oil pump.	Does not reduce the RPM nor does activate the oil pump.	Wear and tear of the teeth due to fatigue (scuffing)	The teeth start to disengage and it may cause the stoppage of the gearing and function interrupt of the oil pump.	4	1	-	3	12	110
		Corrosion in the teeth (pitting)	The materials become less resistant and, ultimately, even break.	4	1	-	3	12	
		Wear and tear of the sealing elements (gaskets, retaining rings, thrust rings and nuts)	There are leaks of the oil, which can cause accelerated wear and tear of the gearing teeth and even its seizing.	3	2	-	3	18	
		Wear and tear of the radial/thrust bearings		3	2	-	3	18	
		Wear and tear of the adjusting spring		3	2	-	3	18	
		Fatigue in the turbine shaft with pinion	Can cause several damages to the system and in the case of fracture by fatigue, can break both the components of the turbine and the pump.	4	1	-	4	16	
		Fatigue in the gear shaft with wheel		4	1	-	4	16	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Power unit **Made by:** **Made in:** 25-07-2017

Equipment: Rotor **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Mechanism that uses the steam in a rotating movement that turns the shaft (solidary coupled to the rotor).	The rotor does not rotate or not rotates efficiently.	Fatigue and fracture of the blades	Blade delaminating and fracturing.	7	1	-	4	28	52
		Corrosion of the blades and steam injection channels	Due to the loss of mechanical properties, the blades become weaker	4	2	- -	3	24	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Power unit **Made by:** **Made in:**

Equipment: Shaft stuffing box **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
It is the casing of the shaft. It helps to reduce the vibration and the deformation.	The casing of the shaft is not performed correctly.	Wear of the carbon rings	The shaft has additional vibration, which leads to an incorrectly performance of the system and even to a misalignment on the shaft coupling.	4	3	-	3	36	72
		Wear of the annular pressure spring		4	3	-	3	36	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

Sub-system: Regulating and lubricating oil circuit **Made by:** **Made in:** 25-07-2017

Equipment: Cranking system **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
Stores the oil, helps to purge the impurities in the oil and helps in the heat dissipation of the oil.	The reservoir does not store the oil.	Fissuring or hole in the reservoir	Leak of the oil and possibility of entering air in the system	5	1	-	3	15	37
		Failure in the adjustment of the drain-pipe	Cavitation in the pump	3	2	-	3	18	
		Dowel bad closed	Drop of pressure	2	1	-	2	4	

System: Turbine AF 3.5 – TP2302A/B **FMECA nº:** **Revision nº:**

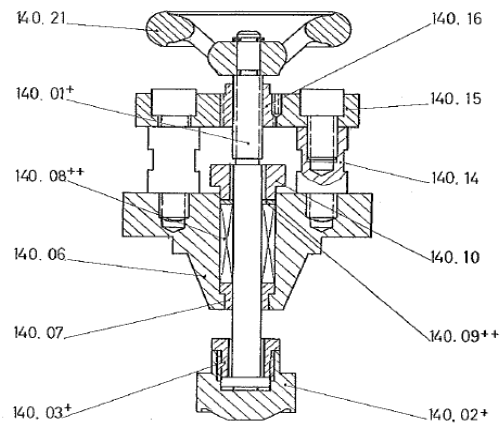
Sub-system: Miscellaneous **Made by:** **Made in:** 25-07-2017

Equipment: Hood **Page:** 1/1

Function	Function failure	Failure mode	Potential effects of the failure in the system	Severity	Occurrence	Current modes of detection	Detection	RPN	GC
External protection of the system. It guarantees mechanical resistance to external treats.	Does not protect the equipment from external treats.	Failure by fissuring due to fatigue	The system turns more vulnerable to external attacks and to the environment conditions.	4	1	-	3	12	20
		Corrosion of the hood materials		4	1	-	2	8	

6.3. Components Description

6.3.1. NOZZLE VALVE



140.01+	valve spindle	140.09++	gasket
140.02+	valve cone	140.10	gland
140.03+	cap screw	140.14	distance bolt
140.06	stuffing box	140.15	arch
140.07	bottom bush	140.16	threaded bush
140.08++	steam packing	140.21	handwheel

Figure 21 – Schematic of Nozzle Valve. (KKK manual, 1967)

This is a valve that actuates as a safety valve. When the pressure of inlet side of the valve increases to a predetermined pressure, to open the valve disc and discharge the steam; and when the pressure decreases to the prescribed value, to close the valve disc again. Safety valve is so-called a final safety device which controls the pressure and discharges certain amount of fluid by itself without any electric power support. Safety Valve is mainly installed in a chemical plant, electric power boiler, gas storage tank, preventing the pressure vessels from exploding or damaging.

1. "Nozzle" inside the Safety Valve starts to receive a higher pressure from the inlet side of the valve.
2. When the pressure becomes higher than the set pressure, "Disc" starts to lift and discharge the fluid.
3. When the pressure decreases until the predetermined pressure, the force of the spring closes "Disc".

In this component the critical parts to wear and tear are the steam packing and the gasket, while the valve spindle, the valve cone and the cap screw are normally susceptible to be damaged.

6.3.2. SHAFT STUFFING BOX

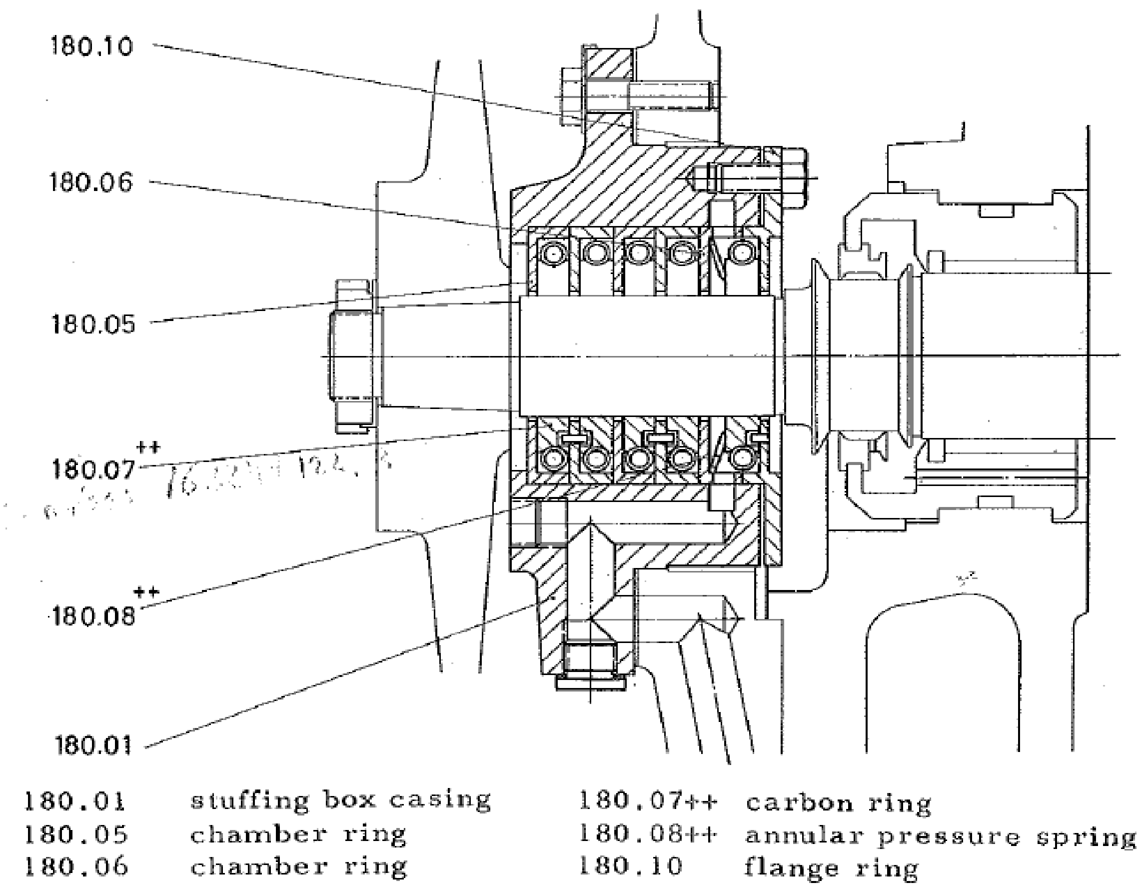


Figure 22 – Schematic of Shaft Stuffing Box. (KKK manual, 1967)

This is the cage where the shaft that connects the turbine to the pump rotates.

The carbon ring and the annular pressure spring are the critical parts to wear and tear.

6.3.3. GEARING

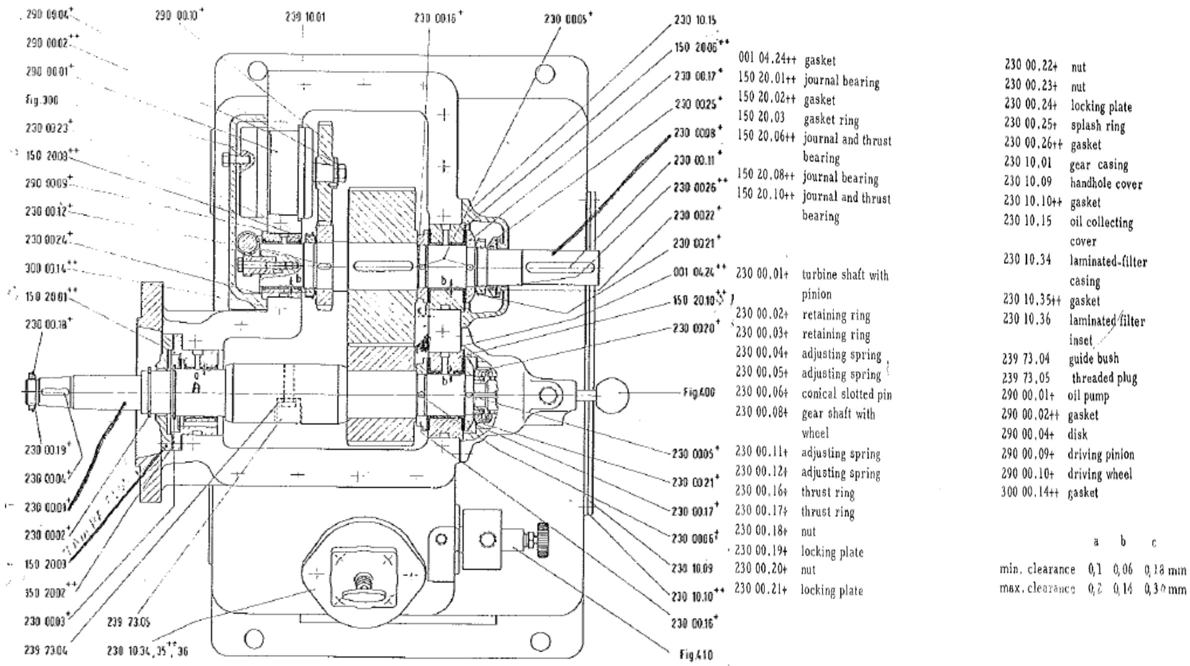
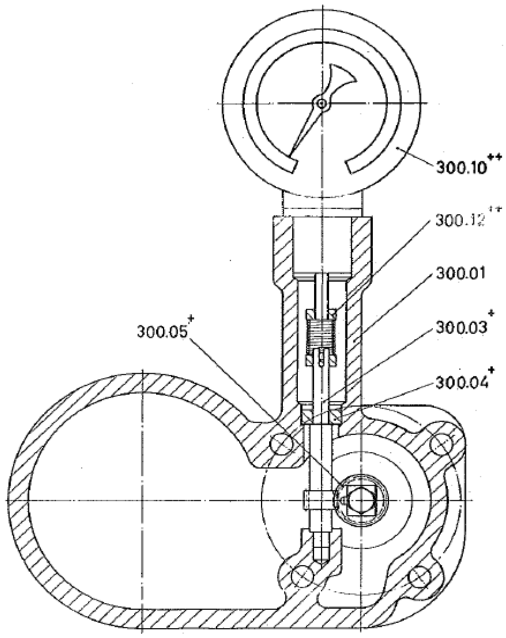


Figure 23 – Schematic of Gearing. (KKK manual, 1967)

The gearing system works like a RPM reducer as the inlet rotation of the primary shaft of the turbine rotates at 8584 RPM and the secondary shaft that connects with the pump rotates at only 2900 RPM. This gearing system has also the function of starting the main oil pump.

6.3.4. TACHOMETER DRIVE



300.01	tachometer casing	300.10++	tachometer
300.03+	spiral gear		
300.04+	bushing		
300.05+	spiral gear	300.12++	spring clutch

Figure 24 – Schematic of Tachometer Drive. (KKK manual, 1967)

A tachometer is a sensor device for measuring the rotation speed of an object such as the shaft in a turbine. This device indicates the revolutions per minute (RPM) performed by the object. The device comprises of a dial, a needle to indicate the current reading, and markings to indicate safe and dangerous levels.

Here, the critical parts to wear and tear are the spring clutch and the tachometer.

6.3.5. LUBE-OIL TRIP

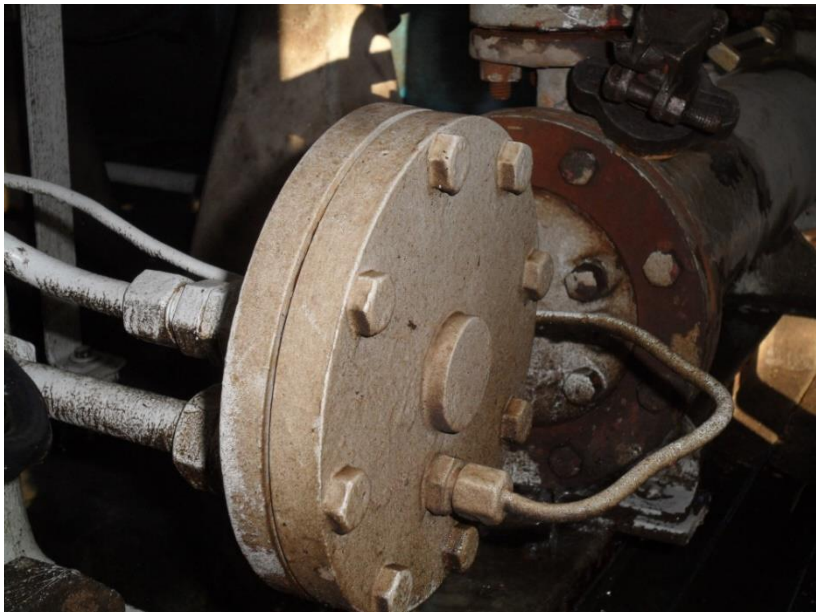


Figure 25 – Lube-oil Trip. (Hugo Araújo, 2017)

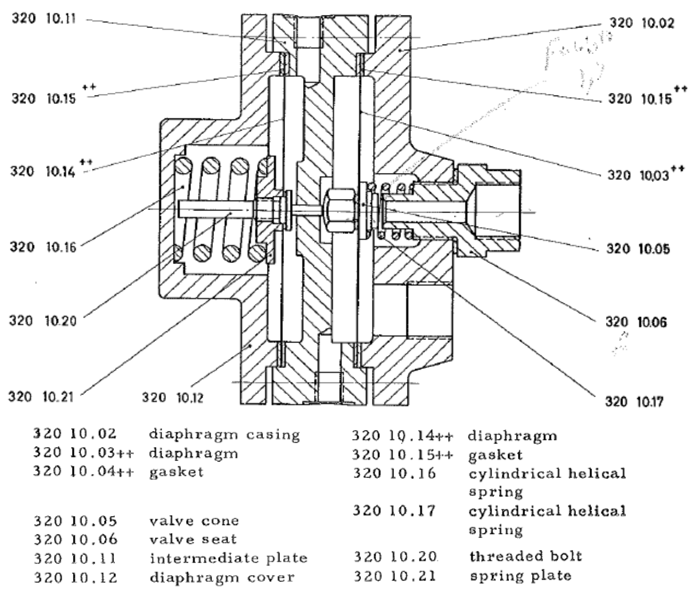


Figure 26 – Schematic of Lube Oil Trip. (KKK manual, 1967)

This is a valve of the diaphragm type and it works to equalize both regulating pressure and the lubrication pressure. Once the pressures are not equal ($\pm 7kg/cm^2$ to regulating and $\pm 1kg/cm^2$ to lubrication) this component has two different springs that allows compensating the difference.

When the pressures are equal, the oil passes and put the piston to movement letting the steam pass in the inlet station. Whenever the two pressures are not equal, the oil is discharged to the carter, the piston does not move and the turbine does not start.

6.3.6. TURBO OIL - PUMP FOR STARTING

Figure 27 – Turbo Oil for Starting. (Hugo Araújo, 2017)

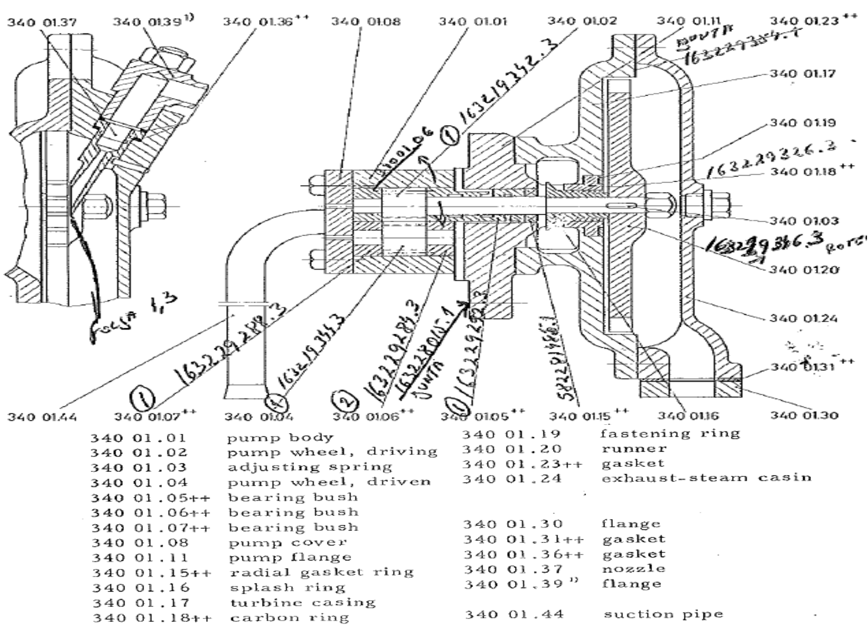


Figure 28 – Schematic For Turbo Oil – Pump For Starting. (KKK manual, 1967)

6.3.7. EMERGENCY GOVERNOR AND RELAY

Figure 30 – Emergency Governor and Relay. (Hugo Araújo, 2017)

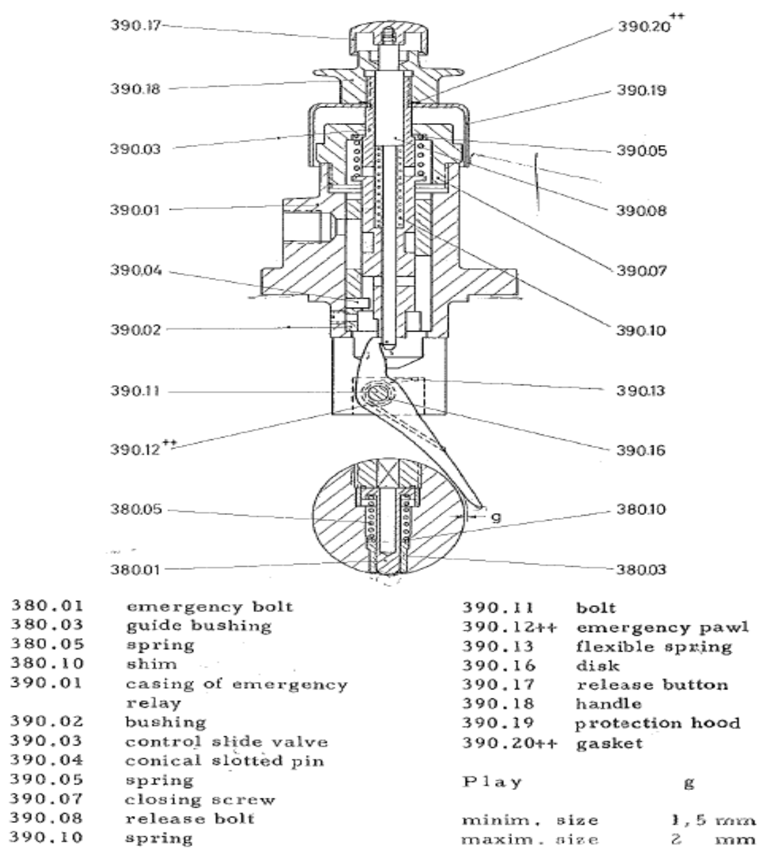


Figure 29 – schematic of emergency governor and relay. (KKK manual, 1967)

6.3.8. CANTILEVER SPRING SPEED GOVERNOR

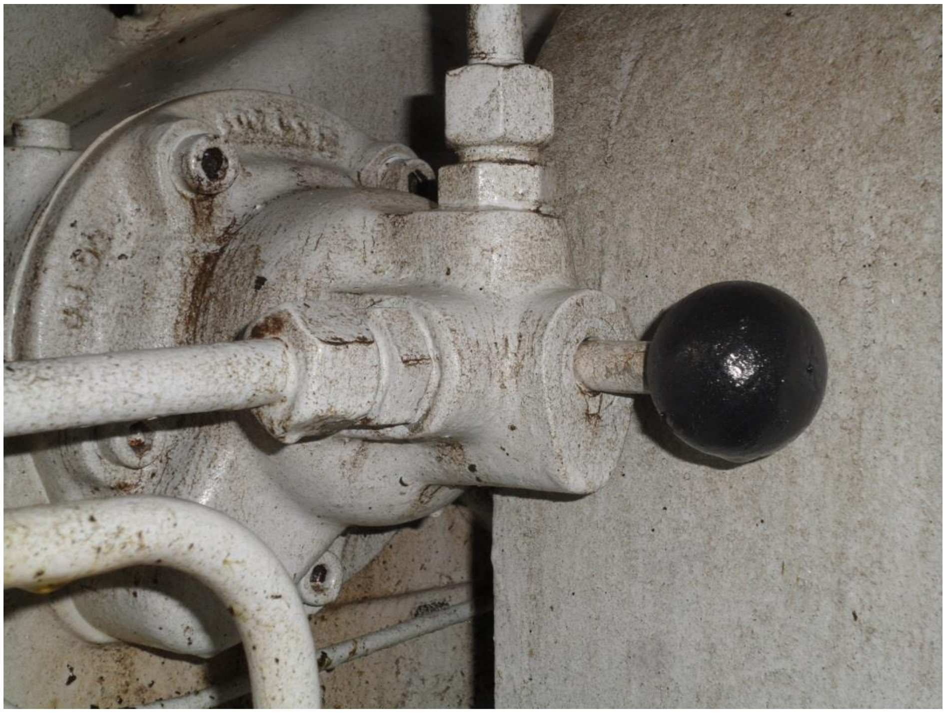


Figure 31 – Cantilever Spring Speed Governor. (Hugo Araújo, 2017)

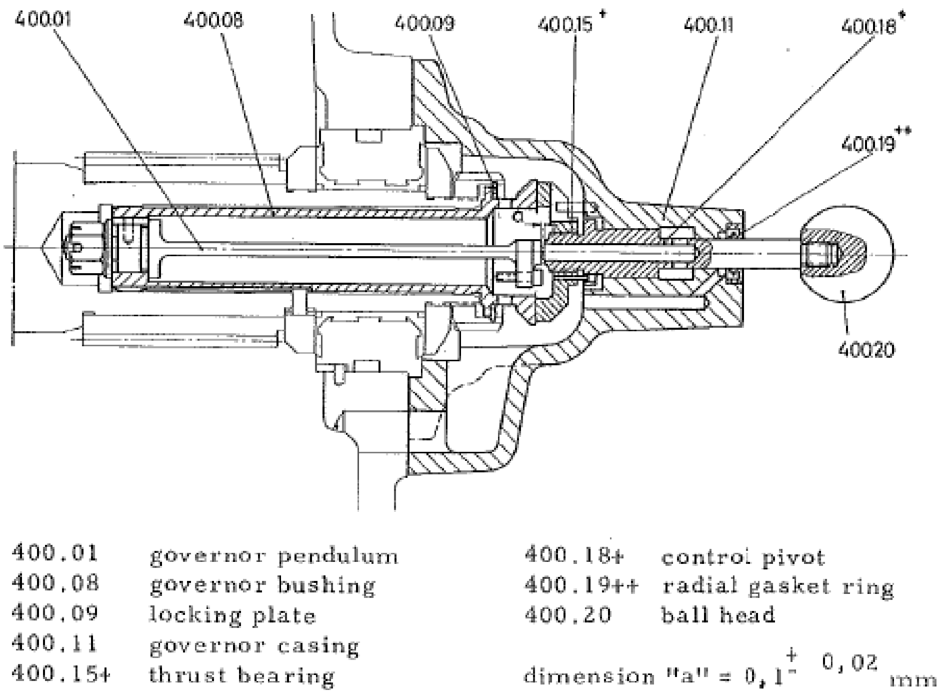


Figure 32 – Schematic of Cantilever Spring Speed Governor. (KKK manual, 1967)

Cantilever Spring Governor notes

According to the information provided by the manufacturer in the steam turbine manual, it was integrally transcript the following information:

One side of the cantilever spring with its eccentrically arranged head is tightly clamped inside the turbine shaft. The control pivot loaded by oil pressure is supported by the turbine shaft through the thrust bearing. This helps to keep constant the gap between the head of the cantilever spring and the control nozzle of the control pivot. Pipe connects the chamber at the control pivot with the chamber of the regulating valve. By means of the nozzle needle, the cross section of passage of the throttle bore of the control pivot can be adjusted.

How it works

An oil pump supplies control oil the pressure of which amounting to 10 atm and the gauge is kept constant by an overflow valve. The control oil is led to the control pivot of the cantilever-spring speed governor via the pipe line. Through the throttle bore the oil flows, on the one hand, to the control and, on the other hand, via the pipe line to the servomotor of the regulating valve. The turbine being out of operation, the control oil at the control nozzle can only flow off through the small gap between control nozzle and control pivot.

When the turbine shaft rotates, the cantilever spring is bent due to the centrifugal force of the eccentrically arranged head of the cantilever spring. Via the sickle-shaped gap thus forming, a larger quantity of oil flows off than in the initial position of the cantilever spring. Therefore, increasing speed results in decreasing regulating oil-pressure in the control nozzle. Thus the pressure in the space before the power piston of the servomotor diminishes to such an extent that the equilibrium has again been reached between the force of the valve spring and the steam forces at the valve cone on the one hand and the oil force on the other hand.

If, for instance, the load of the operating machine decreases, the speed of the turbine augments. At the same time the deflection of the cantilever-spring head and thus the sickle-shaped gap enlarge.

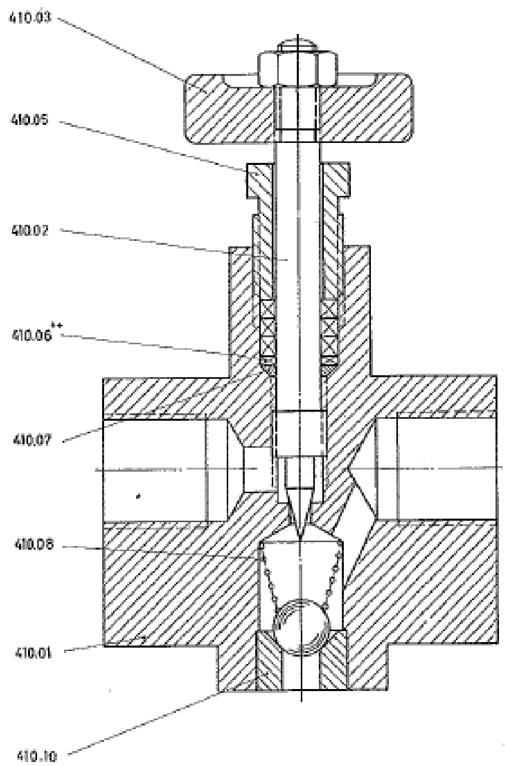
A larger quantity of oil flows off, the pressure in the space decreases and the valve closes so far that the state of equilibrium has again been realized. The droop, i.e.the speed difference between full load and no load necessary for stable control, amounts to 8% to 10% with the cantilever-spring speed governor.

The speed of the turbine can be adjusted by the nozzle needle down to 10% below and up to 5% above the operating speed.

The cantilever-spring speed governor is characterized by the following remarkable qualities:

1. Absolutely frictionless control and thus a maximum of durability.
2. Absolutely reliable response so that a particular safety governor can be dispensed with.

6.3.9. SPEED ADJUSTING DEVICE

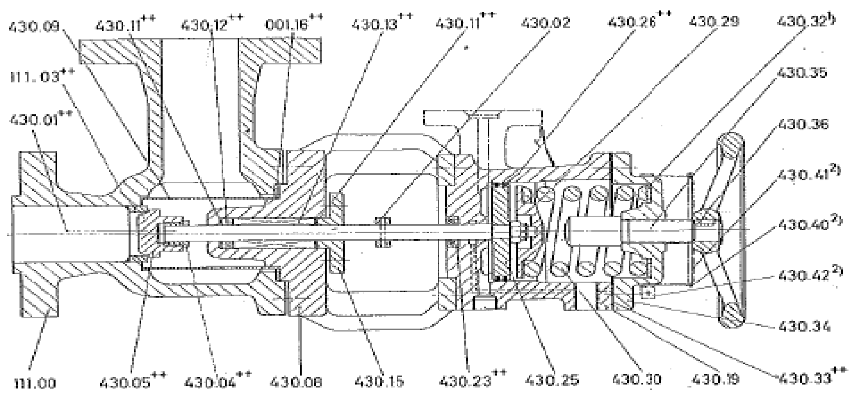


410.01	casing	410.06++	oil packing
410.02	needle	410.07	bottom ring
410.03	handwheel	410.08	spring
410.05	cap screw	410.10	bushing

Figure 33 – Schematic of Speed Adjusting Device. (KKK manual, 1967)

6.3.10. REGULATING VALVE WITH SERVOMOTOR

Figure 34 – Regulating Valve with Servomotor. (Hugo Araújo, 2017)



001.16++	gasket	430.23++	radial gasket ring
111.00	valve casing	430.25	regulating piston
111.03++	valve seat	430.26++	piston ring
430.01++	valve spindle	430.29	spring plate
430.02	splash ring	430.30	emergency spring
430.04++	cap screw	430.32 1)	spring washer
430.05++	valve cone	430.33++	gasket
430.08	stuffing box	430.34	cover
430.09	steam strainer		
430.11++	gasket	430.35	threaded spindle
430.12++	carbon ring	430.36	adjusting spring
430.13++	steam packing	430.40 2)	collar
430.15	gland	430.41 2)	cover
430.19	regulating cylinder	430.42 2)	protecting plate

+ and ++ see service instructions, chapter 7

1) These items are not always installed

2) Only in the case of outdoor erection.

Figure 35 – schematic of regulating valve with servomotor. (KKK manual, 1967)

Table 15 – Steam turbine KKK possible troubles.

TROUBLE	CAUSE	REMOVAL
Control-oil pressure too low	Filter became dirty	Clean filter
Insufficient pressure of lubricating oil	1)Lubrication throttle at the slit filter became dirty 2)Bearings worn out	Clean throttle Check bearings, if necessary readjust throttle or install spare bearings
Steam or oil packing of regulating and emergency valve untight	Wear	Tighten the gland slightly, install a new packing and a new radial gasket if necessary
Steam packings of the turbine shaft untight	Wear	Install necessary spare parts
Water in oil	Steam packing at turbine shaft untight	Install new packings
Unsteady running	1)Wear of bearings 2)Rotor deformed by water shock 3)Unbalanced running parts	Check clearances and install new spares Test the rotor for truth of rotation, install a spare rotor if necessary Balance the rotating elements dynamically
Oscillation of speed	1)Gap on the cantilever-spring speed governor too small 2)Control pivot stuck	Readjust the gap Pull the knob of the control pivot several times

Emergency mechanism does not release	Corrosion	Check mechanism and replace damaged parts
Regulating and emergency valve does not function	1)Stuffing box too strongly tightened 2)Valve spindle covered with salt	Loosen stuffing box Clean valve spindle
Turbine does not stop when regulating and emergency valve is closed	Valve seat untight	Regrind the valve seat or install suitable spares
Maximum turbine output is no longer obtained	Nozzle system contaminated by salt	Open turbine and clean nozzles

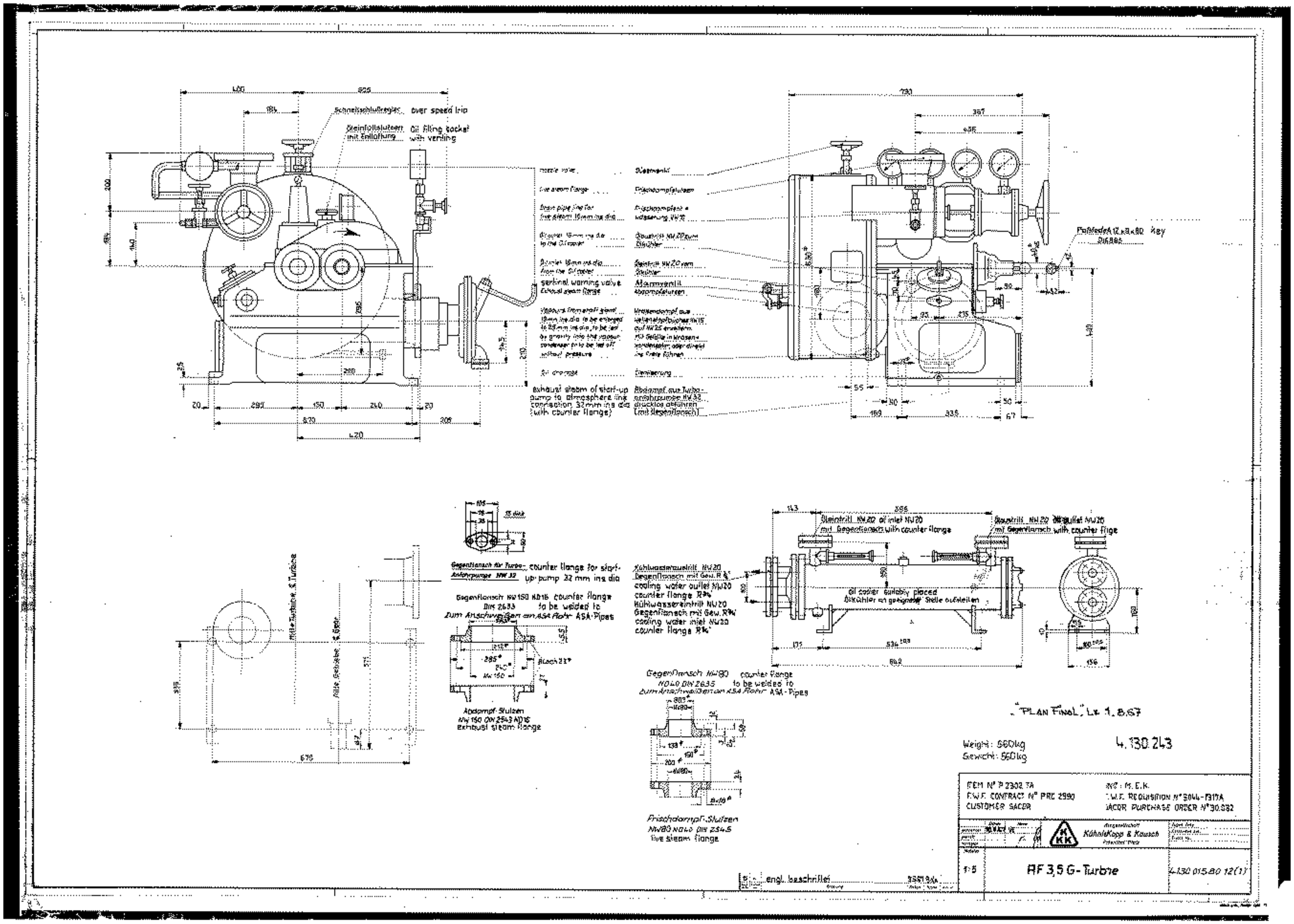


Figure 36 - Exploded View of the Turbine. (KKK manual, 1967)