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Bacheloroppgave Maskin

ING3039

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Engelsk tittel *:	A RCM program for the maintenance of the cooling system of a compressor		
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Jeg bekrefter at jeg har registrert oppgavetittelen på norsk og engelsk i StudentWeb og vet at denne vil stå på vitnemålet mitt *:	Ja		

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Gruppenummer:	6
Andre medlemmer i gruppen:	103

Jeg godkjenner avtalen om publisering av bacheloroppgaven min *

Ja

Høgskulen på Vestlandet

BACHELOROPPGAVE

Utføre en RCM analyse for vedlikehold av kjølesystemet til en kompressor.
A RCM program for the maintenance of the cooling system of a compressor

Marius Didriksen Hansen & Elise Eide Arnesen

Ingeniør, maskin
Høgskulen på Vestlandet, avd. Haugesund
08.05.2019

Jeg bekrefter at arbeidet er selvstendig utarbeidet, og at referanser/kildehenvisninger til alle kilder som er brukt i arbeidet er oppgitt, *jf. Forskrift om studium og eksamen ved Høgskulen på Vestlandet, § 10.*

BACHELOR'S THESIS

Students names:	Elise Eide Arnesen Marius Didriksen Hansen
Study programme	Mechanical engineering, Design of Marine Structures
Thesis:	**A RCM program for the maintenance of the cooling system of a compressor**

Assignment text:

The maintenance department at Hydro Karmøy requested a maintenance analysis for one of the air compressors. The analysis of the compressor contains two analytical methods, FMECA (failure mode, effects, and criticality analysis) and RCM (reliability centred maintenance). By delimiting the compressor to a subsystem; cooling system, it will be possible to get further in the analysis. To perform maintenance on a system there are four fundamental questions which needs to be considered: What type of maintenance, where to maintain, when to maintain and why.

The result of the thesis is to be cost-effective, reduce the safety risk and optimize the availability maintenance plan.

Final assignment given:	Friday, March 8th, 2019
Submission deadline:	Wednesday, May 8th at 12:00
Internal tutor:	*Ajit Kuma Verma - HVL Haugesund*
External tutor:	*Leif Tore Larsen - Hydro Karmøy* *LeifTore.Larsen@hydro.com*
Approved by program coordinator:	J. C. Lindaas
Date:	30/4-19

Thesis A RCM program for the maintenance of the cooling system of a compressor			Rapport number
Students name Marius Didriksen Hansen Elise Eide Arnesen			
Study programme Mechanical engineering		Study programme Design of Marine structures and International	
Grading Open	Submission deadline 07.05.2019	Tutors Ajit Kuma Verma Leif Tore Larsen	

I samarbeid med Hydro Karmøy (Norsk Hydro ASA) er det skrevet en bacheloroppgave, som inngår som en del av den treårige ingeniørutdannelsen ved Høgskulen på Vestlandet, avd. Haugesund. Oppgaven innebærer å utføre en analyse for vedlikehold av kjølesystemet til en kompressor. Målet for oppgaven var å komme frem til et vedlikeholdsprogram som ville føre til at prosessen ble mer kostnadseffektiv og redusert nedetid.

Oppstartsfasen gikk ut på litterær studie, møter med operatørene på kompressoren, samt å avklare hvordan vedlikeholdet på Hydro Karmøy blir utført. På bakgrunn av innsamlede data ble systemet delt opp og satt inn i et systemhierarki. Det ble gjort for å få en bedre oversikt.

Industri 4.0 er allerede i gang med å sette sitt preg på industrien. For Hydro Karmøy sin del kan den nye industrien være med på å utvikle et nytt system, hvor all sensorering blir koblet sammen og kan bli overvåket fra start til slutt.

Preface

This bachelor thesis is a part of the theme "ING 3039 – Bacheloroppgave Maskin" at Western Norway University of Applied Sciences, campus Haugesund. The theme is a completion project for a three-year education in mechanical engineering. It consists of a written report, a poster and an oral presentation.

The thesis was given by Hydro Karmøy, based on disciplines that we have been associated with through lectures. Our thesis is mainly based on knowledge from study subjects "Materialer og tilvirkning", "Varme- og strømningslære" and "Prosessteknikk 1". Since we only had limited experience with maintenance and reliability, we spent a relatively long time to familiarize with different theories around this subject.

We want to thank our tutors Ajit Kuma Verma and Leif Tore Larsen, who spent their time through meetings and regular communication, and of course for excellent guidance. We also want to thank Steinar Alne and Odd Erik Jensen for helpful information about the compressor from Atlas Copco and maintenance on heat exchangers. We would like to thank Philip Sjøen Eide for assistance in obtaining information and his knowledge.

Summary

The assignment is given by Hydro Karmøy, where the task is to set up a maintenance analysis for one of the compressors on the plant. The group chose to consider the cooling system to a screw compressor supplying the Karmøy plant with compressed air. The reason for this choice is based on the experience from the employees, where the cooling system usually leads to downtime for the compressor. The aim of the thesis was thus to prepare a maintenance program that can help reduce downtime and make the production of compressed air more efficient.

The project began by acquiring theory within maintenance, gathering experience from service technicians, and verifying Hydro Karmøy's maintenance routines. With this knowledge, among other things, hierarchies were set up for the system and methodological analyses. During the analytical process, the external supervisor came up with recommendations and critical questions about what was done.

Today's industry wants a trend towards Industry 4.0, where monitoring of production is one of the main points. Such monitoring will allow a plant to read values of machines or components while operating. This means that the company or plant will, among other things, get a better maintenance plan and better collection of information about the state of the equipment. The result of this will be lower downtime, and cost-effective, safe and reliable production.

For an overview of the analysis, it was put in a scheme, based on the steps after the reliability centered maintenance (RCM) analysis. Where the group started with failure mode, effects, and criticality analysis (FMECA), to split up the system and come up with an overview over the critical items. After executing the FMECA analysis, the group gained a fundament to start with the RCM procedure. Through the RCM analysis different maintenance actions were selected for each component and the group came up with suggestions for inspection or sensor.

The objective for the thesis was to come up with a RCM program for the maintenance of the cooling system of a compressor. The scheme is the product, where the FMECA, RCM and risk analysis are presented. For the maintenance program, based on the analysis, the aim was to come up with a suggestion for maintenance action and maintenance interval. Because of the amount of available data, it was not possible to decide a maintenance interval.

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Abbreviations

α	Ageing parameter
ALARP	As low as reasonably practicable
F	Functional failure
FBD	Functional block diagram
FFA	Functional failure analysis
FMECA	Failure mode, effects, and criticality analysis
FSI	Functional significant items
MSI	Maintenance significant items
MTTF	Mean time to failure
n	Aggregated time in service
NDT	Non-destructive testing
OREDA	Offshore and Onshore Reliability Data
P	Potential failure
PM	Preventative maintenance
RCM	Reliability centered maintenance
RPN	Risk Priority Number
T	Number of failure

1. Introduction

1.1 Background

The authors of this report are two students in mechanical engineering, one from study programme “Design of marine structures” and one from “International”. Students at Western Norway University of Applied sciences (Haugesund) are obligated to develop and write a bachelor report as part of their three-year engineering degree. The thesis is in cooperation with an external company within a relevant industry. Based on the thesis, the group was provided with two tutors, one internal from the academy and one external from the involved company.

“Hydro – Karmøy Metal Plant” is a local, industrial company that produces aluminium. The group found Hydro Karmøy interesting and decided to contact them. This in order to question if they had a relevant project suited for a bachelor project.

Through meetings with Leif Tore Larsen, maintenance engineer at Hydro Karmøy, a provided thesis statement was given. Afterwards the thesis was discussed with Ajit Kuma Verma, the internal tutor representing the academy. Based on these discussions, he gave a go-ahead to continue, and also supplied relevant information for the further work.

1.2 Norsk Hydro ASA

Norsk Hydro ASA is a Norwegian aluminium and renewable energy company, headquartered in Oslo. It is one of the largest aluminium companies worldwide, with 35 000 employees. It has operations in some 40 countries around the world and is active on all continents. There are fifteen locations with 4060 employees in Norway (Norsk Hydro ASA, 2019a).

Hydro ASA was founded in 1905 and is a journey of evolution, spanning more than a century, many industries and several continents. But through it all, three characteristics have remained consistent; the spirit of entrepreneurship, a dedication to innovation and careful nurturing of a system of values. These traits have created the company that Hydro is today (Norsk Hydro ASA, 2019b).

1.2.2 Hydro aluminium Karmøy

On the location at Karmøy, Hydro has upstream and downstream activities. The plant produces primary aluminium and rolled aluminium strip. Except from that unit, they have casthouses, one delivering extrusion ingot for profile production, another producing wire rod for high voltage cables, and a sheet casthouse for the rolling mill. In addition, there is a research and development facility located at Karmøy (Norsk Hydro ASA, 2019b).

Figure 1 Hydro Aluminium Karmøy

(Norsk Hydro ASA, 2019b)

422 employees work in the primary production. They produce 190 000 tonnes of primary aluminium and 194 000 tonnes of casthouse products annually. Their specialties are primary aluminium, casthouse products, research and development. That is why Hydro operates different plants connected to the aluminium value chain. The largest facility is the plant producing primary aluminium, or liquid aluminium. This is one of Europe's largest integrated aluminium plants, and its energy supply comes from their locally situated hydropower plants in Røldal and Suldal (Norsk Hydro ASA, 2019c).

In cooperation with the primary production, the rolling mill receives liquid primary aluminium from the Karmøy metal plant, which is the background to Hydro Aluminium Rolled Products AS Karmøy. Within this production area there is 230 employees producing 75 000 tonnes of rolled products annually. Their specialties are rolled aluminium products such as foil, plates, sheet and coils (Norsk Hydro ASA, 2019d).

Figure 2 Aluminium rolled products

(Norsk Hydro ASA, 2019d)

1.3 Objective

The purpose of the task is to present a maintenance analysis for the cooling system of the compressor. One will start by getting an overview of the entire system, with all components. Most of the focus is set on the cooling system as subsystem, oil cooled and water cooled. The analysis will then be "Walk the dog" through the methodologies FMECA and RCM. The objective is to make a recommendation for a maintenance system that can help reduce the risk and improve cost- efficiency.

1.4 Refinements

There has been put refinements on the tasks both of the group and through recommendation from tutors. The main system, compressed air production, is delimited from where the industrial water and the air are drawn into the heat exchangers and air filters, to the medium and the compressed air leaving the heat exchanger and dehumidifier. The group chose to delineate the analysis to the cooling of the main system. The reason for this is to perform a qualitative method in which one delves deep into the most critical parts, oil cooling and water cooling. Making such a delimitation will make it easier to reach the set time limit the task has. Due to the lack of data from Hydro Karmøy, information about the failure rate from Offshore and Onshore Reliability Data (OREDA) was obtained.

2. Theory

2.1 The system

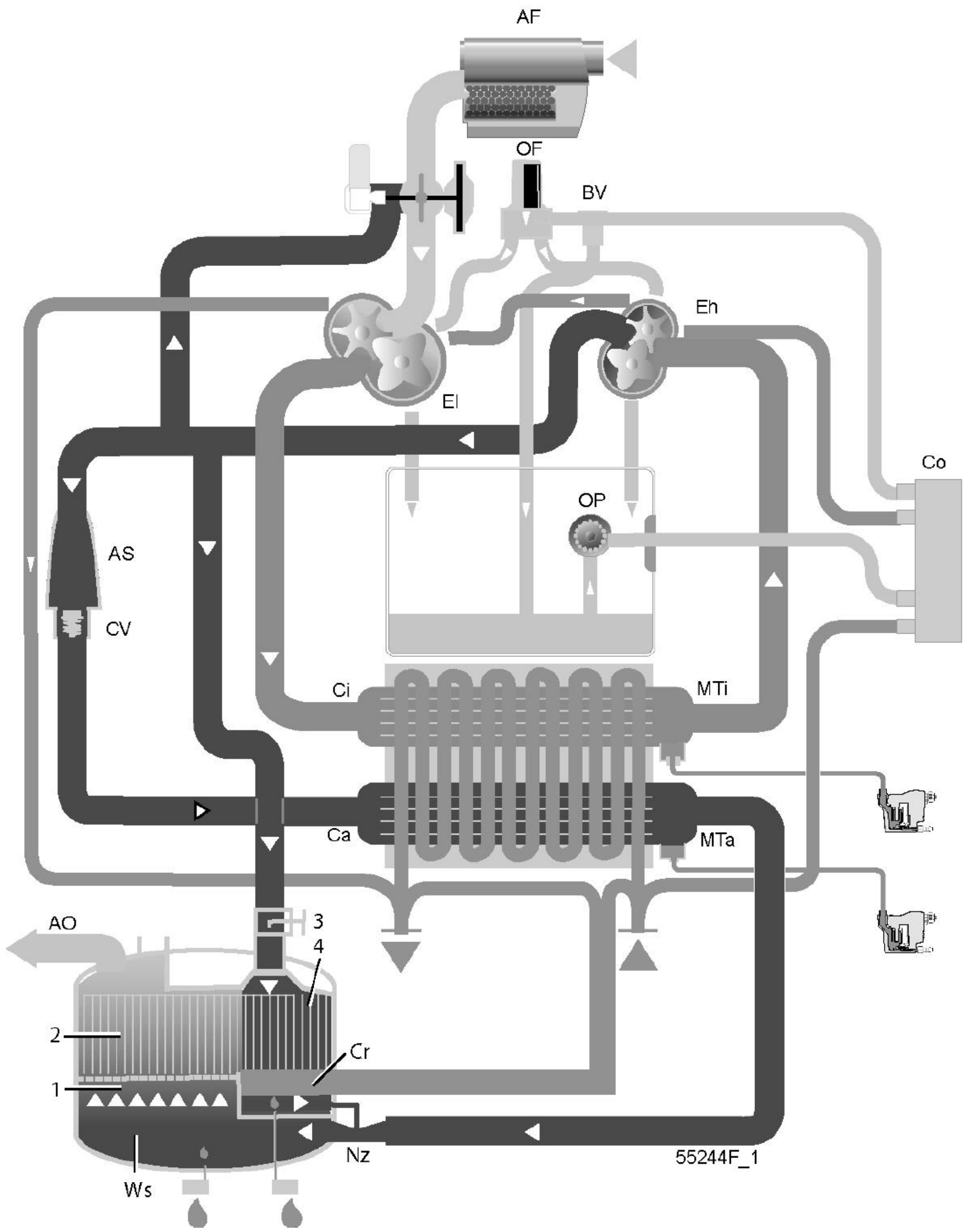


Figure 3 Flow chart of the production of pressurized air

Reference	Description
AF	Air filter
AO	Air outlet
AS	Soundsilencer
BV	Bypassvalve
Ca	Aftercooler
Ci	Intercooler
Co	Oilcooler
Cr	Regeneration aircooler
CV	Check valve
Eh	High pressure compressorelement
El	Low pressure compressorelement
Mta	Waterseperator aftercooler
Mti	Waterseperator intercooler
Nz	Ejector nozzle
OF	Oilfilter
OP	Oilpump
Ws	Waterseparator
1	Demisting
2	Rotor
3	Flow reducing valve
4	Strainer

Table 1 List of parts in the system

(Atlas Copco, personal communication, 30. January 2019)

Description Air system

Air flows through the filter (AF), get compressed in the Low-pressure compressor element (EI). On the ZR-compressors the pressured air flows through the intercooler (Ci). The cooled air will then get compressed again in the High-pressure compressor element (Eh) and trough the sound silencer into the after cooler (Ca.) On the ZR/ZT 132 VSD and ZR 315 VSD there is a check valve (CV) fitted after the sound silencer. The wet air from the after cooler will then circulate into the water separator (Ws) through the ejector nozzle (Nz). In the demisting (1) the drops of water will get removed from the air. The air flows through the rotor (2) and absorbs the water particles. The compressed air leaves the compressor through the air outlet (AO) (Atlas Copco, personal communication, 30. January 2019).

Description Cooling system

Cooling water flows through the oil cooler (Co), cooling capes to the High-pressure compressor elements (Eh) and Low-pressure compressor elements (El), these also flow through the intercooler (Ci) and the after cooler (Ca) (Atlas Copco, personal communication, 30. January 2019).

Description Oil system
Oil circulates by the pump (OP) from the tank into the gear and through the cooler (Co.) Oil passes through the oil filter (OF) against the bearings and the timing gear. The valve (BV) opens if the oil pressure rises to a certain value (Atlas Copco, personal communication, 30. January 2019).

2.2 Compressor

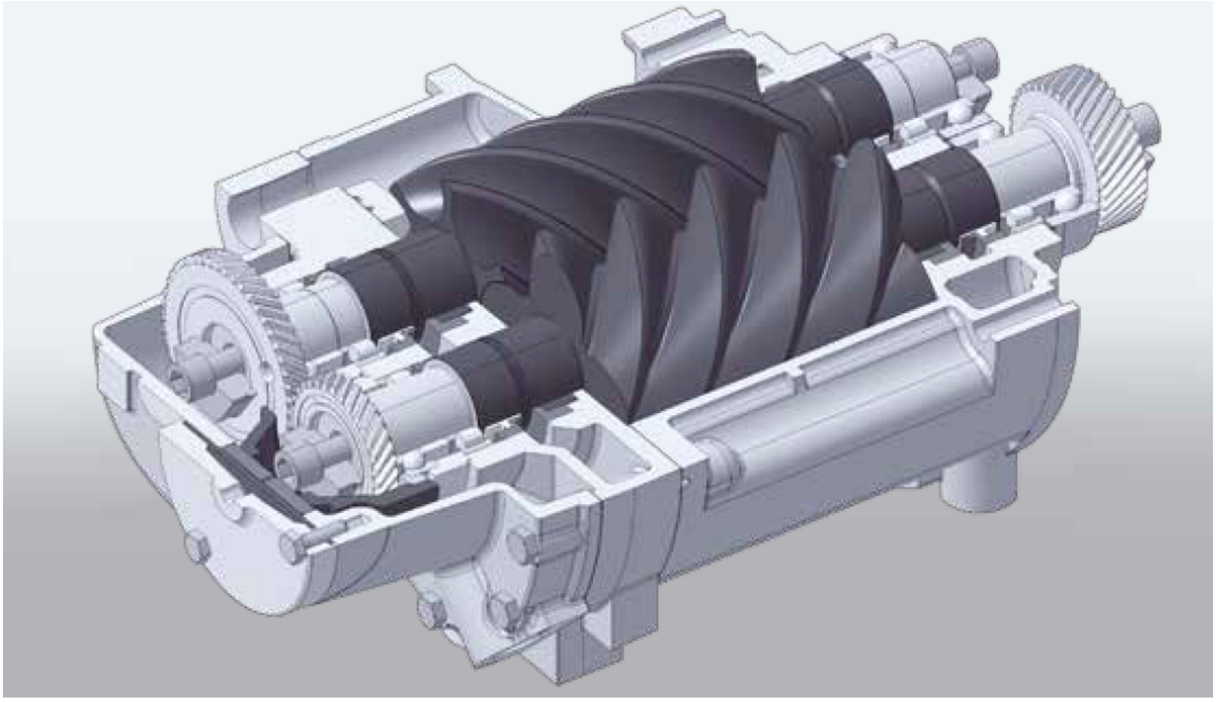
Air compressors are used to power an incredible array of different devices in the industry. The machines are also being used in cars and helicopters. There are different types of compressors, such as piston-, twin screw-, tooth compressors just to mention some. Compressors could either be oil free or not. Oil free means that there is no oil injected into the compression chamber. Picture 1 is an example of an oil free air compressor.

Compressors work by taking air from the surrounding atmosphere and compressing it to higher pressure. When the air has gained the desired pressure, it will be sent out to tools or the task it is needed for. The compressor will automatically restart the process when the pressure is too low and will then deliver the gas with the required pressure (Atlas Copco, 2015, p. 20).

2.2.1 Screw compressor

The compressor which is being analysed is an Atlas Copco screw compressor. It is also an oil-free compressor. Its purpose is to deliver the desired air pressure to the plant at Hydro Karmøy.

Screw compressors are positive displacement machines. It has two rotors called male and female rotor. These rotors have an asymmetric profile and rotates in the opposite direction of each other. The volume between them and the housing decreases. The air is drawn into one or more compression chambers, which are then closed from the inlet. Gradually the volume of each chamber decreases, and the air is compressed internally. When the pressure has reached the designed build-in pressure ratio, a port or valve is opened, and the air is discharged into the outlet system due to continued reduction of the compression chamber's volume. To get the preferred temperature on the air, the compression is divided into several stages. The air is then cooled after each stage before being compressed further to the final pressure (Atlas Copco, 2015, p. 34).



Picture 1 Oil-free screw compressor

(Atlas Copco, 2015, p.37)

Since the rotors neither meet each other nor with the compressor housing the rotors are kept in a synchronized rotational speed relationship by timing gears. This would not be a problem if it was a wet system. The bearings and gears are being lubed and cooled down with oil. This is separated from the screws and the air (Atlas Copco, 2015, p. 35).

2.2.2 Effects of failure

It is not often a machine, in this case the compressor element, is kept in operation out the estimated hours stated by the supplier. The compressor will eventually fail if the condition is rough enough and/or lasts long enough. Failures such as insufficient cooling, poor filtration and inadequate lubrication can all serve as warning signs of a gradually failing system.

Rotary screw compressor consists of complex parts, including the rotary screw element with its low tolerance, which can cause problems in many ways. If the problems are not detected or maintained, a small problem could cause costly failures and part replacement.

The failures which can occur under the production of pressurized air can affect the screw elements. Some of them are more critical than others. One of the most important components in the system is the water cooling. If a problem occurs here it will not just affect the rotary screws itself, but the whole production. A problem which often occurs at summer time is that the cooling medium has been heated because of warm weather. Mostly this affects the rotary screw elements. Since the element is made of metal, the increase of temperature leads to thermal expansion. This could lead replacement of the screws because they work with little tolerance. (O.E. Jensen, personal conversation, 15. February.2019)

The expansion of the screw could also be a scenario if the filter gets plugged. This is a huge problem for the water cooling subsystem, and it is a common problem at plant. Why it often occurs is because of the cooling medium is polluted of grass and soil. Picture 2 shows the shell and tube heat exchanger. (O.E. Jensen, personal conversation, 15. February.2019).

Picture 2 An example of a polluted cooling system, it is usually worse.

(Personal, 15.02.19)

Although this is an oil-free process, both the gears and bearings need lubrication and cooling from the oil. This oil-cooling system is totally separated from the air compression which is oil-free. The oil itself is dependent on the water cooling subsystem. If the oil does not have the working temperature, the viscosity will decrease, i.e. the oil will get thinner. This will both affect the lubrication and cooling of the gears and bearings. Another problem which can occur in the oil system related to the oil filter. If the oil filter loses its effect of collecting particles, it may result in more resistance to gears as the particles accumulate between the gear teeth. Over time, it can lead to wear and tear, and the efficiency decreases as energy is lost in the form of heat to oil (Kaishan, 2018).

2.2.3 Heat exchanger (co-system)

2.2.3.1 General

A heat exchanger is a device where two moving fluid streams exchange heat without mixing, in some cases with different temperatures. One fluid flow in the inner pipe, and the other in the annular space between the two pipes. A heat exchanger is widely used in various industries, and they come in various designs. Many criteria play a role in the selection of heat exchangers, such as pressure loss, vibration, corrosion, formation of scale or thermal expansion (Cengel and Boles, 2015).

Tube- and shell, are the most universal units that covers the entire pressure area from vacuum to extremely high pressure. Heat is transferred from the hot fluid to the cold one through the wall separating them. Sometimes the inner tube makes a couple of turns inside the shell to increase the heat transfer area, and thus the rate of heat transfer (Cengel and Boles, 2015).

The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates. This principle can also be expressed as follows: Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant (Cengel and Boles, 2015).

2.2.3.2 Plate heat exchanger

Consist of many plates, often manufactured out of a thin alloy material, that are bolted together. The patterns are shaped such that the medium is distributed over the entire surface. Between the plates there are gaskets to prevent leakage. The plates are mounted in a carrier structure. Plate heat exchangers can be cleaned much more easily than other types of heat exchangers. These normally have all the pipe nozzles on one side of the casing. For moderate pressures and temperatures these heat exchangers often constitute an optimum with respect to investment, flexibility, weight, and space requirement (Cengel and Boles, 2015).

Plate heat exchangers are normally used for moderate pressure (<16 bar) and temperature (<250 degree Celsius). Since there is a continuous development of the products, these values should be understood as a guideline (Cengel and Boles, 2015).

2.2.3.3 Compact heat exchanger

Composed of laminated plates that are arranged such that metallic contact between the plates is established. The flow passages are very tiny (typical 5-10 times less than shell and tube heat exchangers), thus aiming for clean products. Compact heat exchangers have, to a certain degree, become the standard solution for gas cooling (Cengel and Boles, 2015).

In the first years a couple of instances of damage due to thermal fatigue were observed. This can be avoided by selecting a suitable slow control of the cooling medium and further by ensuring that the cooling medium flow never stops, irrespective of operation point (Cengel and Boles, 2015).

2.3 Main steps of an RCM analysis

"The RCM analysis may be carried out as a sequence of activities or steps:

1. Study preparation
2. System selection and definition
3. Functional failure analysis (FFA)
4. Critical item selection
5. Data collection and analysis
6. FMECA
7. Selection of maintenance actions
8. Determination of maintenance intervals
9. Preventative maintenance comparison analysis
10. Treatment of noncritical items
11. Implementation
12. In-service data collection and updating

The various steps are discussed in the following chapters."(Rausand, 2004, p. 403)

2.3.1 FMECA

FMECA is an analytical method for failure analysis of a system. The analysis is a tool to detect all failure modes of a part of the chosen system. It will also identify the effects of the failure modes on the system and categorize/prioritize them after the risk. With this type of methodology, the operator will be able to detect possible failures on the system and eliminate them by making improvements.

The failure analysis was developed by the U.S. Military in 1949. The guideline was called MIL-P-1649. Today the methodology is being used in different types of industries. It is an equipment and technique to improve safety, reliability and decrease cost.
In many cases the FMECA is performed in the early stages of product/system development. This is to eliminate potential failure modes, and it is a lot cheaper making changes early in the design process than later in the production. In this case the analysis will list every failure mode and effect of each part of the oil/water cooling subsystem. (Verma, personal communication, 4. March 2019)

It is important to state that the analysis only looks at one part at the time, where the other parts in the system are considered to function perfect. With this type of mindset, the analysis will not uncover critical combinations of component failure. (Aven, 2006, page 45)

2.3.1.1 Preparation

The setup and content of the scheme varies from how it is utilized. How deep and detailed the methodology should be depends on the boundaries. Even if the analysis becomes more complete by going into detail, it may be a waste of time and money. Therefore, these boundaries are important and should be set before the analysis starts:

- Which part or subsystem of the construction or equipment to be analysed.
- Level of detail, how far should the analysis dig to find the cause of failure.
- Choose how many columns needed for the analysis.

(Bye, 2009, page 48)

To make it easier to complement the analysis, the whole system should be illustrated with a hierarchical tree diagram, displayed in figure 4. The diagram starts with the system on top and breaks down into subsystems and components depending on the level of detail desired. With this tool the user should get an image of how the system is put together, and from this may make some changes on which subsystems or parts to analyse.

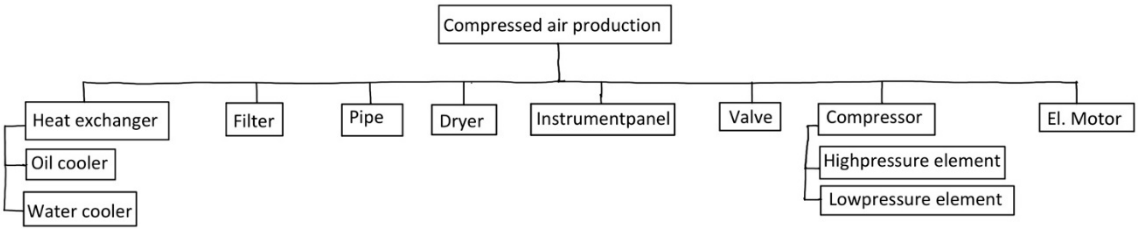


Figure 4 System hierarchy, compressed air production

Another way to get an overview and understanding of how the different systems are connected is by using functional block diagram (FBD). Figure 5 illustrates the production of compressed air.

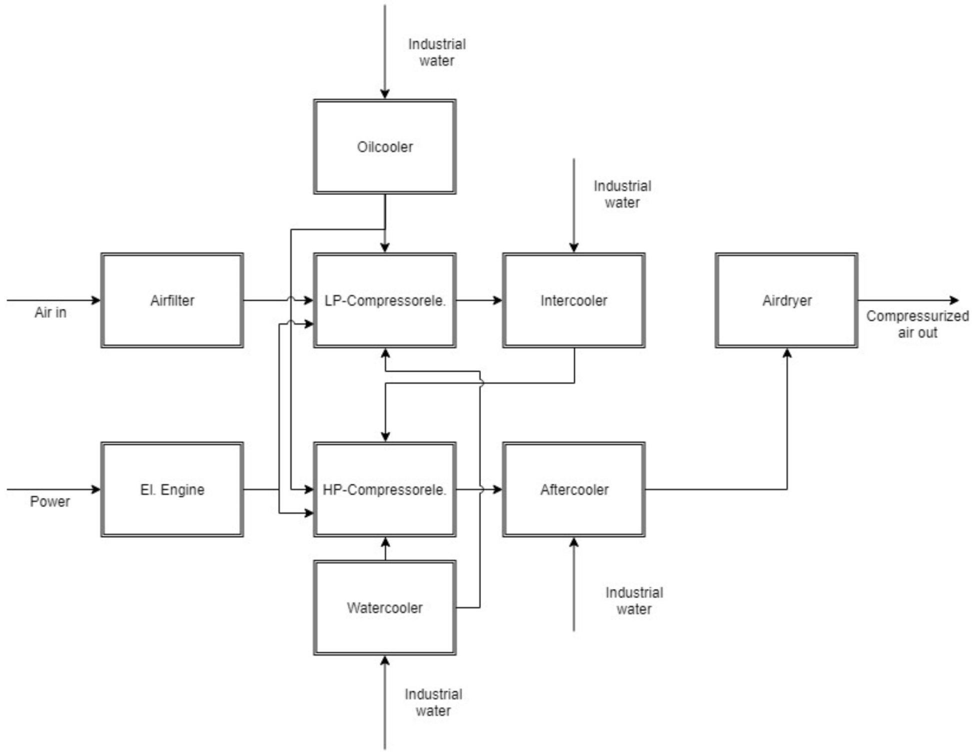


Figure 5 Functional block diagram

From these system overviews it would be possible to make a choice for which subsystems to analyse. By taking the whole system under one analysis it requires a lot to deal with, as it consists of many parts. In some cases that is necessary. The most ideal is to divide the system into subsystems. In this way, the analysis is performed only on the parts belonging to the subsystem and in a qualitative manner.

The operators at Hydro Karmøy believed that the cooling system of the compressor is the most critical system. The reason for this is that failure often occurs in this system. Based on the experience from the operators, the subsystems oil- and water cooling subsystems are chosen.

A failure hierarchy is a good way to list up possible failures for each of the components in the subsystem. The layout of the hierarchy consists almost of the same terms used in the FFA. An example of a failure hierarchy is shown in figure 6 and 7. The hierarchy consists of five levels:

1. Component
2. Function
3. Failure mode
4. Failure cause
5. Failure mechanism

(Bye, 2009, side 49)

The failure mechanisms in the hierarchy are gathered from OREDA. The data in the book is based on collection and analysis of maintenance and operational data from several offshore companies.

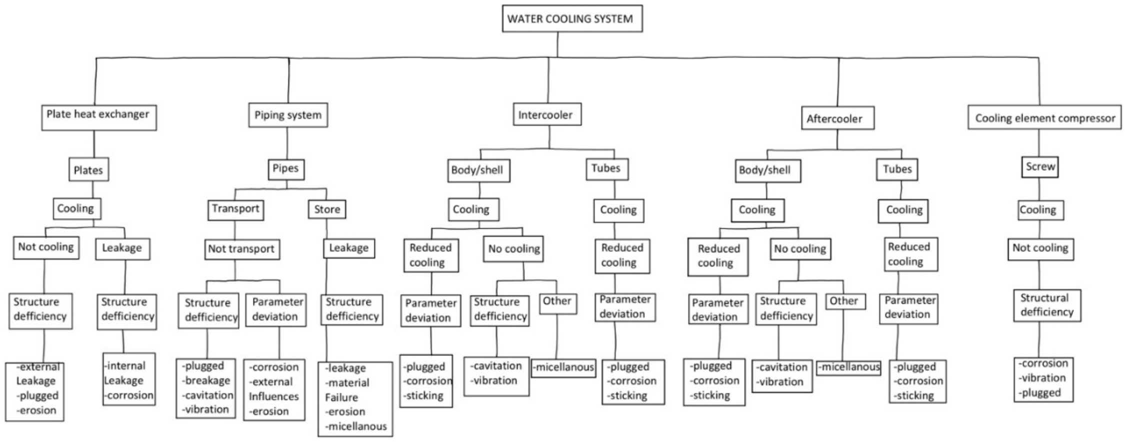


Figure 6 Failure hierarchy for the water cooling subsystem

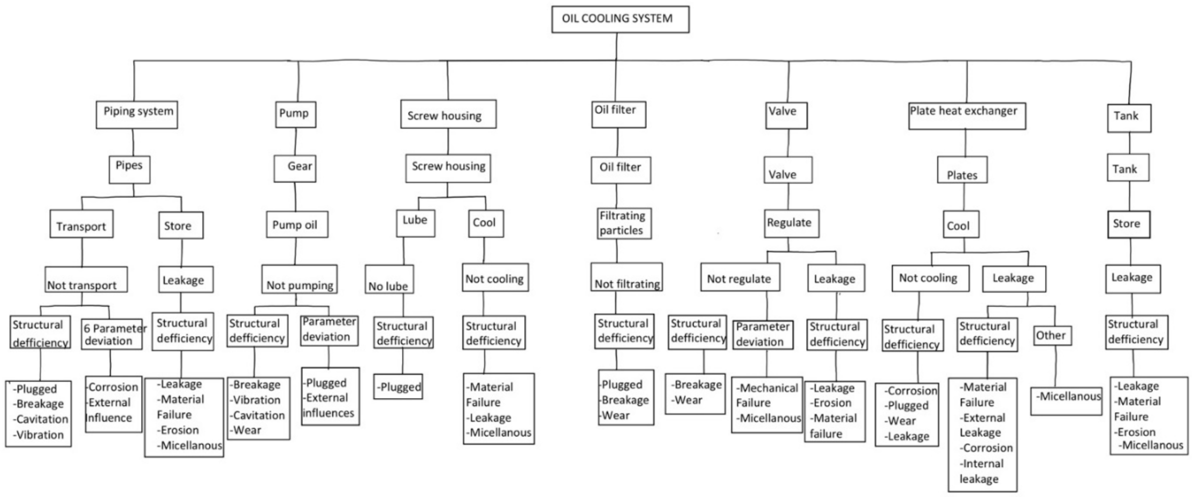


Figure 7 Failure hierarchy for the oil cooling subsystem

Some parts are more critical than others if they fail. These parts are denoted functional significant items (FSI). To identify could be simple or difficult and needs a formal analysis. Which items that have influence on the system function could be identified by experience, and is obvious that it is a FSI. In other occasions where the system is more complex, failure rate and other necessary input data is needed to calculate the importance of the various analysis items. By screening out items which are irrelevant for the main system function, the plant or project does not waste money or time analysing irrelevant components. (Jørn Vatne, 2007, side 89)

Before implementing the FMECA scheme it is necessary to collect data for the analysis. This is done to establish a foundation for calculations of, for example, intervals to be set up later in the analysis.

2.3.1.2 Implementing the FMECA

The FMECA worksheet can vary from system to system and situation. Some of the columns are more standard than others. The form is developed in conjunction with previous forms from the industry and it involves several important aspects so that the analysis will be as thorough as possible. The same scheme is being used for both water- and oil cooling subsystem. When going through the analysis it is important to focus on each part separately from the other parts and take the analysis step by step, walking the dog.

Basic questions that should be taken into consideration when undergoing the FMECA analysis:

- How can each component conceivably fail?
- What cause or mechanism could produce the failure mode?
- What could the effect of the failure be?
- Is the failure in the safe or unsafe area?
- How is the failure detected?
- What can be done to prevent the failure to occur?

(Rausand, 2009, page 92)

The same FMECA scheme is used in both subsystems. The scheme is shown under Results, figure 14 and 15.

Component, column 1
Start by giving the component a name

Component part, column 2
If the component consists of several parts list them up.

Function, column 3
Describe the function of each component or part participating in the subsystem. It should be precise and short. The component can have more than one function, every function must be listed up in the form.

Failure mode, column 4
For every operational condition there should be identified relevant failure modes for the given component. The component does not necessarily have just one failure mode. A question to ask when mapping failure modes is “What can we expect to go wrong in this particular operational mode?” Most of the failure modes are based on experience from years of usage of similar components.

Detection of failure, column 5
Describes different methods to detect failure modes, failure cause and failure mechanism on the system. The operator must recommend for example periodic testing or condition monitoring.

Failure cause or mechanism, column 6
For each of the failure modes which are identified, every single fail or mechanism will be listed in this column. For example; corrosion, cavitation, breakage, wear.

Effect of failure on the subsystem, column 7
Does the failure effect other subsystems? If so list up the possible occasions.

Effect of failure on the system main function, column 8
Specify whether the system's main function is affected by the individual failure modes.

Fatigue phenomenon Yes/No, column 9
Aging can be the cause of the failure mechanism. For example, fatigue fracture on metals.

Is the failure Visible/Hidden, column 10
The failure cause or mechanism can be visible or hidden for the inspectors. Cavitation is a hidden failure mechanism.

Does there exist indicators which will alert failures Yes/No, column 11
Is it possible to detect failure or the condition of the component?

Type of control, column 12
The type of control to detect the condition of the component. Visual inspection, Non-Destructive Testing (NDT), sensors, are some of the controls.

Maintenance strategy, column 13
Maintenance strategy carried out by a given failure mode. Run to failure, periodic preventative maintenance, condition based maintenance.

Maintenance action, column 14
The maintenance action will be monitoring, inspection, control. It is based on the failure mode which can occur.

Frequency of activity, column 15
Describes how often the activity should be performed. This will be decided from earlier data from the component and experience. It will then be possible to calculate an interval for how often it needs to be maintained. This is relevant when the maintenance strategy is periodic

preventative. For condition based maintenance the component is often monitored, that way the operator will get indications of when it will fail.

Risk, column 16, 17, 18 and 19
Column 16 is the frequency of the effect of failure. Column 17 is the consequence of the effect of failure. Column 18 is the risk priority number (RPN), which is the sum of column 16 and 17. It tells the operator the criticality of failure. Column 19 "Is the activity considered risky? Yes/No". This depends on where it is placed in the risk matrix.

2.3.1.3 Benefits

In the analysis, each individual fail or failure mode is studied separately, as independent events without correlation with any other errors in the system. This will come handy in situations where the system will fail due to failure in individual parts. By performing the FMECA, the operator must familiarize himself with the system in order to implement failures associated with the components.
(Rausand, 2009, side 151)

2.3.1.4 Limitations

- Since each fail or failure mode are being analyzed as separate incidents without relation to other faults in the system, FMECA is then not suitable for systems that have a significant degree of redundancy. Redundancy means parallel units or standby-units takes the full service if the primary unit fails.
- The methodology has insufficient focus on the human- and procedural failure.
- How the result of the analysis is dependent on the analyst.
  (Rausand, 2009, side 151)

2.3.2 RCM

The RCM was first originated within the aircraft industry. Based on the grounds that too many failures and accidents occurred despite extensive preventative maintenance programs. There was a need to develop a methodology to prioritize preventative maintenance where it had an impact on safety. (Bye, 2009, p. 100)

Today, RCM analyses are used as decision support tools in all industry branches, both onshore and offshore, in order to establish a cost-effective maintenance program that meets the current internal and external requirements. (Bye, 2009, p.100)

2.3.2.1 What is RCM?

RCM is "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context." (John Moubray, personal)

It is a structured methodology used in connection with maintenance technical analyses in all phases of a plant/equipment lifetime. (Bye, 2009, p.100)

2.3.2.2 Objective

The main objective is to reduce the maintenance cost by focus on the most important functions of the system and avoid or remove maintenance tasks that are not strictly necessary. (Rausand, 2004) As a result, it is supposed to establish an optimal maintenance program for all devices in a facility based on internal and external criteria related to the system/equipment's functional context and consequences of malfunctions for health, environment, safety, quality, availability, economy or other management parameters the company may have. (Bye, 2009, p. 100)

2.3.2.3 Performance

The RCM analysis is carried out in collaboration with one or more interdisciplinary groups composed of experienced personnel from the various disciplines represented in the company (mechanical, electrical, operation, etc.). It is not necessary that all personnel categories participate in all stages of the analysis. (Bye, 2009, p.100)

While the internal and external forces do the improving work, it is only the professional reviews of the analysis that will burden the professional maintenance personnel. (Bye, 2009, p.100)

2.3.2.4 Approach

In the chapter earlier "Main steps of an RCM analysis", it was mentioned that there are twelve steps in an RCM analysis. Based on the choice to split it up in the first six and the last six, this chapter is about the last six steps.

When it is time to select maintenance action, this step is the most novel compared to other maintenance planning techniques. It is normal to use a decision logic to guide the analyst through a question and answer process, where the input is the dominant failure modes from the FMECA. The main idea is for each dominant failure mode to decide whether a preventative maintenance (PM) task is applicable and effective, or it will be best to let the item deliberately run to failure and afterwards carry out a corrective maintenance task. (Rausand, 2004, p.410-412)

"Three main reasons for doing a PM task:

1. To present a failure
2. To detect the onset of a failure
3. To discover a hidden failure

Where the following basic maintenance tasks are considered:

1. Continuous on-condition task
2. Scheduled on-condition task
3. Scheduled overhaul
4. Scheduled replacement
5. Scheduled function test
6. Run to failure "

(Rausand, 2004, p.410)

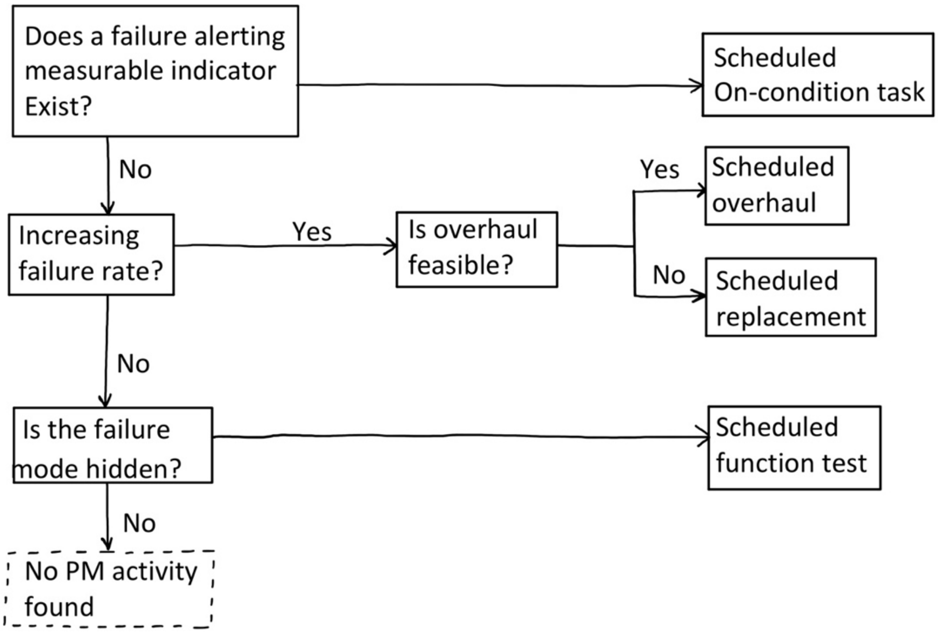


Figure 8 Decision logic

(Rausand, 2004, p.410)

Successful implementation of RCM will lead to reduction in costs, higher system reliability, more machine uptime, and the system to be operated for its full life cycle.

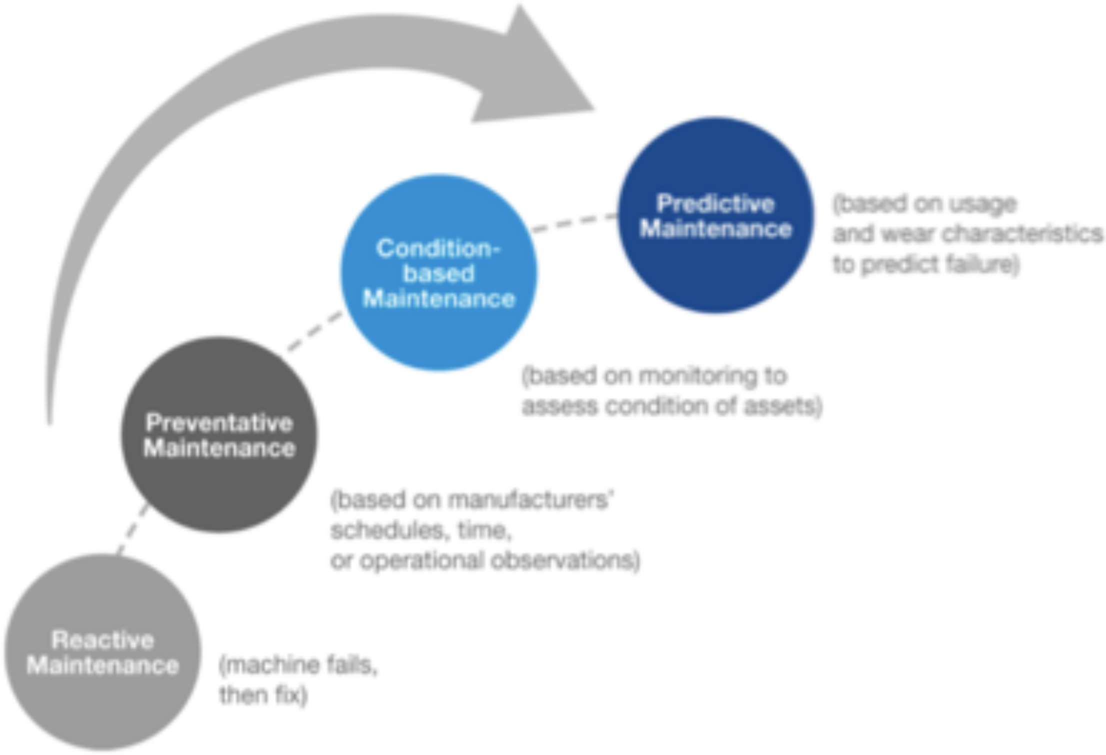


Figure 9 Maintenance actions

<u>Reactive maintenance</u>
Also known as breakdown maintenance, refers to repairs that are done when equipment has already broken down and is a part of the corrective maintenance. When the machine fails it will be in its order to restore the equipment to its normal operating condition.
Machine fails, then fix. It is unpredictable when the machine will fail, this can lead to long down-time because, for example the reason is unknown, or the replaceable part is not available. This type of maintenance activity will have high costs and long down-time. (Rausand og Høyland, 2004, p. 364)

<u>Preventative maintenance</u>
Equipment showing age-related failures. Based on the principle that restoring or discarding the equipment at a specific time before the occurrence of failure can manage the probability of failure in the best possible way. PM tasks are performed at set intervals of time or cycles of operation irrespective of whether failure is imminent or not. (Rausand og Høyland, 2004, p. 380)

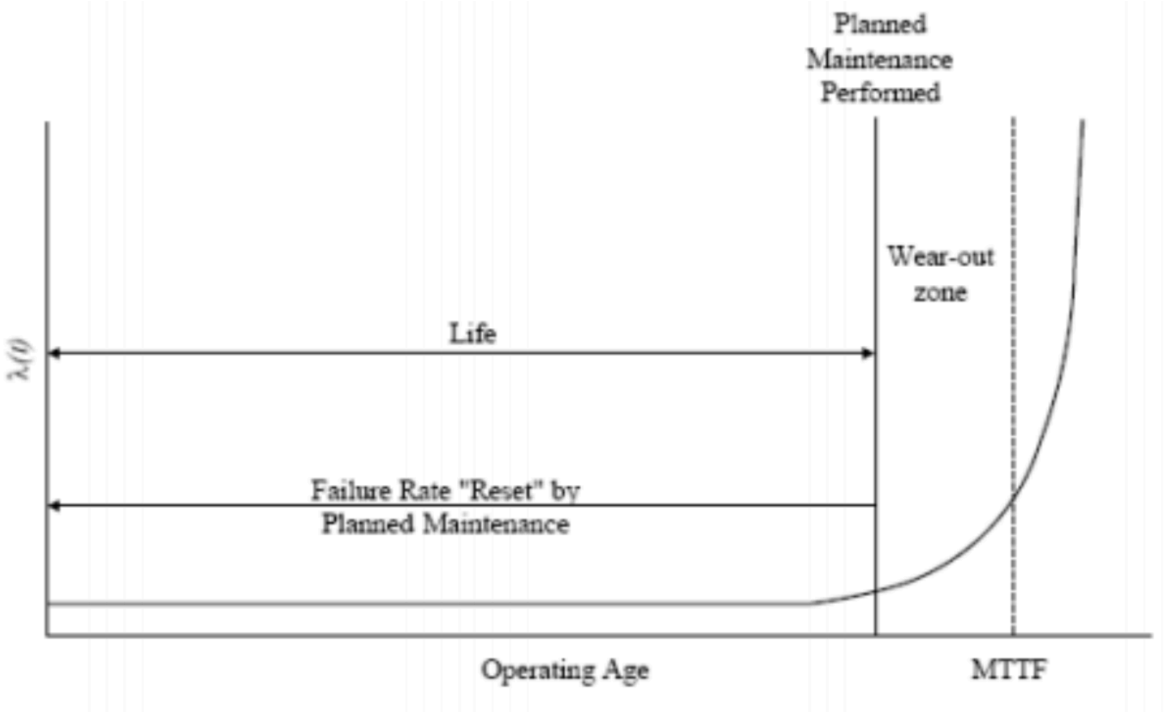


Figure 10 Failure profile illustrating the effect of performing a planned task

Condition based maintenance
A maintenance action decided based on measurement of one, or more, variables that are correlated to degradation, or a loss of performance, of the system. The variables can be physical (e.g., temperature or pressure), system performance variables (e.g., quality of produced items or number of discarded items), or variables related to the residual life of the system (Rausand and Høyland, 2004, p.363).

Condition based maintenance is suited for failure modes which give some sort of indication that failures are in the process of occurring or about to occur (Verma, personal communication, 4. March 2019). Its policy requires a monitoring system that can provide measurements of selected variables, and a mathematical model that can predict the behaviour of the system deterioration process (Rausand and Høyland, 2004, p.363).

The time interval from which it is possible to reveal a potential failure (P) and the currently used monitoring technique until a functional failure (F) occurs is called the PF interval, as shown in figure 4. (Rausand, 2004, p.410).

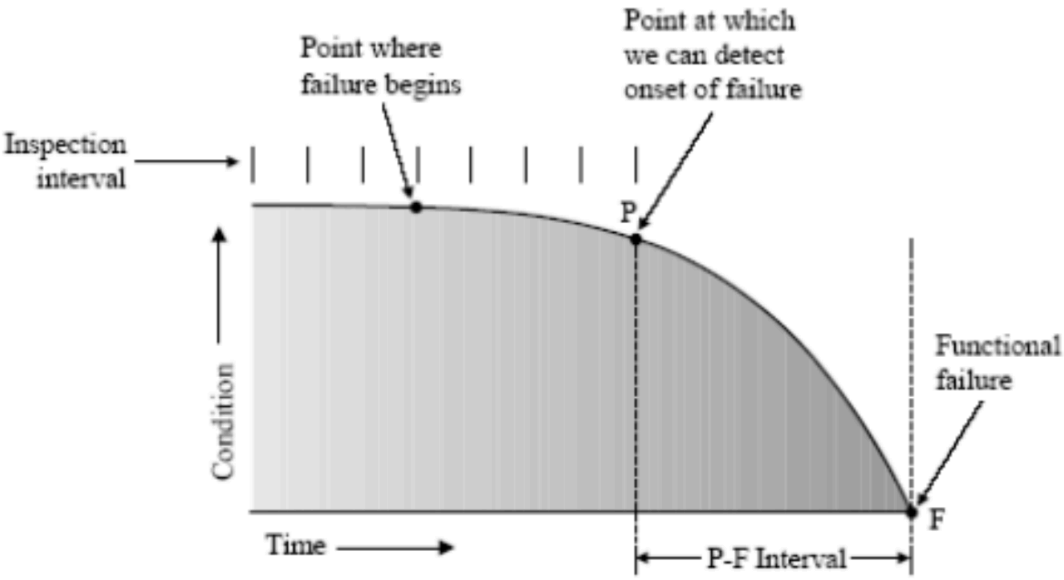


Figure 11 PF curve

When an item is exposed to random shocks, it produces a potential failure in the item that, in time, will develop into a critical failure. Since it is not possible to observe shocks but may be able to reveal potential failures sometime after the shock has occurred. As shown in the figure over, P is the point of time (after a shock) when an indication of a potential failure can be first detected, and F is the point where the item has functionally failed. The time interval between P to F is called PF interval (Rausand and Høyland, 2004, p.410).

Predictive maintenance

A technique to predict the future failure point of a machine component, so that the component can be replaced, based on a plan, just before it nails. Thus, equipment downtime is minimized, and the component lifetime is maximized. Predictive maintenance activities are carried out as the machines are running in their normal production modes (Garrido, 2015).

Based on the Trond Espeset (2016) Master-thesis, it tells us that a type of condition-based maintenance performed after notice derived from repeated analyses or known properties and evaluation of the significant parameters of the device degradation. With this maintenance it is easier to predict when components are expected to fail (p. 17).

Since some of the PM tasks are to be performed at regular intervals, it is necessary to determine the optimal interval. It has to be based on information about the failure rate function, the likely consequences and cost of the failure the PM task is supposed to prevent, the cost and risk of the PM task, and so on.

Based on what type of maintenance strategy chosen for the component, there must be set an optimal interval. This is specially for the periodic preventative maintenance tasks, for example periodic function test. For condition-based maintenance gathered data from the condition of the component will show when it might fail, and then perform the maintenance just before it does.

Periodic preventative maintenance intervals can be calculated in different ways, dependent on what the situation is. There are four basic failure models (p. 51-53);

- Observable gradual failure progression
- Observable "sudden" failure progression
- Non-observable failure progression
- Shock

To get an indication of how long a component is in service, mean time to failure (MTTF) is often used. "MTTF express the time from a new component is put into service until it fails in average" (Veien frem til "World Class Maintenance": Maintenance Optimisation, Jørn Vatn, Trondheim 2007 NTNU, side43). An estimate of the MTTF might be set like this for one unit:

$$MTTF = \frac{Aggregated\ time\ in\ service}{Number\ of\ failure} = \frac{t}{n}$$

Since this will be a rough estimate and give an idea on how long the component operates before it fails, one will set a security margin. 80 percent of MTTF will be a good safety margin. One should set up more calculations to get a better estimate to rely on, not just MTTF as it is a bit vague. There are more reliable methods in which several factors and variables are considered, like the ageing parameter (α).(Side 132)

The function of the P-F interval is to provide an indication of when the maintenance of the system should be performed. The problem then is often when in the interval this is to be planned. A rule of thumb is to take the P-F interval and divide it by two. The selection may also be based on experience. Hopefully you will then be able to carry out maintenance or replacement before total failure occur. (Rausand and Høyland, 2004, p.410).

When it comes to selecting maintenance tasks, there are two overriding criteria that are used:

1. It must be applicable
2. It must be effective

Applicability means that the task is applicable in relation to out reliability knowledge and in relation to the consequences of failure. For a PM task to be applicable, it can eliminate a failure, or at least reduce the probability of the occurrence of failure to an acceptable level or reduce the impact of the failure. (Rausand, 2004)

If the task does not cost more than the failure(s) it is going to prevent, it is cost effective. The PM task's effectiveness is a measure of how well it accomplishes its purpose and if it is worth doing. When it comes to evaluating the effectiveness of a task, it is balancing the cost of performing the maintenance with the cost of not performing it (Vatn, 2007, p.14).

Earlier in the work, critical items were selected for further analysis, more specific in step 4: Critical item selection. Now a remaining question is what to do with the items which are not analysed. It depends on if there is a maintenance program already existing, if so, a brief cost evaluation should be carried out. On the other hand, if the existing maintenance cost related to the non-MSIs (maintenance significant items) is insignificant, it is reasonable to continue this program. (Rausand, 2004)

Implementation in this case, for an RCM analysis, a necessary basis for implementing the result of the analysis is that the organizational and technical maintenance support functions are available. A main issue can be to ensure that these support functions are available. Based on experience, it shows that many accidents occur either during maintenance or because of inadequate maintenance. It is of vital importance to consider the risk associated with the various maintenance tasks when implementing a maintenance program. (Rausand, 2004)

A full benefit of the RCM analysis is only obtained when operation and maintenance experience is fed back into the analysis process. In the updating process, there are three major time perspectives that should be concentrated on:

1. Short-term interval adjustments
2. Medium-term task evaluation
3. Long-term revision of the initial strategy

The failure characteristics, for each significant failure that occurs, should be compared with the FMECA. If the failure was not covered adequately in the FMECA, the relevant part of the RCM analysis should, if necessary, be revised. (Rausand, 2004)

2.4 Risk analysis

Risk analysis is performed to reveal the risk associated with delivery security and operation. The analysis will provide the basis for decisions, either to not allow an activity due to high risk, or to take measures that reduce the risk and the activity can nevertheless be implemented (Bye, 2009).

2.4.1 General

An analysis with a systematic approach to describe and/or compute risk. Used in cases to reveal the risk, connected to different measures, activities, systems or situations, and carried out by answering the three basic questions:

1. What can go wrong?

- Overview over which undesirable incidents can occur and which can cause damage to values that are desired to be taken care of.

2. What is the probability for that the unwanted events occur?
   - Define how often these unwanted events occur, the answer is given by frequency or probability.
3. Which consequences can each of the unwanted events cause?
   - Uncover what damages the undesirable events may cause to the values mentioned in paragraph 1.

(Rausand and Utne, 2009, p.4).

2.4.2 The ALARP principle

The ALARP (as low as reasonably practicable) principle can be utilised based on the following acceptance criteria:

1. Area with unacceptable risk
   - The risk is only acceptable in very special situations.
     - Must take risk-reducing measures.
2. ALARP or tolerated area
   - The risk can be perceived as tolerable if the usefulness of the business is significant.
     - Only risk reducing measures are introduced if the costs are disproportionately large in relation to the risk reduction achieved by the measure.
3. Acceptable area
   - Low and general accepted risk.
     - Not necessary to identify and analyse risk reducing measures.

(Rausand and Utne, 2009, p. 70-71)

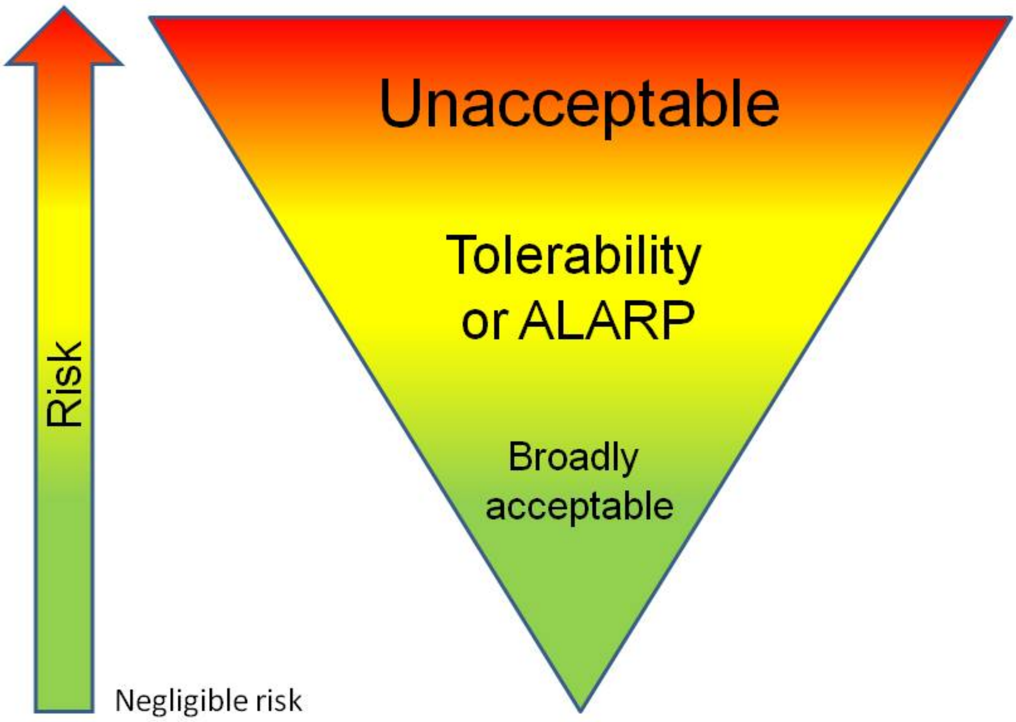


Figure 12 ALARP

(Bridget Leathley, 2016).

It is important with arrangements that prevent moving into the unacceptable area.

2.4.3 Risk matrix

The unwanted events plotted into a risk matrix to highlight the risk. A risk matrix shows clearly which events is the most serious and will be helpful when it comes to prioritize risk-reducing measures. The risk matrix is a table, where the events on the right top in the matrix have the highest risk, while the events on the left bottom have the lowest risk. With the risk matrix it will be clearly which events that are the most serious, and that are why it is so helpful when prioritize risk-reducing measures. The position of a risk in the risk matrix is based on the product of the risks probability to occur, and severity of possible consequence if the event occurs.

The risk matrix is divided into three parts, illustrated with the colours green, yellow and red.

- Red area: not acceptable events and need risk-reducing measures.
- Yellow area: events that need a closer review. Cost-effective measures can reduce risk.

- Green area: events with acceptable risk. If existing cost-effective measures, can be an alternative to reduce the risk.

(Rausand and Utne, 2009, p. 65)

Note: This table is similar to the criticality matrix below (Consequence and frequency axis is reversed). All other number combinations than those described gives NA (not applicable).	Frequency	Consequence					
		0	1	2	3	4	5
	1	0	L	L	L	M	M
	2	0	L	L	M	M	H
	3	0	L	L	M	H	H
	4	0	L	M	M	H	H
	5	0	M	M	H	H	H

Tabell 2 Risk matrix

Risk matrix												
This is Hydro's Risk matrix for Criticality classification and RCM detail analysis - Estimation of RISK								Probability class (see more detailed explanation below)				
			Economic loss and/ or Downtime					1	2	3	4	5
			Economy		Downtime			Is possible, but has not heard of / Maybe an event in the world.	Has heard of / Are aware that it has happened elsewhere.	Has happened to us.	Happens with us from time to time.	Happens often with us.
Criticality class	Personal safety	Environment (external)	Economical loss (Production- and equipment loss)	Production continuity	In hours	In days	Quality deviation	Unlikely 1/1000 year	Very rare 1/100 year	Rare 1/10 year	Probable 1/ year	Often 10/year
5	Multiple deaths	very large irreversible damage to the external environment. (> 5 years of recovery.)	Operation of electrolysis: > 500 MNOK Remelters: > 100 MNOK Unit at fabric: >20 MNOK	Factory or unit at factory (> 3 months with loss in the production)	120	5,0	Can lose customer relationships that make up more than 10% of sales.	Medium	High	High	High	High
4	Death or seious injury (Disability, loss of arm or eye)	great effect, but can be restored over a long time. (2-5 years of recovery time)	Operation of electrolysis: > 50 MNOK Remelters: > 20 MNOK Unit at fabric : > 2 MNOK	Unit at factory: > 1 week with loss in production	60	2,5	Can lose customer relationships that make up more than 3% of sales	Medium	Medium	High	High	High
3	Permanent injury (loss of fingers, broken arm or foot)	great effect, but can be restored over a short time. (<2 years of recovery time)	Operation of electrolysis: > 10 MNOK Remelters: > 5 MNOK Unit at factory: > 0,5 MNOK	Unit at factory: > 1 day with loss in production	30	1,3	Can lose a customer or impaired reputation by customer evaluation.	Low	Medium	Medium	Medium	High
2	Absence due to injury	Effect of short duration	Operation of electrolysis: > 2 MNOK Remelters: > 1 MNOK Unit at factory : > 50 kNOK	Stop in installation: < 1 day loss in production, but no effect on fabric	12	0,5	Weakened customer reputation	Low	Low	Low	Medium	Medium
1	First Aid	Negligible effect	Operation of electrolysis: < 2 MNOK Remelters: < 1 MNOK Unit at factory: < 50 kNOK	Stop in installation: almost none effect for production	6	0,3	Deviation from specification.	Low	Low	Low	Low	Medium
0	None - irrelevant	None	None - irrelevant	None - irrelevant	1,2	0,1	None	0	0	0	0	0

Tabell 3 Risk matrix

COSEQUENCE class - Detailed explanation							
Consequence	Personal safety	Environment (external)	Economical loss	Production continuity	Critical downtime (defined in hours)	Quality deviation	Weakened reputation - applies to all categories. Reputation with respect to the event (regardless of category)
5	Multiple deaths	very large irreversible damage to the external environment. (> 5 years of recovery.)	Complete destruction of the plant or large parts of it. Very long shutdown in production. Operation of electrolysis: > 500 MNOK Remelters: > 100 MNOK Unit at factory: >20 MNOK	Factory or unit at factory (> 3 months with loss in the production)	Critical downtime. Almost complete destruction of the plant and / or large parts of the plant. Very long production shutdown.	Can lose customer relationships that make up more than 10% of sales.	**Significantly irreversible damage to reputation, Event characterized by:** 1: Intensity: extremely strong reaction, characterized by great national attention eg. in the form of serial in the media. 2: Duration: Lasting changed attitudes. 3: Actors: Large customers as the Government, owner or other actors with particularly great influence. Apportionment of fault: A lot of blame on Hydro.
4	Death or seious injury (Disability, loss of arm or eye)	great effect, but can be restored over a long time. (2-5 years of recovery time)	Serious material damage. Large affect on the production / long shutdown. Operation of electrolysis: > 50 MNOK Remelters: > 20 MNOK Unit at factory: > 2 MNOK	Unit at factory: > 1 week with loss in production	Critical downtime. Serious material damage. Great impact on production and / or long-term production shutdown.	Can lose customer relationships that make up more than 3% of sales	**Large affect on reputation, but reversible on long term. Event characterized by:** 1: Intensity: Strong reaction, characterized by some national attention. 2: Duration: Longterm reactions. 3: Actors: Customers, influential actors nationally and internationally (national industry associations and associations). Apportionment of fault: : Much of the blame on Hydro.
3	Permanent injury (loss of fingers, broken arm or foot)	great effect, but can be restored over a short time. (<2 years of recovery time)	Substantial material damages. Large affect on production. Operation of electrolysis: > 10 MNOK Remelters: > 5 MNOK Unit at factory: > 0,5 MNOK	Unit at factory: > 1 day with loss in production > 1 dag produksjonstap	Long downtime. Significant material damage. Some impact on production.	Can lose a customer or impaired reputation by customer evaluation.	**Serious damage to reputation, but reversible on short term, Event characterized by:** 1: Intensity: Significant reaction, but to a limited extent national attention. 2: Duration: Medium 3: Actors: Actors with medium influence nationally and internationally (regional industry associations and interest associations). Apportionment of fault: Medium blame on Hydro.
2	Absence due to injury	Effect of short duration	Less material damage. Less affect on production. Operation of electrolysis: > 2 MNOK Remelters: > 1 MNOK Unit at factory: > 50 kNOK	Stop in installation: < 1 day loss in production, but no effect on fabric	Almost no downtime at all. Less material damage. Less impact on production.	Weakened customer reputation	**Medium effect on reputation, Event characterized by:** 1: Intensity: Moderate reaction, but to a small extent national attention. 2: Duration: Short 3: Actors: Actors with moderate influence. Apportionement of fault: Some blame for Hydro. With consequence: LTO: Moderate impairment
1	First Aid	Negligible effect	Less material damage. Less affect on production. Operation of electrolysis: < 2 MNOK Remelters: < 1 MNOK Unit at factory: < 50 kNOK	Stop in installation: almost none effect for production	Minor disturbances. Less material damage. Less affection on the production.	Deviation from specification.	**Less Effect on Reputation, Event characterized by:** 1: Intensity: Registration, but almost no reaction. 2: Duration: over in no time. 3: Actors: Peripheral with little influence. Apportionment of fault: Little or no blame for Hydro.
0	None - irrelevant	None	None - irrelevant	None - irrelevant	None - irrelevant	None	None

Tabell 4 Risk matrix

Consequence	Designation	Critical downtime Factor in %
5	higher than value	100
4	higher than value	50
3	higher than value	25
2	higher than value	10
1	higher than value	5
0	higher than value	1

Tabell 5 Risk matrix

2.5 Sensor

We live in a world where sensors make our everyday lives easier. Sensors can be found in our phones, homes, cars etc. With a light sensor in our phone it can detect our presence, smoke sensors make our homes a safer place and with a speed sensor we are able to track the speed of our car. Sensors are used to gather information and combining this with automation todays industry are much more effective than before.

The definition of what a sensor is can be explained as an input device that provides an output signal with a defined quantity. Sensors can also be divided into different classifications. Usually we speak about active and passive sensors, active sensors require an external signal, but passive sensors do not require any form of signal to generate an output response. We can also divide sensors based on how the sensor detect a signal, if its electric, chemical, biological etc. In the industry we are known with the terms digital and analogue sensors, were the digital sensor work with digital data applying an on/off output while the analogue sensor generates a continuous output signal were values are measured. Also, there are different types of sensors, these measure physical values like pressure, temperature, flow, vibration, position, velocity etc.

2.5.1 Industry 4.0

The fourth industrial revolution is currently happening, often named as Industry 4.0. It started with the first industrial revolution, which brought steam power and mechanization through spinning mills. Next up was the second revolution, with mass production, but best known through the assembly lines. Followed up by the third revolution, introduction of computers and automation in manufacturing. Right now, it is the fourth industrial revolution, cyber-physical systems (allaboutlean, 2015)

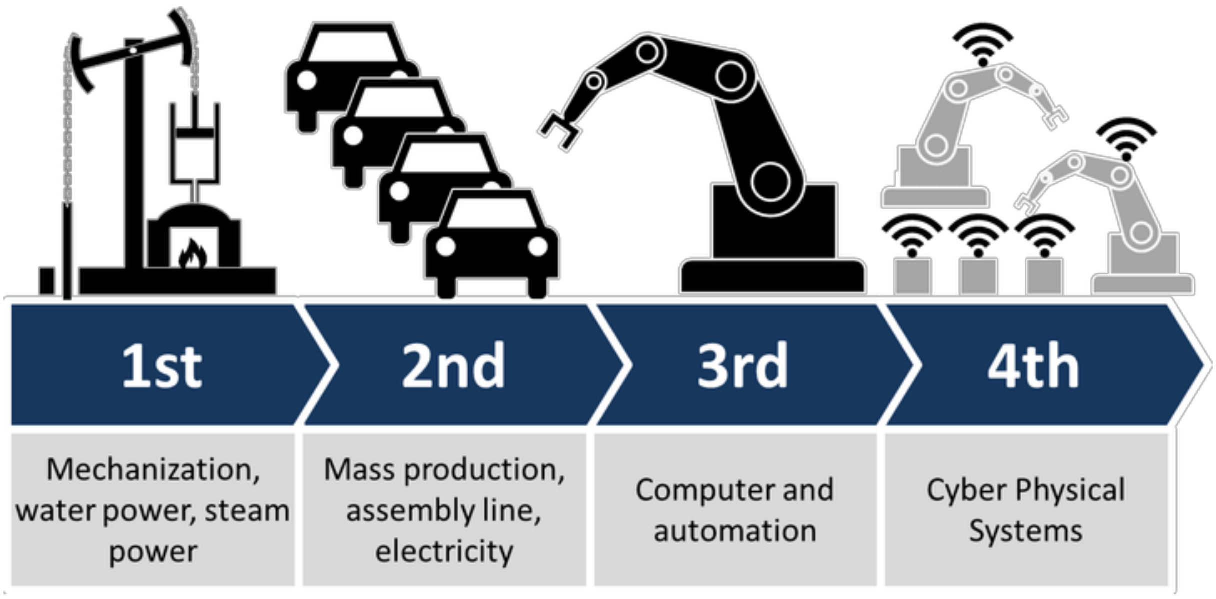


Figure 13 Illustration of the industrial revolution

The technological infrastructure, where product design and development under Industry 4.0 take place in simulated laboratories and utilize digital fabrication models has now started to be common (Allaboutlean, 2015)

With sensors it is possible to track everything from cradle to grave, but for the fourth industrial revolution this can lead to cyber-physical systems. An example is Land Rover's plan, where they will use sensors to track when their cars are driving into bumps in the road, in co-operation with the State highways authority, they know when it is necessary with maintenance on the roads (Allaboutlean, 2015).

3. Method

In connection with a scientific study you have to make multiple decisions that are related to different research methods, as e.g., how to analyse empirical data and how to collect data (Busch, 2013, p. 48). When you choose a research method, the choice is mainly between qualitative and quantitative methods, often presented as opposites. Quantitative method is seen as a deductive while qualitative method is seen as inductive (Postholm and Jacobsen, 2014, p. 40). The quantitative method is considered as deductive because the researcher has formed one or more hypotheses as he wants to verify or deny, with help from the data collection (Postholm og Jacobsen, 2014, p.40). The qualitative method is considered as inductive because the researcher has an open mind when he collects data (Postholm og Jacobsen). It is important that the choice of method is considered related to the actual problem. In this thesis qualitative method will be used.

3.1 Qualitative method

Qualitative method is based on abundant written or oral sources that give the investigator the opportunity to interpret. For a qualitative process it is important to:

1. Define the problem
2. Choose context and informants
3. Collecting data using different techniques
4. Description and interpretation of data (results)
5. (Develop concepts and further develop theories)
6. Assess the quality

(NTNU PP, Leif Tore)

The qualitative method is based on quality and credibility.

3.2 Literary study

The method used in this thesis is traditional literary study. It was necessary to start here, based on earlier knowledge and experience. By literary study it means that others research and explorations is used and adapted. Information is collected from books, internet and expert opinions. Some information (earlier lectures and input from Hydro Karmøy) is also given by both internal and external tutor, in the form of meetings and mail.

Due to lack of relevant data from the producer of the components, a decision was made to use OREDA-data in the analysis.

The suggestion for a maintenance program was made in Excel, based on research and an existing example for another component (not for a compressor).

3.3 Experience

Since the Hydro Karmøy's facilities are located nearby, it was possible to have meetings with the external tutor at Hydro Karmøy and have site visits in the relevant compressor station. At the tour it was possible to see the whole compressor and each component, which was very helpful because of little earlier experience.

3.4 Interview

After a lot of research and discussions in the group, a decision to contact the operator of the compressor was taken as there were several unanswered questions, and more details were needed to understand the compressor and how it was operated. A meeting was therefore arranged where both the operator/mechanic and a specialist from Atlas Copco participated, giving useful answers to our questions, and described it in an overall setting.

4. Results from analysis

This scheme contains the analysis of FMECA and RCM. Each column is described earlier 2.3.1.2 Implementation.

Subsystem: Water cooling

Description of unit			Description of failure			Effect of failure		Fatigue phenomenom Yes/No	Is the failure Visable/Hidden	Does there exist indicators which will alert failures? Yes/No	Type of control	Continuously surveilance Yes/No	Maintenance strategy	Maintenance action	Frequence of activity (Year)	Risk			Is the activity considered risky? Yes/No	Comments
Component	Component part	Function	Failure mode	Detection of failure	Failure cause or mechanism	On the subsystem	On the system function									Frequency	Consequence	RPN		
Piping	Piping	Transport	Not transporting	Flow deviation alarm	Plugged	Not cooling	Air production system will shut down	No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring		3	2	5	NO	
				NDT/visual inspection	Breakage			Yes	Visable	Yes	NDT/Visual	No	Condition	Replace broken pipe						
				NDT inspection	Cavitation			Yes	Hidden	No	NDT	No	Condition	Inspection						
				Accelerometer deviation alarm	Vibration			No	Visable	Yes	Accelerometer	Yes	Condition	Monitoring						
				Visual inspection	Corrosion	Reduced cooling	Less effective air production	Yes	Visable	No	Visual	No	Periodic	Controll		3	1	4	NO	
				N/A	External influences			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
				NDT inspection	Erosion			Yes	Hidden	No	NDT	No	Condition	Inspection						
		Store	Leakage	Flow deviation alarm	Leakage	Reduced cooling	Less effective air production	No	Visable	Yes	Flow sensor	Yes	Condition	Monitoring		5	1	4	NO	
				NDT/visual inspection	Material failure			No	Visable	No	NDT/Visual	No	Periodic	Inspection						
				NDT inspection	Erosion			Yes	Hidden	No	NDT	No	Condition	Inspection						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
Intercooler	Body/shell	Cooling	Reduced cooling	Flow deviation alarm	Plugged	Reduced cooling	Wrong air production temperature and pressure	No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring and Inspection		2	1	3	NO	
				NDT/visual inspection	Corrosion			Yes	Visable	No	NDT/Visual	No	Periodic	Inspection						
				N/A	Sticking			Yes	Hidden	N/A	N/A	N/A	N/A	N/A						
			No cooling	Ultrasonic deviation alarm	Cavitation	No cooling	Reduced effect and casualty of system	Yes	Hidden	No	Ultras. sensor	Yes	Condition	Monitoring		1	2	3	NO	
				Accelerometer deviation alarm	Vibration			No	Visable	Yes	Akselerometer	Yes	Condition	Monitoring						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
	Tubes	Cooling	Reduced cooling	Pressure deviation alarm	Plugged	Reduced cooling	Wrong air production temperature and pressure	No	Hidden	Yes	Pressure	Yes	Condition	Monitoring and Inspection		4	1	5	NO	
				Visual inspection	Corrosion			Yes	Hidden	No	Visual	No	Periodic	Controll						
				N/A	Sticking			Yes	Hidden	N/A	N/A	N/A	N/A	N/A						
Aftercooler	Body/shell	Cooling	Not cooling	Flow deviation alarm	Plugged	Reduced cooling	Wrong air production temperature and pressure	No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring and Inspection		2	1	3	NO	
				NDT/visual inspection	Corrosion			Yes	Visable	Yes	NDT/Visual	No	Periodic	Controll						
				N/A	Sticking			Yes	Hidden	N/A	N/A	N/A	N/A	N/A						
				Ultrasonic deviation alarm	Cavitation	No cooling	Reduced effect and casualty of system	Yes	Hidden	Yes	Ultras. sensor	Yes	Condition	Monitoring		1	2	3	NO	
				Accelerometer deviation alarm	Vibration			No	Visable	Yes	Akselerometer	Yes	Condition	Monitoring						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
	Tubes	Cooling	Not cooling	Pressure deviation alarm	Plugged	Reduced cooling	Wrong air production temperature and pressure	No	Hidden	Yes	Pressure	Yes	Condition	Monitoring and Inspection		4	1	5	NO	
				Visual inspection	Corrosion			Yes	Hidden	Yes	Visual	No	Periodic	Controll						
				N/A	Sticking			Yes	Hidden	N/A	N/A	N/A	N/A	N/A						
Plate heat exchanger	Plates	Cooling	Not cooling	Flow deviation alarm	External leakage	No cooling	Thermal expansion, breakage of parts	No	Visable	Yes	Flow sensor	Yes	Condition	Monitoring and visual controll		3	1	4	NO	
				Pressure deviation alarm	Plugged			No	Hidden	Yes	Press. Sensor	Yes	Condition	Monitoring and Inspection						
				NDT inspection	Erosion			Yes	Hidden	No	NDT	No	Periodic	Control						
			Leakage	NDT/visual inspection	Corrosion	Reduced cooling	Reduced effect and casualty of system	Yes	Hidden	No	NDT/Visual	No	Periodic	Control		4	1	5	NO	
				Flow deviation alarm	Internal leakage			No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring and visual						
Cooling element Compressor	Screw	Cooling	Not cooling	NDT inspection	Corrosion	No cooling	Thermal expansion, breakage of parts	Yes	Hidden	No	NDT	No	Periodic	Control		2	3	5	NO	
				Accelerometer deviation alarm	Vibration			No	Hidden	Yes	Accelerometer	Yes	Condition	Monitoring						
				Flow deviation alarm	Plugged			No	Hidden	No	Flow sensor	Yes	Condition	Monitoring and Inspection						

Figure 14 Analyses of the water cooling subsystem

Høgskulen på Vestlandet

Hydro

Subsystem:	Oil cooling																			
Description of unit			Description of failure			Effect of failure		Fatigue phenomenon Yes/No	Is the failure Visable/Hidden	Does there exist indicators which will alert failures? Yes/No	Type of control	Continuously surveilance Yes/No	Maintenance strategy	Maintenance action	Frequency of activity (Year)	Risk			Is the activity considered risky? Yes/No	Comments
Component	Component part	Function	Failure mode	Detection of failure	Failure cause or mechanism	On the subsystem	On the system function									Frequence	Consequence	RPN		
Piping	Piping	Transport	Not transporting	Flow deviation alarm	Plugged	Not cooling	Wrong air production temperature and pressure	No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring		2	1	3	NO	
				NDT/visual inspection	Breakage			Yes	Visable	Yes	NDT/Visual	No	Condition	Replace broken pipe						
				NDT inspection	Cavitation			Yes	Hidden	No	NDT	No	Condition	Inspection						
				Accelerometer deviation alarm	Vibration			No	Visable	Yes	Accelerometer	Yes	Condition	Monitoring						
				NDT inspection	Corrosion	Reduced cooling		Yes	Visable	No	NDT	No	Periodic	Control		1	1	2	NO	
				N/A	External influences			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
		Store	Leakage	Pressure deviation alarm	Leakage	Reduced cooling/lubing	Reduced effect and casualty of system	No	Visable	Yes	Pressure sensor	Yes	Condition	Monitoring		2	3	5	NO	
				Visual inspection	Material failure			Yes	Visable	Yes	Visual	No	Condition	Inspection						
				NDT inspection	Erosion			Yes	Hidden	No	NDT	No	Condition	Inspection						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
Pump	Gear	Pump oil	Not pumping	Flow/RPM deviation alarm	Breakage	No lube/cool on the system	Breakage of parts and components	Yes	Hidden	Yes	Flow/RPM sensor	Yes	Periodic	Replace broken gear		1	3	4	NO	
				Accelerometer deviation alarm	Vibration			No	Visable	Yes	Accelerometer	Yes	Condition	Monitoring						
				Ultrasonic deivation alarm	Cavitation			Yes	Hidden	No	Ultrasonic sen.	Yes	Condition	Monitoring						
				Flow/RPM deviation alarm	Wear			Yes	Hidden	No	Flow/RPM sensor	Yes	Periodic	Monitoring and periodic replacement						
				Pressure/flow deviation alarm	Plugged			No	Hidden	Yes	Press./Flow	Yes	Condition	Monitoring and inspection		1	3	4	NO	
				N/A	External influences			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
Screw housing	Screw housing	Lube	No lube	Flow deviation alarm	Plugged	No lube	Breakage of parts and components	No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring		1	4	5	NO	
		Cool	Not cooling	NDT/visual inspection	Material failure			Yes	Hidden	No	NDT/Visual	No	Condition	Inspection		1	4	5	NO	
				Visual inspection	Leakage			Yes	Visable	Yes	Visual	No	Condition	Inspection						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
Oil filter	Oil filter	Filtrating particles	Not filtrating	Pressure/flow deviation alarm	Plugged	Pressure increase	Breakage of parts and components	No	Hidden	Yes	Press./Flow	Yes	Condition	Monitoring and inspection		2	3	5	NO	
				Visual inspection	Breakage	Contaminate critical parts, gear		Yes	Visable	Yes	Visual	No	Periodic	Replace filtre		1	4	5	NO	
				Visual inspection	Wear			Yes	Visable	No	Visual	No	Periodic	Periodic replacement						
Valve	Valve	Regulate	Not regulating	Function test/pressure deviation alarm	Mechanical failure	Pressure to high	No oil to the screws, too hot and no lubing	Yes	Hidden	Yes	Pressure sensor	Yes	Condition	Function test		2	3	5	NO	
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						
				Function test/pressure deviation alarm	Breakage			Yes	Hidden	Yes	Pressure sensor	Yes	Condition	Function test		1	3	4	NO	
				Pressure deviation alarm	Wear			Yes	Hidden	No	Pressure sensor	Yes	Periodic	Monitoring and periodic replacement						
			Leakage	Pressure deviation alarm	Leakage	Reduce the transport of oil	Less effective air production	No	Hidden	No	Pressure sensor	Yes	Condition	Monitoring		3	1	4	NO	
				NDT inspection	Erosion			Yes	Hidden	No	NDT	No	Condition	Inspection						
				NDT/visual inspection	Material failure			Yes	Hidden	No	NDT/Visual	No	Condition	Inspection						
Plate heat exchanger	Plates	Cool	Not cooling	Visual inspection	Corrosion	No cooling effect	Thermal expansion, breakage of parts	Yes	Hidden	No	Visual	No	Condition	Inspection		1	4	5	NO	
				Flow deviation alarm	Plugged			No	Hidden	Yes	Flow sensor	Yes	Condition	Monitoring						
				NDT inspection	Wear			Yes	Hidden	No	NDT	No	Periodic	Periodic replacement						
				Flow deviation alarm	Leakage			No	Visable	Yes	Flow sensor	Yes	Condition	Monitoring						
			Leakage	NDT inspection	Material failure	Reduced cooling	Reduced effect and casualty of system	No	Visable	No	NDT	No	Condition	Inspection		2	2	4	NO	
				Flow deviation alarm	External leakage			No	Visable	Yes	Flow sensor	Yes	Condition	Monitoring and visual						
				Visual inspection	Corrosion			Yes	Visable	Yes	Visual	No	Condition	Visual control						
				Flow deviation alarm	Internal leakage			No	Hidden	No	Flow sensor	Yes	Condition	Monitoring						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A	N/A	N/A		
Tank	Tank	Store	Leakage	Level deviation alarm	Leakage	Reduced cooling/lubing	Reduced cooling and lubing to the compressor elements	No	Visable	Yes	Level sensor	Yes	Condition	Monitoring and inspection		2	2	4	NO	
				Visual inspection	Material failure			No	Visable	No	Visual	No	Condition	Inspection						
				Visual inspection	Erosion			Yes	Hidden	No	Visual	No	Condition	Inspection						
				N/A	Micellanous			N/A	N/A	N/A	N/A	N/A	N/A	N/A						

Figure 15 Analysis of the oil cooling subsystem

5. Discussion and recommendation for further work

5.1 The system

In the beginning of the thesis, it took some time to understand the overall system and how it was built up. There were many components that the group needed to look more into and understand its function, in order to decide which component that was the most critical. It was also necessary to understand how it all worked as a composed function, see the entire picture, and understand how the critical item could affect the rest of the system.

After literary study and discussion within the group, the agreed meeting with the operators of the compressor was very constructive, and a lot of questions were answered. This was very helpful for the understanding of the air compressor system and its functionality, which made the basis for the further analysis. At the meeting the group also got to see the actual compressor, which was more interesting than just looking at a picture in the instruction handbook.

5.2 Compressor

At Hydro Karmøy they have three different compressor stations, where every compressor is a part of the compressed air production. The effect of failure for the chosen compressor, can be detected as low. It is possible to shut down the compressor, without a high risk for the production. This is because there is built in redundancy in the overall compressed air system, where two out of three compressors can cover the normal demand for compressed air in the production. However, if more than one compressor has problems at the same time, this can be an issue for the production. If for example two compressors are down simultaneously because of failure, it will take longer time for the operators to perform the maintenance tasks. With lack in production of compressed air, this can lead to problems for operation of the process at Hydro Karmøy and potential reduced production.

The result of understanding the system and its function pinpointed the cooling system as most critical. The consequence of failure in the cooling system can lead to stop for the compressor, which means reduced production of compressed air. For that reason, the group decided to perform an RCM analysis.

5.3 Main steps of an RCM analysis

In the theory it was presented 12 steps for an RCM analysis. The group decided not to focus on Step 9: “Preventative maintenance comparison analysis”, and Step 10: “Treatment of non-critical items”. For this thesis it was founded not relevant. Performing an analysis by following each step, makes the final result more clearly based on what has been done, and it is easier to follow for another system since they can use the same approach.

5.3.1 FMECA

Since the maintenance study was not known to the group, it was necessary to acquire theory and information on how maintenance is planned and performed. Hence, began to look at the various maintenance methods that are relevant for this case, where the goal is to optimize the maintenance and map the components of the system or subsystem, and their interconnection. Based on suggestions from the tutors and obtained theory, FMECA was the most relevant for this case.

Initially it was necessary to get knowledge of how the air compressor works and its function for the plant. The group was given the opportunity to get a tour to see how the process takes place in practice. In this way, it was possible to ask the operators about every detail and importance of the individual components and system. The information extracted from these tours and conversations with the operators influenced on which subsystems should be analysed and selection of FSI. For the preparation of the analysis, the information gained from the operators made it easier setting up the FBD, figure 5. Selecting the subsystem to be analysed was mainly based on the operator's expertise, but also from theory about air compressors and the FBD. The subsystems water- and oil-cooling were selected. These subsystems have an impact on the production of pressurized air, and where most of the failure modes appear. Since the group wanted to carry out the entire process of setting up FMECA, type of maintenance and interval, and the choice of sensors, it was necessary to address these subsystems.

Failure hierarchy was used to list up possible failures for each component of the subsystems. By listing the errors that may occur, the implementation of FMECA became more manageable. The problem for the group was to determine possible failures each part could be exposed of. The book OREDA was used to collect relevant failure modes for the hierarchy. Although this is data obtained from the oil and gas industry, it will be relevant to the subsystems as it consists of elementary components. The failure modes selected from OREDA are those with the greatest percentage of total failure rate for the given part. Through the whole process of implementing, both FBD and failure hierarchy were two important tools. This would make it easier for the operators working with the system to get an understanding of how it is set up and avoid spending too long preparing for each time maintenance is done.

FMECA analyses each part as separate incidents without relation to other faults in the system. This means that the rest of the components are assumed in perfect condition. In our case the industry water is supposed to cool down the pressurized air and the oil. A problem with the industry water is that it is polluted by grass and soil. This could cause blockage of both heat exchangers, plate and shell, and tube. When analysing the component shell and tube from the water cooling subsystem, the failure mode could be blockage and can cause increased temperature on the pressurized air. The same blockage could appear at the same moment on the plate heat exchanger, where the blockage could lead to impaired lubrication of ball bearings and gears because of the change in temperature. The FMECA analysis in this occasion does not take into account the failure that occurs in parallel to the shell and tube heat exchanger. This failure mode could at worst lead to destruction and breakdown of the gears of the screw elements.

The operators or personnel performing the FMECA analysis should have some understanding of how the system is built up. The reason for this is the execution and the result of the analysis to a certain degree depends on the analyst. One of which do not understand how the system is structured and functioning, will cause the quality and reliability of the results is low. In our case we were two students who carried out the implementation. Some hours of self-study and expert help were used during the implementation. For the operator the necessary time spent on performing the implementation would have been considerably less, as he could base his choices on experience and knowledge. In the result of FMECA there may be critical defects and the like, that group have not thought of, but are relevant to this system. One source of failure of complementing the FMECA can thus be the group.

The arrangement of the analysis with number of columns, the group has taken a decision of what is relevant for this system. The number of columns and what they contain is based on the program used on the plant and the literature study. During the actual implementation, columns were also added or removed. The scheme consists of FMECA, RCM and risk based columns. Guidance from tutors was useful in order to be able to confirm and disprove what was necessary in the form.

The group is left with the impression that the FMECA analysis is a solid tool and important process for the further implementation of the RCM. The analysis starts with getting to know the given system and terminates setting up possible errors and criticality with each component. After completing the FMECA, the group concluded that there was a need for experience and knowledge for such an analysis. By having more participants during the FMECA execution, one will achieve more suggestions and perspectives, for example, on possible failures.

5.3.2 RCM

For a complete analysis it is necessary with enough data. The group used time in the beginning to understand the thesis and which data that was needed. Available data was limited, because most of the procedures was based on routine, time was limited and available reports from the supplier Atlas Copco was limited. On the other hand, the interview and tour in the compressor station was very helpful.

Selection of maintenance actions are as mentioned earlier, the most novel step for the RCM analysis. Lack of data can lead to wrong maintenance action, which is critical regarded to cost and risk. There a multiple maintenance actions that can be used. The selection depends on available data and the intention of the analysis. Another limitation can be how deep the analysis is supposed to be.

In figure 9 it is shown different maintenance actions, which are the ones that the group decided to focus on. The reactive maintenance is a part of the corrective maintenance. While the other three, periodical preventative, condition-based and predictive maintenance, are a part of the preventative maintenance.

Reactive maintenance is the first/lowest step in figure 9, which means that this is the step with highest down-time and high costs. The maintenance method is based on waiting for the machine to fail, and then fix, which is unpredictable because you do not know when it will fail, and there can be a long downtime e.g. to order in new parts. It can also be more expensive than necessary, for example if it is possible to do maintenance on the part instead of buying a new one.

Since the group decided to do cost-effectively maintenance, reactive maintenance was not desirable. On the other hand, in some cases, it can be more cost-effective to replace the actual part instead of performing maintenance frequently over a short time.

Preventative maintenance where the maintenance is performed at set intervals of time or cycles of operation. This maintenance is well suited for hidden failures, where you cannot see when the failure will happen, but with the correct set of intervals the maintenance will be performed before failure happens. It is not necessarily cost-effective, sometimes the maintenance is performed more frequently than needed. It can be difficult to find the right balance between how often the maintenance should be performed to prevent failure, and the consequence of having non-expected failures. As earlier mentioned, this is mainly based on the experience with the specific component, and a calculation of what a non-intended failure will cost.

It is unknown when age-related failures will happen, but with preventative maintenance you can set the interval to for example; - do maintenance after 500 hours operation. For this type of maintenance, it is necessary with enough data that can provide the set of intervals. If there is lack of data, there is a possibility that the set of intervals will be wrong, and the maintenance is not as cost-effective as wanted.

Condition-based maintenance is based on monitoring to assess condition of assets. It is the third step, which means that the maintenance is wanted. To do a condition-based maintenance it is necessary with monitoring, where e.g. sensors can be very helpful. There are multiple range of sensors for different situations depending on the purpose. On the compressor there are already some existing sensors that are monitoring flow, temperature and pressure.

If the pressure gets too high in the cooling system, this is easy to discover by monitoring with a sensor. When the sensor shows that the pressure is too high, a possibility can be to drain the water to lower the pressure.

The main goal for the analysis, was to come up with a maintenance program that included the predictive maintenance. It is the last step in figure 9, where it is most cost-effective.
The group ended up with focusing on the preventative and condition-based maintenance, mainly because of the time limit and not enough data. With the fourth industrial revolution, Industry 4.0, this can also be a part of the predictive maintenance with the cyber physical system in the future.

The group was going to determine maintenance interval for condition based and periodic maintenance by using calculations. Due to lack of data this was not possible to perform. Another option was to determine maintenance interval based on assumptions, which was the plan, but could not be performed because of limited with time.

As mentioned earlier, implementation for an RCM analysis is to pay attention to the risk while implementing the maintenance tasks. Therefore, the combination of FMECA, RCM and risk analysis, can lead to a maintenance program. But is important to pay attention to the risk during the maintenance.

5.4 Risk analysis

To find critical components and failures based on previous knowledge and experience, can be difficult as this might vary over time. Lack of data can also be a source to insufficient maintenance routines. The risk analysis is, on the other hand, an easy approach when followed step by step. This can for example be performed by using the ALARP principle.

The risk matrix we have utilised is from Hydro Karmøy, a format which they use in their daily operations. We chose to only focus on cost and risk for the operation of the compressor. Because we want a maintenance program that ensures a compressor with low downtime and cost-effectiveness, we rated each effect of failure by consequence and probability/frequence.

When we chose to only focus on cost and risk for the compressor, it means we did not consider the risk for either the environment nor the personal safety. This choice is based on the information and data we have, where we decided that the risk related to environment issues and personal safety is too low to consider.

For a maintenance program it is necessary to know which maintenance tasks that needs to be done. The risk analysis where RPN is the total of frequency and consequence, describes the need of each maintenance task. The group decided which maintenance tasks that needed to be prioritized, based on the value of RPN.

5.5 Sensors

In our product we have selected several sensors to help monitor certain values and levels that are considered critical regarding the operation and maintenance of the compressor and the cooling system. The positioning of the sensors is performed with a high focus on economy and usability. As an example, we have placed a pressure sensor between an oil filter and a valve, as this will reduce the total amount of sensors needed in the compressor and cooling system to get an overview of the process. Here is a complete list of different types of sensors that has been used in our product:

- Flow sensor
- Accelerometer
- Pressure sensor
- RPM sensor
- Ultrasonic sensor
- Level sensor

Summarized we found that the use of flow and pressure sensors gave most valuable data in this type of system, and in addition such sensors non-expensive and easy to use.

The fourth industrial revolution is as mentioned earlier currently happening. As a result of the revolution, sensors and measurement instruments are less expensive and gives more online data, making the compressor more cost-effective and having higher productivity. The use of Industry 4.0 can prevent breakdowns, because sensors can predict when a breakdown will happen and then maintenance can be done to avoid it.

5.6 Results

The result of the RCM analysis is set up in a scheme, figure 14 and 15, which is the product of the thesis. Such scheme covers both the water and oil cooling subsystem, where the analysis goes deeper into each component of the subsystems. The scheme is based on the main steps of an RCM analysis, where it is performed schematically.

From column one to column eleven, the FMECA is shown, where the subsystem is split up into component, function, failure mode, etc. After accomplishing the FMECA, an overview of critical items in the subsystems and possible failure modes is revealed.

From column twelve to column sixteen covers the RCM, where a set of maintenance actions are suggested, based on earlier analysis from the FMECA and maintenance strategy. The intention of column sixteen is to show a proposed maintenance interval, but the amount of necessary data was not available to establish this.

The rest of the scheme is the risk analysis, where the RPN is the total product of frequency and consequence. By use of RPN it is possible to rate the effect of failure.

After accomplishing this analysis for Hydro Karmøy, a proposed scheme is prepared that contains each component on the cooling system and which failures that can occur. From the scheme it is possible to prioritize which maintenance action that is the most critical, based on the risk analysis. The plan was to set up a complete maintenance program, with necessary maintenance action and interval of the maintenance. As mentioned earlier, the group was not able to set a maintenance interval due to not sufficient available data.

5.7 Recommendation for further work

Although the maintenance program is not fully completed, it is good fundament for further action. Based on our experience, it may be possible that potential causes of failure have been overlooked, but it will still be of interest and can be of great help to arrive at a complete maintenance program. For further work and completion of the maintenance program, the group will present relevant recommended actions for way forward:

- Collect relevant data related to how long the components have been in operation. in addition, how many errors have occurred during the operating period. This to calculate the MTTF.
- To achieve a more reliable and implemented FMECA, it will be relevant to gather data and experiences from experts in the given field of study.
- Ensure continuously feedback in to the system, with experience data from the operation of the system. This could include maintenance intervals, failures seen in the field, correlations between different types of failures etc. To prepare a valid maintenance database, it is required that all experiences with the monitored system is fed into the database on a continuous basis. In addition the operators should be familiar with this database, in order to encourage a continuous update.

6. Conclusion

The objective of this study was to come up with a RCM program for the maintenance of the cooling system of a compressor. The group believe with great certainty that the selected and processed theory in this paper will be an answer to this, with reservation to the amount of available data and limit of time.

A lot of time in the beginning was used on literary study and to understand the compressor functions. This was necessary for the group in order to perform an RCM analysis. The group focused on theory that was relevant for understanding the function of a compressor and how the analysis was performed.

For an overview of the analysis, it was put in a scheme, based on the steps of the RCM analysis. The group started with FMECA, to split up the system and come up with an overview over the critical items. After executing the FMECA analysis, the group gained a fundament to start with the RCM procedure. Through the RCM analysis different maintenance actions were selected for each component and the group came up with suggestions for inspection or implementation of sensor.

The objective was to come up with a maintenance program for the cooling system, where the program describes what maintenance needs to be done and how often. As there was not enough available data, it was not possible for the group to accomplish. An option was to set the maintenance interval based on assumptions, but lack of time and experience made it hard for us to set a believable interval. We decided therefor to leave out the maintenance interval, instead of advising an unreasonable proposal.

The group is satisfied with the result of the analysis, but a feeling of disappointment since the maintenance program is not complete without the maintenance interval. It was interesting to look more into maintenance and reliability, and to perform it in real life. Since this is such an interesting subject, there was an excessive use of time under the whole analysis, where the group got caught up in curiosity.

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