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Risk Based Maintenance for Compressor Systems

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MASTHER THESIS

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Summary

This thesis reviewed part of the maintenance activities in a compressor system using the risk based maintenance philosophy. The goal was to verify if a contribution could be made to the maintenance plan of the system.

The risk based maintenance philosophy is applied according to the recommendations in NORSOK Z-008. A reliability model is proposed to verify the impact of the new maintenance approach and to make better informed decisions in the maintenance management process. The model used data from both industry database and from the maintenance history of the FPSO from the case study. The model simulated the maintenance behavior of the compressor system using the MAROS software from DNVGL.

The reciprocating compressor was found to be the equipment with the lowest mean time to failure from the main equipment in the high pressure compressor trains, according to data from the reliability database. For this reason it was selected to be modeled for preventive maintenance. Simulation results indicate that the frequency of preventive maintenance interventions being used in the FPSO of the case study could be reviewed and possibly reduced, with advantages to the availability of the system. The results also indicate that it is beneficial to include conditional monitoring in the reciprocating compressors.

Preface

This thesis is submited to the Norwegian University of Science and Technology (NTNU) for partial fullfilment of the requeriments for the degree of master in science during the spring semester of 2015.

The work has been carried out with support of and FPSO operator company made anonymous and Oceaneering Asset Integrity (OAI). The FPSO operator provided maintenance data for the case study and OAI provided sotfware licenses and database for developing failure mode and effects analysis, consequence classification and generic maintenance concepts for the case study. The idea for this project was brought up during the conclusion of the thesis project carried out during the autumn semester of 2014.

This work has been performed at the Institute of Marine Technology, NTNU, Trondheim, with supervision of Professor Arne Ulrik Bindingsbø and co-supervision of Dr. Erlend Meland from the company Oceaneering Asset Integrity.

This work presents an application of the risk based maintenance method to a case study and a reliability model to assess the impact of maintenance activities in a system. Target audiences are:

- Engineers and Technicians working for the offshore oild and gas industry interested in maintenance improvement using a risk based approach.
- Engineering students with a special interest in risk based maintenance and reliability modeling.

Acknowledgment

I would like to thank the following persons for their help during this project:

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The **Operation Strategies & Support** and the **Senior Technical Integrity Engineer** at the company owner of the FPSO used as case study in this thesis, for making data available and for creating the opportunity for this project.

My boss, **Kjersti Løken**, LCI Manager at OAI, also for creating the opportunity for this project.

My colleagues **Mads Herdahl**, Asset Management Engineer at OAI, **Kim E. Holsen**, Asset Management Engineer at OAI and **Haaken A. Moe**, for being useful discussion partners and providing me with hints and resources that have been to great assistance in my work.

Finally, I would like to thank my grandmother **Zélia Pereira** and my partner **Håkon Risbakk** for being the most supportive duo I could ever wish for.

N.M.O.

List of Acronyms

CM Corrective maintenance

CMMS Computerized maintenance management system

EN European Standard

FH Functional hierarchy

FMEA Failure mode and effects analysis

GMC Generic maintenance concept

HSE Health, safety and environment

ISO International Organization for Standardization

MF Main function

O&G Oil and gas

OREDA® Offshore and onshore reliability data

P&ID process and instrumentation diagram

PM Preventive maintenance

PSA Petroleum Safety Authority

RBI Risk based inspection

RBM Risk based nmaintenance

RCM Reliability centred maintenance

TH Technical hierarchy

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Chapter 1

Introduction

1.1 Background

An offshore oil and gas (O&G) platform is a complex environment that comprises equipment working under extreme conditions. When a component belonging to a critical system fails, severe accidents may occur. [28] explores major offshore accidents in the O&G industry, one of which being Piper Alpha in 1990, when a gas leak in the compression area started an accident that claimed 166 lives. Offshore O&G operators spend a considerable amount of effort and resources in maintenance strategies to avoid such catastrophic events.

Besides being important to protect lives, adequate maintenance is also paramount not to harm the environment and promote a profitable operation of the platform. Inadequate maintenance may lead to lower availability of installations. This is not a desired characteristic of an installation, as it reduces the production of the installation and consequently the income of the operator. [2]

1.1.1 Integrity of Offshore Platforms

According to [3], asset integrity

"is achieved when facilities are structurally and mechanically sound and perform the processes

and produce the products for which they were designed and is the result of good design, good construction and good operating practices."
The same report also defines asset integrity briefly as “the prevention of major incidents”. There are many sources of incidents in an offshore platform, and currently the best way to account for all of them is to make a comprehensive model for risk assessment, as proposed by [5].

1.1.2 Maintenance Philosophies

The last century maintenance evolved from being an activity only performed to restore components to its operational state, to also including activities that are aimed at preventing equipment failure. In some forefront industries, these preventive maintenance activities started to escalate operational costs of new developments to economically inefficient levels. In the search for a new approach, the commercial aircraft industry, later followed by the military forces, the nuclear power industry and the offshore O&G industry the philosophy of a Reliability Centered Maintenance (RCM) was developed ([25], [21]). As [21] states, “RCM was designed to balance the costs and benefits, to obtain the most cost-effective Preventive Maintenance (PM) program”. Cost benefit considerations of choosing RCM are dealt with in [25].

RCM managed to bring a new way of thinking when it prioritized function preservation instead of equipment preservation. The impact of a failed component in the functions of the system should be taken into account in the prioritization of maintenance activities. RCM expanded the study of failure modes. By understanding their nature and how they may hinder the different functions of the system, maintenance tasks can be made more efficient and applicable.

Risk Based Maintenance (RBM) builds on the RCM concepts, taking it further in implementing risk considerations [9]. As safety and maintenance are not unrelated subjects, the RBM approach aims at unify both subjects under a single umbrella. Maintenance is now done in a cost-effective way to keep system functions operational while taking overall safety under consideration.

1.2 Research Question

Maintenance is an important subject because of what it can accomplish. [7] lists the following maintenance objectives: availability, cost reduction, product quality, environment preservation, safety and asset value preservation. When the maintenance management of assets is optimal according to the maintenance objectives, an organization can expect to increase production, while using less resources and keeping people and the environment safe. In the O&G sector making the right maintenance decisions directly impacts the success of offshore platform operation.

A maintenance plan is never considered finished, and can always be improved. This is because the knowledge of a system increases with time, and that degradation due to aging gradually takes its toll. Adjustments to the maintenance plan can be made during the useful life of any asset. In the quest for maintenance improvement of any system, it is important to bear in mind that,

"absolute and lasting optimization of the maintenance of any working system is not possible; the optimum is never achieved because it is a moving target and because the data for its estimation are never quite complete or up-to-date, and seldom sufficient in number." [23]

If absolute and lasting optimization of the maintenance of a system is not possible, it is important to be able to judge when improvements to maintenance should be implemented .It is also important to evaluate what can be gained from that improvement.

The challenge of increasing the availability of a system includes being able to make informed decisions about how to handle the maintenance of an asset. From this necessity, the research question is raised:

RQ1 Is there potential for improvement of the availability of a system when applying a risk based maintenance philosophy?

1.3 Objectives

The following objectives were outlined from the research question presented.

Objective 1 Apply the principles of the risk based maintenance philosophy to the gas compression system of a platform.

Objective 2 Create a reliability model of the gas compressor system, using a reliability database.

Objective 3 Compare the outcome of the new philosophy applied to the system.

Chapter 2

Theory

2.1 Maintenance

2.1.1 Overview

[7] defines maintenance as the *''combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function''.*

[7] further divides maintenance primarily in two subgroups: corrective and preventive actions. Corrective actions, or corrective maintenance (CM), are actions intended to restore the system or component to its up state. Preventive actions, or preventive maintenance (PM), are actions intended to restore the system or component to a "as good as new state", or as close as possible to it, hopefully avoiding failure completely.

CM can be further divided into deferred and immediate, as it may be advantageous to postpone a repair due to an unimportant failure consequence and limitation of maintenance resources.

PM can be further divided into predetermined and condition based (CBM). Predetermined actions are based either on calendar time or running time/cycles, being scheduled at regular intervals. CBM actions are triggered by a degradation threshold. Inspections are one of the many

PM actions available. They can be scheduled at regular intervals, following national regulatory standards or can have their scheduling optimized by following conditional intervals that depend on the present degradation state of the item. This last approach is called Risk Based Inspection (RBI) and is developed in the recommended practice [6].

Today, optimization principles prioritize maintenance actions that are condition based or run to failure, depending on the consequence of failures. These principles try to avoid unplanned CM (unexpected failures) and calendar based PM because of the higher costs, production losses, and fail introduction associated with these activities. Maintenance optimization is a 3rd generation concept, and started with the reliability centered maintenance (RCM) philosophy [21].

Figure 2.1 shows the introduction of each type of maintenance action in its generation.

2.1.2 Evolution of Maintenance

[18] makes reference to three generation of maintenance philosophies. The first generation lasted until the beginning of World War II. Then, maintenance consisted of repair work when something failed. Corrective maintenance was the norm and preventive maintenance was not given much consideration.

The second generation was introduced by the need of keeping production up and minimizing downtime. This was caused by the demand pressure for goods present in the war time and a more mechanized industrial environment. It was no longer enough to repair a broken component, but it was necessary to avoid component failures altogether. In this generation preventive maintenance is introduced.

The third generation was caused by a cost dilemma. Engineers created increasingly complex machinery and the maintenance scope and costs grew accordingly. It was clear that some sort of prioritization had to be done to discriminate which maintenance activities were worthwhile. This was the birth of RCM that deals with the preservation of functions instead of preservation

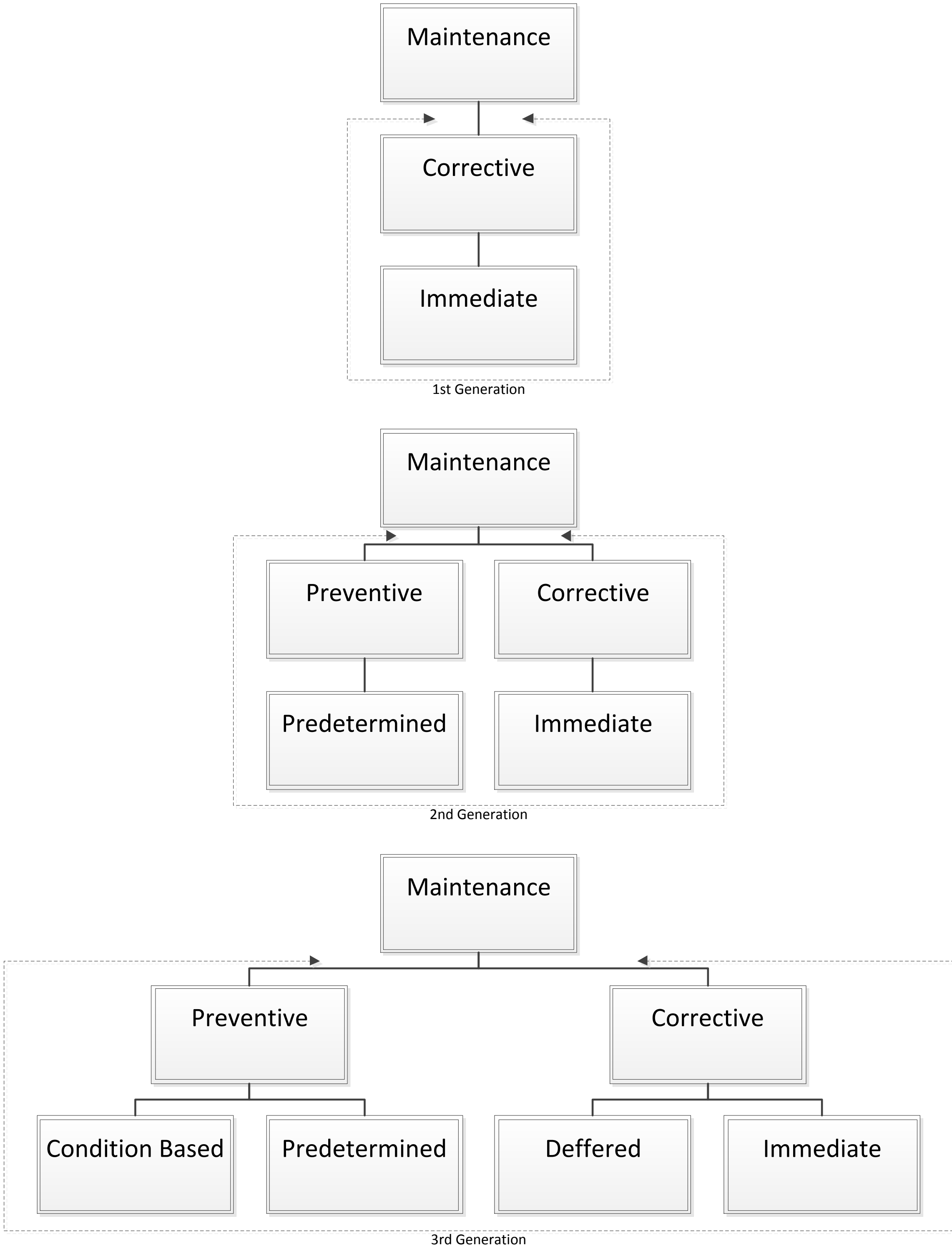


Figure 2.1: Overall view of maintenance

of components. More on RCM is found in section 2.4. CBM strategies were also introduced during this generation, together with an extensive development of maintenance management practices.

[9] builds on [18] and suggests a fourth generation of maintenance philosophy. This last generation has increased awareness of safety and the realization that maintenance and safety should be treated as one single matter, as maintenance greatly influences safety and should be planned having safety in mind. In this context Risk Based Maintenance (RBM) was introduced, RBM is discussed further in section 2.2 .

In a nutshell, maintenance evolved from fixing components, to avoid system failure, to cost-effective operations, to risk reducing measures. Figure 2.2 shows how each generation's philosophy expanded on the previous one.

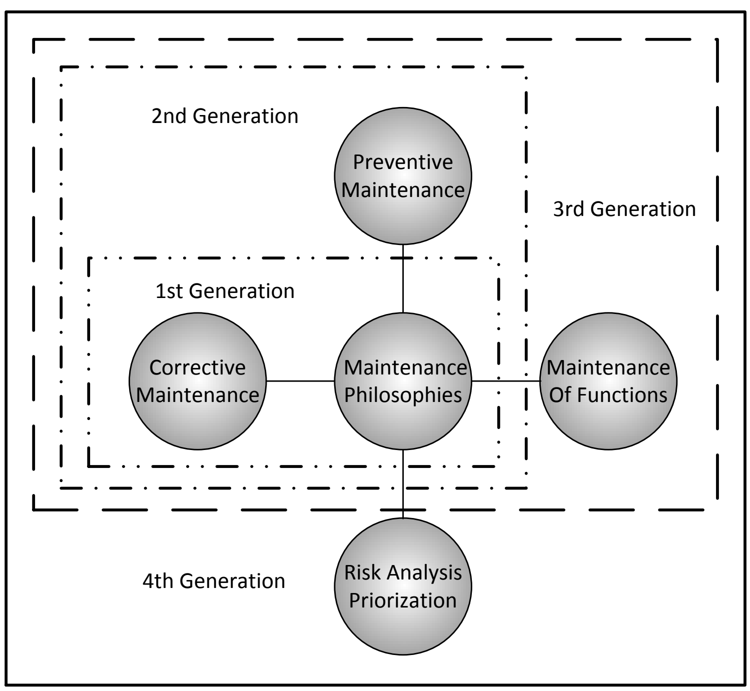


Figure 2.2: Maintenance generations

2.1.3 Maintenance Management

As previously stated, the third generation introduced management theories to organize and control the maintenance activities. Maintenance management encompasses all activities that determine maintenance goals, strategies and responsibilities as well as how they are put in practice, in terms of planning, control and continuous improvement [7]. The Norwegian Petroleum Safety Authority published in 1998 a maintenance management loop that is replicated in figure 2.3. This image is also printed in the in NORSOK Z-008 standard [8]. [17] proposed a similar approach for a generic maintenance management model.

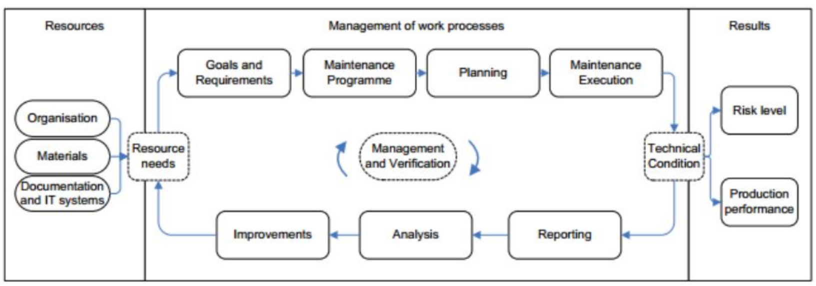


Figure 2.3: Maintenance management loop according to PSA as presented in NORSOK Z-008.

A maintenance management process starts with the definition of the maintenance objectives. These goals should be aligned with the company goals and with the operational objectives and strategies. According to [17] these are often inconsistent with each other and a suggestion to reconcile them is the selection of key performance indicators (KPIs) that are relevant to the company mission and are aligned with its strategy. The standard [2] offers a comprehensive list of KPIs for maintenance.

To create the maintenance program it is necessary to define priorities, which is done following a selected strategy. After priorities are identified, PM plans and resources are taken care of, starting by the systems of higher impact.

It is important to note that a maintenance management model does not belong to a specific maintenance philosophy, but is simply a way of organizing and controlling all the work involved in the subject, which is necessary for complex system maintenance.

2.1.4 Maintenance Activities

Maintenance activities were classified by [17] in the following types:

- Inspection
- Monitoring
- Routine maintenance
- Overhaul
- Rebuilding
- Repair

One way to exemplify the difference between inspection and monitoring is that while inspection is done before, during or after another maintenance activity, monitoring happens in the operating state. While inspection checks if a characteristic or property complies with a given specification, monitoring evaluates changes in parameters with time. Online condition monitoring is often expensive, but when the value of the process is high enough, as it is in O&G installations, it justifys the application [26]. Condition monitoring can trend the health of internal components and alert before a failure occurs

Routine maintenance activities are usually scheduled following recommendations from manufactures or best practices and involve simple tasks such as cleaning, lubricating, visual checks, tightening of connections, etc.

Overhauls are performed either partially or complete and entails the dismantling of the item to bring it to a "as good as new condition". When the item is improved or modified during reasembly, it becomes a rebuilding action.

Repair is executed to restore an item to a state in which it can perform its required function. Repair happens in three stages: fault diagnosis, fault correction and function check-out.

These activities are selected according to the failure modes expected for each item, and also according to prioritization.

2.2 Safety and Risk

Safety refers to the state of being safe or freedom from the occurrence or risk of injury, danger, or loss. It can also be defined as the quality of averting or not causing injury, danger, or loss. To increase a system's safety is to minimize the chances of an accident to occur [28].

Safety and risk are two concepts that relate closely to each other. Risk can be defined as the combination of the probability of an event and its consequence ([4]). According to [28], the most common way of expressing risk is by its expected value, which, being a statistical expression may never be observed.

2.2.1 Dimensions of Risk

There are different ways of approaching the dimensions of risk. Dividing it in risk to personnel, to the environment and to the asset is one common way of doing it ([28]). Another approach is the division in cost, production and safety. Here, the safety dimension incorporates every risk related to health, safety and environment (HSE), the production dimension relates to every risk that compromises the installation production, and the cost dimension to events that only bring cost consequences without affecting production or safety.

2.2.2 Risk Matrix

Risk matrices are largely used in risk analysis. Probability is plotted against consequence and the result is the risk level of an event. Companies define their risk matrices based on their corporate acceptance of risk and on national regulations. In the risk based maintenance strategy, risk matrices are used for consequence classification and for stock strategy of spare parts.

Freq. cat.	Freq. per year (*), (**)	Mean time between failure (year)	RISK		
F4	> 1	0 to 1	M	H	H
F3	0,3 to 1	1 to 3	M	M	H
F2	0,1 to 0,3	3 to 10	L	M	H
F1	< 0,1	Long	L	L	M
			Loss of function leading to:		
Consequence category			**C1**	**C2**	**C3**
Consequence safety			No potential for injuries. No effect on safety systems.	Potential for injuries requiring medical treatment. Limited effect on safety systems.	Potential for serious personnel injuries. Render safety critical systems inoperable.
Consequence containment			Non-flammable media Non toxic media Natural/normal pressure /temperature media	Flammable media below flashpoint Moderately toxic media High pressure/ temperature media (>100 bar/80 °C)	Flammable media above flashpoint Highly toxic media Extremely high pressure /temperature media
Consequence, Environment; restitution time (***)			No potential for pollution (specify limit) < 1 month	Potential for moderate pollution. 1 month – 1 year	Potential for large pollution. > 1 year
Consequence production			No production loss	Delayed effect on production (no effect in x days) or reduced production	Immediate and significant loss of production
Consequence other			No operational or cost consequences	Moderate operational or cost consequences	Significant operational or cost consequences

(*) Based on failure mode
(**) Typical failure rate ref OREDA(®: 1-100 * 10^-6 for rotating equipment (0.01-1 1/yr)
(***)The consequences to the external environment differ significantly depending on the chemical composition of the released substance, volume and the recipients (open sea, shore, earth or atmosphere). Here restitution time is used as a common denominator.

Figure 2.4: Risk matrix example from NORSOK-Z008

Figure 2.4 presents an example of risk matrix used for consequence classification and for decisions.

2.2.3 Risk Assessment

Risk assessment is the consideration of something using the risk perspective. The ISO31000 [5] standard proposes a largely accepted risk assessment process composed of seven parts.

2.3 System Reliability

Reliability of technical systems emerged just after World War I and was then used in connection with comparing operational safety of airplanes. The reliability was measured as the number of accidents per hour of flight time [22]. During the World War II, a probability product law of series components was developed by the engineer Robert Lusser (Lusser's Law) to explain the behavior of a missile system that presented many failures, even when using high-quality parts and being assembles with careful attention to details.

Lusser's law states that the reliability of a series system is equal to the product of the reliability of its component subsystems, if their failure modes are known to be statistically independent. It demonstrates that if the system is assembled in series and has a large number of components, the system reliability will be low, even if the individual components have high reliability.

The variations of time to failure of an item can be modeled as probabilistic distributions depending on the characteristics of the item and the behavior of the failure mode. Commonly used distributions to model failure are: binomial, Poisson, normal, lognormal, exponential and Weibull [10].

The reliability function (sometimes called survivor function) of one item is defined by

$$R(t) = 1 - F(t) = Pr(T > t) \quad \text{for t} > 0 \tag{2.1}$$

or

$$R(t) = 1 - \int_0^t f(u)\,\mathrm{d}u = \int_t^\infty f(u)\,\mathrm{d}u \tag{2.2}$$

where $F(t)$ denotes the probability that the item fails within the time interval (0,t], and $f(u)$ is the probability density function, defined by

$$f(t) = \frac{\mathrm{d}}{\mathrm{d}t}F(t) \tag{2.3}$$

The failure rate function, which is the probability that an item will fail in a given point in time (or within a time interval $(t, t+\Delta t]$ with Δt small), is defined by

$$z(t) = \frac{f(t)}{R(t)} \tag{2.4}$$

If a large number of identical items is put into operation at time $t = 0$, then $z(t)\dot{\Delta} t$ will roughly represent the relative proportion of items still functioning at time t. The plot of these results can take many forms (figure 2.5) and indicates how the failure rate behaves in time.

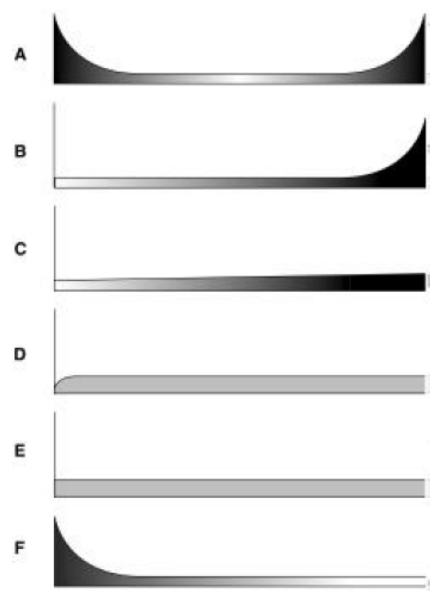


Figure 2.5: Patterns of failure.

Figure 2.5.A is known as the bathtub curve and represents an item that has high failure rate in its initial phase (burn-in period) and in the end of its life (wear-out period), while presenting a stable failure rate in between (useful life period). Infant mortality can be reduced with factory testing while the wear-out period can sometimes be postponed with maintenance interventions.

The mean time to failure (MTTF) of an item is defined by

$$MTTF = E(t) = \int_0^{\infty} t f(t) \mathrm{d}t \tag{2.5}$$

and if MTTF < ∞, it can be also expressed as

$$MTTF = \int_0^{\infty} R(t) \mathrm{d}t \tag{2.6}$$

2.3.1 Statistical Failure Distributions

The different failure behaviors can be modeled as statistical distributions. The gamma and the exponential distributions are presented next. These distributions play an important role in reliability problems. Time to failure of component parts and electrical systems are often nicely modeled by the exponential distribution [29].

The gamma distribution derives from the gamma function. The gamma function is defined by

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} \mathrm{d}x \tag{2.7}$$

The continuous random variable x has a gamma distribution with parameters $\alpha > 0$ and $\beta > 0$, if its density function is given by

$$f(x;\alpha,\beta) = \begin{cases} \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2.8}$$

The mean and variance of the gamma distribution are respectively

$$\mu = \alpha\beta, \quad \text{and} \quad \sigma^2 = \alpha\beta^2 \tag{2.9}$$

The exponential distribution is a special case of the gamma distribution when $\alpha = 1$. Its density function is given by

$$f(x,\beta)=\begin{cases}\frac{1}{\beta}e^{-\frac{x}{\beta}} & \text{if } x>0\\ 0 & \text{elsewhere}\end{cases} \tag{2.10}$$

The mean and variance of the exponential distribution are respectively

$$\mu=\beta, \quad \text{and} \quad \sigma^2=\beta^2 \tag{2.11}$$

One important property of the exponential distribution is that its failure rate is constant.

2.3.2 Markov Process

A Markov chain is a stochastic process that possesses the Markov property. A process is said to have the Markov property if

$$Px(X(t+s)=j|X(s)=i, X(u)=x(u), 0\le u<s) \tag{2.12}$$

$$=Pr(X(t+s)=j|X(s)=i) \tag{2.13}$$

$$\text{for all possible } x[u], 0\le u<s \tag{2.14}$$

That is, if the present state of the process is known, the future development of the process is independent of anything that has happened in the past. A continuous-time Markov chain is called a Markov process. Markov processes are used to model systems that possess more than two states (operational and failed). State transition rates matrix and transition diagrams are used to calculate the time that a system spends in each of its states.

2.4 Reliability Centered Maintenance

2.4.1 Principles

The idea behind RCM is to establish a logical process to design appropriate maintenance activities to support complex systems, with optimal frequency, reduced maintenance shutdowns and consequently decrease costs.

RCM identifies maintenance activities and their frequencies based on functional analysis of an operational context. According to [25], the four unique features of the RCM methodology are:

1. Preserve functions
2. Identify failure modes that can defeat the functions
3. Prioritize function need
4. Select only applicable and effective PM tasks

These four features can be presented also as the answer to seven questions ([18]). Feature one: 1) What are the functions and associated performance standards of the asset in its present operating context? 2) In what way does it fail to fulfill its functions? Feature two: 3) What causes each functional failure? 4) What happens when each failure occurs? Feature three: 5) In what way does each failure matter? Feature four: 6) What can be done to predict or prevent each failure? 7) What should be done if a suitable proactive task cannot be found?

In RCM, a failure mode and effects analysis (FMEA) is normally used to answer questions 1 to 4. For a subsystem, for example, an FMEA worksheet will include a list of functions performed by that subsystem, a list of failures affecting each functions (functional failures), a cause or causes for that failure to occur (failure mode), and a short description of what happens when each failure occurs (failure effect).

The answer to the fifth question addresses consequences of failures, and introduces notions of risk and safety. Although the consequences could be captured in the failure effect part of the FMEA, the likelihood of the event isn't introduced in the analysis, so it is the norm that only the reasonably likely failures are registered, regardless of the consequences [18].

2.5 Compressor System

The stream produced by an oil well is composed of gas, oil, water and solid particles. This stream travels through the production wellheads and through the production test manifolds before separation. When reaching the production separators, each phase follows a different path. The gas is directed to the gas compressors, which is the system being worked in this thesis. If the compressor system is down, production must stop.

A standard compressor system is composed of a high and a low pressure train, both consist of several stages. Each stage takes gas from a suitable pressure level form the separators and from previous stages in the compression train. A typical stage has a heat exchanger, a scrubber and a compressor. The heat exchanger is used to cool the gas, as a lower temperature in the gas requires less energy to compress this gas. The scrubber to remove small fractions of liquid from the gas (either water or hydrocarbon), as liquid droplets entering the compressor will contribute to the erosion of the compressor's blades.

The division in several trains is aimed at improving the maintainability and availability of the system, as well as improving the capacity of the system. Compressors are driven by gas turbines or electrical motors.

The compressor performance control has the objective of keeping the operating point close to the optimal set point by means of controlling the outputs, such as the speed setting.

The compressor system investigated in this thesis is comprised of three sections: low pressure booster compressor, high pressure suction and high pressure compression. The high pressure compression section is divided in three identical compression trains (trains A, B and C). The compression trains were designed to function to 33% of the capacity each, in the peak production years, and later to 50% each, with one train in standby, which will mean an increase in the redundancy of the system.

Each high pressure compression train consists of four compressor stages with interestage cooling and vapor/liquid separation, with condensate liquids returning to the previous compression stage . The following process description is taken from the compressor system operating guide:

(...) gas from the high pressure compressor suction manifold (at 30°C) is separated within the 1st stage high pressure compressor suction scrubber, with liquids returned to the closed drain system. the separated gas is then compressed in two parallel throws of a reciprocating compressor, from 11.3 barg to 30.6 barg. The vapor discharge, along with the condensate return from the 3rd stage high pressure compressor suction scrubber is cooled in the 2nd stage hp compressor suction cooler to a temperature of 30°C.

The gas/liquid from the 2nd stage high pressure compressor suction cooler are separated within the 2nd stage high pressure suction scrubber, with liquids returned to the high pressure compressor common suction scrubber. The separated gas is then compressed in two parallel throws of the reciprocating compressor, from 29.9 barg to 79.2 barg. The vapor discharge, along with the condensate return from the 4th stage high pressure compressor suction scrubber to a temperature of 35°C. The higher temperature is to avoid hydrates in the liquid recycle line from the 3rd stage high pressure compressor suction scrubber.

The gas/liquid from the 3rd stage high pressure compressor suction cooler are separated within the 3rd stage high pressure suction scrubber, with condensate/water returned to the 2nd stage high pressure compressor suction cooler. The separated gas is the compressed in a single throw of the reciprocating compressor, from 78.5 barg to 170.9 barg. The vapor discharge is cooled in the 4th stage high pressure compressor suction cooler to a temperature of 30°C.

The gas/liquids form the 4th stage high pressure compressor suction cooler are separated within the 4th stage high pressure compressor suction scrubber, with water (low flow rates) returned to *the 3rd stage high pressure compressor suction cooler. The separated gas is then compressed in a single throw of the reciprocating compressor, from 169.9 barg to either 352 barg, or the back pressure exerted by the gas reinjection reservoir (typically 300 bar). The vapor discharge is then routed to the high pressure fuel gas system or the gas reinjection pipeline, depending upon which supply is required. The final discharge temperature is kept below 65°C in accordance with the Design Basis.*

The compression trains have 4 stages. Each 1st stage is composed of a reciprocating compressor and a scrubber. 2nd to 4th stages are composed of a cooler, a reciprocating compressor and a scrubber. To control the process, there are level, temperature and pressure transmitters, as well as control valves. As previously stated in the RCM and GMC sections, 2.4 and 3.2.5, it is important to understand the failure modes of a maintainable item in order to select appropriate maintenance activities for that item. The next sections present the FMEA for these items.

2.5.1 Reciprocating Compressor FMEA

FMEA stands for Failure Mode and Effects Analysis. It is a technique used to identify and analyze all significant failure modes and effects associated with the particular system under consideration.

An FMEA is recommended when critical or complex systems or tools are being used. An FMEA is a step by step walk through of a system, where possible failure modes are evaluated and their leading up to an unwanted event are listed. Here, only the reciprocating compressor will be analyzed, but all equipment and instruments belonging to the gas compressing system should undergo the same procedure so that appropriate maintenance activities can be selected to form the generic maintenance concepts.

The following fields are part of an FMEA:

Failure Mode is the manner in which the inability of an item to perform a required function occurs [7]. A failure mode may have one or more failure mechanisms.

Failure Mechanism is a physical, chemical or other process which may lead to failure [7]. Examples of failure mechanisms are corrosion, fatigue, wear, etc.

Effect of failure is the immediate consequence of a failure. That is, what happens to the system or process if the failure mode takes effect.

Failure cause is the circumstance during specification, design, manufacturing, installation, use or maintenance that result in failure[7]. That is, the underlying reason that caused a failure to occur.

Process function	Failure Mode	Effect of failure	Failure Mechanism	Failure cause
Gas Compression	Abnormal instrument reading	Faulty signal causes unsafe operation of compressor train	Faulty signal/indication/alarm	Instrument failure, open circuit, short circuit, out of adjustment, software failure, vibration
Gas Compression	Abnormal instrument reading	Bearing failure causes compression to shut down	Vibration	
Gas Compression	Breakdown	Breakage of mechanical component causes compression train to shut down	Mechanical failure - general	Wear, vibration, wrong assembly
Gas Compression	Breakdown	Surge causes compression train to shutdown	Instrument failure - general	open circuit, short circuit, out of adjustment, software failure, vibration
Gas Compression	Breakdown	Foreign object in compressor causes compression train to shutdown	Misc. External influences	Wrong assembly
Gas Compression	Breakdown	Bearing failure causes compression to shut down	Vibration	Bearing failure
Containment	External leakage - process medium	Hydrocarbon release causing unsafe operation	Corrosion	Chemical reaction
Containment	External leakage - process medium	Failure of seals/gaskets causing unsafe operation	Material failure - general	Wear
Gas Compression	External leakage - utility medium	Failure of seals/gaskets causing unsafe operation	Clearance/alignment failure	Wrong assembly, vibration, wear
Gas Compression	External leakage - utility medium	Failure of seals/gaskets causing unsafe operation	Leakage	Material failure
Gas Compression	Fail do stop on demand	Unsafe operation of compression train	Combined causes	Mechanical failure, instrument failure
Gas Compression	Fail do stop on demand	Unsafe operation of compression train	Instrument failure - general	open circuit, short circuit, out of adjustment, software failure, vibration

Table 2.1: Process reciprocating compressor FMEA

Chapter 3

Case study: Compressor System

This chapter is about the method used. It starts explaining the selection of the gas compression system as a case study. Next, the principles of risk based maintenance and consequence classification are presented. Finally, the reliability model is explained.

3.1 Selection of case study

[11] investigated the maintenance work history from an offshore platform located in the North Sea. Results concluded that the gas compression system was a major cause for unplanned production downtime through the years. The investigation also revealed that the three high pressure compressor trains (systems 431, 432 and 433 in figure 3.1) were primarily responsible for the high demand of corrective works in the period, followed by the high pressure gas fuel system (system 434).

The high pressure gas compression trains were selected to illustrate the RBM methodology with the prospect of contributing to reduction of downtime in the FPSO.

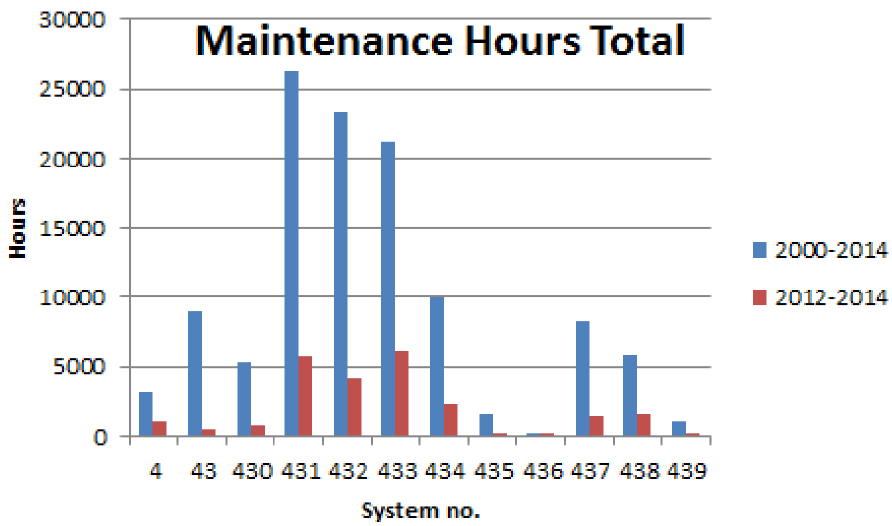


Figure 3.1: Maintenance hours in the gas compression and treatment system.

3.2 Risk based maintenance and consequence classification

3.2.1 Principles

[15] divides the risk based maintenance methodology in four modules: identification of the scope, risk assessment, risk evaluation, and maintenance planning, while [9] states that there are two stages (risk assessment and maintenance planning based on risk), comprised of six modules: hazard analysis, likelihood assessment, consequence assessment, risk estimation, risk acceptance and maintenance planning. [8] describes four key elements: consequence classification of functional failure, creation of generic maintenance concepts (GMC), FMECA/RCM/RBI when GMCs are not applicable, and use of consequence classification and additional risk factors to create priorities concerning corrective maintenance and handling of spare parts. The outcome is a maintenance plan where risk is used to prioritize and order resources and maintenance activities.

[8] explains that “consequence classification expresses what effect loss of function can have on HSE, production and cost/other”. Figure 3.4 shows the consequence classification process.

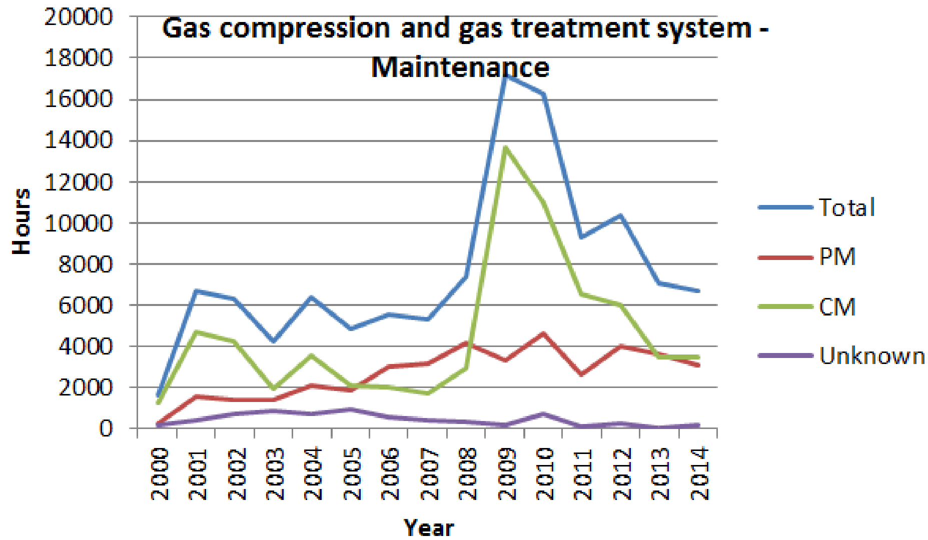


Figure 3.2: History of maintenance hours in the gas compression and treatment system through the years.

3.2.2 System definition and technical hierarchy

A technical hierarchy (TH) describes the technical structure of the installation in a hierarchical format and is created for the following reasons:

- to show equipment interdependencies
- to organize documentation
- to organize various information in a CMMS
- to plan operations
- to allocate cost
- to plan maintenance activities, etc.

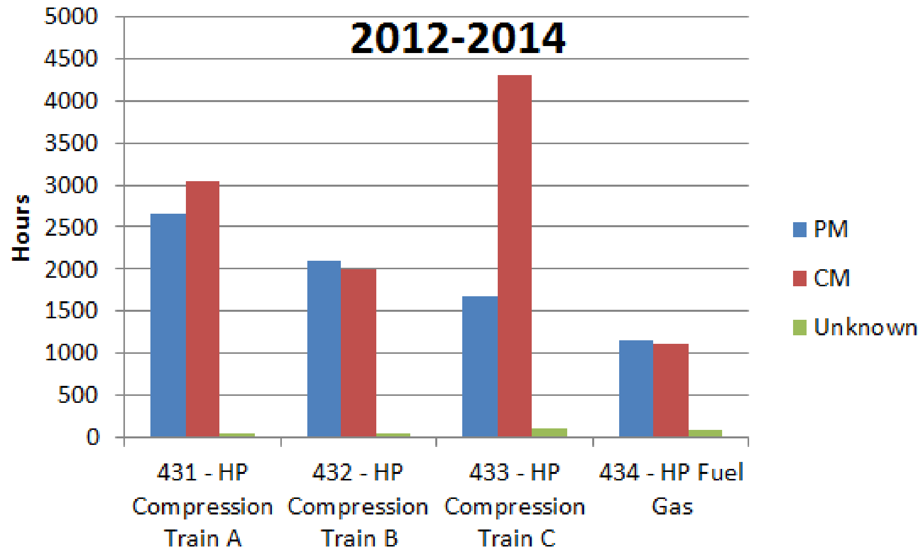


Figure 3.3: PM and CM hours.

The TH is created based on technical documentation such as P&IDS, block diagrams, flow charts, and equipment lists.

Main equipment or skids are used as superior levels while instruments and other equipment that serve the top equipment are placed in inferior levels under the previous ones. To exemplify, the first compressor would be below the compressor train, but in the same level as the second compressor. A pressure transmitter connected to the first compressor would be placed under the first compressor. Figure 3.5 illustrates this example. Figure 3.6 illustrates the workflow to create a TH.

The three gas compression trains are identical. The technical hierarchy of the high pressure gas compression train C is presented in annex A and contains all equipment with the exception of manual valves. These were excluded from the analysis because of their typical failure modes with low failure rates that are connected mainly to material degradation and don't impact significantly when availability calculations are made.

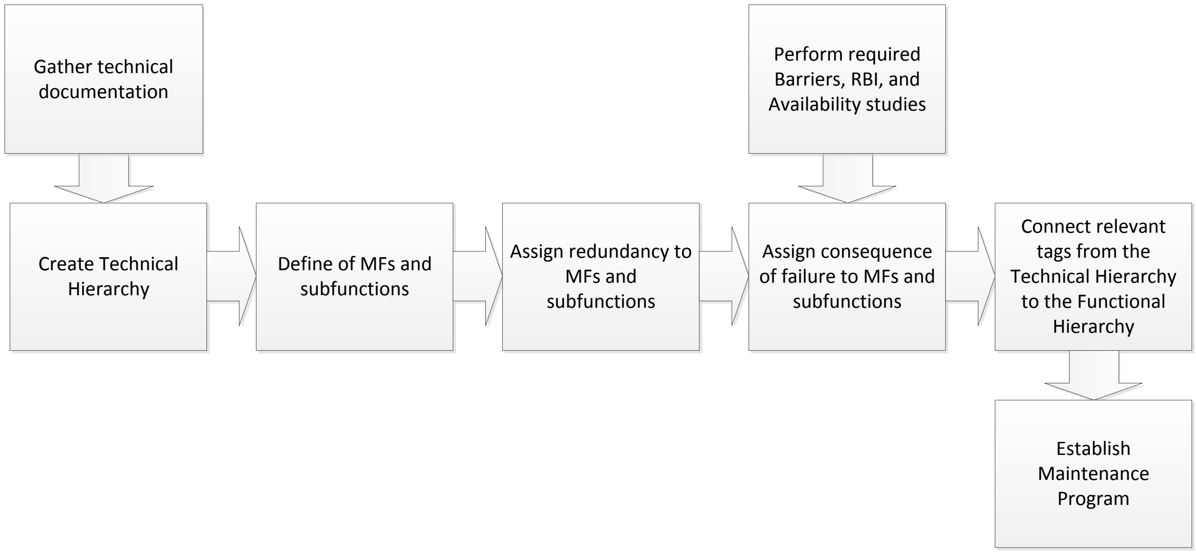


Figure 3.4: Consequence classification process.

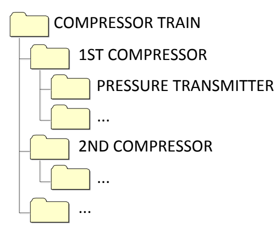


Figure 3.5: Example of technical hierarchy.

Figure 3.11 shows a simplified block diagram of the gas compressor train, containing only main equipment.

3.2.3 Functional hierarchy

A functional hierarchy is somewhat similar to a technical hierarchy, but in the former equipment is structured according to their functions instead of their physical location and physical connection with other equipment. The functional hierarchy is done after the technical hierarchy is concluded.

The first task to create a functional hierarchy is the definition of main functions (MFs). Main functions traditionally receive the name of the principal tasks performed by the equipment. Main functions names aim to describe an active function names, some examples are "pumping", "cooling", "compressing". Figure 3.7 shows how a functional hierarchy may look like.

Main functions are then divided into subfunctions. These subfunctions can be standardized across the installation. The standard subfunctions from figure 3.8 are proposed in [8].

Main function boundaries are drawn on P&IDs in order to define which tags shall be included in the main function. Figure 3.9 shows the boundaries from main function HF2020 drawn in a P&ID.

In the gas compression system, "high pressure gas compressing" is the main function that contains the three high pressure gas compression trains. Other main functions in the system are "utility system", "low pressure gas compressing" and "common equipment" (this last function contains equipment common to low and high pressure compressor trains).

Annex A also shows where each tag in the compression train C was placed in the functional hierarchy.

Normally meetings are held with the technical personnel responsible for the operation of the system, to define system limits, redundancy and consequence of functional failure. Here, system limits, redundancy and consequence of functional failure are defined by the author based on functional hierarchies and functional hierarchy documentation from similar installations that are available for Oceaneering Asset Integrity employees. Subfunctions are created following recommendations in 3.8.

The high pressure compressor trains are modeled following the design in the P&IDs of the system but the reliability database presents failure data by equipment units, instead of presenting it by maintainable item. The model contains the equipment in the P&IDs but is built in blocks of equipment units. That is, inside the main function boundaries, the reliability database adds

an extra “main equipment boundary” that defines which maintainable items are included in the failure modes considered. Figure 3.10 is a representation of this “main equipment boundary” for the compressor unit. It shows that the driver, along with interestage conditioning and starting systems are not included in the failure data of the compressor unit, but power transmission and control and monitoring equipment are included. Blocks in blue in the figure were included in the reliability model, while blocks in red were not.
Annex B presents a list of maintainable items considered when capturing the reliability data for each equipment item.

3.2.4 Redundancy and Criticality

Redundancy is assigned to main functions and subfunctions. Grade A is assigned when there is no redundancy, B when one parallel unit can fail without causing loss of function, and C if two or more parallel functions can fail.

The system in the case study was designed to operate using all three compressor trains during early production phase. Later two trains would work while the third one is in standby. The risk analysis considers the later stage, with redundancy equal to 3 x 50%, or grade B, for the high pressure gas compressing main function. Other main functions in the system receive grade A.

The main function high pressure gas compressing is classified as low on safety, high on production and low on cost. The reason for this is that failure of this function will directly affect production, stopping it, as the system loses the ability of recompressing the gas produced. It also stops feeding the high pressure fuel gas system. The failure of this function does not affect any of the safety functions. Consequences on cost are taken under consideration when both safety and production have rated as less than high.

The main functions utility systems, low pressure gas compressing, and common equipment are also low on safety, high in production and low in cost. The reason for this is that failure of these functions will directly affect the gas compressing main function, shutting it down.

Main function	Redundancy	Safety Criticality	Production Criticality	Cost Criticality
High pressure gas compressing	B (3 x 50%)	Low	High	Low
Utility systems	A (1 x 100%)	Low	High	Low
Low pressure gas compressing	A (1 x 100%)	Low	High	Low
Common equipment	A (1 x 100%)	Low	High	Low

Table 3.1: Criticality Matrix.

Table 3.1 presents redundancy and criticality for these main functions.

3.2.5 Maintenance Plans and Generic Maintenance Concepts

In the risk based maintenance method, the main objective of a maintenance program is to control all risks associated with degradation of equipment [8].

Equipment manufacturers provide maintenance manuals to their products, but given the complexity of an offshore installation it is desirable that maintenance routines are conformed to installation needs.

Generic maintenance concepts (GMCs) are a way of introducing operational knowledge (knowledge gained while operating the system for a time) in the maintenance management process. It saves resources by standardizing activities and facilitating analysis of equipment. It assures minimal maintenance standards based on best practices and facilitates inside company knowledge transfer from one installation to another.

A GMC should be used when equipment has similar design, failure modes, failure rates and operational conditions. Local adjustments can be made to a GMC according to need. Examples of local adjustments are: changes in consequence class, different level of redundancy and slightly different operational conditions.

A generic maintenance concept is composed of a set of maintenance activities, as the ones listed in section 2.1.4. The activities are chosen according to their suitability to prevent a given failure mode, or to follow the evolution of insipient failures.

A failure mode and effects analysis (FMEA) is part of a generic maintenance concept. The analysis presents the failure modes applicable to the maintainable item. The generic maintenance concept provides one or more maintenance activity that relates to the failure modes identified by the analysis. A generic maintenance concept should also clearly specify what (maintainable item) is covered or excluded by the concept.

[8] highlights that in any installation, all tags should be linked to a relevant generic maintenance concept in its CMMS. Annex D.4 of [8] presents an example of a generic maintenance concept.

Generic maintenance concepts are adjusted to local conditions. If generic maintenance concept is not applicable, other types of analysis must be conducted. Safety assessment and cost benefit analysis are carried out. Maintenance intervals are based on cost benefit analysis for the relevant items, and low consequence items receive a planned corrective maintenance strategy. Once these steps are carried out for the whole installation, maintenance tasks can be packed and scheduled considering production plans and availability of resources, generating the installation maintenance program.

3.3 Reliability model

The goal of the reliability model is to capture the influence of maintenance activities in a system. If this is achieved, it is possible to compare the outcome of different maintenance approaches. There are two challenges of including the influence of maintenance activities to a reliability model.

The first challenge is to gather relevant reliability and maintenance data to feed the model. Industry databases such as OREDA [24] present failure data belonging to equipment that receives maintenance interventions, but these interventions are not made explicit. If the equipment investigated was subjected to a run-to-failure situation, failure rates would have a different behavior, and for some equipment the assumption of exponential distribution would not be valid.

The second challenge is to properly model the effect of a maintenance activity. An overhaul or repair activity can restore equipment to as good as new condition, but can also restore it to an intermediate condition that is better than the present and worse than the as good as new condition.

Simple routine maintenance activities such as lubrication and cleaning also influences failure rates for some equipment, but does not restore it to as good as new condition.

A maintenance activity can even introduce new failures, since in maintenance work is performed by people, and people are error-prone.

These considerations can lead to a complex model. Assumptions are made to simplify the model, in order to keep it manageable. These assumptions are as follows:

- items are always restored to as good as new condition
- reciprocating compressors have two failure modes, one is influenced by wear and the other has a constant failure rate
- other main equipment in the system have one failure mode with constant failure rate
- preventive maintenance activities are modeled only for the reciprocating compressors, other equipment is run to failure
- the compressor system has four system states and three outputs (100%, 50% and 0%).

Figure 3.11 shows a screen shot of the model in Maros.

3.3.1 Data collection

OREDA [24] is a database that contains reliability and maintenance data for exploration and production equipment in the offshore industry. Maintenance-induced failures (failures initiated by humans) are included in the failure rates estimates implicitly.

The failure rate information in OREDA assumes that a constant distribution is being observed, or in other words, that equipment being observed is in their useful life phase of the bath-tub failure rate curve. This assumption is applied throughout the database for all equipment. This introduces a challenge to the reliability model, because constant failure rates that are characteristic of exponential distribution are not affected by preventive maintenance actions.

Preventive maintenance actions aim at reducing the failure rate of equipment by renewal of its condition or delay of its degradation. In both cases it is assumed that the equipment possesses a failure distribution that increases in frequency with time. This assumption is not true for all equipment. Some present a pattern of failure as in curve E in figure 2.5. That means that preventive maintenance activities do not influence the probability of failure.

The assumption of the bathtub curve for failure distribution assumes an equivalent behavior of curve E to the useful lifetime of the equipment, the flat part of the curve.

Table 3.2 presents the reliability data for critical failures in equipment in belonging to the MAIN, CONTROL and safety functions of the gas compression trains. This table shows that the shortest mean time to failure belongs to the reciprocating compressor, and it is less than three and a half months. The second shortest MTTF belongs to the electric motor and is equal to a year, roughly three times larger than the smaller MTTF. These values show that the failure modes affecting the reciprocating compressor have a shorter time interval than the other items in the system.

This led to the assumption that the failure modes of the reciprocating compressor are divided in

Equipment Type	Failure rate Mean (OREDA)	MTTF (years)	Mean restoration man-hours	Max restoration man-hours
Reciprocating compressor	347.08	0.3	13	250
Suction cooler	16.64	7	5*	14*
Suction scrubber	20.62	6	8	28
Electric motor	113.19	1	16	48

Table 3.2: Reliability and Maintenance data from OREDA.

wear-out and non-wear-out, while failure modes of other equipment presented behavior similar to curve E, since this is a valid approximation for the period between maintenance interventions on the compressors (flat part of the bathtub curve).

For the reciprocating compressor, failure modes were analyzed with regard to failure causes. OREDA presents a table with percentages for each failure cause contributing to each failure mode. The failure causes were divided into wear-out, non-wear out and unknown (table 3.3). Values from the unknown group were equally divided between the two previous groups. Some failure causes were classified in more than one group, depending on the failure mode caused. This division resulted in 81% of the failures being connected to wear-out and 19% related to non-wear-out. These percentages were then used to create failure distributions for the two failure modes modeled in the components of the reciprocating compressor.

The non-wear-out failure mode is modeled by an exponential distribution with parameter β = 1.8 (see table 3.6). Equation 2.10 is used to estimate the probability density function of the non-wear-out failure:

$$f(x,\beta) = \begin{cases} \frac{1}{1.8} e^{-\frac{x}{1.8}} & \text{if } x > 0 \\ 0 & \text{elsewhere} \end{cases} \tag{3.1}$$

The wear-out failure mode uses a different approach. [30] suggests the use of a gamma distribution to model deterioration of a component when the only information available from reliabil-

Failure Cause	Failure group	Failure Cause	Failure group
Blockage/plugged	Unknown	Material failure - general	Wear-out
Breakage	Mixed	Mechanical failure - general	Wear-out
Clearance/alignment failure	Wear-out	Misc. External influences	Unknown
Combined causes	Unknown	Miscellaneous - general	Unknown
Contamination	Unknown	No cause found	Unknown
Control failure	Non wear-out	Open circuit	Non wear-out
Corrosion	Wear-out	Other	Unknown
Deformation	Unknown	Out of adjustment	Unknown
Electrical failure - general	Non wear-out	Overheating	Unknown
Erosion	Wear-out	Short circuiting	Non wear-out
External influence - general	Unknown	Software failure	Non wear-out
Faulty signal/ indication/ alarm	Non wear-out	Unknown	Unknown
Instrument failure - general	Mixed	Vibration	Wear-out
Leakage	Wear-out	Wear	Wear-out
Looseness	Wear-out		

Table 3.3: Failure causes classification.

ity databases is the mean time to failure given from an exponential distribution. The mean and upper failure rate values in OREDA[1] are used to define the α and β parameters of the gamma distribution.

The mean of a gamma distribution is calculated by equation 2.9, i.e. MTTF = $\alpha\ \beta$.

The upper value of the failure rate in OREDA was used to define the MTTF of the 10% of the cumulative probability in the gamma distribution, as the upper value in OREDA is calculated using the 90 percentile of the failure distribution.

The MTTF and the 90 percentile yielded to shape parameter $\alpha = 1.8$ and scale parameter $\beta = 0.\overline{2}$. Equation 2.8 is used to estimate the probability density function of the wear-out failure, with the

[1]The failure rate distribution data in OREDA presents two means, lower and upper values, and the standard deviation. One mean is calculated by the OREDA estimator, which weights differently the different installations in the sample, and the second mean is simply the total number of failures divided by the total time in service. Since the OREDA estimator accounts for the differences in the installations (multi samples-problem), the first mean value was used. This estimator establishes a 90% confidence interval on the samples observed to calculate the mean value, as well as to define the lower and upper values.

Cumulative Probability	MTTF in years
0%	0
10%	0.096
25%	0.181
50%	0.329
75%	0.542
90%	0.798
100%	2.000

Table 3.4: Cumulative probability table of failure modes influenced by wear.

calculated α and β:

$$f(\alpha,\beta) = \begin{cases} 16.0936e^{-4.5x}x^{0.8} & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

The gamma distribution is not built it in the data entry of the software that run the simulations on the reliability model. For this reason the equation above is introduced as a cumulative probability table (table 3.4).

With respect to maintenance data, OREDA provides two measures: the active repair time and the restoration man-hours. The OREDA handbook has no information on total down time, run-down or ramp-up. All these parameters are illustrated in figure 3.12.

During the test trials, two repair models were tested. One model had repair performed in constant time, using the restoration man-hours mean. The second model used a triangular distribution defined by the restoration man-hours mean as the most common value and the upper value as the highest value. This trial demonstrated that the repair time distribution played a considerable part in the uptime of the system.

Repair time information was available in the raw FPSO maintenance data from the previous project [11]. An investigation revealed the repair time distribution presented in figure 3.13. The investigation considered only the repair time for the reciprocating compressors, excluding the hours spent in the compressors with other maintenance activities. This distribution was ad-

Cumulative probability	Restoration man-hours	Total downtime
0%	0	8
11%	2	10
16%	3	11
37%	6	14
74%	13	21
91%	33	41
98%	83	91
100%	250	258

Table 3.5: Cumulative probability of repair time table for reciprocating compressors.

Equipment failure	Failure rate distribution	Failure parameters	Repair distribution	Repair parameters
Reciprocating compressor, wear-out	gamma(α, β)	$\alpha = 1.8, \beta = 0.\overline{2}$, MTTF = 0.4 , table 3.4	calibrated by FPSO data	table 3.5
Reciprocating compressor, non-wear-out	exponential	MTTF = 1.8	calibrated by FPSO data	table 3.5
Suction cooler	exponential	MTTF =7	constant time	13
Suction scrubber	exponential	MTTF= 6	constant time	16
Electric motor	exponential	MTTF =1	constant time	24

Table 3.6: Reliability and Maintenance data used in the model.

justed for the mean and upper values in OREDA and a cumulative probability table was created to input the repair time distribution for all the reciprocating compressors in the three compressor trains.

To estimate the total downtime, the preparation time was estimated as eight hours. This was added to the values in OREDA for the repair of all types of equipment, as can be observed in tables 3.5 and 3.6. Ramp-up was estimated as two hours.

System state	No. of compressor trains available	System output
3	3	100%
2	2	100%
1	1	50%
0	0	0%

Table 3.7: Model system states.

3.3.2 Model structure

The model was created as a four state Markov process. States are defined in table 3.7. In state three, two compressor trains are operational and one is in stand by. In state two, two compressors are operational and one is being repaired or undergoing preventive maintenance. In state one only one train is operational and two trains are either broken or undergoing preventive maintenance. In state zero there are no operational trains available.

Production efficiency is calculated by multiplying the time spent in a given state by the output of that state. Using the states defined in the previous paragraphs, suppose that the system is in state 3 for 40% of the time, in state 2 for 45%, in state 1 for 10% and in state zero for 5%. The outputs of these states are given in table 3.7 and the production efficiency would be calculated by

$$PE = 0.4 \times 1 + 0.45 \times 1 + 0.1 \times 0.5 + 0.05 \times 0 = 90\% \tag{3.3}$$

The system moves from one state to a state bellow when a scheduled preventive maintenance activity or a critical failure occurs.

Critical failures follow the distributions described in table 3.6. Scheduled preventive maintenance activities are presented in the different scenarios described in table 3.8. These scenarios are created to compare the outcome of different maintenance approaches.

Only two preventive maintenance activities are implemented in the model: overhaul and condition monitoring

Scenario	PM frequency	Condition Monitoring
1	-	no
2	Monthly	no
3	Biannually	no
4	Annually	no
5	Biannually	yes
6	Annually	yes

Table 3.8: Scenarios.

Overhaul activities are programed to renew the compressors failure modes that are affected by wear (a screen shot of Maros is shown in figure 3.14). The overhaul was modeled to shut down only one train per time and restore the compressors to as good as new condition. The repair type of the activity is defined as constant and equal to 13 hours and the scheduling placed overhauls starting on the Fridays of the first three weeks of the month (overhaul of train A is done in the first week, train B in the second week and train C in the third week).

Biannual overhaul was planned so that each overhaul was scheduled to take place at the end of a different month. Annual overhauls were scheduled in the same way, one at the end of a different month. Because in this model the compressor will fail with 100% chance after 1.2 year, the annual overhaul was the longest planned interval modeled.

Condition monitoring is introduced in the model as a change in the repair time distribution. Assuming that with conditioning monitoring a critical failure will be identified before breakdown of the equipment, the preparation time is subtracted and the repair time for the wear-out failure mode is constant and equal to the mean in OREDA.

3.3.3 Simulation Parameters and Limitations

Maros is the simulation software used to design the reliability model proposed. Maros is an established system effectiveness analysis software tool developed by DNVGL.

Two types of model runs are executed: test run and a simulation run. A test run comprises of a single simulation of the system running for twenty years. This type of execution is used to test the model and to test how the model responds to changes in certain parameters. A simulation run comprises of two hundred and fifty simulations of the system running for twenty years. It was verified that with two hundred and fifty simulations the results of the model were stable.

Only equipment belonging to the high pressure gas compression main function is modeled. Equipment belonging to other main functions from the compressor system is not considered in the model.

Only critical failures are considered. Degraded and insipient failures are not included in the model.

Considerations on availability of manpower and spare parts are not made. The model assumes that a repair crew will be instantly available when needed, with all the material necessary at hand. The possibility of not being able to execute a repair job is not taken under consideration.

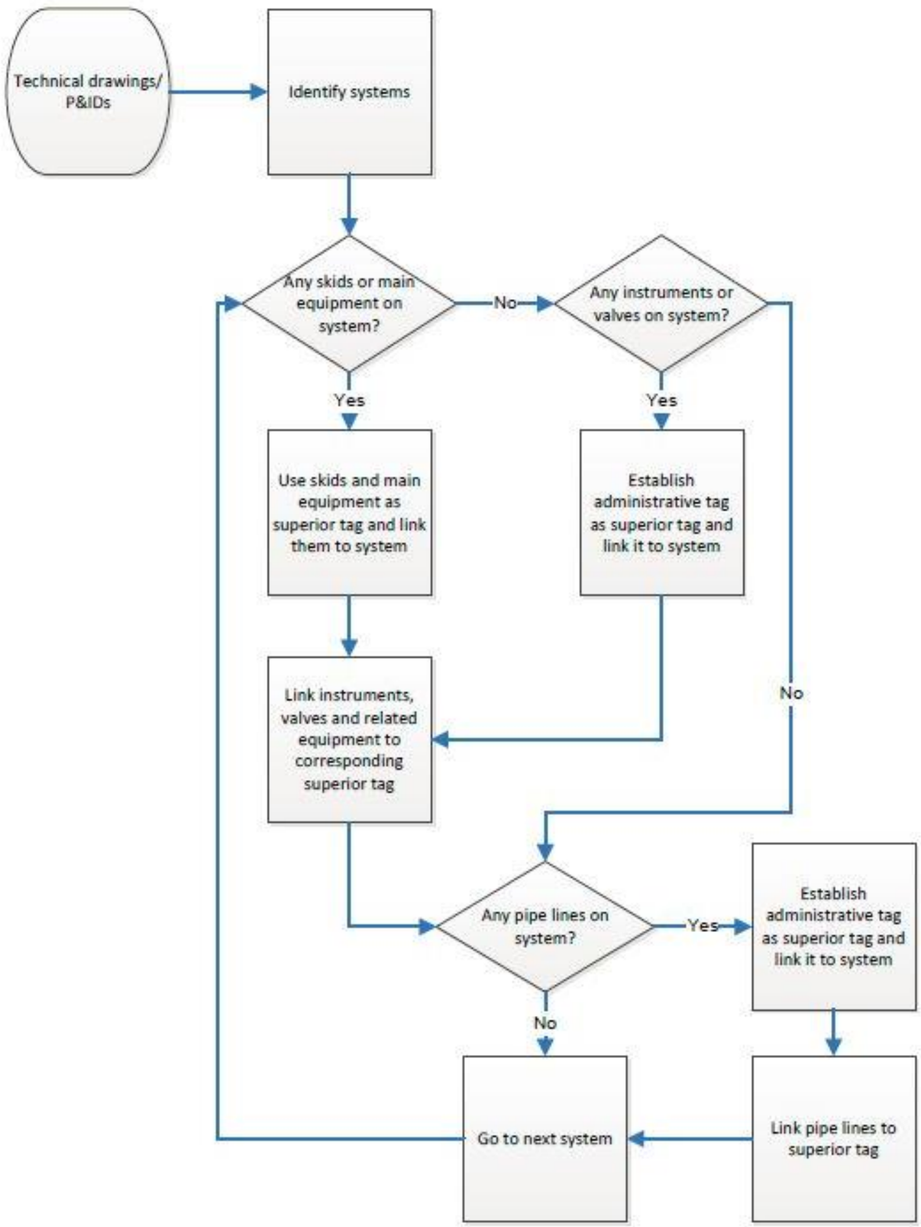


Figure 3.6: Work process to create technical hierarchy.

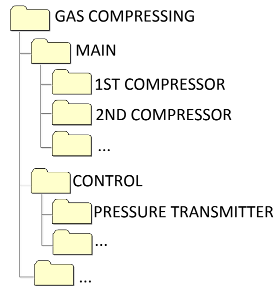


Figure 3.7: Example of functional hierarchy.

Standard sub function	Classification of loss of function				Comment
	RED	HSE	PROD	Other	
Main task	MF	MF	MF	MF	
Pressure, relief	Configu ration	H	L	L	**RED:** No redundancy for the failure mode 'Fail to operate on demand'
Shut down, process	A	H	L	L	**RED:** No redundancy for the failure mode 'Fail to operate on demand'.
Shut down, equipment	MF	M	L	MF	**Other:** Inherits the highest consequence from the MF
Controlling	MF	MF	MF	MF	
Monitoring	MF	M	L	L	
Local indication	MF	L	L	L	
Manual shutoff	MF	(MF)	(MF)	(MF)	

HSE/PROD/Other See examples and definitions in Annex C
H/M/L Consequence "High", "Medium" or "Low"
MF Will inherit MFs
RED Redundancy, see definition in Table C.2.
( ) Reduce with one level from MF

Figure 3.8: Standard subfunctions.

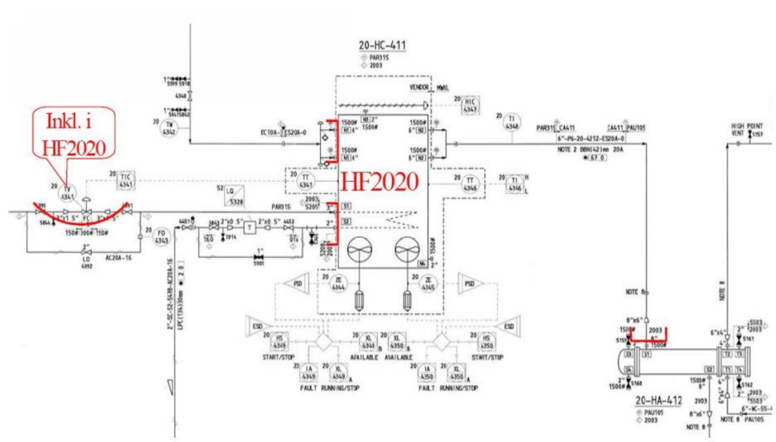


Figure 3.9: Example of main function boundaries.

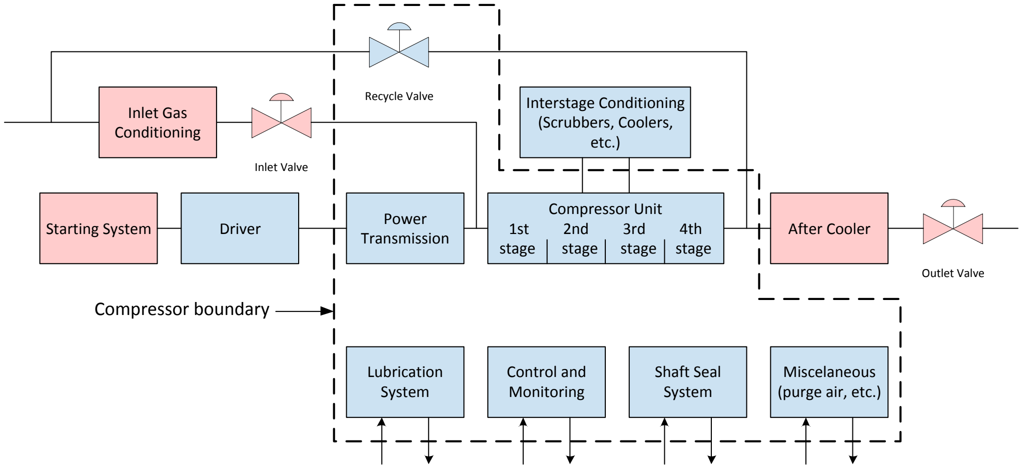


Figure 3.10: Boundary definition for compressor as defined in OREDA.

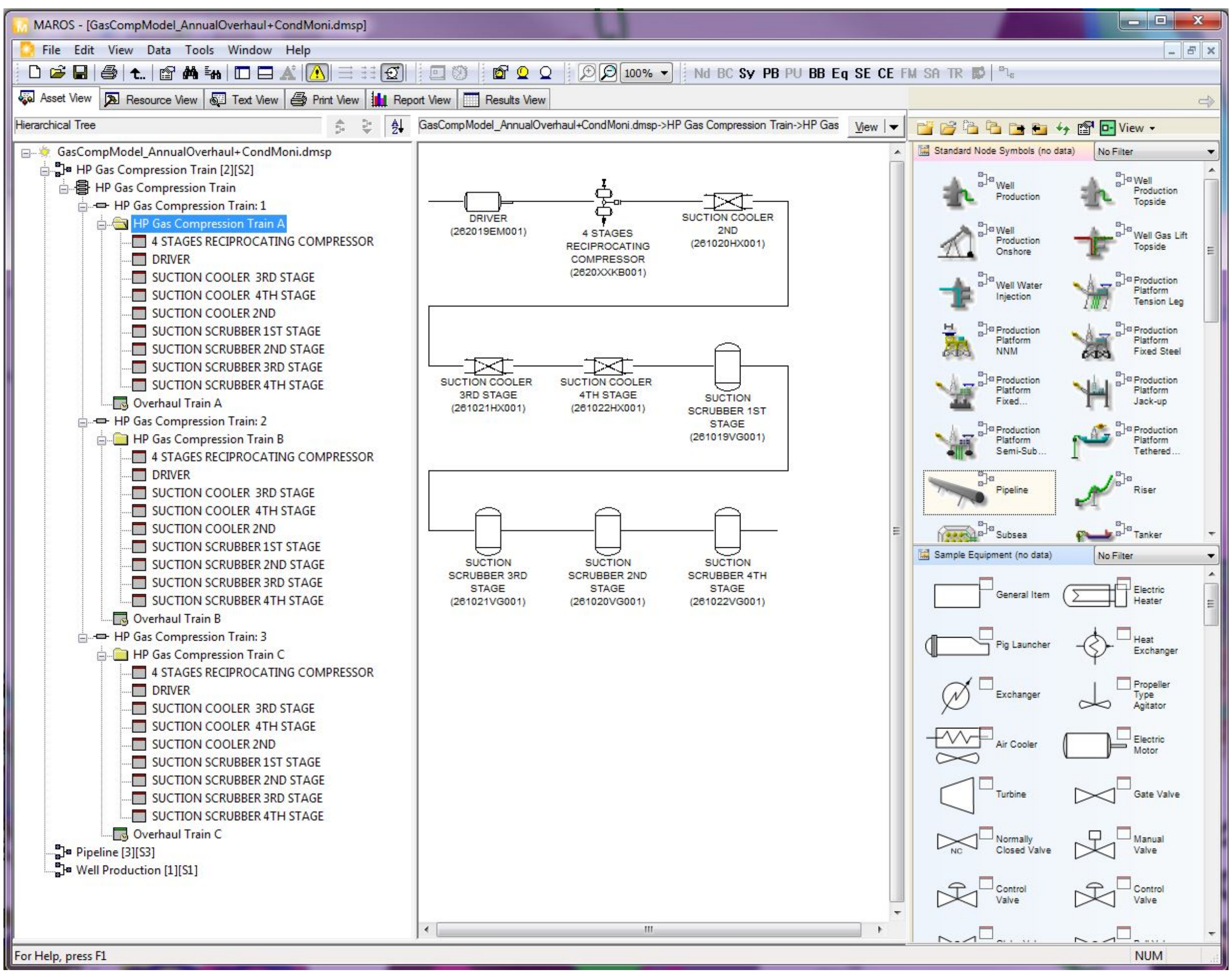


Figure 3.11: Compressor train in Maros.

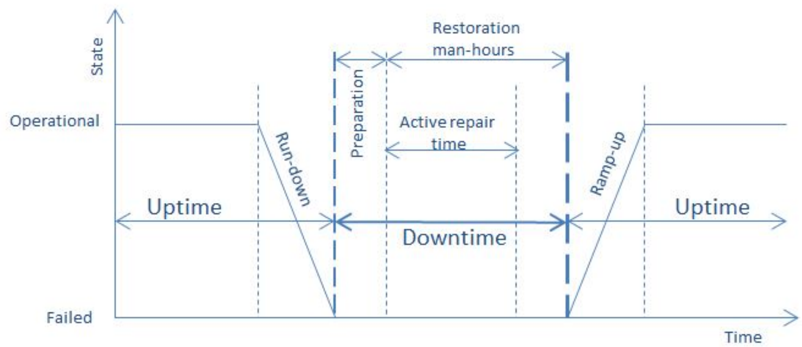


Figure 3.12: Restoration times according to ISO 14224.

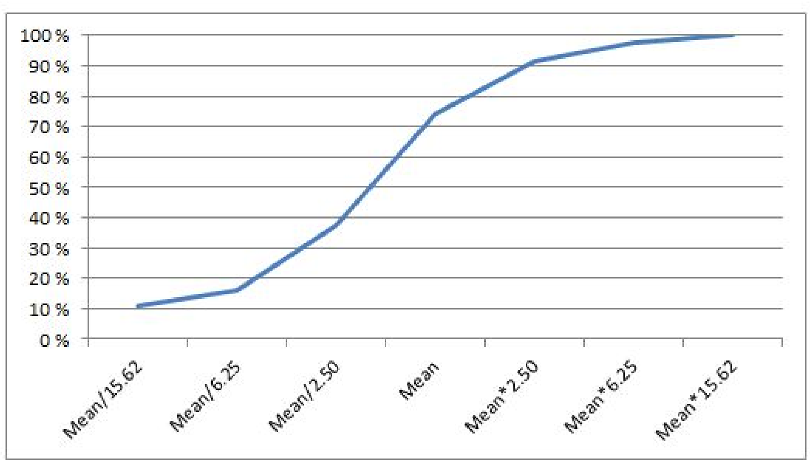


Figure 3.13: Cumulative probability of repair time for reciprocating compressors according to FPSO maintenance data.

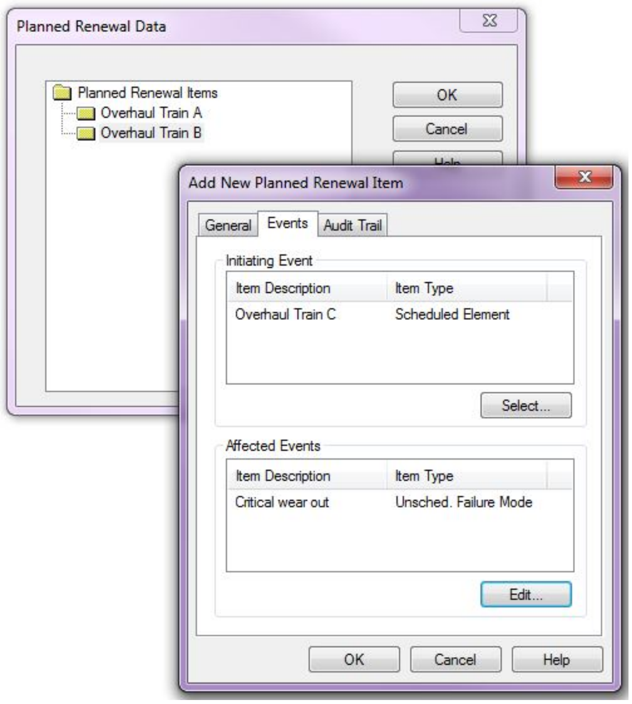


Figure 3.14: Overhaul definition windows.

Chapter 4

Results

The maintainable items identified by the RBM methodology to receive PM were approximately the same that are considered in the FPSO original PM plan. There are some differences in the activities and the frequencies recommended. The maintenance activities aimed at the reciprocating compressors are presented in the following section.

4.1 Reciprocating compressor maintenance activities

4.1.1 FPSO original plan

The FPSO original plan is composed of seven distinct events, described below.

1- Monthly check:
Evaluates the log check list and do the overhaul if necessary
Check level of oil in container for fog. lubricant to actuators
Lubricate around free end of actuator shaft on all actuator-operated valves.

2 - Biannual check (or 4000 hours):
Perform the daily and monthly checks, evaluate the findings and do the overhaul.
Check lubrication divider block for proper operation

Drain and Refill oil on Lubrication Box for cylinder and rod packing lubrication.

Replace Main Lubrication filters (duplex and simplex).

Clean strainer basket on suction side of main lubrication oil pump

Tighten up all flanges and tubing connections

Check for loose bolts and cracks on compressor frame, cylinders and electric motor

3 - Also biannual and coordinated with the engine maintenance:

Clean valve

Check valve for correct and readable tag number

Check valve, actuator, hand wheel, flanges, packer elements and bolts for visual defects, wear and corrosion

Check pack box for leak, retighten if necessary, and confirm that pack box has correct position

Check valve and flanges for leaks

Operate valve after having confirmed with System/area responsible Technician

Use correct grease and grease gear, stem and other actual grease nipple.

Operate valve, and grease until valve operates easily. If the valve moves badly or is stuck, generate corrective WO

Operate the valve to correct position

Remember to lock or Car Seal where necessary

Confirm that valves with open spindle are protected with densotape or other protection

For actuator operated valves with body grease:

For valves with lubrication units: Refill the lubrication unit For other valves: Fill some doplets lubrication oil in the air supply line.

If there is leakage from inspection gate in the grease nipple body, change grease nipple if possible. Alternatively, generate corrective WO and tag the defect equipment with WO number.

Check valve position local and in SCR

4 - Annually or every 8000 hours, the following activities are scheduled:

Change oil filter or when differential pressure exceeds 15 psi

Perform the monthly and 6-months PM-program

Measure crosshead guide clearance, if outside the limits, replace the affected parts.

Grease VVCP stem threads

Clean crankcase breather filter

Inspect auxiliary and chain drive for sprocket teeth undercutting and chain for excessive stretching. Adjust drive chains.

Re-tighten hold down stud-nuts to proper torque values and perform a measuring with mm gauge

More than 0.05 mm pull down require re-chiming and re-alignment.

Coupling alignment to be within 0.13 mm TIR.

5 - Every 32000 hours, the following activities are scheduled:

Perform 6 and 12-months PM-program

Check main and connecting rod bearing clearances by using a dial indicator and pry bar. Disassembly to check clearance is not recommended. Disassembly should be performed only if the pry bar check indicates excessive clearance.

Check crosshead guide clearance with feeler gauges. Re-shim crosshead guide to support, if required, and retighten fasteners to proper torque

Check crosshead pin to crosshead pin bore and connecting rod bushing bore by removing crosshead pins

Check for excessive wear in the auxiliary end drive chain tightened

Check for excessive ring groove wear in pistons.

Check main lube pump internal pressure valve relief setting

6 - Every 48000 hours, the following activities are scheduled:

Replace main and connecting rod bearing shells and bushings

Replace crosshead bushings

7 - Every 60 months all high pressure and low pressure hoses are replaced.

4.1.2 Activities from Generic Maintenance Concept

The maintenance activities selected for the reciprocating compressors according to the standard GMC used by Oceaneering are:
Continuous vibration monitoring
Monthly visual inspection
Monthly functional test for lubricators
Yearly close visual check (requires shutdown)
Trimestral thermodynamic inspection
Trimestral oil analysis for viscosity and water content (consider oil exchange)
Semestral oil analysis for particle count
Biannual (24 months) functional test of emergency stop function

Each activity is intended to address one or more failure causes identified in table 2.1.

4.1.3 Comparison of activities

While the earlier shutdown required for the second plan happens annually, the first plan may require monthly shutdown so that overhaul can be performed, depending on the condition of the equipment. If this overhaul is scheduled to happen in one train while the other two are operational, the direct effect is the change in redundancy of the system for the duration the overhaul is being carried out.

Condition monitoring information was not available in the maintenance information from the FPSO, and the lack of data hinders the comparison of this activity.

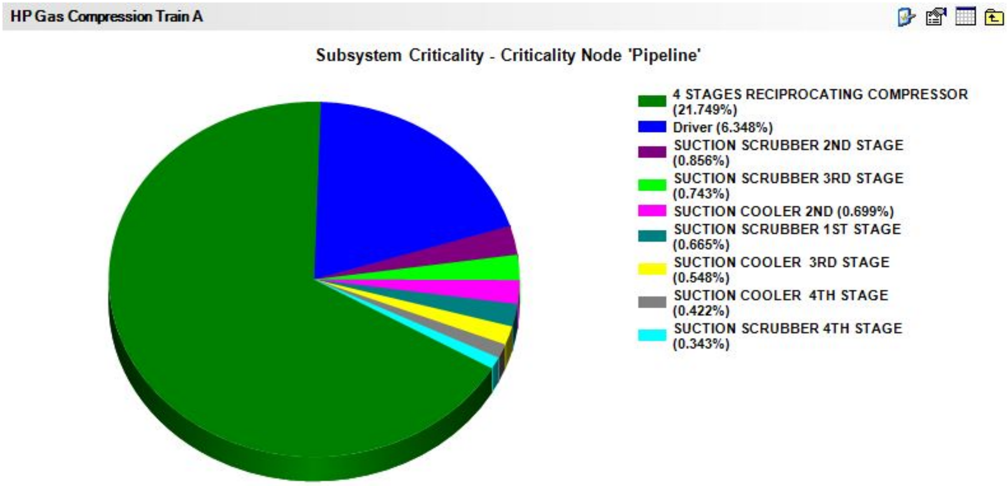
4.2 Model results

As stated in the previous chapter, modeling the failure modes and the repairs is a challenge in this project. To have a better grasp of how to appropriately model repair, at first, two cases were tested considering only one compressor train (a redundancy A type of system) and changing the repair times of the reciprocating compressors. The two cases use constant repair time equal to the mean repair time in OREDA, and a triangular distribution repair time, based on OREDA's mean and maximum value for repair time.

This trial run included only repair (no preventive maintenance). The production efficiency for the gas compressor train is calculated as 96.83% for constant repair and 87.10% for the triangular distribution. After calibrating the repair times using FPSO data, a cumulative distribution function was used to represent the repair time of the reciprocating compressors in the model.

Scenario 1 shows a much higher production efficiency than the trial runs, on account of the three gas compressor trains operating with redundancy grade B (3 x 50%). Figures 4.1, 4.2, and 4.3 show the production efficiency losses per equipment type in each gas compression train. As expected, the reciprocating compressor leads with global losses around 22% per compressor.

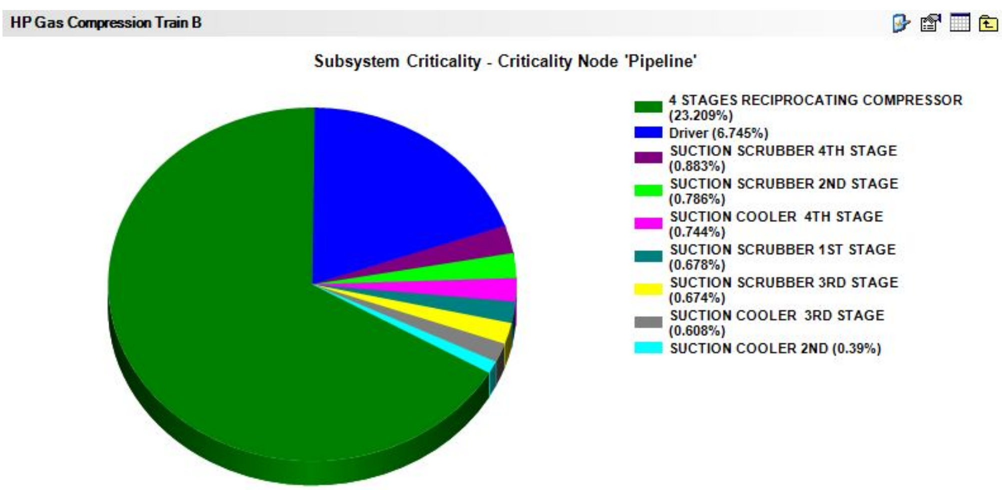
Table 4.1 presents the results obtained during the simulations. The introduction of monthly maintenance activities increased the time the system spends in state one, as the chances of a critical failure occurring while one compressor is being maintained are higher. The best overall results are the ones that involve longer overhaul intervention and the use of condition monitoring.



HP Gas Compression Train A

Description	Global Rel.Loss%	Local Rel.Loss%	Mean Failures	Abs.Loss Mean%	MTBF (Years)	Unique ID
4 STAGES RECIPROCATING COMPRESSOR	21.7493	67.1829	30.148	0.0063	0.3317	95
Driver	6.3481	19.6091	9.828	0.0018	1.0175	293
SUCTION SCRUBBER 2ND STAGE	0.8558	2.6437	1.64	0.0002	6.0976	104
SUCTION SCRUBBER 3RD STAGE	0.7431	2.2953	1.66	0.0002	6.0241	113
SUCTION COOLER 2ND	0.6988	2.1587	1.416	0.0002	7.0621	87
SUCTION SCRUBBER 1ST STAGE	0.6648	2.0535	1.688	0.0002	5.9242	101
SUCTION COOLER 3RD STAGE	0.5482	1.6934	1.384	0.0002	7.2254	110
SUCTION COOLER 4TH STAGE	0.4218	1.3028	1.388	0.0001	7.2046	119
SUCTION SCRUBBER 4TH STAGE	0.3434	1.0607	1.708	0.0001	5.8548	122

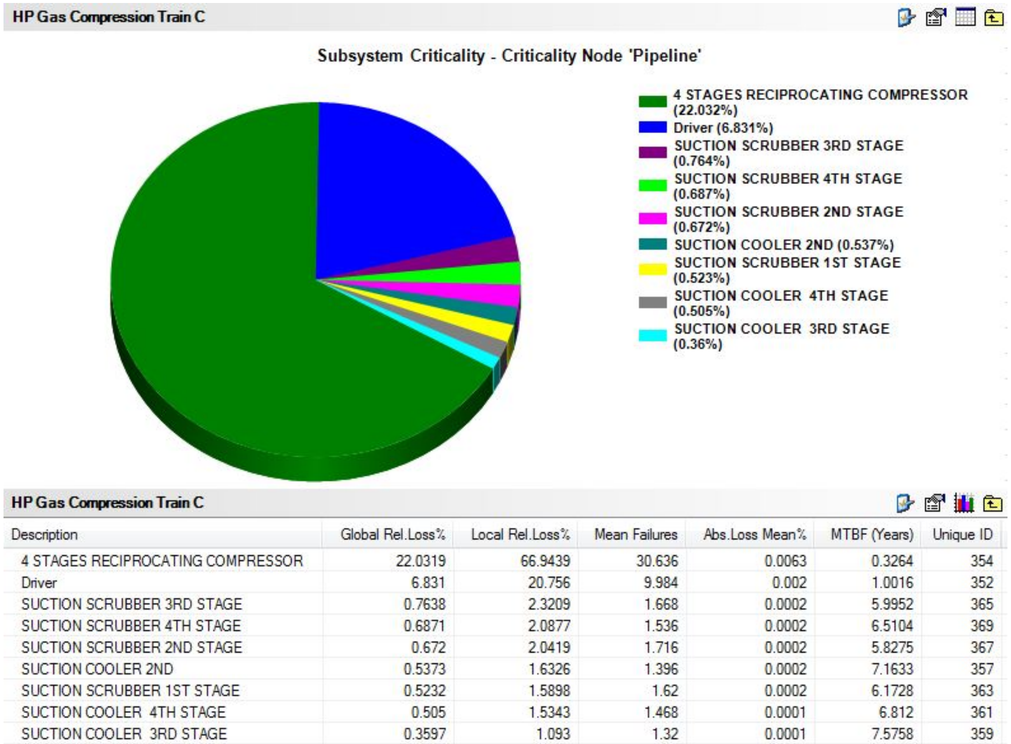
Figure 4.1: Production efficiency loss per equipment type train A.



HP Gas Compression Train B

Description	Global Rel.Loss%	Local Rel.Loss%	Mean Failures	Abs.Loss Mean%	MTBF (Years)	Unique ID
4 STAGES RECIPROCATING COMPRESSOR	23.2085	66.8532	30.116	0.0067	0.332	322
Driver	6.7445	19.4278	10.292	0.0019	0.9716	320
SUCTION SCRUBBER 4TH STAGE	0.883	2.5436	1.656	0.0003	6.0386	337
SUCTION SCRUBBER 2ND STAGE	0.7856	2.2628	1.512	0.0002	6.6138	335
SUCTION COOLER 4TH STAGE	0.7442	2.1436	1.524	0.0002	6.5617	329
SUCTION SCRUBBER 1ST STAGE	0.6777	1.9522	1.6	0.0002	6.25	331
SUCTION SCRUBBER 3RD STAGE	0.6742	1.942	1.688	0.0002	5.9242	333
SUCTION COOLER 3RD STAGE	0.6077	1.7505	1.464	0.0002	6.8306	327
SUCTION COOLER 2ND	0.3903	1.1243	1.48	0.0001	6.7568	325

Figure 4.2: Production efficiency loss per equipment type train B.



Description	Global Rel.Loss%	Local Rel.Loss%	Mean Failures	Abs.Loss Mean%	MTBF (Years)	Unique ID
4 STAGES RECIPROCATING COMPRESSOR	22.0319	66.9439	30.636	0.0063	0.3264	354
Driver	6.831	20.756	9.984	0.002	1.0016	352
SUCTION SCRUBBER 3RD STAGE	0.7638	2.3209	1.668	0.0002	5.9952	365
SUCTION SCRUBBER 4TH STAGE	0.6871	2.0877	1.536	0.0002	6.5104	369
SUCTION SCRUBBER 2ND STAGE	0.672	2.0419	1.716	0.0002	5.8275	367
SUCTION COOLER 2ND	0.5373	1.6326	1.396	0.0002	7.1633	357
SUCTION SCRUBBER 1ST STAGE	0.5232	1.5898	1.62	0.0002	6.1728	363
SUCTION COOLER 4TH STAGE	0.505	1.5343	1.468	0.0001	6.812	361
SUCTION COOLER 3RD STAGE	0.3597	1.093	1.32	0.0001	7.5758	359

Figure 4.3: Production efficiency loss per equipment type train C.

Scenario	Production efficiency	Standard deviation	loss of production efficiency due to PM	Time with 50% output	Time with 100% output
1	99.971%	0.020%	0%	0.06%	99.94%
2	99.937%	0.022%	13.316%	0.13%	99.87%
3	99.970%	0.016%	4.639%	0.06%	99.94%
4	99.971%	0.018%	2.344%	0.06%	99.94%
5	99.979%	0.011%	7.091%	0.04%	99.96%
6	99.982%	0.011%	4.884%	0.04%	99.96%

Table 4.1: Model results.

Chapter 5

Discussion

5.1 Model

A model is a representation, usually simplified, to show the construction of something. A simulation model that can be used to predict performance in the real world is a useful tool.

A model evaluation protocol according to [19] consists of three main elements: scientific assessment, verification and validation.

Elements of the scientific assessment are: comprehensive description of the model, assessment of the scientific content, limits of applicability, limitations and advantages of the model.

The reliability model was used for the case study of a part of the compressor system of an FPSO but it can be used for other systems possessing failure modes with similar behavior.

As the model assumes there are infinite and readily available manpower and resources for repair, the possibility of not being able to execute a job or the need to postpone it is not evaluated. The model is not ready to consider prioritization of tasks as it is.

One advantage of the model is the use of the mean and upper values given in a commercial database to create a failure distribution that belongs to a failure mode that is connected to wear.

This requires the separation of the failure modes in two categories (wear-out and non-wear-out), which can be easily done when a FMEA of the equipment is available.

Another advantage of the model is that it can be expanded to include more equipment and more failure modes with by doing a task as easy as adding a new line in a spreadsheet containing the entry data.

Verification of the model is done during its development, when results are tested against specification. The specification for the model is outlined as being able to use data from a reliability database and to be useful to compare between different maintenance approaches.

The model uses information from a commercial reliability database and was used to compare the outcome of different frequencies of maintenance interventions. The model runs with different frequencies for the maintenance activities revealed that if the system behavior can be captured by the failure averages in OREDA, the current maintenance frequency for overhauls on the compressor is excessive. In reality this might not be the case if the failure rate of the real system is far from the values in the reference database. But given that the reliability data is representative for the system, the model can provide an useful perspective when comparing between different maintenance approaches.

Model validation deals with the relevance of the results to the situation in question and is explored in section 5.2. Relevance of results comprises, among other factors, of: database selection, model characteristics and parameter selection.

Values from OREDA are manipulated to generate failure distributions with a different behavior than the original exponential distribution. Using a gamma process to create wear-out failure distributions has been done before for degradation of material due to corrosion [14] and for degradation of stator winding connections [30]. This strategy is used in this work to deal with the problem of constant failure rate distributions representing equipment failure that does not follow this pattern.

The modeling of preventive maintenance actions consisted of two activities, which is a simplification from the real case. The modeling of failure is also restricted to critical failures, as degrading and insipient failures were not considered. Degrading failure modes can decrease the output of a system without shutting it down or without shutting down one of its components. If these are considered in the model, intermediate model states would have to be introduced in table 3.7. Insipient failure modes can be used to prevent failure when identified by condition monitoring, either continuous or intermittent. If these are considered in the model, they can be used to schedule maintenance booking resources in advance, in a case that maintenance logistics should be taken under consideration.

The model fails to capture the probability of maintenance-induced failures explicitly. This means that the failure rate due to these types of failure does not increase with the increment of maintenance interactions with the system. Maintenance-induced failures have been reportedly a cause for fatal accidents in many industries with complex systems. If in the past, industrial accidents were reported mainly in terms of technological malfunctions, now the role of human factors has become more apparent [13]. Examples of human errors that may cause failures are installation/reassembly errors, fault insulation, test or inspection error, introduction of foreign object causing damage, among others [16].

Availabilty of man-power and spare parts are also not taken into consideration. These factors will most likely increase the duration of downtime in the event of equipment breakdown. They can be included in the model in Maros by defining resources used to perform a service. These resources can be skills, crews, spare parts, accessories, etc. Availability, quantity and mobilization time can be defined for the resources [12]. These features were omitted from the model to keep it manageable in complexity and to avoid introducing parameters without data to populate it.

5.2 Model Results

The results from scenarios 5 and 6 are worth investigating. Both these scenarios achieved similar production efficiency but scenario 5 requires the double of preventive maintenance interventions of scenario 6. If the failure rates behave similarly to the ones modeled in the simulation, this result should also be true to the case study. If the failure rates are different than ones used in the model, but are known, they can be replaced in the model and the new result can be analyzed.

The results from the model assume that other equipment than the reciprocating compressor in the system can run to failure. This assumption was made because of the nature of the failure distribution modeled for this equipment. Possessing a exponential distribution, preventive maintenance activities would not affect the failure probability and they would fail with the same frequency as if no preventive action was carried out. Considering that some failure modes in these equipment are not acceptable, they should be taken into consideration.

Unlike what was observed in need for repair in the FPSO case study (figure 3.1), the three compression trains have similar production efficiency results because they were modeled equally. The real behavior of different failure rates between trains could be replicated if an underlying reason is discovered, such as significant age difference or operational conditions to which each train experiences. Another possibility is if one of the trains is in stand by and in a new condition, it can present a higher failure rate than the other two, if it is in its burn-in phase.

Chapter 6

Conclusion and Further Work

6.1 Conclusion

The research question asked if there is potential improvement for the availability of a system when applying a risk based maintenance philosophy. To answer that question, a model was created to weight the differences obtained from a maintenance approach based on the risk based maintenance method and the current maintenance approach being used in the system presented in the case study. The risk based maintenance philosophy was applied according to the recommendations in NORSOK Z-008. It proposed the use of a reliability model to make better informed decisions in the maintenance management process. The model simulated the maintenance behavior of the compressor system using the MAROS software from DNVGL.

Results from the simulation using this model with these two maintenance approaches showed a superior outcome with the maintenance intervention interval proposed by the risk based maintenance method. The results indicated that the frequency of preventive maintenance interventions could be reviewed and possibly reduced, with advantages to the availability of the system. The result also indicated that it is beneficial to include conditional monitoring in the reciprocating compressors.

6.2 Suggestions for Further Work

There are several points of improvement in the incipient model that if developed could capture more complex interactions between failure modes not included in the analysis (degraded and insipient failure modes) and the appropriate preventive maintenance activities.

Failure data - There is a challenge in applying data from OREDA directly in the model presented in this thesis. The probability distribution used in OREDA to calculate failure parameters does not accommodate analysis of the effectiveness of preventive maintenance activities. Research could be done to identify typical failure mode behavior, so that this information could be readily available to be used for modeling systems. Issues of using this database in connection with maintenance implementation purposes have been previously addressed by [27]. However, OREDA still remains as the main source of information for such work.

Repair data - Similar to the previous point, better understanding of repair times distribution can potentially improve the results from the reliability model. Data available in the CMMSs used throughout the oil industry are a possible and viable starting point of study. It may be possible to create an algorithm that mines data in the CMMSs to acquire the repair data according to failure mode.

Aging and imperfect repair - Repairing an item to a as good as new condition is not always a reasonable assumption. Also, performing preventive maintenance activities on an item that has aged will not yield the same results as performing it on a new item. It is not straightforward to quantify the level of degradation and include it into reliability models [20]. Imperfect repair models could be associated to the model presented in this thesis.

Maintenance resources and logistics - Maros has built-in capabilities to model spare parts management and man-power availability, as well as the logistics involved when required parts or human resources are available at a different location [12]. The model presented in this thesis could be further developed to accommodate for these parameters.

Appendix A

Technical and Functional Hierarchies

Technical Hierarchy	TAG AS IN P&ID	FH - SUBFUNCTION	FH - MAIN FUNCTION
FPSO			
GAS COMPRESSION AND TREATMENT SYSTEM			
HP COMPRESSION TRAIN C			
1ST STAGE			
SUCTION SCRUBBER 1ST STAGE 43311 - TRAIN C	261019VG001	MAIN	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339101 - TRAIN C	261019LT002	PSD	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339111 - TRAIN C	261019LT003	CONTROL	HP GAS COMPRESSING
GAUGE LEVEL 4339115 - TRAIN C	261019LG001	INDICATION	HP GAS COMPRESSING
TRANSMITTER DIFF PRESSURE 4339251 - TRAIN C		INDICATION	HP GAS COMPRESSING
BDV 1ST STAGE SUCT SCRUBBER	261019BDV002	PSD	HP GAS COMPRESSING
PSV 4338201 4338201 - TRAIN C	261019PSV001	PSV	HP GAS COMPRESSING
CONTROL VALVE 4338801 - TRAIN C	261000XV007	PSD	HP GAS COMPRESSING
CONTROL VALVE 4338802 - TRAIN C	261000XV008	PSD	HP GAS COMPRESSING
CONTROL VALVE 4338803 - TRAIN C	261019XV001	PSD	HP GAS COMPRESSING
CONTROL VALVE 4338804 - TRAIN C	261019LV003	CONTROL	HP GAS COMPRESSING
FLOW ORIFICE INLET SUCTION SCRUBBER 4339501 - TRAIN C	261019FO002	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE INLET SUCTION SCRUBBER 4339502 - TRAIN C	261000FO004	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE OUTLET SUCTION SCRUBBER 4339503 - TRAIN B	261019FO001	INDICATION	HP GAS COMPRESSING
LINE FROM HP COMPRESSOR COMMON SUCT. SCRUBBER	26-10-99-1000-DC21S-10-400	MAIN	HP GAS COMPRESSING
LINE TO COMPRESSOR 262019KB002	26-10-99-0800-DC-21S-10-401	MAIN	HP GAS COMPRESSING
LINE TO HP FLARE HEADER	26-10-99-0200-DC21S-10-409	PSV	HP GAS COMPRESSING
LINE TO PSV 261019PSV001	26-10-99-0200-DC21S-10-418	PSV	HP GAS COMPRESSING
1ST STAGE COMPRESSOR 43306 - TRAIN C	262019KB001	MAIN	HP GAS COMPRESSING
CONTROL VALVE	262019XY002	CONTROL	HP GAS COMPRESSING
CONTROL VALVE	262019XY001	CONTROL	HP GAS COMPRESSING
LINE TO 2ND STAGE COMPRESSOR SUCTION COOLER	26-20-99-0800-DC21S-10-400	PSV	HP GAS COMPRESSING
SUCTION BOTTLE 1ST STAGE 4330401 - TRAIN C	261039VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339505 1ST STAGE - TRAIN C	261019FO003	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339506 1ST STAGE - TRAIN C	261019FO004	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339201 - TRAIN C	261019PT001	PSD	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 1ST STAGE 4339401 - TRAIN C	261019TT001	PSD	HP GAS COMPRESSING
DISCHARGE BOTTLE 1ST STAGE 4330501 - TRAIN C	261040VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339507 1ST STAGE - TRAIN C	262019FO001	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339508 1ST STAGE - TRAIN C	262019FO002	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339202 - TRAIN C	262019PT002	PSD	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339203 - TRAIN C	262019PT003	MONITORING	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 1ST STAGE 4339402 - TRAIN C	262019TT002	PSD	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 1ST STAGE 4339403 - TRAIN C	262019TT004	PSD	HP GAS COMPRESSING

2ND STAGE			HP GAS COMPRESSING
SUCTION COOLER 2ND STAGE 43316 - TRAIN C	261020HX001	MAIN	HP GAS COMPRESSING
PSV 4338203 4338203 - TRAIN C	401500PSV015	PSV	HP GAS COMPRESSING
PSV 4338202 4338202 - TRAIN C	262019PSV001	PSV	HP GAS COMPRESSING
LINE TO PSV 262019PSV001	26-20-99-0300-DC21S-10-405	PSV	HP GAS COMPRESSING
CONTROL VALVE 4338806 - TRAIN C	261020TV002	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 2ND STAGE 4339404 - TRAIN C	261020TT002	CONTROL, MONITORING	HP GAS COMPRESSING
CONTROL VALVE 4338807 - TRAIN C	261020FV001	CONTROL	HP GAS COMPRESSING
LINE TO 2ND STAGE HP COMPRESSOR SCRUBBER	26-10-99-0600-DC20S-10-402	MAIN	HP GAS COMPRESSING
LINE TO 1ST STAGE HP COMPRESSOR SCRUBBER	26-10-99-0400-DC20S-10-403	MAIN	HP GAS COMPRESSING
LINE TO CONTROL VALVE 261020FV001	26-10-99-0400-DC20S-10-424	MAIN	HP GAS COMPRESSING
SUCTION SCRUBBER 2ND STAGE 43312 - TRAIN C	261020VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339510 2ND STAGE - TRAIN C	261020FO001	INDICATION	HP GAS COMPRESSING
PSV 4338204 4338204 - TRAIN C	261020PSV001	PSV	HP GAS COMPRESSING
LINE TO PSV 261020PSV001	26-10-99-0200-DS20s-10-420	PSV	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339103 - TRAIN C	261020LT002	PSD	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339112 - TRAIN C	261020LT003	CONTROL, MONITORING	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339205 - TRAIN C	261020PT001	CONTROL, MONITORING	HP GAS COMPRESSING
GAUGE LEVEL 4339116 - TRAIN C	261020LG001	INDICATION	HP GAS COMPRESSING
TRANSMITTER DIFF PRESSURE 4339252 - TRAIN C		INDICATION	HP GAS COMPRESSING
INDICATOR DIFF PRESSURE 4339551 - TRAIN C		INDICATION	HP GAS COMPRESSING
CONTROL VALVE 4338809 - TRAIN C	261020XV001	PSD	HP GAS COMPRESSING
CONTROL VALVE 4338810 - TRAIN C	261020LV003	CONTROL	HP GAS COMPRESSING
LINE TO COMPRESSOR 262020KB002	26-10-99-0600-DC21S-10-404	MAIN	HP GAS COMPRESSING
2ND STAGE COMPRESSOR 43307 - TRAIN C	262020KB002	MAIN	HP GAS COMPRESSING
LINE TO 3RD STAGE HP COMPRESSOR SUCTION COOLER	26-20-99-0600-DC21S-10-401	PSV	HP GAS COMPRESSING
CONTROL VALVE	262020XY001	CONTROL	HP GAS COMPRESSING
CONTROL VALVE	262020XY002	CONTROL	HP GAS COMPRESSING
TEMPERATURE TRANSMITTER	262020TT002	PSD	HP GAS COMPRESSING
TEMPERATURE TRANSMITTER	262020TT004	PSD	HP GAS COMPRESSING
SUCTION BOTTLE 2ND STAGE 4330402 - TRAIN C	261041VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339511 2ND STAGE - TRAIN C	261020FO002	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339512 2ND STAGE - TRAIN C	261020FO003	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339206 - TRAIN C	261020PT002	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 2ND STAGE SUCTION BOTTLE	261020TT003	PSD	HP GAS COMPRESSING
DISCHARGE BOTTLE 2ND STAGE 4330502 - TRAIN C	261042BG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339513 2ND STAGE - TRAIN C	262020FO001	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339514 2ND STAGE - TRAIN C	262020FO002	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339515 2ND STAGE - TRAIN C	262020FO003	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339207 - TRAIN C	262020PT002	PSD	HP GAS COMPRESSING
3RD STAGE			HP GAS COMPRESSING
SUCTION COOLER 3RD STAGE 43317 - TRAIN C	261021HX001	MAIN	HP GAS COMPRESSING
PSV 4338205 4338205 - TRAIN C	262020PSV001	PSV	HP GAS COMPRESSING
LINE TO PSD 262020PSV001	26-20-99-0200-DC21S-10-407	PSV	HP GAS COMPRESSING
PSV 4338206 4338206 - TRAIN C	401500PSV008	PSV	HP GAS COMPRESSING
LINE TO 3RD STAGE HP COMPRESSOR SUCTION SCRUBBER	26-10-99-0600-DC20S-10-405	LINE	HP GAS COMPRESSING
CONTROL VALVE 4338811 - TRAIN C	261021TV002	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 3RD STAGE 4339408 - TRAIN C	261021TT002	CONTROL, MONITORING	HP GAS COMPRESSING
SUCTION SCRUBBER 3RD STAGE 43313 - TRAIN C	261021VG001	MAIN	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339113 - TRAIN C	261021LT002	PSD	HP GAS COMPRESSING
GAUGE LEVEL 4339117 - TRAIN C	261021LG001	INDICATION	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339105 - TRAIN C	261021LT003	CONTROL, MONITORING	HP GAS COMPRESSING
TRANSMITTER DIFF PRESSURE 4339253 - TRAIN C		INDICATION	HP GAS COMPRESSING
INDICATOR DIFF PRESSURE 4339552 - TRAIN C		INDICATION	HP GAS COMPRESSING
CONTROL VALVE 4338812 - TRAIN C	261021LV003	CONTROL	HP GAS COMPRESSING
PSV 4338207 4338207 - TRAIN C	261021PSV001	PSV	HP GAS COMPRESSING
LINE TO PSV 261021PSV001	26-10-99-0600-DC20S-10-419	PSV	HP GAS COMPRESSING
LINE TO COMPRESSOR 262021KB001	26-10-99-0300-DC21S-10-406	LINE	HP GAS COMPRESSING

3RD STAGE COMPRESSOR 43308 - TRAIN C	262021KB001	MAIN	HP GAS COMPRESSING
LINE TO 4TH STAGE COOLER	26-20-99-0400-FC21S-10-402	PSV	HP GAS COMPRESSING
LINE TO CONTROL VALVE 262021FV001	26-20-99-0200-FC21S-10-403	MAIN	HP GAS COMPRESSING
LINE TO 2ND STAGE COMPRESSOR SUCTION COOLER	26-20-99-0200-DC21S-36-417	MAIN	HP GAS COMPRESSING
SUCTION BOTTLE 3RD STAGE 4330403 - TRAIN C	261043VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339517 3RD STAGE - TRAIN C	261021FO001	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339211 - TRAIN C	261021PT001	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 3RD STAGE 4339410 - TRAIN C	261021TT003	PSD	HP GAS COMPRESSING
DISCHARGE BOTTLE 3RD STAGE 4330503 - TRAIN C	261044VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339518 3RD STAGE - TRAIN C	262021FO001	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339209 - TRAIN C	262021PT001	PSD	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339210 - TRAIN C	262021PT003	CONTROL, MONITORING	HP GAS COMPRESSING
CONTROL VALVE 4338813 - TRAIN C	262021FV001	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 3RD STAGE 4339411 - TRAIN C	262021TT002	PSD	HP GAS COMPRESSING
4TH STAGE			HP GAS COMPRESSING
SUCTION COOLER 4TH STAGE 43318 - TRAIN C	261022HX001	MAIN	HP GAS COMPRESSING
PSV 4338208 4338208 - TRAIN C	262021PSV001	PSV	HP GAS COMPRESSING
PSV 4338209 4338209 - TRAIN C	401500PSV012	PSV	HP GAS COMPRESSING
LINE TO PSV 262021PSV001	26-20-99-0300-FC21S-10-409	PSV	HP GAS COMPRESSING
LINE TO 4TH STAGE SCRUBBER	26-10-99-0400-FS20S-10-407	MAIN	HP GAS COMPRESSING
CONTROL VALVE 4338815 - TRAIN C	261022TV002	CONTROL	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 4TH STAGE 4339413 - TRAIN C	261022TT002	CONTROL, MONITORING	HP GAS COMPRESSING
SUCTION SCRUBBER 4TH STAGE 43314 - TRAIN C	261022VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339520 4TH STAGE - TRAIN C	261022FO001	INDICATION	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339114 - TRAIN C	261022LT002	PSD	HP GAS COMPRESSING
GAUGE LEVEL 4339118 - TRAIN C	261022LG001	INDICATION	HP GAS COMPRESSING
TRANSMITTER LEVEL 4339107 - TRAIN C	261022LT003	CONTROL, MONITORING	HP GAS COMPRESSING
TRANSMITTER DIFF PRESSURE 4339254 - TRAIN C		INDICATION	HP GAS COMPRESSING
INDICATOR DIFF PRESSURE 4339554 - TRAIN C		INDICATION	HP GAS COMPRESSING
PSV 4338210 4338210 - TRAIN C	261022PSV001	PSV	HP GAS COMPRESSING
LINE TO PSV 261022PSV001	26-10-99-0200-FS20S-10-421	MAIN	HP GAS COMPRESSING
CONTROL VALVE 4338817 - TRAIN C	261022LV003	CONTROL	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339213 - TRAIN C	261022PT001	CONTROL, MONITORING	HP GAS COMPRESSING
LINE TO COMPRESSOR 262022KB001	26-10-99-0200-FC21S-10-408	MAIN	HP GAS COMPRESSING
4TH STAGE COMPRESSOR 43309 - TRAIN C	262022KB001	MAIN	HP GAS COMPRESSING
BDV 4TH STAGE	262022BDV003	PSD	HP GAS COMPRESSING
FLOW INDICATOR 4339531 - TRAIN C	262022FO002	INDICATION	HP GAS COMPRESSING
FLOW INDICATOR 4339532 - TRAIN C	262022FO003	INDICATION	HP GAS COMPRESSING
SUCTION BOTTLE 4TH STAGE 4330404 - TRAIN C	261045VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339521 4TH STAGE - TRAIN C	261022FO002	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339522 4TH STAGE - TRAIN C	261022FO003	INDICATION	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 4TH STAGE 4339415 - TRAIN C	261022TT003	PSD	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339214 - TRAIN C	261022PT003	CONTROL	HP GAS COMPRESSING
DISCHARGE BOTTLE 4TH STAGE PRIMARY 4330504 - TRAIN C	261045VG001	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339523 4TH STAGE - TRAIN C	262022FO004	INDICATION	HP GAS COMPRESSING
FLOW ORIFICE 4339524 4TH STAGE - TRAIN C	262022FO005	INDICATION	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 4TH STAGE 4339416 - TRAIN C	262022TT003	PSD	HP GAS COMPRESSING
TRANSMITTER TEMPERATURE 4TH STAGE 4339417 - TRAIN C	262014TT002	PSD	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339215 - TRAIN C	262022PT001	PSD	HP GAS COMPRESSING
DISCHARGE BOTTLE 4TH STAGE SECONDARY 4330505 - TRAIN C	261045VG002	MAIN	HP GAS COMPRESSING
FLOW ORIFICE 4339525 4TH STAGE - TRAIN C	262022FO006	INDICATION	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339216 - TRAIN C	262022PT003	CONTROL, MONITORING	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339217 - TRAIN C	262022PT004	CONTROL, MONITORING	HP GAS COMPRESSING
TRANSMITTER PRESSURE 4339218 - TRAIN C	262022PT005	CONTROL, MONITORING	HP GAS COMPRESSING
PSV 4338211 4338211 - TRAIN C	262022PSV001	PSV	HP GAS COMPRESSING
LINE TO PSV 262022PSV001	26-20-99-0200-GC30S-06-412	PSV	HP GAS COMPRESSING
LINE TO GAS INJECTION MANIFOLD	26-20-99-0300-GC30S-10-404	PSV	HP GAS COMPRESSING
PSV 4338212 4338212 - TRAIN C	26-20-22-PSV001PX	PSV	HP GAS COMPRESSING

CONTROL VALVE 4338818 - TRAIN C	262022XV001	PSD	HP GAS COMPRESSING
CONTROL VALVE 4338819 - TRAIN C	262022XV002	PSD	HP GAS COMPRESSING
ELECTRIC MOTOR FOR COMPRESSOR	262019EM001	MAIN	HP GAS COMPRESSING
EMERGENCY STOP/START BUTTON	262019EB001	EQSD	HP GAS COMPRESSING
HP COMPRESSOR C START	262019HS001	EQSD	HP GAS COMPRESSING
HP COMPRESSOR C STOP	262019HS002	EQSD	HP GAS COMPRESSING
COOLING MEDIUM FOR HP COMPRESSOR MOTOR		MAIN	HP GAS COMPRESSING
LEVEL SWITCH - COOLER	401500FI014	INDICATION	HP GAS COMPRESSING
SWITCH / PURGE LOW	REF TO 262019EM001	EQSD	HP GAS COMPRESSING
SWITCH / PURGE L/L	REF TO 262019EM001	EQSD	HP GAS COMPRESSING
LINE FROM COOLER HEADER	40-15-99-0200-AC21-10-422	MAIN	HP GAS COMPRESSING
LINE TO COOLING RETURN	40-15-99-0200-AC21-10-423	MAIN	HP GAS COMPRESSING
PRESSURIZATION SYSTEM FOR ELECTRIC MOTOR	262043PT002	PSD	HP GAS COMPRESSING
TEMPERATURE ELEMENT - MOTOR WINDING PH 1 4333001 - TRAIN C	262019TE005	PSD	HP GAS COMPRESSING
TEMPERATURE ELEMENT - SPARE MOTOR WINDING PH 1 4333002 - TRAIN C	262019TE006	MONITORING	HP GAS COMPRESSING
TEMPERATURE ELEMENT - MOTOR WINDING PH 2 4333003 - TRAIN C	262019TE007	PSD	HP GAS COMPRESSING
TEMPERATURE ELEMENT - SPARE MOTOR WINDING PH 2 4333004 - TRAIN C	262019TE008	MONITORING	HP GAS COMPRESSING
TEMPERATURE ELEMENT - MOTOR WINDING PH 3 4333005 - TRAIN C	262019TE009	PSD	HP GAS COMPRESSING
TEMPERATURE ELEMENT - SPARE MOTOR WINDING PH 3 4333006 - TRAIN C	262019TE010	MONITORING	HP GAS COMPRESSING
TEMPERATURE ELEMENT - MOTOR AIR TEMPERATURE 4333009 - TRAIN C	262019TE011	CONTROL	HP GAS COMPRESSING
VIBRATION PROBE 4333051 - TRAIN C	262019VT002	PSD	HP GAS COMPRESSING
VIBRATION PROBE - MOTOR 4333052 - TRAIN C	262019VT001	PSD	HP GAS COMPRESSING
MAIN LUB OIL SYSTEM 43350 - TRAIN C		-	HP GAS COMPRESSING
LUB OIL PUMP 4335001 - TRAIN C		MAIN	HP GAS COMPRESSING
LEVEL CONTROLLER OIL SUMP 4335002 - TRAIN C	262040LC004	MAIN	HP GAS COMPRESSING
LUB OIL PUMP PRE LUB 4335005 - TRAIN C	262043PF001	MAIN	HP GAS COMPRESSING
AIR MOTOR 4335006 - TRAIN C		MAIN	HP GAS COMPRESSING
LUB OIL FILTER DUPLEX 4335010 - TRAIN C		MAIN	HP GAS COMPRESSING
LUB OIL FILTER SIMPLEX 4335011 - TRAIN C		MAIN	HP GAS COMPRESSING
CJC FILTER 4335012 - TRAIN C		MAIN	HP GAS COMPRESSING
LUB OIL DAYTANK 4335009 - TRAIN C	262040TB001	MAIN	HP GAS COMPRESSING
LEVEL GAUGE - LUB OIL DAYTANK 4335010 - TRAIN C	262040LG001	INDICATION	HP GAS COMPRESSING
LEVEL SWITCH - LUB OIL DAYTANK 4335011 - TRAIN C	262040LSL002	CONTROL	HP GAS COMPRESSING
LUB OIL COOLER 4335012 - TRAIN C		MAIN	HP GAS COMPRESSING
LUB OIL TANK ON SKID 4335013 - TRAIN C	262040TB002	MAIN	HP GAS COMPRESSING
LEVEL SWITCH OIL SUMP 4335014 - TRAIN C	262040LS003	PSD	HP GAS COMPRESSING
INTERNAL PRESSURE RELIEF VALVE - MAIN LUBE OIL PUMP 4335015 - TRAIN C	262040PSV010	PSV	HP GAS COMPRESSING
OIL HEATING SYSTEM 43351 - TRAIN C		-	UTILITY SYSTEM
CIRCULATION PUMP OIL HEATER	262040PA010	MAIN	UTILITY SYSTEM
OIL HEATER	262040HA010	MAIN	UTILITY SYSTEM
ELECTRIC MOTOR CIRCULATION PUMP		MAIN	UTILITY SYSTEM
EMERGENCY STOP CIRCULATION PUMP		MAIN	UTILITY SYSTEM
JUNCTION BOX		MAIN	UTILITY SYSTEM
FLOW SWITCH		PSD	UTILITY SYSTEM
TEMPERATURE TRANSMITTER CONTROL	262040TT010	CONTROL	UTILITY SYSTEM
TEMPERATURE TRANSMITTER TRIPP	262040TT011	PSD	UTILITY SYSTEM
LO SYSTEM FOR CYLINDER 1-2 43355 - TRAIN C		-	UTILITY SYSTEM
LUBRICATOR HP COMPRESSOR C		MAIN	UTILITY SYSTEM
FORCE FEED LUBRICATOR PUMP		MAIN	UTILITY SYSTEM
DISTRIBUTION BLOCK AND PIPING		MAIN	UTILITY SYSTEM
FLOWSWITCH 26-20-47-FSL 001 STAGE 2	262047FSL001	CONTROL	UTILITY SYSTEM
FLOWSWITCH 26-20-47-FSL 002 STAGE 3	262047FSL002	CONTROL	UTILITY SYSTEM
FLOWSWITCH 26-20-47-FSL 003 STAGE 1	262047FSL003	CONTROL	UTILITY SYSTEM
PACKING VENT AND DRAIN TANK	262000TB003	MAIN	UTILITY SYSTEM
LEVEL GAUGE - PACKING VENT AND DRAIN TANK	262000LG003	INDICATION	UTILITY SYSTEM
LO SYSTEM FOR CYLINDER 3-4 43360 - TRAIN C		-	UTILITY SYSTEM
LUBRICATOR FOR THROW 1-2-3-4-5-6		MAIN	UTILITY SYSTEM
FORCE FEED LUBRICATOR PUMP		MAIN	UTILITY SYSTEM

	STARTING BOX LUBRICATIOR CYLINDER NO 1-2-3-4		MAIN	UTILITY SYSTEM
	ELECTRIC MOTOR FOR LUBRICATOR CYLINDER NO 1-2-3-4	262048EM001	MAIN	UTILITY SYSTEM
	DISTRIBUTION BLOCK AND PIPING		MAIN	UTILITY SYSTEM
	FLOWMETER / INDICATOR		INDICATION	UTILITY SYSTEM
	FLOWSWITCH 26-20-48FSLL 001 STAGE 4	262048FSLL001	CONTROL	UTILITY SYSTEM
	CYLINDER OIL DAY TANK		MAIN	UTILITY SYSTEM

Table A.1: Technical and functional hierarchy table.

Appendix B

List of maintenable items in the reliability model

External	Internal	Control and Monitoring
Support	Body	Actuating device
Body	Instruments	Cabling & junction boxes
Valves	Plates, trays, vanes, pads	Control Unit
Piping	Corrosion protection	Instruments
Instruments		Monitoring
Coupling		Internal power supply
Electric motor (electric actuator)		Valves

Table B.1: Scrubber maintenable items.

External	Internal	Control and Monitoring
Support	Body	Actuating device
Body	Instruments	Cabling & junction boxes
Valves	Plates	Control Unit
Piping	Gaskets	Instruments
Instruments	Tubes	Monitoring
		Internal power supply
		Valves

Table B.2: Cooler maintenable items.

Power transmission	Compresor unit	Control and Monitoring	Lubrication system	Shaft seal system	Miscellaneous
Gearbox	Antisurge system	Instruments	Check valves	Buffer gas system	Base frame
Bearing	Casing	Cabling & junction boxes	Reservoir	Dry gas seal	Cooler
Seals	Cilinder liner	Control Unit	Piping	Instruments	Control, isolating and check valves
Lubricaiton	Dummy piston	Actuating device	Pump with motor	Overhead tank	Magnetic bearing control system
Couplings	Instruments	Monitoring	Filter	Reservoir	Piping
Instruments	Shaft seals	Internal power supply	Cooler	Scrubber	Purge air
	Thrust bearing	Valves	Oil	Filter	Silencer
	Interstage seals		Instruments	Valves	
	Internal pipping		Seals	Seal gas	
	Valves			Seal Oil	
	Piston				
	Packing				
	Rotors with impelers				

Table B.3: Compressor maintenable items.

Cooling system	Electric motor	Control and Monitoring	Lubricating system	Miscellaneous
Heat Exchanger	Casing	Actuating device	Check valves	Hood
Fan with motor	Circuit breaker	Cabling & junction boxes	Reservoir	
Filter	Coupling	Control Unit	Pump witn motor	
Valves	Excitation	Instruments	Filter	
Piping	Instruments	Monitoring	Cooler	
Pump	Overload protection	Internal power supply	Valves	
Instruments	Radial bearing	Valves	Pipping	
	Rotor		Oil	
	Stator		Instruments	
	Thrust bearing		Selas	

Table B.4: Driver maintenable items.

Valve	Actuator	Control and Monitoring
Bonnet	Case	Actuating device
Closure member	Diaphragm	Cabling & junction boxes
Flange	Electric motor	Control Unit
Other valve components	Gear	Instruments
Packing	Indicator	Monitoring
Seals	Instrument, position	Internal power supply
Seat rings	Pilot valve	Valves
	Piston	
	Positioner	
	Quick exhaust	
	Seals (gaskets)	
	Spring	
	Stem	

Table B.5: Valve maintenable items.

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Risk Based Maintenance for Compressor Systems

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Abstract

Interruptions in production and poor system reliability still represent a high annual cost to the O&G industry. Maintenance is paramount to manage equipment deterioration and failure, addressing directly the unplanned downtime issue. Introduction of new technologies has changed how maintenance is done. However, the introduction of these new technologies cannot compromise on risk levels for the asset, for personnel or for the environment. The goal of this research is to evaluate the impact in the uptime of a system when the RBM approach is applied. Research showing that risk reduction and availability increase were obtained by the RBM approach has been published; however, more can be done to clarify the difference that such approach brings in terms of system, or installation uptime. This work applies the RBM methodology to a part of a production system that has been presenting operational problems and compares the results with the results obtained by the former maintenance approach. This can be replicated in many other systems to assess the outcome of a maintenance plan change in the system uptime.

Introduction

An offshore O&G platform is a complex environment that comprises equipment working under extreme conditions. When a component belonging to a critical system fails, severe accidents may occur.

Offshore O&G operators spend a considerable amount of money in maintenance strategies to avoid such catastrophic events. But **adequate maintenance is paramount to promote profitable operations** besides being important to protect lives and the environment. An installation with low availability related to maintenance isnt desirable as it influences negatively the oil or gas production and ultimately influences the oil companys profit, both as it reduces its production and increases costs with repairs.

A previous project investigated the maintenance work done in an offshore platform in the North Sea. Results concluded that the gas compression system was a major cause for unplanned production downtime through the years. A closer look at the hours spent in the period of January 2012 to November 2014 revealed that one of the compressor trains used the most hours for corrective jobs (see figure 1). This train was selected to be investigated regarding the changes that the RBM approach could introduce.

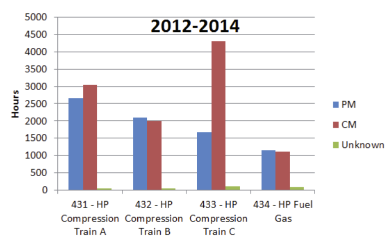

Figure 1: Compressor trains PM and CM hours

Main Objectives

1. Define a critical part of the compressor system by listing its components and create an structure that clarifies technical and functional connections between equipment.
2. Make a risk assessment of this system part.
3. Propose maintenance actions based on the risk assessment.
4. Create a reliability model of a critical part of the compressor system, using a reliability database.
5. Compare the different maintenance approaches.

Contribution

1. Ilustrate an implemetation of the RBM approach in a system in a offshore platform.
2. Verify the viability of comparison between two maintenance approaches using a reliability model.

Method

The NORSOK standard Z-008 Risk based maintenance and consequence classification was used as the guideline to develop the RBM part of this work. The reliability model was created based on the technical documentation of the compressor system being investigated, and the equipment reliability data used was taken from OREDA.

RBM - Risk Based Maintenance

The RBM methodology is divided in four modules: identification of the scope, risk assessment, risk evaluation, and maintenance planning. NORSOK Z-008 appoints four key elements of the RBM methodology: consequence classification of functional failure, creation of generic maintenance concepts (GCM), FMECA/RCM/RBI when GCMs are not applicable, and use of consequence classification and additional risk factors to create priorities concerning CM and handling of spare parts.

Figure 2 shows the steps of the consequence classification process.

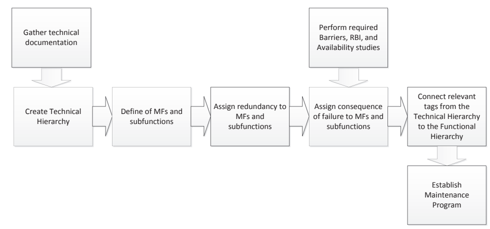

Figure 2: Consequence classification process

Reliability Model

After the functional hierarchy was created, only equipment belonging to the main and control subfunctions were selected to integrate the reliability model. Equipment and failure modes are going to be simulated in MAROS®, as well as the old and new maintenance strategies.

Results

So far, the tags collected from the technical and functional hierarchy were classified according to the risk assessment performed.

		TAGS	
MAIN FUNCTION	TOTAL	Old Maint. Plan	New Maint. Plan
Gas Compressing	127	68	93
Helping Systems	63	33	61
TOTAL	190	101	154

Table 1: Overview of TAGS included in the maintenance plans

Two main functions were identified: Gas Compressing, where equipment with main objective to compress the gas received from the separation system was placed, and Helping Systems; where equipment that supports the operation of the equipment in the previous main function was placed. Examples of the later are equipment necessary for lubrication and heating.
Table 1 gives an overview of the comparison of the old maintenance plan and the new, generated when applying the RBM methodology. 37% more tags were included in the new maintenance plan from the Gas Compressing main function, and 85% from the Helping Systems function.

Forthcoming Work

When the Generic Maintenance Concepts are generated, the new maintenance plan will be created. At this point, a more detailed comparison between old and new plans will be made. Also, the new maintenance strategy will be part of the reliability model. The uptime of the model running with both maintenance plans will be compared.

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