Availability increase: A model in maintenance optimization for spare parts at Hydro Karmøy

Bachelor done at

Høgskolen Stord/Haugesund – Study engineering

Machine, Process- and energy technique and Marine Construction technique

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Haugesund   *Spring 2016*

BACHELOR'S THESIS

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Study programme	Mechanical engineering, Process and Energy Technology and Design of Marine Structures
Thesis:	*Availability increase: A model in maintenance optimization for spare parts at Hydro Karmøy*

Assignment text:

There shall be conducted a theoretical analysis of maintenance, with a limitation in comparing corrective- and preventative maintenance. Parallel with this there shall be developed a theoretical model that will assist Hydro Karmøy with optimized spare part management.

To display the theoretical model, it is decided to do so with the help of a newly started project at Hydro Karmøy. Further on, the group shall discuss the quality of the different alternatives that is portrayed in the theory. Final choice of system must be done with appropriate justification. The group must take into consideration to economy, availability, HSE and daily operations.

Final assignement given	Thursday March 2th 2016
Submission deadline:	Wednesday May 4th 12:00 am

Internal tutor	Ajit Kumar Verma – HSH, phone: 52 70 27 76
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Approved by program coordinator:	J. C. Linde
Date:	2/5 - 16

Preface

This bachelor thesis is a part of the theme "ING 3039 – Bacheloroppgave Maskin" at Høgskolen Stord/Haugesund.

The assignment of this report was given by Hydro Karmøy, an industrial company that produces aluminum. They have a desire to optimize their maintenance system, and gave the group the task of looking at this subject. It has been both challenging and interesting, since the members of the group did not have experience with the subject it took some time to learn about different theories.

There is a computer program which have been made about maintenance optimization and is discussed in the text, but there will be made a product description as well after submission of the report itself. It is our intention that Hydro Karmøy will use this product in prospective projects.

The group have to give the tutors Leif Tore Larsen, Ajit Kumar Verma and Jens Christian Lindaas a special thanks for excellent guidance. The group also have to thank Gisle Kleppe for helping with programming in Visual Basic.

Summary

With increasingly focus on efficiency, reliability and safety, the industry faces new challenges in areas where conservative thinking and outdated methods are current. This report analyses, debates and compares established routines with new thinking and research in an effort to create a model for optimized spare part management.

The report is centered around keywords like:

- Reliability Centered Maintenance
- Failure Mode Effects and Criticality Analysis
- Decision Logic
- Preventative and Corrective maintenance

The methods that are used is literature study, experiences from skilled personnel and a continuous contact with personnel at Hydro Karmøy.

In the report there are used a case from the PILOT project at Hydro Karmøy, specifically transport of Oxide, with focus on critical components on the tankers. This to demonstrate the effects a correctly analyzed spare part management can have on efficacy and reliability when using the correct tools.

As a step towards a more streamlined spare part management system, there have been developed a customized computer program that will perform many of the more demanding calculations and decisions. This program is fully interactive and customizable to fit the actual requests. Because of the reports limitation in terms of time and available information, the group have not had the opportunity to test the program. It is therefore recommended that it will be performed a test of the program, on basis of the theory the group has presented in the report.

Trough solid research, calculations and analysis the group also provides recommendations to further areas of work to ensure that Hydro Karmøy´s maintenance program will be an industry standard, both internal and hopefully externally as well.

Table of contents

Figure List

Table List

Picture List

1. Introduction

1.1 About Hydro

Hydro ASA is a global supplier of aluminum with activities throughout the value chain, from bauxite extraction to the production of rolled and extruded aluminum products and building systems. Its headquarter is in Oslo, Norway. and it is one of the largest aluminum companies worldwide, and have customers including automotive, packaging and building industries [1]. The company has 13000 employees in more than 50 countries on all continents.
Hydro ASA was founded in 1905 and became one of Norway's first industrial giants, now with more than 85 years of experience as a light metals producer [2] [3].

Hydro Karmøy Primary Production started in 1967, and Hydro Karmøy Rolled Products started in 1968. They are both located on the same location just outside Haugesund in Rogaland, Norway. All together there are about 1000 people working in that division.

Hydro Karmøy consists of two cast houses, one delivering extrusion blocks for profile production, another producing wire rod for high voltage cables. There is also a research and development facility located at Karmøy [4].

1.1.1 Karmøy Technology Pilot

Analyses shows that demand for aluminum will be 25-40 percent higher in 2020 than today, which makes it important to make changes to a more climate- friendly production. [5]

Hydro ASA aims to be the world's most energy- and climate effective aluminum production. The energy consumption will be reduced by 15 % per kg aluminum compared to the world average, and Hydro ASA has a goal to become the aluminum production company that has the lowest emissions of CO_2. By replacing coal with hydroelectric power, the new pilot project reduces CO_2 emissions by as much as 1 million tons. The new pilot plant will be built at Hydro Karmøy and production will hopefully start during 2017.

The project has not only positive effects in terms of the environment, it will also give Hydro Karmøy more jobs and the capacity of production will increase by approximately 40 %. Which means that they can produce 75 000 tons' aluminum [6].

The whole process of the new technology is estimated to take around two years. If they succeed, it will be a possibility of another extension, but it's difficult to say something about that so early in the stage. That decision will not be possible to take until 2019.

The entire project has a total cost of 3.9 billion NOK. Enova, a Norwegian government enterprise, want to support the project because of its focus on climate and gave 1.5 billion in support.

During development, Hydro has taken consideration to the local population and the environment nearby. Emissions that get in contact the water will be diluted after a short time, and the emissions in the air will not have negative consequences for the ecological condition [7].

Picture 1: Karmøy Pilot

1.2 Brief Background

As part of the engineering's degree at "Høgskolen Stord/Haugesund" students are obligated to develop and write a bachelor report in cooperation with an external company within a relevant industry. The writers behind this report consists of three individuals, two from "Marine Construction technique" and one from "Process- and Energy technique". There was also provided two tutors, one internal from the academy, and one external from the company which the group will be writing for. The tutors were chosen based on the thesis to ensure the best tutoring was provided. In this case there was also assigned a resource person from the academy, the role of this individual was to give additional support and guidance but within the framework laid out by the group and the two tutors.

"Hydro – Karmøy Metal plant" was questioned about if they had a relevant project suited for a bachelor project. Hydro was very welcoming and gave the feeling that they had a genuine wish to provide a relevant, but yet challenging thesis to write about.

After meeting with Leif Tore Larsen which would take the role as external tutor at Hydro, the group discussed the provided thesis statement with the academy and were given the all clear. It was then decided to pursue the collaboration with Hydro.

1.3 Thesis and Objective

The thesis is "Availability increase: A model in maintenance optimization for spare parts at Hydro – Karmøy Metal plant".

In an increasingly more demanding marked, focus on efficiency and competitive prices is more and more crucial. As a step to improve quality and to lower costs, Hydro Karmøy recognizes the importance of ensuring that the plant and it is components run as consistently and efficiently as possible.

The maintenance department at Hydro Karmøy had a wish to create and develop a new model for spare part management to improve on their routines to ensure smooth operations. In relation to the pilot project mentioned above there is purchased three trailers dedicated to a

temporary aluminum oxide transport system. The group decided to delimit to this system and create a transferable spare part management model.

The objective with the thesis is to assist Hydro Karmøy in developing a maintenance system which can contribute to high reliability and strengthen the economic growth.

1.4 Limitation

Based on the assignments scope, the group have been obliged to take some limitations. The following limitations have been done:

- All the failure rate data are data from OREDA, since reliability data from the producer and Hydro Karmøy was not available.
- The group limited to look at the Aluminum Oxide components of the tank, and not the complete system.
- It was chosen to look at the critical components and exclude non-critical components in the analysis.
- The data and formulas used in this paper are expected to be accurate.
- Although there are several critical components the group have chosen to focus on two of those components, namely the safety valve and the pinch valve.

1.5 The silo semi-trailer

The silo semi-trailer from Feldbinder are designed to transfer powder. All of the tankers at Feldbinder can adapt to customer's needs. The silo semi-trailers that are used at Hydro Karmøy are EUT 40.3 – 2/2 models, and accommodates 40 000 l.

Picture 2: Silo semi-trailer

1.5.1 Filling and discharging aluminum oxide – Operating the tanker

On Hydro Karmøy, aluminum oxide is transported from ships to big storage silos on the dock. From there the oxide is transported on a conveyer belt, and fed into the ovens. Due to upgrade of the conveyer belt, Hydro Karmøy has bought three trailers, as showed at picture 2, that will transport the aluminum oxide from storage silos to the ovens. The route the tankers will drive is illustrated on picture 3. This route takes approximately 50 minutes.

Picture 3: Tankers route

The silo tanks are filled with the help of gravity; no extra equipment is used to get the oxide into the tanks. The procedure to connect to the tanker works as follows; connect the loading nozzle into the manhole or connect the filling hose to a filler coupling. Starts with filling the silo tank through the man lids or filler couplings. When the product flow has stopped, remove the loading nozzle and swing it away, or remove the loading hose from the filler coupling. [8]

The following safety equipment is mandatory to use when you discharge the silo tank.

Picture 4: Safety Equipment

At Hydro Karmøy they discharge the tank with compressed air. Compressed air is supplied from an external compressor. The driver has to remember to open the valves before starting the compressor, or it may damage the compressor.

Before beginning to discharge the aluminum oxide from the tank, it is necessary to make sure all the manlids and filler couplings are sealed. Then the material hose is connected to the material discharge. Connecting the air coupling to the compressor and open the stop valve on the air distributor to aerate the chamber.

The compressor is engaged and set it to specified pressure. Slowly the pressure will increase in the silo tank, and when adequate pressure is reached, the stop valve is opened for injected air. Then open the shut off valve of the chamber to be discharged. The oxide is pressed out of the tanker. Under this process one cannot leave the tanker, it is necessary to monitor the silo tank. Sudden drop in pressure on the pressure gauge indicates end of discharge process.

After the discharge process is complete, it is important to ensure that shut-off fitting in the material line and the stop valves for top air and injection air is closed. It is necessary to open and close the stop valves for aeration several times in succession. Then open the shut-off fitting in the material line. Switch off the compressor, and disconnect the compressor from the air line. Close all valves and shut-off fittings in the air and material lines. Then the caps are attached and the tank is ventilated slowly by open the exhaust air valve. Exhaust air valve should be kept open until next loading operation, to avoid vacuum damage. Finally, the material hose is removed, and the tanker is ready for travel. [9]

1.5.2 Aluminum Oxide

Aluminum oxide (Alumina) is a chemical compound of oxygen and aluminum, it has the chemical formula A_2O_3. Aluminum oxide is formed by churned bauxite. By using hot solution of oxide of sodium and oxide of calcium, aluminum gets excreted. The heated are being filtered and aluminum oxide desiccates, then it becomes white powder. Oxide is an intense substance which will cause considerable wear on the equipment.
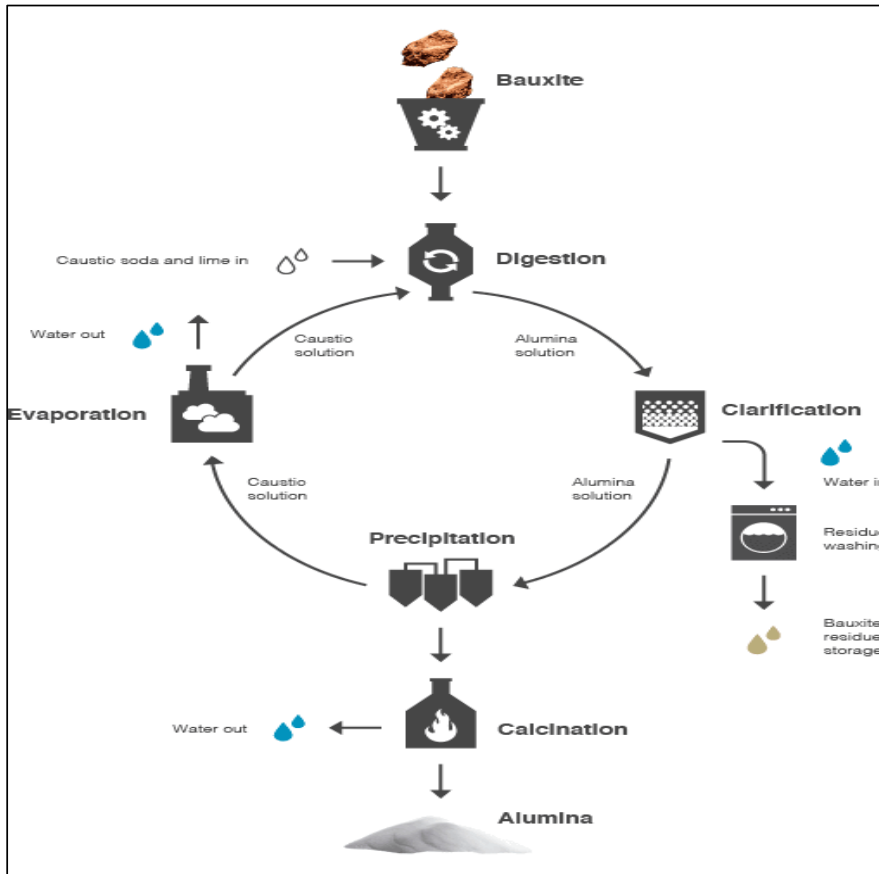
Picture 5: Aluminum Production Process

1.5.3 Critical Components

In cooperation with Hydro Karmøy the group have made an assessment of which components that are critical for the transport of oxide. There were several critical components, it was decided to take a closer look at safety valve and pinch valve.

1.5.3.1 Safety valve

The main function for the safety valve is to ensure that nobody gets hurt or that nothing gets damaged. A defective safety valve can cause the tank to explode if the pressure is way excessive.

It is important that the safety valve can operate at all time and in every circumstances.

The maximum working pressure is 2 bar.

More information about the valve is found in the appendix D.

Picture 6: Safety valve

1.5.3.2 Pinch valve

The function for the pinch valve is to control the oxide out of the tank. The pinch valve is controlled by material discharge and discharge vessel.

The pinch valve depends on pressure, if the pressure is too low the function will not work.

More information in the appendix D.

Picture 7: Pinch valve

1.6 Abbreviations and word explanation

In the report there is used a number of abbreviations. Here is an overview of abbreviations and words which is generally not known.

Abbreviation	Acceptation
SPMS	Spare Parts Management System
RCM	Reliability Centered Maintenance
FMECA	Failure mode, effects and criticality analysis
Feldbinder	Specialist on semi-trailers, tank trailers, rail wagons and containers
MTBF	Mean Time Between Failure
OREDA	Offshore and Onshore reliability data
PM	Preventative maintenance
CM	Corrective maintenance
MTTF	Mean Time To Failure
RSPL	Recommended spare parts list
NOK	Norwegian Kroner
EUR	Euro
VBA	Visual Basic for Applications

Table 1: Abbreviations and words explanation

2. Method

In this chapter the overall process of maintenance optimization will be explained.

2.1 Literary study

The method used in this thesis is traditional literary study. Literary study means that others research and explorations is used and adapted. Information is collected from books, internet and expert opinions. There is also used information given by extern tutor, through conversations and mail.

Because relevant data from the producer on the components was not available a choice to use OREDA-data in the analysis was taken.

Models of optimization have been made in Excel; using Visual Basic. The group have chosen to use a real case study, this model is transferable and can be used in other contexts.

2.2 Experience

There was conducted a meeting with Hansen & Sønner, operator of the trailers, regarding experiences from transport of oxide. They started testing the transport system in December, and have already started making valuable experiences regarding challenges regarding transporting aluminum oxide. There is already signs of considerable wear on valves and gaskets.

2.3 Interview

It has been conducted an interview with a company that has an own section which work with FMECA and preventative maintenance. The company will not be mentioned by name in the report, because of their demand to be anonymous. To strengthen the interview validity, the interview object received the questions by mail prior to the meeting. This was done to provide them with the opportunity to prepare the answers.

3. Maintenance optimization

Maintenance is a combination of technical and administrative activities. There are two types; preventative maintenance and corrective maintenance. While PM focus on periodic interchanging, CM accomplishes interchanging when the component is broken.

The focus in this report is preventative maintenance and periodic interchanging. By using RCM- and FMECA analysis the report will give an overview of the process.
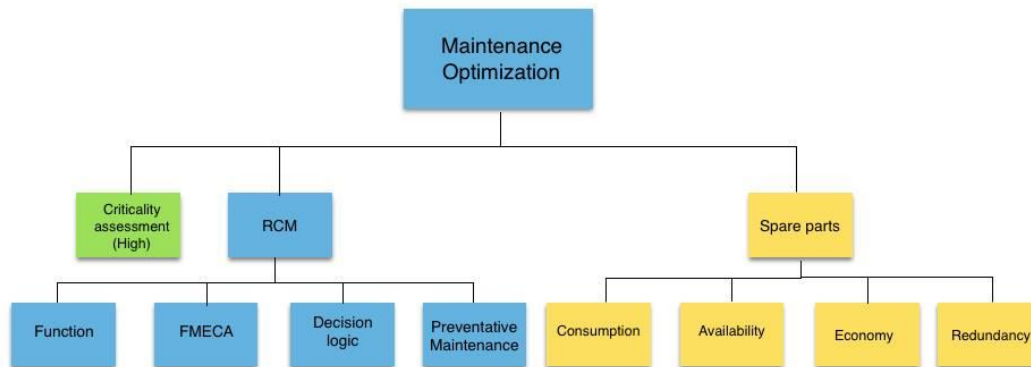
Figure 1: Maintenance Optimization Flow Chart

3.1 Critical classification

Components needs to be analyzed to find out where they shall be located. According Hydro ASA: Systematic Maintenance Standard, shall items be classified into three main criticality classes; high, medium and low. The report looks at the components which are defined as high, in critical classification. [10]

Figure 2: Criticality Model

4. Qualitative System Analysis Description

The report focuses on RCM and FMECA since they are well renowned methods in the industry both on-and offshore. This will give the report validity and be in correlation with the most used techniques.

4.1 Reliability-centered Maintenance

Reliability-centered maintenance (RCM) is a systematic way of selecting the right type of preventive maintenance for each different item in a system, taking into consideration failure consequences. It is a process to ensure that equipment continues to fulfill their intended function. It is generally used to achieve improvements in fields such as safe minimum levels of maintenance and production optimization. Successful implementation of RCM will lead to reduction in costs, higher system availability, more machine uptime, and the system to be operated for its full life cycle. [11]

RCM definition: *"a process used to determine what must be done to ensure that any physical asset continues to fulfill its intended functions in its present operation context."* [12].

Over the past twenty years, maintenance has gone through many changes. The changes are due to a huge increase in the number of plants, equipment and buildings. The equipment has a much more complex design nowadays and new maintenance techniques has been developed.

Maintenance is also responding to changing expectations in the industry. These includes a growing knowledge that equipment failure can have a huge impact on safety and/or the environment. There is also a growing awareness about the connection between maintenance and product quality. If you cut down on maintenance program, it will most likely affect the quality of your product, and the increasing pressure to achieve high plant availability and at the same time keep your cost down. [13]
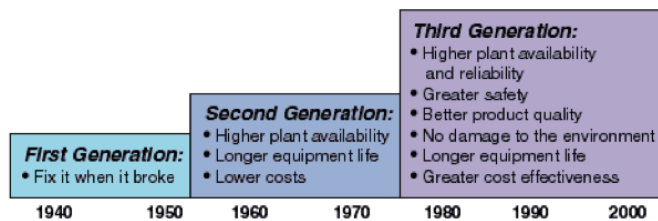
Figure 3: Growing expectations of maintenance

As seen from the figure above, availability and reliability have now become key issues. Nowadays, in a company's total operating costs, maintenance cost has a much larger role. Today´s businesses are more automated, and even small breakdowns are now much more likely to stop a whole plant. Failures today have bigger safety and/or environmental consequences, then they had just a decade ago. [13]

As *figure 3: Growing expectations of maintenance* shows, there has been a huge growth of new maintenance techniques since 1980s.
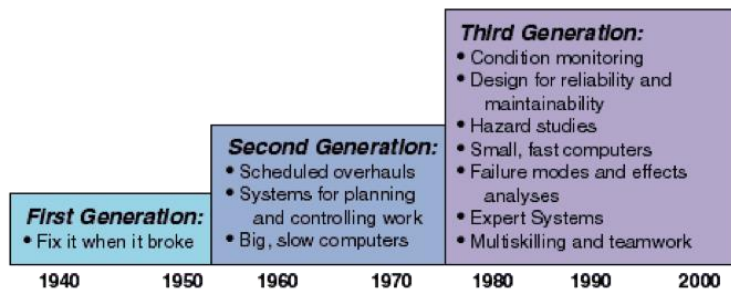
Figure 4: Changing maintenance techniques

The new techniques include;

- Decision support tools, such as failure modes, effects analyses and hazard studies
- Condition monitoring, monitor the equipment and take action when you see a change in the condition
- Cheaper and smaller computers do more of our work.
- Designing equipment with much greater focus on reliability and maintainability. [13]

Once a decision to perform the RCM is made and the system is selected, it is important to collect as much data and information as possible. The data and information that is required to support the RCM may include:

- Design information and technical specification
- Operating performance of the system.
- Historical maintenance data. Such as downtime and cost of maintenance.
- Reliability data, like MTBF, failure rate and preventative maintenance task frequency.
- Support data, such as support costs and level of support. [11]

Before analyzing the maintenance requirements of a system, it is necessary to know what those systems are, decide which system to be used in the RCM process and ask the seven basic questions.

The seven basic questions, quoted from John Moubray, Reliability-centered Maintenance, page 8:

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfill its functions?
3. What causes each functional failure?
4. What happens when each failure matter?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventive task cannot be found? [14]

A description of these questions are in the following text.

4.1.1 Functions and performance standards.

The RCM process starts by defining the functions and performance standards of each asset. Product quality, customer service, environmental issues, operating costs and safety are all important examples that these standards cover. This step alone can take up to a third of the time involved in an RCM analysis.

4.1.2 Functional failures

Before applying different failure management tools, it is necessary to find out what failures that can occur. The RCM first ask how the item can fail to fulfill its functions, then by asking what can cause each failure. If an item fails to fulfill its functions, it is known as functional failures.

4.1.3 Failure Modes

When each functional failures is mapped out, the next step is to identify all failure modes that are likely to cause loss of function. This help the personnel to understand preventable incidents.

4.1.4 Failure Effects

After looking at each failure mode, the failure effects are also recorded. These reveals what would happen if a failure mode did occur. Downtime, effects on product quality, evidence that the failure has occurred, probable corrective action and threats to safety or the environment would be examples of this. All this data makes it easier to decide how much each failure matters, and what kind of preventative maintenance is needed.

4.1.5 Failure Consequence

Each of the failures affects the company in different ways. If a failure has serious consequences, there is likely to be performed a lot of work to try to prevent it from happen. On the other hand, if the failure has no or little consequence, it may be decided to take no preventive action beyond basic cleaning and lubrication routines. [13]

The RCM process classifies the failure consequences into four groups:

- **Hidden failure consequences:**
  Hidden failures have no direct impact. When the equipment is needed and if there is a fault, that prevent you to operate it, it may have serious consequences for the business.

- **Safety and environmental consequences:**
  A failure has a safety consequence if it could hurt or kill someone. It has an environmental consequence if it breaches any national, regional or company environmental standard.

- **Operational consequences:**
  If a failure affects production it has operational consequences. By production we mean product quality, customer service, operating cost and the cost to repair. Failure that affects production will also lead to potentially large expenses. How much the failures costs suggest how much need to spend to prevent them.

- **Non-operational consequences:**
  Failures that do not affect production neither safety, only the cost to repair.

4.1.6 Preventive Tasks

Earlier, the industry thoughts about maintaining components, was that components should be replaced at fixed intervals. Still today this is the common way of thinking, that the best way to optimize plant availability is to do some kind of proactive maintenance, on a routine basis. [13]
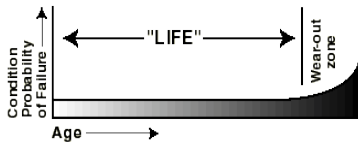
Figure 5: Classic curve

Figure 5 is based on the acceptance that most items operate fine for a period of time, and then wear out. Classical thinking suggests that gathering a lot of data about equipment failure, will help to determine the components lifespan and then make plans to fix the item shortly before the item is due to fail.

This curve is true to some certain type of simple equipment, and for equipment that comes in direct contact with the product. Age related failures are also often associated with equipment that is exposed to vibration, corrosion, fatigue and evaporation. However, equipment nowadays is much more complex than it was some years ago. This has led to changes in the patterns of failures, as shown in figure 6.
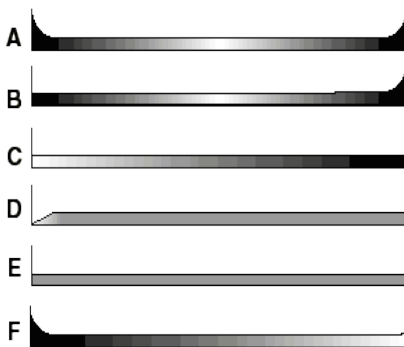
Figure 6: Patterns of failure

A: "Bathtub" curve

B: Slowly increasing probability of failure.

C: Shows slowly increasing probability of failure, but no clear wear out age.

D: Low probability of failure when the item is new, then a rapid increase to a constant level.

E: Constant probability of failure at all ages (random failure)

F: Starts with a high probability of failure, which drops eventually to a constant or a very slowly increasing probability of failure.

Studies done on civil aircraft showed that 4% of the items matched with curve A, 2% to B, 5% to C, 7% to D, 14% to E and 68% to F. The numbers of times these patterns occur in the aircraft industry, is not necessarily the same in any industry. As equipment becomes more complex, more and more of the curves match curve E and F. [13]

4.1.7 Failures that is not age-related.

The more complex an item is, the more likely is it to be like pattern E and F. These patterns are typically associated with electronics, hydraulic and/or pneumatic equipment.
The most important characteristic of curve D, E and F is that after the initial period, there is little or no relation between reliability and operating age. In these cases, age limits do little or nothing to reduce the probability of failure. In fact, scheduled maintenance can actually introduce small defects into the system and increase overall failure. These facts have led some people to abandon the idea of preventative maintenance altogether. Although this can be the right thing to do for failures with smaller consequences. When failure consequences are more serious, something must be done to prevent the incident from happening, or at least to avoid the consequences. The continuing need to prevent certain types of failures, are the reason of a growth in new techniques. One of the most popular among these new techniques are on-condition maintenance. [15]

4.1.8 On-Condition Maintenance

On-condition maintenance is a type of preventative maintenance, performed either continuous or at interval to monitor a system. It is based on the fact that many failures do not happen suddenly, but actually develop over a period of time. If some proof that failure is under way, it may be possible to take action to prevent the failure and/or to avoid the consequences. Potential failure is the point where it is possible to find out what is failing and where it is possible to detect it. Examples of potential failures include:

- Vibration indicating bearing failure
- High temperature in bearing indicating bearing failure
- Cracks showing metal fatigue
- Particles in gearbox oil showing gear failure

There are hundreds of ways to finding out if failures are in the process of occurring.
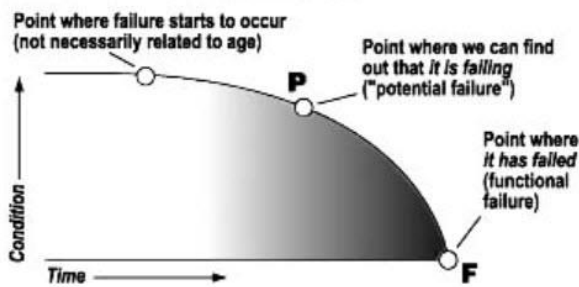
Figure 7: PF-Curve

Figure 7 illustrates the process. This process is called P-F curve, because it shows how a failure starts. Worsen to the point that it is failing (potential failure point "P") and then, if it is not detected and corrected, continues to get worse until it reaches the point of functional failure (point "F"). There are two possibilities if a potential failure is detected between point P and F:

- *To prevent the functional failure*. Sometimes it is possible to repair the component before it fails completely. In this case, prevention of the failure and avoidance or reduced the consequences.
- *To avoid/reduce the consequence of the failure*. Even if it is detected a potential failure, no one can be sure it helps us prevent it from failing, but it still makes it possible to avoid or reduce the consequence. [15]

This leads to the concept of on-condition.

"On-condition tasks entail checking equipment for potential failures, so that action can be taken either to prevent the functional failure or to avoid the consequences of the functional failure." [16]

It is also smart to consider the amount of time that elapse between the point where it is detectable, and the point where it becomes a functional failure. This interval is known as the P-F interval. The P-F interval is important because it tells how often the on-condition task must be done. If a desire to detect the potential failure before it becomes a functional failure, a check of the equipment with a frequency less than the P-F interval is needed. If on-condition is performed with intervals that are longer than the P-F interval, it is possible to miss the failure. On the other hand, if too small intervals are chosen, money and personnel are wasted to check it too often The longer the P-F interval, the more time you have to make a good decision and take correct action.

The P-F interval is also known as the warning period or the lead time to failure. For different failure modes, it can vary in length from seconds to several months. [15], [17]

4.2 Failure Mode, Effects and Criticality Analysis (FMECA)

When it comes to reliability analysis FMECA is considered to be one of the most widely used methods. Standard reference is US MIL-STD-1629 [18] and here is the following definition of FMECA given as such:

> *"The objective of an FMECA is to identify all modes of failure within a system design, its first purpose is the early identification of all catastrophic and critical failure possibilities so they can be eliminated or minimized through design correction at the earliest possible time."* [19]

15

There are four special features of FMECA:

    (i)   Fault identification
    (ii)   Potential effects of the fault
    (iii)   Existing or projected compensation and/or control
    (iv)   Summary of the analysis

[20]

Item one is used to identify of any conceivable but realistic hazardous conditions. Item two explains the impact the fault uncovered in item one has on the system. Described in the third one is what can be done to compensate or to control the situation. In the last item it is evaluate whether the described situation is under control or further steps need to be considered.

In many cases it would be favorable to quantify the criticality and estimate probability occurrence for the failure modes mapped in the items mentioned above. The reason for this is to provide key personnel with enough information so they can decide corrective actions, their priorities and establish acceptable risks. To execute this, it is taken a closer look at the possible outcomes of each failure mode: In performing a specific job, human safety, system safety, how to improve maintainability and the specific maintenance requirements and the overall performance of the system. [19]

The basic question to be answered by an FMECA:

1. How can each component imaginable fail?
2. What are the causes of the failure modes?
3. What could the consequences be if failure did occur?
4. Is there a risk of human threats?
5. Is the failure detectable? And if so, how?
6. What is done to prevent the failure mode?
7. How dangerous is each failure mode?

Advantages:

- Effective analysis for individual components
- The components are accurately considered

Limitations:

- Does not look at the connection between the components
- The analysis is based on the analyst's understanding

HØGSKOLEN STORD/HAUGESUND

HYDRO

Criticality classification at Hydro ASA

Criticality class	Personal safety	Environment	Economy (NOK) *	Quality deviation ***	Probability class				
					1	2	3	4	5
					Unlikely 1/1000y	Very rare 1/100y	Rare 1/10y	Probable 1/y	Often 10/y
5	Multiple deaths	Damage > 5 years	>20 millions**	Consequence to customers customer	High	High	High	High	High
4	Death	Damage 2 - 5 years	2-20 millions	Complaints < 1 - 10 million	Medium	High	High	High	High
3	Permanent injury	Damage < 2 years	500 000 - 2 millions	Complaints < 1 million	Medium	Medium	Medium	High	High
2	Absence due to injury	Short term damage	50 000 - 500 000	No consequence for customer	Low	Low	Low	Medium	Medium
1	First Aid	Negligible damage	0 - 50 000	No deviation	Low	Low	Low	Low	Medium

* Economic loss due to production loss, repair costs and costs due to other damages

** All events that leads to a shutdown of the "electrolyze" more than 4 hours, is given criticality class 5.

*** The column for quality deviation is used when relevant. Example the foundry and others that have external customers

Table 2: Criticality Classification

Consequence class	Personal safety	Environment	Economy	Quality deviation
5	Multiple deaths	> 5 years recovery time	Total ruination of plant. Loss of production for a long time. Losses for more than 20 MNOK.	Quality deviation that effects customers customer
4	Death	2 - 5 years recovery time	Severe material damages. Big impact on production/loss of production. Loss: 2mill - 20 MNOK.	Quality deviation that leads to complaints for < 10 MNOK.
3	Permanent injury	< 2 years recovery time	Some material damages. Big impact on production. Loss: 500 000 - 2 MNOK	Quality deviation that leads to complaints for < 1 MNOK.
2	Absence due to injury	Short term damage	Less material damages. Less impact on production. Loss: 50 000 - 500 000 NOK	Quality deviation that has no effect for customer
1	First Aid	Negligible damage	Hardly material damages: Little impact on production. Loss: 0 - 50 000 NOK	No quality deviation

Table 3: Consequence Class

Probability class		Description	Frequency
1	Unlikely	Is possible but highly unlikely. Maybe one event in the world	1/1000 year
2	Very rare	Has heard of / Has happened another place.	1/100 year
3	Rare	Has happened at our facility	1/10 year
4	Probable	Happens from time to time	1/year
5	Often	Happens quite often	10/year

Table 4: Probability Class

4.2.1 Description of FMECA form

In this section the group will implement all of the data and concerns given in the sections above into a FMECA form. 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.

Unit (1), (2):

Start by giving the individual components their unique reference number and a coherent name which can be traced back to the parts list included as a separate page in the excel document. As you will notice a component will have a main number for example the number 1. Then a subsequent number might be added depending on the different modes the particular component will operate in. As seen in the document the Pinch Valve will have two main operating modes, open and closed. The group have numbered it with 1.1 and 1.2. This feels like the most natural way to maintain a clear overview on the different causes and failure modes it may have under the different operating modes.

Description of unit (2), (3)

In this section the goal is to describe the unit's functions and operational mode in a simple but logical manner as possible. As seen from the form the descriptions are short and concise. The reason for giving the components different reference numbers is more logical here. If looked at the *Pinch Valve, 1.1 and 1.2* it has two different operational modes, namely open and closed, and by subsequently two very different functions. One where the components function is to maintain closed to secure no leakage, and one where open to ensure free flow of the medium.

Description of failure (4), (5), (6)

This section is crucial to get right and can be a real challenge to ensure all potential failure modes and causes are covered. The analysts experience and insight into the system is important to be sure you have covered all possible aspects of the particular component. It could be a good idea to include personnel that operates the equipment on a daily basis, HSE, maintenance department as well as qualified and trained personnel in doing analytic work like this.

Failure mode (4)

Failure mode is the foundation to understanding the different causes of failure and the risks they involve. It can be a good idea to keep it simple when explaining the failure mode, as can see as an example for the *pinch valve* the three different failure modes mapped out:

- The valve does not open when it is required.
- The valve just partially opens when it should fully open.
- The valve does not maintain closed when needed.

A good question to ask when mapping failure modes is: "*What can we expect to go wrong in this particular operational mode?*" Many of these failure modes is based on experience from years of usage of similar components.

Failure cause (5)

This column is meant to provide the cause of the given failure mode. For example, if an air operated valve does not open, one cause may be that it does not receive air. It is important to

early in the process decide the system boundaries so that one do not include problems that occurs on a different system, and by effect impact the system in question.

How to discover the failure (6)

In many cases there is indicators that provide you with the information you need to establish if there is a failure in development, here it is needed to map out what personnel must be on a lookout for. Some of the failure modes are not detectable before it is too late, but this will covered in greater extent in chapter 4.4 Decision logic.

So back to the *pinch valve* again. If the failure mode is that the valve does not open, and the cause is that the valve does not receive pressurized air, failure can be discovered by looking if the system unloads aluminum oxide correctly.

Effect of failure (7), (8)

The mapped failures will have an effect of varies scale on two things. The system, and sub-system. In this case the system was the entire oxidation transportation tank consisting of an air system, the tank itself, and the oxide transportation system. The group chose the sub-system to be the oxide transportation.

On subsystem (7)

Let´s say the pinch valve does not open at all, or partially. The effect this will have on the sub-system is that if the valve does not open at all it will not be possible to unload any aluminum oxide. If the valve partially opens it will deliver oxide, but at reduced speed. This is important to be aware of since the reduced delivery speed will subsequently slow down production of the aluminum plant, and in worst case not get the needed amount of aluminum oxide and is in danger of shut down.

On system (8)

If one of the failures mentioned above occurs, it is possible to draw direct effects lines to the main system. If for example not being able to unload oxide to the aluminums plant, the trailer might possible be pulled out of operation due to maintenance. If this is the case, it is necessary to have a redundancy system in place to prevent slowdown in production or in worst case complete shutdown, which is not acceptable.

Risk (9), (10), (11), (12)

These columns are there to classify risks based on *Safety (9), Environment (10), Cost (11) and Risk classification (12)*.

Here is the following the guidelines provided by Hydro ASA. The referenced guidelines are given in in Figure 9. Note the number that matches the evaluated consequence in its coherent column.

(12) is based on *table 2 criticality classification*. Use the selected value from criticality class, move across the table to intersect the correct probability class. Where they intersect is the correct classification.

Risk reducing measures (13)

This column is there to map out the risk reducing measures which need to be implemented to secure that the risks are as minimal as possible. The different measures are developed in

collaboration of the different divisions attending the FMECA analysis. The different risk reducing measures can be everything from regular maintenance to periodic surveillance.

4.3 FMECA Execution

Unit		Description of unit		Description of failure mode			Effect of failure mode		Risk				Risk reducing actions		
Ref. Nr.	Name	Function	Operational Mode	Failure mode	Failure Cause	How to discover failure	Main System	Sub-system	Safety	Environment	Cost	Risk Classification		Responsible	Note
(1)	(2)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1.1	Pinch Valve	Open volume flow oxide	Open	Valve does not open	Airleakage	Look for pressure buildup / Listen/look for leakage around flens	Unable to unload / Reduced volume flow	Tank pulled out of service for maintenance	1	1	3	High	Periodic check of valve		
				Valve opens partially	Damaged rubber membran				1	1	3	High	Periodic check of valve		
1.2	Pinch Valve	Turn of volumeflow oxide	Closed	Valve does not close	Broken spring / Damaged/worn rubber gasket	Periodic functiontest/observation	Leakage	Pulled out of service for maintenance	1	1	3	High			
2.1	Fluoresent cloth	Fluorise aluminum oxide for unloading	Unloading oxide	Reduced airsupply	Airleakage / Cloged Cloth	Listen/look for leakage	Looses partial fluorisation ability	Unable to completely empty tank / Tank is pulled out of service / Unable to empty tank	2	1	2	Medium	Periodic check of airsupply		
				No arisupply	Airleakage / Cloged Cloth / Defect compressor	Listen/look for leakage / Visuel inspection / No volumeflow	Looses fluorisation ability completely	Tank is pulled out of service	2	1	3	High	Periodic check of airsupply / Periodic check of cloth		
2.2	Fluoresent cloth	Fluorise aluminum oxide for loading	Loading Oxide	Reduced airsupply	Airleakage / Cloged cloth	Listen/look for leakage / Check load weight	Looses fluorisation ability partialy	Unable to utilize load capacity / Tank pulled out of serviece / Unable to utilize load capacity	2	1	2	Medium	Periodic check of airsuply		
				No arisupply	Airleakage / Cloged Cloth / Defect compressor	Listen/look for leakage / Visuel inspection / No volumeflow of oxide / Check load weight	Completely looses fluorisation ability	Tank pulled out of service	2	1	3	High	Periodic check of airsuply / Periodic check of cloth		
3.1	Storz fixed coupling	Connection for unloading	Unloading Oxide	Unable to seal	Worn treads	Measure treads / Listen/look for leakage / Feel after appearant leakage	Leads to further wear / Reduces volumeflow / Might cause moist / Leads to further wear	Unable to transport optimal amount oxide / Preassure drop / Reduced deliveryspeed	2	2	2	Medium	Daily maintenance		
					Defect gasket	Listen/look for leakage / Feel after appearant leakage	Reduces volumeflow / Might lead to moist	Unable to deliver optimal amont oxide / Pressure drop / Reduced deliveryspeed	2	2	2	Medium	Daily maintenance and cleaning / Replace gaskets at intervals		
4.1	Pipes	Transport of oxide from tank	Unloading Oxide	Reduced volumeflow	Partial cloged due to resedue together with moist / Internal wear on pipes	Observe deliveryspeed / Observe pressure	Lead to damage on valves / Reduce quality on oxide	Significant reduced deliveryspeed / Increased deliverytime	1	1	2	Low	Blow trough after unloading		
5.1	Safety Valve	Release Pressure above 2.0 bar	Normal Closed	Does not open	Erosion	Look at Gauge to control correct pressure	Lead to leakage / Lead to damges on other components	Delivers to much oxide	3	2	3	High	Daily maintenance and cleaning		
5.2	Safety Valve	Release Pressure above 2.0 bar	Normal Open	Does not close	Erosion	Look at Gauge to control correct pressure	Unable to unload oxide		1	1	3	High	Daily maintenance and cleaning		

4.4 Decision logic

The purpose of decision logic is preventive maintenance, which can give better operational safety and economy. Flow chart, "Figure 9: Decision Logic Hydro Karmøy" shows result of Hydro ASA´s way of thinking around decision logic, an example of such an analysis of a component is also included. The group also have some explanations of various codes that are provided.

4.4.1 Codes and terms

O/S: Here it must be cleared if the maintenance activity can be performed while the equipment is in use or if they have to stop the activity. If the maintenance can be performed during operation, mark it O. If the maintenance requires stop, mark it with S.

Int: Constitutes the interval that the periodic activities have to be performed by. That maintenance activity which is not periodic does not have an interval. The people who does the analysis shall give assessments of estimation of interval.

To estimate the interval, the following assessment is assumed:

Periodic test/Inspection (Pt): How often they have to check/inspect the equipment to have enough safety in terms of efficiency. If criticality is high, the interval becomes short.

Periodic condition monitoring (Cm): To find the time it takes before an error is detected until a failure occurs it must be a time interval; this is called a PF-interval. It is very difficult to estimate the length of such an interval; therefore, there will be considerable uncertainty.

Periodic change (Pc): Components changes before it is expected to fail. It does not execute any service before it gets replaced.

U: A decision whether the maintenance activity should be done as an inspection or as maintenance. A supervisor does an inspection; his/her function is to control the equipment. If the maintenance activity should be done as maintenance it is not enough to control it, the staff also have to perform the maintenance.

The following assessment is assumed:

Ie	Inspection electrical
Io	Inspection operator
Im	Inspection mechanical
Ic	Inspection construction
E	Electrical maintenance
M	Mechanical maintenance
C	Construction maintenance

Spare part(s): Which spare parts that are necessary to implement the maintenance.

Availability: An overview of which availability it should be for spare part(s). Following tags are used:

> **S** – should lie in store

> **N**– purchased when needed (when errors occur)

> **P**– purchased in connection with preventive maintenance

> **C-** If the comparison analysis indicates that there is no reason to change the maintenance that was set up, it can be written 0 in the column. If some changes must be done, they can be marked with 1,2,3…

Changes can be written in the comment section [21].

4.5 Decision logic flow chart explanation

The purpose of making a flow chart in this fashion is to answer questions for a specific component to decide which maintenance procedure the component in question will receive. It is easy to see what judgments that have been laid as a foundation for each decision.

The way decision logic is executed is by making a flowchart over some essential questions and have a line from each of them with either a Yes or No. Depending on what the answer to that specific question is you are presented with another follow up question. Eventually, by following the questions and answering to the best of the analyst ability you will arrive at a recommended maintenance procedure.

The questions and the recommended maintenance procedures will differ from company to company, the group have made a flowchart based on information provided by Hydro Karmøy. The report will explain the different questions and the recommended activities in the following sections.

1. **Are there indicators; Can they alert on appearing errors?**
   Typical here are measurable data, deviations are normally cause for further investigation.

2. **Is continuous surveillance possible?**
   Sometimes it is not favorable even though it is possible to do continuous surveillance. Continuous surveillance is mostly done where the component in question is easily visible or measuring equipment is easily fitted as a permanent solution.

3. **Are there aging/wear signs?**
   A very visible indicator that something is wrong, can be easily detected, but in some cases next to impossible.

4. **Is overhauling possible?**
   Depending on the component a overhauling may be very difficult to execute, and in many cases it is better to replace an existing part with a new one to save time, and by effect money.

5. **Is the failure mode concealed?**
   Some failure modes may be impossible to discover with the naked and may need periodic function test to secure correct operational mode.

6. **No preventative actions**
   If you end up at nr.6 you will have no choice but to run to failure

4.5.1 Decision Logic Flow Chart Hydro Karmøy

Continuoues Surveillance — CS

Yes

2 — Is continuous surveillance possible?

No

Periodic Surveillance — PS

Yes

Periodic overhauling — PO

Yes

1 — Are there indicators? Can they alert on appearing errors?

No

4 — Is ovehauling possible?

No

Periodic replacement — PR

Yes

3 — Are there aging/wear signs

Yes

Periodic Function test — PFT

No

Yes

5 — Is the failuremode concealed?

No

6 — No Preventative actions — NPA

Figure 8: Decision Logic Hydro Karmøy

Decide maintenance method and interval															
Department:				Maintenance			Number		1002653		Maintenance Unit			Pinch Valve 5 "	
Failure Mode	Desicion Logic							Maintenance activity			D/S	Int	U	Spare part(s)	Availability	S

Failure Mode	1	2	3	4	5	6	Code	Maintenance activity	D/S	Int	U	Spare part(s)	Availability	S
Valve opens partially	J	N	-	-	-	-	PO	Function Test	D	Tk	Is		-	
Valve does not open	N	J	N	-	-	-	PU	Replace unit	S	Os	M	Pinch Valve	L	
Comment:														

Table 5: Decision Logic Form - Example

5. Execution of Analysis

This chapter discusses mathematical methods to optimize the maintenance. By calculating order quantum, periodic replacement and timetable for spare part management, the company will get suggestion for recommended maintenance.

5.1 Spare Parts Management

An adequate inventory is important in every business to maintain a cost-effective maintenance. Companies must look at the criticality of the various components to determine whether it is necessary to have the part at stock, as it is expensive to have spare parts at stock. Experience data from Hydro Karmøy estimates that a spare part in stock represents approximately 20 % of the purchase price per year. By performing an analysis of the spare level the company can make it possible to reduce costs.

Magnus Rasmussen, professor at NTNU, gives a short summary of a typical material-storage system, where he lists the typical functions. They are:

- Registration of spare parts
- Requisition
- In and out from storage
- Corrections of stock
- Overview

There are numerous factors to consider in ordering and storing spare parts. Storage capacity, weight, storage cost, shipping frequency and costs, lifespan of the different spare parts, acceptable downtime, criticality of the different components. [22]

5.1.1 Interview with a maintenance program specialist

The group has had an interview with a maintenance program specialist from a Norwegian oil & gas company about spare parts strategy. Due to confidentiality requirements the company- and persons name is not given.

Q: What is your company's strategy for management of spare parts?

A: Norsok standard Z-008 is the foundation for our spare parts management and evaluation of spare part needs for maintenance tasks. The number of spare parts, location and warehouse are determined by; consequence classification, redundancy, operational requirements and delivery time. It has been taken into consideration the suppliers recommendation and delivery terms such as price, warranty and good will into account. The number of spare parts used for planned maintenance are identified based on the preventive maintenance programs i.e. what activity is to be performed and when it has to be performed. Spare parts from corrective maintenance and condition-based maintenance are based on history, reliability data from OREDA, supplier and experience.

Different teams onshore have different roles regarding spare parts management, but the technical authorities have the overall responsibility for spare part stocking levels and optimizing spare parts needs. Our maintenance is divided in planned/preventive maintenance and corrective maintenance. PM01 is planned maintenance and PM02 is corrective maintenance. For PM01, it should be imperative to ensure that the necessary spare parts are available when the job is scheduled to start. For corrective maintenance (PM02) the min/max stock level and location for the spare parts is based on consequence classification, redundancy, experience, MTBR, MTTR and demand. When considering the need for spares it is important to know both the operational- and suppliers demand. Some of the examples are:

Operational demands:

- Environment
- Age
- Criticality and redundancy on the equipment
- Maintenance strategy
- Repair – send it onshore or fix it offshore?
- Capacity
- Competence

Supplier demands:

- Delivery time
- RSPL
- Price
- Shelf life
- Availability in the future
- Interchangeability
- Does the supplier have a warehouse, with the equipment in stock?

To ensure optimal operations it is necessary to place the spare parts based on needs and consequence for the operations. Material management decides where to store spare parts according to the following matrix.

	Low	Medium	High
First line spare parts. Frequently used.	Stock at onshore warehouse/OLA	Minimum stock at offshore warehouse, and any additional spare parts at onshore warehouse/OLA	Adequate stock at site
Not frequently used	No stock/OLA	Stock at onshore warehouse/OLA, no stock at offshore warehouse	Stock at onshore warehouse/OLA, and minimum stock at offshore warehouse if convenient
Insurance spare parts. Seldom or never used.	No Stock/OLA	No stock/OLA	Stock optimized by use of risk assessment case by case

Table 2: Stock Location Decision Table

*OLA = Outline agreement with supplier

Q: Can you talk about your company repair philosophy?

A: When considering repairing spare parts, the following notes should be taking into account:

- Price to repair – If repair costs more than 60% off new price, a new part should be ordered.
- Availability on new part – is it possible to buy new part?
- Delivery time
- Condition of the part

5.2 Yearly cost and optimal ordering for a specific component

The following mathematical model has some weaknesses, among other it relies on a constant consumption over time. There is not accounted for any discounts connected to larger shipments, but non the less it provides a fairly good idea about the principle. Figure 10: *Optimal ordering diagram*, shows the principle in a diagram.
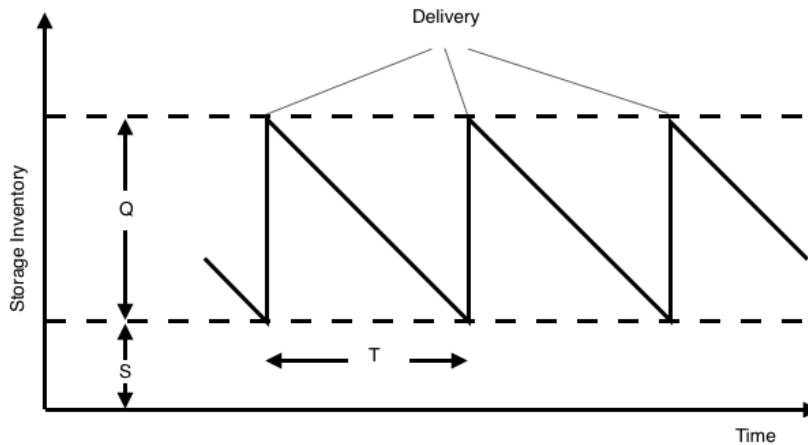
Figure 10: Optimal ordering diagram

To decide on the most optimal quantum, follow a simple formula:

i) Yearly consumption equals X quantum, and unit cost is C_0. This gives yearly costs of these units by $X \cdot C_0$.

ii) Consumption is X and ordering quantum each time is Q; this gives the number of orders each year X/Q

iii) Shipping- and delivery costs pr. order is C_1. Yearly the costs are $\frac{X}{Q} \cdot C_1$

iv) Capital costs per unit is C_2. From the figure above that average stock is given by $\left(S + \frac{1}{2} \cdot Q\right) \cdot C_2$.

v) Total yearly costs are: $C = X \cdot C_0 + \frac{X}{Q} \cdot C_1 + \left(S + \frac{1}{2} \cdot Q\right) \cdot C_2$

The derivative of this equation with consideration of Q, it provides optimal Q as:

$$Q_{opt} = \sqrt{\frac{2 \cdot X \cdot C_1}{C_2}}.$$

[23]

As derived from the groups analysis of the oxide transportation trailer it will now be decided optimal ordering quantum for the critical components involved. More specific description of the acronyms will be explained in the product later. All shipping prices are estimated via UPS.com [24].

Acronym	Description
C_0	Unit cost
C_1	Shipping- and delivery costs
C_2	Capital costs per unit
X	Consumption per period
S	Spare part safety limit

Pinch Valve:

$$C_0 = 447.55 \, EUR \approx 4225 \, NOK$$

$$C_1 = 1603.28 \, NOK$$

$$C_2 = 500$$

$$X = 3$$

$$S = 3$$

$$Q_{opt} = \sqrt{\frac{2 \cdot X \cdot C_1}{C_2}} = \sqrt{\frac{2 \cdot 3 \cdot 1603.28}{500}} = 4.4$$

$$C = X \cdot C_0 + \frac{X}{Q} \cdot C_1 + \left(S + \frac{1}{2} \cdot Q\right) \cdot C_2$$

$$C = 3 \cdot 4225 + \frac{3}{4.4} \cdot 1603.28 + \left(3 + \frac{1}{2} \cdot 4.4\right) \cdot 500 = 16368.15 \, NOK$$
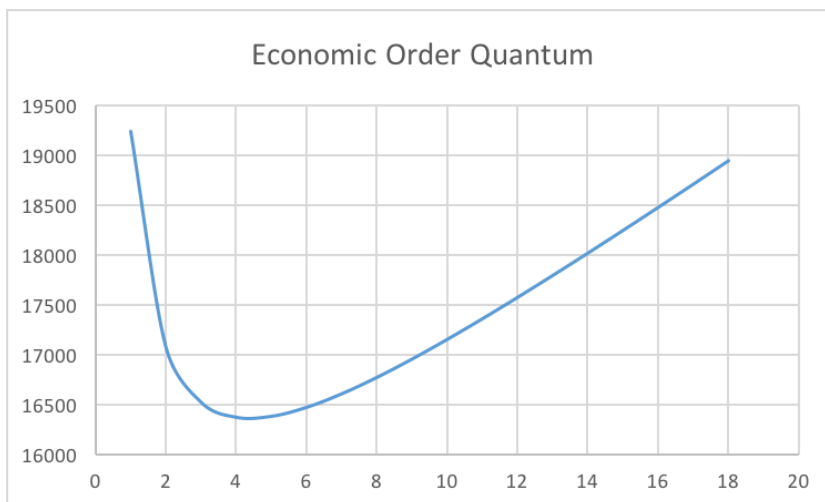
Figure 11: Economic Order Quantum, Pinch Valve

Safety Valve:

$$C_0 = 120.45 \ EUR \approx 1137 \ NOK$$

$$C_1 = 795 \ NOK$$

$$C_2 = 150$$

$$X = 3$$

$$S = 3$$

$$Q_{opt} = \sqrt{\frac{2 \cdot X \cdot C_1}{C_2}} = \sqrt{\frac{2 \cdot 3 \cdot 795}{150}} = 5.64$$

$$C = X \cdot C_0 + \frac{X}{Q} \cdot C_1 + \left(S + \frac{1}{2} \cdot Q\right) \cdot C_2$$

$$C = 3 \cdot 1137 + \frac{3}{5.64} \cdot 795 + \left(3 + \frac{1}{2} \cdot 5.64\right) \cdot 150 = 4706.9 \ NOK$$
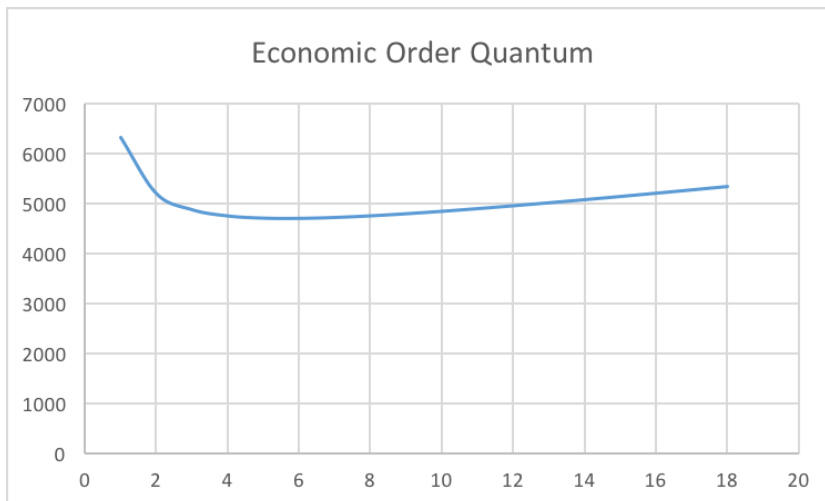
Figure 12: Economic Order Quantum, Safety Valve

If one considers the numbers used in the calculation to be accurate, it is easy to see how a total cost for the units evolve depending on numbers of units. For the pinch valve the report clearly indicates this development. The optimal ordering quantum is 4.4 units, and this will give a yearly costs of 16368,15 NOK. If, however the number of units ordered were increased to 10 units, the graph displays the costs to be approximated 17200 NOK. The results depict in a very clear way the savings that are possible by making calculations like this.

5.3 Corrective and preventative maintenance

In all essence it is separated between two types of intervals in regards to replacing components in maintenance:

- Periodic replacement/overhauling after a pre-determined <u>age</u>
- Periodic replacement/overhauling after a pre-determined <u>time</u>

It is up to the different companies and departments to decide whether to measure time in hours, days, months, years etc. It all depends on the stress the specific component is under and the criticality of this component being operational.

The group believe that periodic replacement/overhauling after a pre-determined time is the best option, as shown under in Figure 13: *Pre-determined time strategy*, the interval is calculated in set time interval from the last preventative maintenance action regardless if there have been one or more corrective maintenance operations in-between.

Merknad [TF1]: Motstridenes i konklusjon?

Merknad [JS2]: Er ment som den beste av de to nevnte alternativene for preventativt vedlikehold. Ikke s total løsning ☺

X = Preventative
△ = Corrective
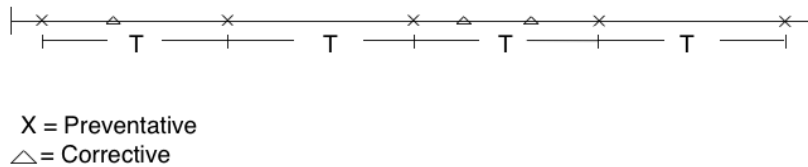
Figure 13: Pre-determined time strategy

As mentioned above the interval T, is case-decided to whatever feels necessary. Costs are defined as direct + downtime, for a corrective action this is C_c and accordingly for preventative actions C_p.

Anticipated numbers of failures in the given time period is provided by this formula:

$$M(T) = \sum_{j=1}^{\infty} F^j \cdot (T)$$

$F^j \cdot (T)$ is the probability for j independent failures with the distribution $F(T)$

This means that the average costs for each interval is as follows:

$$c(T) = \frac{C_p + C_c \cdot M(T)}{T}$$

The same goes for when you analyze discrete distributions.

$$\sum_{i=1}^{n} P_i = 1$$

If the interval k between the preventative actions the costs per. period is:

$$c(k) = \frac{C_p + C_c \cdot M(k)}{k}$$

$M(k)$ is calculated by defining probability f for failure x number of periods after the last preventative action.

$$M(k) = f_1 + f_2 + f_3 + \cdots + f_k$$

For calculating f_x it is needed to take a look at how long the component that fails in period (x) have been in operation. If it has been operational in m periods (m<x), and it has

probability for failure p_m there must also have been a failure in the period (m-x). Thusly $f_x(x = 1, 2, 3, ..., k)$:

$$f_1 = p_1$$

$$f_2 = p_2 + p_1 f_1$$

$$f_3 = p_3 + p_2 f_1 + p_1 f_2$$

$$f_4 = p_4 + p_3 f_1 + p_2 f_2 + p_1 f_3$$

.

.

.

.

$$f_k = p_k + \sum_{i=1}^{k-1} p_{k-1} \cdot f_i$$

Optimal interval, meaning lowest cost is calculated from (3.2.6) using a graphical representation of the result with k as variable. The first minimum point on the graph is not necessarily the absolute minimum, be aware of this.

To secure an acceptable level of calculation it is recommended to calculate c(k)- values to the first minimum, and in addition calculate c(k) for $k = \infty$, and choose the lowest one.

When $k \to \infty$, the function c(k) go to $c_c \cdot M(k)/k$ because c_p/k will go towards 0. Expected lifespan (MTBF) is equal to the time period divided with the number of failures.

$$MTBF = \lim_{k \to \infty} k/M(k)$$

and thusly

$$c(k \to \infty) = c_c \cdot \frac{M(k)}{k} = c_c/MTBF$$

where:

$$MTBF = \sum_{i=1}^{n} i \cdot p_i$$

n equals the maximum lifetime registered of the specific component, meaning all components have failed after n periods. [25]

5.4 Computer Program

As part of the study it is supposed to developed and create a product besides the actual thesis. The product has formed itself in conjunction with the thesis. When started doing the analysis the group discovered the tedious process of calculating the different aspects covered by the theory provided in this thesis.

It was also perceived the importance of implementing this into a serious company, to be able to improve efficiency and economy. The group has also acknowledged the heavy theory that is the basis for doing so, and that this might be considered to be redundant. That is why the group have developed an "easy-to-use" excel based program that will give the user the needed results with some easy inputs without the heavy theory.

5.4.1 Program Language

The language used to develop the program is macro in Visual Basic for Applications. A build in developer's tool in excel. It is similar to many other programming languages. The reason one uses macros are in many cases to automate repetitive processes.

5.4.2 Different sections in the program

The product focuses on three different calculations:

- Periodic replacement interval
- Optimal ordering quantum
- Timetable for spare part management.

As a part of a total evaluation there will be written a more complete description of the program that will function as a production manual. In this section there will be given a brief description of what the program does and the layout.

The periodic replacement interval:
This section of the program calculates the optimal periodic replacement interval on basis of reliability data provided by the manufactory. The layout is such that the user only has to input the different likelihood of failure in a given period for example on a monthly basis. When the user then hits calculate, the user is provided with likelihood of failure up until a given period, mean time between failure, expected number of failures, costs of each period and optimal interval for replacement and the corresponding cost of this interval.

Periodic Replacement Interval

Costs	
Preventative	Corrective
10000	25000

Propability for failure in period (month)		Probability for failure after x-number of periods		Number of periods	Expected number of failures in the	Costs per. Periode (kr)	MTBF
January	0,25	f_1	0,25	1	0,25	16250,00	4,00
February	0,20	f_2	0,26	2	0,51	11406,25	3,90
March	0,15	f_3	0,27	3	0,78	9817,71	3,86
April	0,15	f_4	0,31	4	1,08	9278,32	3,69
May	0,10	f_5	0,31	5	1,39	8955,66	3,59
June	0,10	f_6	0,34	6	1,73	8888,68	3,46
July	0,05	f_7	0,33	7	2,07	8811,41	3,39
August	0,05	f_8	0,36	8	2,43	8832,40	3,30
September	0,10	f_9	0,44	9	2,86	9064,12	3,14
October	0,15	f_10	0,55	10	3,41	9520,54	2,93
November	0,20	f_11	0,68	11	4,09	10211,43	2,69
December	0,25	f_12	0,86	12	4,96	11160,08	2,42

Optimal Interval	
Kostnad	Periode
8811,41	July

Calculate

Reset values

Picture 8: Optimized replacement interval

Optimal ordering quantum:

This section of the program is meant to provide the user of information of the recommended ordering quantum based on some variables that they have to input, such as; consumption, unit costs, delivery costs, storage costs and a safety buffer. The user can also decide to view a table and graph depicting how the costs vary based on quantum. And at the bottom they will be provided with a recommended ordering quantum, and the costs connected with this quantum.

Optimal Ordering Quantum

			Ordering quantum	Yearly costs of x-number components	Yearly costs connectet to ordering and delivery	Average Stock	Total yearly costs
Consumption	X	10,0					
Unit costs	C_0	2000,0	1	20000,0	150000,0	750,0	170750,0
Delivery costs	C_1	15000,0	2	20000,0	75000,0	900,0	95900,0
Storage costs	C_2	300,0	3	20000,0	50000,0	1050,0	71050,0
Ordering quantum	Q	8,0	4	20000,0	37500,0	1200,0	58700,0
Safety buffer	S	2,0	5	20000,0	30000,0	1350,0	51350,0
			6	20000,0	25000,0	1500,0	46500,0
Total yearly costs	C_tot	40550,0	7	20000,0	21428,6	1650,0	43078,6
			8	20000,0	18750,0	1800,0	40550,0
			9	20000,0	16666,7	1950,0	38616,7
			10	20000,0	15000,0	2100,0	37100,0
			11	20000,0	13636,4	2250,0	35886,4
			12	20000,0	12500,0	2400,0	34900,0
Calculate			13	20000,0	11538,5	2550,0	34088,5
			14	20000,0	10714,3	2700,0	33414,3
			15	20000,0	10000,0	2850,0	32850,0
			16	20000,0	9375,0	3000,0	32375,0
			17	20000,0	8823,5	3150,0	31973,5
			18	20000,0	8333,3	3300,0	31633,3
			19	20000,0	7894,7	3450,0	31344,7
Reset values			20	20000,0	7500,0	3600,0	31100,0
			Opt.quantum			Opt.costs	

Picture 9: Optimal ordering quantum

Timetable for spare part management:

The third section of the program is meant to give the user information on when to expect errors to occur, it will provide dates on critical errors as well as degraded errors. It will also give information on suggested replacement date, and ordering date. Basis for calculation is error rate provided by manufacturer and the date the component was started in operation.

Timetable for spare part management										
Component	Error rate (pr.10^6 hrs)		Date put in use	Estimated date for error		Recommended date for replacement		Recommended ordering date		
	Critical	Degraded		Critical	Degraded	Critical	Degraded	Critical	Degraded	
safety valve	11,30	55,30	01.06.2016	06.07.2026	24.06.2018	02.07.2025	10.04.2018	18.06.2025	27.03.2018	
Cloth	12,55	45,60	01.06.2016	04.07.2025	01.12.2018	06.08.2024	01.09.2018	23.07.2024	18.08.2018	
gasket	18,30	63,40	01.06.2016	25.08.2022	20.03.2018	10.01.2022	13.01.2018	27.12.2021	30.12.2017	

Calculate

Reset values

Picture 10: Timetable for spare part management

As seen from the images above, the programs layout is simplistic and easy to understand. However, the script behind the manipulators is more complex and filled with the theory provided in this report to give as accurate result as possible.

It is the intention that Hydro Karmøy will implement this program in their analysis and decision making. It is also the intention that personnel from different departments can go in and examine for example the recommended date for a specific components replacement date.

5.5. Maintenance costs

Maintenance costs are those costs incurred to keep the equipment in good enough condition. It is impossible to have a system which never fail, each part will eventually decay. Then it is important to have a system which can repair the parts for a minimum cost, and at the same time ensure that availability, safety and integrity is taking care of.

5.5.1 Total cost

Total cost of maintenance task is the sum cost of direct and indirect costs:

Direct cost = the cost of maintenance resources directly used during the execution of the maintenance task. (CMT)

Indirect cost = management and administration staff, overhead costs, cost of lost production. (CLR)

IHR = Income hourly rate

DT = Total down time

Variables	Costs
C_s	Spare parts
C_m	Material
C_p	Personnel
C_{te}	Tools and support equipment
C_f	Facilities
C_d	Technical data

Table 3: Total costs variables

$$CMT = CMR + CLR$$

$$CMR = C_s + C_m + C_p + C_{te} + C_f + C_d$$

$$CLR = (DMT + DST) \cdot IHR = DT \cdot IHR$$

[26]

In this report it has been used data categorized as worst-case scenario. Values will include that a specialist must be called to fix the part in the middle of the night. Hourly rate in the night is set at 1200kr. A normal hourly rate is set at 600kr. The group asked Hydro Karmøy if they could ask Feldbinder for a price list of the components at the tankers, after a while the list finally was received. The price list is attached in the appendix B. The price was given in Euro, the group used "Norske Bank" to find todays (23.04.16) exchange rate for NOK. Exchange rate was 9.249NOK/EUR.

		Safety valve		Pinch Valve	
	Description	Corrective Maintenance	Preventative Maintenance	Corrective Maintenance	Preventative Maintenance
Cost of spare parts	Price per component	1114kr	1114kr	4137kr	4137kr
Cost of material	In this case same as spare part	-	-	-	-
Cost of personnel	Hourly rate	1200kr/h * 6h = 7400kr	600kr/h * 2h= 1200kr	1200kr/h * 6h = 7400kr	600kr/h * 2h = 1200kr
Cost of tools and support equipment*	Only hand tools are needed. This is included in hourly rate	-	-	-	-
Cost of facilities	20% of cost of spare part	223kr	223kr	827kr	827kr
Cost of technical data	Manuals, datasheet etc.	-	-	-	-
Total cost		**8737kr**	**2537kr**	**12364kr**	**6164kr**

Table 4: Total costs matrix

* Bilfinger is the company that repairs the trailers/tanks. And the tool and equipment they need to fix safety valve and pinch valve are included in their hourly rate.

The table above does not take into account the replacement interval. Notice that the costs related to preventative maintenance is considerable lower than corrective. However early indicators from operators indicates that in case of a preventative maintenance program, components need replacement at quite frequent intervals. It is still too early to say how often replacement is needed, but an estimate on every 3rd month can conclude that preventative maintenance costs actually will rise above the costs related to corrective maintenance.

The decision is case to case based and a general rule is not applicable. The costs are closely related to intervals and can vary greatly depending on factors discussed above.

5.3 Overview of maintenance optimization

After the group have gone through the process for maintenance optimization, the group have seen the importance of a thorough examination in the engineering process. It is important to have clear goals, and a well composed team will make the project more reliable. Figure 14 shows a schematic overview on how the group think the process should be done.
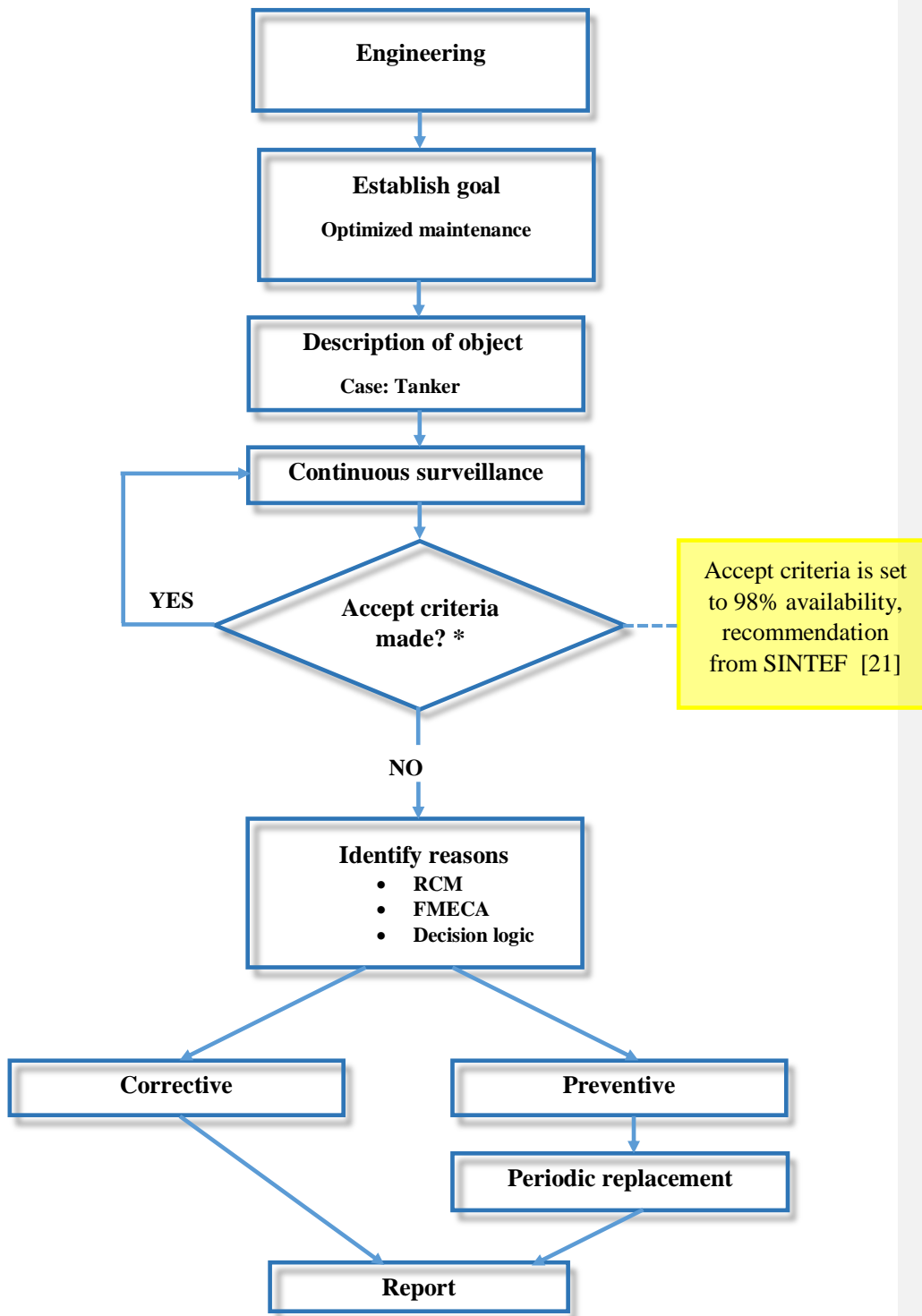
Figure 14: Overview of maintenance optimization

[27]

6. Discussion and suggestion of further work

In this chapter it will be discussed in a chronological sequence each applied piece of theory. The group have chosen to do the discussion in subchapters, in this way the amount of theory and their content is best represented, and will be more easy to grasp.

6.1 Discussion limitations

As mentioned in chapter 1.4 Limitation the group has not had the opportunity to make real calculations for optimal periodic replacement, when it has not been possible to get the actual data before submission deadline. The group has therefore used approximated data which will be fairly accurate compared with today's industry.

6.1.1 RCM

When the group have gone through the theory of RCM, it is clear how the world of maintenance has changed in the last few decades. Due to the more complex design of today´s industry, it is more important than ever to spare some time to complete an analysis of given assets, and make a solid maintenance program. Today there is more knowledge about how defect equipment can have huge impact on safety and/or environment. Take the DeepWater Horizon blow-out as an example. A healthy BOP (blow-out preventer) would reduce the consequences dramatically. A small equipment today can have strings to a huge and complex system, and if this equipment suddenly fails, it could have an enormous impact on a system.

In today´s markets with cost reduction and workforce reductions it is very important to have high plant availability to reduce the costs. There is a strong connection between product quality and maintenance. With a reduction in maintenance costs one could expect a drop in availability for the plant and product quality would drop as well. This is also a very valid point for western companies, when they are competing with companies that produces their products in low-cost countries. Where they might be more straight forward, and condone their maintenance tasks.

One of the key elements in the RCM process, is to get data as early as possible. The group encountered this as a challenge early on. When manufacture was addressed of this they could not help us. Because this project was brand new, Hydro Karmøy did not have any historical data. So already from the start it was some difficulties performing a good RCM.

As time went and the more people got involved, it became apparent that the most used and often most resourceful data for a company regarding RCM process, is historical data. All of the companies contacted said that they used historical data rather than reliability data given from a supplier. It is rather seldom this data is provided from the supplier. Sometimes they took and compared both the reliability and historical data. For most of the equipment that have been in used over some time, they had reliable historical data.

In the groups theory of RCM, it have been used MTBF (mean time between failure) as a standard variable. Experiences after talks with different key personnel in different companies, a possibility might have been that the group rather should have focused MTTF (mean time to failure) instead? MTBF is the total time required for a device to fail and that failure to be

repaired, and MTTF is the time between failures. Repair time is not taken into account when talking about MTTF. For a company that is making a maintenance program, you are interested in when the device is going to fail, and plan accordingly. Some equipment can have a very long repair time, and this will give you a wrong idea on how long time there is between failures.

The group was lacking in some key theory before beginning this assignment, but were aware about the "bathtub curve" as a standard failure curve for all types of equipment. In development of the thesis it became clear that almost none of today´s equipment fit into the "bathtub curve". This is mainly because of the complexity in new equipment, and that the equipment is not age-related.

Most failures that occur do not happen instantaneously, but evolve over a time period. This makes it possible to spot that the failure is under way and take actions to prevent it from happening. This can be done with on-condition maintenance. The critical equipment on the tankers at Hydro Karmøy do not have any form for on-condition monitoring. Maybe it would be better if these devices on the tanker had the possibility to perform on-condition maintenance. It is very popular these days to monitor as much equipment as possible to get this early detection that something is wrong. The safety valve and the pinch valve are both on/off valves. They can only be operated to be fully open or fully closed, and there is no positioner on the pinch valve, providing any feedback signals. If there was a positioner installed it would be possible to measure the feedback signal and compared it to the output signal, to see if the valve began to operate erratic or that the valve travel time increases. This could be signs that indicates the valve is about to fail in the near future. Since the safety valve is only activated if reached to high air pressure, and the failure that could occur in the valve is hidden, it is found to be too complicated to get an on-condition based maintenance on this equipment. It would have to either done a complete rebuild of the equipment, or replaced these valves with more sophisticated valves. The cost to benefit ratio would be very high, and therefore not suitable for most of simple equipment.

6.1.2 FMECA

When started evaluating the different theories used in similar cases like this where you want to optimize maintenance and map the different components involved. It quickly became fairly clear that FMECA is a widely renowned method for doing so in a fairly quick and easy manner.

One of the clear advantages of an FMECA is how easy it is to quickly come up with scenarios for the different failure modes a component might receive and the seriousness of these failure modes. However, it quickly became clear that to be able to create an accurate and trustworthy FMECA, the person or persons doing the analysis have to have a very good and clear understanding of the components, environment, history of similar events, different errors that might occur and so on.

For an experienced individual, FMECA will take a very short time to execute, but for somebody with less experience a lot longer. In addition, if the FMECA is done by someone with less experience there might be some critical components or incidents that are left out and may lead to unwanted episodes.

One clear advantage is that for anyone that views the completed FMECA are able to, with minimal training, to easily understand the different aspects of the components, hazards and things to consider.

The best solution to ensure a high quality FMECA is to include more people in the process, i.e. engineers, operators, maintenance personnel, developers and HSE department.

One of the issues with FMECA is that the analysis looks at each component as individual components and not in coloration with other impacted sections. As an example the group have looked in this thesis on the oxide transport trailers, more specifically the oxide management side of the trailers. This is perfectly fine, and provides a good understanding of the components involved. However, a component in the air system connected to the oxide system might have a big impact on the evaluated parts in question and can lead to overlooked consequences. As an example the group had a meeting with the operators of the trailers, Hansen & Sønner, after some months of operation. It now turns out that the air supply system valves are highly affected by oxide leaking back through the air hoses and clogging the valves, hindering air manipulation. This effect would not have been covered in the FMECA since the parts in question were not included in the evaluated system. The effect of this failure mode, in worst case would be that unloading oxide would not be possible.

As previously mentioned it is important for the personnel doing the FMECA to have an in depth understanding of potential issues and which components that might cause problems. In doing this thesis it was only three individuals in the group, with an in depth understanding of how the trailer functioned, even though considering, after the groups opinion every critical component it now turns out that there is some gasket placed around the filling hole. These gaskets have now started to decade caused by the loading frequency and the load that the trailer carries, oxide. When evaluating the trailers, it was not considered these gaskets to be critical due to history of components like this. After four months they are now struggling with keeping the seal, and if the seal is not sufficient, unloading is not possible. From placing the order for the gasket to delivery was about three weeks. This points out a flaw in the FMECA and proves the importance of including personnel with all variations of experience.

A key aspect of any high quality FMECA is an adequate criticality classification. This classification is normally already established within the company, but the classification may sometimes be outdated in smaller companies and it is important to evaluate the classification table provided. There might occur weaknesses in the FMECA if personnel from HSE department is not represented to back up and provide sufficient understanding for the different classes.

An already established FMECA was not made, so there was develop one specifically for this thesis. This was a disadvantage since no one in the group had experience with this type of work. It was discovered that FMECA is pretty similar from company to company, so the group studied the layout of other FMECA's so that the group were able to design one that fitted Hydro Karmøy. It is the opinion that the disadvantage turned out to be an advantage. Because being forced to evaluate similar studies and understanding the theory behind it provided the group with solid knowledge on how an FMECA should be presented. In the thesis the group were also assisted by competent personnel at Hydro Karmøy to ensure a solid FMECA that included the most important aspects.

In essence the groups experience is that FMECA is a powerful tool to provide a good understanding and to map out the different critical components in a system and their failure modes and preventative actions. However, it requires solid background knowledge about the

system and components, as well as knowledge about the process in a FMECA analysis. It is a clear and easily understandable tool that quickly uncovers faults and consequences.

6.1.3 Decision Logic

In order to carry out preventative maintenance work, is it necessary to undertake an analysis of each component. The advantage of using a decision model is that it easily will show an overview of the type of maintenance that will be most appropriate for the individual component. In some cases, it is not possible to place the component in any of the categories, then it must be made an alternative way to solve the maintenance work. One option is to use a combination of maintenance activities.

If some of the components need periodic maintenance, it must be drawn up a plan that shows the intervals for maintenance activities. Then the personnel must have knowledge about useful life, fail mode etc. After conversations with the staff at the maintenance department, it shows that such data are difficult to obtain. One of the reason is that the supplier has not performed reliability analysis. This must be a prioritized in the future projects, otherwise they can not use the program made for optimized maintenance.

An another advantage about decision logic diagram is that is easy to find the responsible person for the component, since it is clarified from the start. In that way it is important to put a lot of time in the planning process. Routines must be followed up, then they can learn from experiences, and have a goal to continuous improve the RCM.

6.1.4 Preventative or Corrective Maintenance

Although the focus was on preventative maintenance, it has been discovered that in some cases corrective might as well be the best solution. Especially in cases such as this where it is a new system and sufficient historical data is not available, and reliability data from suppliers is scarce. There are clear advantages for preventative, and still considered this to be a very good maintenance strategy. Even though this system is of high criticality there is redundancy systems in place, and the equipment is of medium complexity. The time it will take to replace a critical unit will not take more than highly 6 hours, and the operators informed the group that they are able to deliver a surplus of oxide each weak, meaning that there is a safety buffer in place given maintenance time exceeds 6 hours.

There is however, a few conditions that have to be met before making this decision about choosing preventative or corrective maintenance. The way the case was evaluated there needs to be spare parts in stock at all times one of each critical component so that corrective maintenance will be as effective as possible. One need to remember that these trailers will operate at the same frequency both day and night, but there are no mechanics on site at night.

The groups experience with this study is that there is a wish in the industry of more preventative maintenance, but perhaps it is not always the way to go. Newer systems of medium to low complexity might be more cost effective to be handled under corrective maintenance, given that some conditions are met, such as critical components in stock.

6.1.5 Calculations

It was apparent in an early stage that there was a lot of quantitative in depth materials that was suited for our specific thesis. The challenge was selecting the material that would work for the complexity of the thesis, and that would give an appropriate answer to what the group were searching for.

Since the title of the thesis is "A model in maintenance optimization for spare parts[..]" the group were in the search for something that would solve just that. As the title suggest an optimization for spare parts really comes down to a few key aspects, what is the optimal number of components and how long can you expect to keep a component functional.

As you can read in chapter 4 the group have settled on a few in depth formulas to help us better understand and evaluate the correct choices for Hydro Karmøy. The clear advantage of using formulas is that you will get an unbiased answer, and the research in the field of spare part management is quite thorough. After evaluating the formulas in the group, there is confidence that they will provide an acceptable approximation of a usable result. For example, look at "4.3.2 Yearly cost and optimal ordering for a specific component" the formula includes many factors including such as storage costs and shipping and ordering costs.

However, these variables might be harder to get accurate then first anticipated. For example, in shipping and ordering cost; there is not just the answer on how much the part cost just to deliver and placing the order. There are sub-factors involved, there might be quantum discounts, the costs connected to just ordering comes in to play, a component of a set value of 50 NOK might have and additional cost of 1000 NOK in just administrative expenses. So even though the formula suggest that the optimal ordering quantum is 5 components with a value of 50 NOK each, and ordering frequency is on a monthly basis. The total cost is actually 1250 NOK and not just 250 NOK, and that is just by placing the order. So it is clear that in some cases it might be more preferable to order larger quantum on lower frequency even though the formula suggest otherwise.

On the other hand, as international trading escalates there is a development towards e-trading, where you minimize ordering costs, and the formula will provide you with a much more accurate answer.

At chapter *5.2 Yearly cost and optimal ordering for a specific component*, and the choice of pursuing pre-determined time, it is clear that the formula is complex and requires factors that might be hard to receive. It was the groups experience in requesting reliability data from the manufacture that this was not something they normally had any data on. This is why data from OREDA is used instead. On the other side if the consumer starts to request reliability data, the manufacture have to start providing this, and the group believe that this will be beneficial for both parties. There is however a problem with the calculations, it does not take into consideration the medium which is operated. It can already be seen that there is a considerable wear on the trailer already due to the medium; oxide. This is a great opportunity for a company such as Hydro ASA, to record their own data so that the formulas become as precise as possible.

The group consider the formulas as complex as necessary to provide the material in this thesis, and Hydro Karmøy with a sufficient result and their usage to be of great value in helping us optimize spare part management.

6.1.6 Computer Program

As part of this thesis the group were supposed to come up with a final product besides the actual report. After some careful considerations and discussions with the external tutor, and the natural evolution of the thesis, it became clear for the group that a computer program that would perform the tasks discussed in previous chapters would be a god way to go. As you can read in 5.4 Computer Program, it have been used Microsoft Excel and its internal programmable language in VBA to do the the job. This flexible tool allowed the group to really play around with what was envisioned the program to look like. It was desired that the program was easy understandable and have a comprehensible user interface.

As mentioned there have been worked a lot on the user interface, to make it so that everyone with minimal computer skills will be able to operate it. However, this means hiding away the theory behind it, making the user more ignorant to the foundation of the calculations. This might have some operators question the validity of the results, and feel like the results are wrong compared to their own experiences. On the other side it is evaluated that the theory is on a need to know basis and it is available for anyone via this report. By removing the theory away from plain site into a programmed button will make it more welcoming to use for the average worker. The intension is to make it so that anyone from engineers to operators can go in to the program and help them make correct decisions.

The group believe that this program will be an asset for Hydro Karmøy, and help with making cost saving and efficiency increasing decisions in the future.

6.2 Further work

There remains a lot of work to be done to arrive at the optimal solution for maintenance. However, this report will provide a solid foundation to assist in making more correct decisions in the future, with foundation in thorough research. The group believe that the work has highlighted some key aspects that have been missing in today's maintenance program. Being that this report is a tool to assist in making sustainable choices, there are some suggestions the group want to provide to further push towards the most optimal maintenance program for spare parts.

Suggestions for further work:

- Establish a group consisting by personnel from the maintenance section, and skilled personnel with relevant competence, like operators and the service department. A group such as this will be better equipped to make more accurate decision for the future, by discussing their experience so far.
- Follow-up meetings where the group can exchange experiences, so that they can improve the already existing system.
- Require reliability data when they purchase components.
- Create a long term deal with the supplier, regarding periodic shipment of spare parts where possible to avoid expenses related to ordering.
- Introduce routines involving inspection of the various components where none exists.
- Collaborate with other companies with the intention to share data and experience, this will improve the validity of usable data.
- Introduce the importance of an effective maintenance program to all employers involved in such work tasks. This to increase the understanding of sustainable and efficient operations.
- Establish a routine for registration of lifespan in various spare parts. This register will provide a valuable data source in the future and give Hydro Karmøy the upper hand and help to become a model for maintenance.

The bullet points above are meant to be a supplement to todays established model, and with implementation of the represented methods in this report, further work will help rise Hydro Karmøy maintenance program to a more sustainable level.

7. Conclusion

After reviewing new and old science on the subject of maintenance and compared it to today's existing maintenance model at Hydro Karmøy. The group believe with great certainty that the selected and processed theory in this paper will be an answer to the thesis: "Availability increase: A model in maintenance optimization for spare parts at Hydro Karmøy"

This claim is founded in solid research, usage of renowned methods such as RCM and FMECA and with supplement in mathematical calculations to assist with new thinking in helping to provide Hydro Karmøy with the best result possible.

The group have extracted some key elements for the conclusion:

- Semi- to low complexity systems that has an existing redundancy system in place and easy to replace components will not require a preventative maintenance solution. As described in the thesis, it is recommended having enough spare parts at stock to re-establish operations of one transport unit. This is based on redundancy with having one spare trailer, easily replaceable components and the fact that today's operation provides a surplus of oxide each week. This will maximize lifespan of critical components at minimum expenses.
- Evaluate each system and its component replacement interval before considering preventative maintenance up against corrective maintenance. Do this to get an estimate of costs related to each choice.
- Criticality assessment groups should consist of relevant personnel from more than one department to ensure highest possible quality judgment.
- If a system is of high criticality and of high complexity, it is recommended a preventative maintenance plan with basis in periodic replacement maintenance after a pre-determined time. This is to minimize risks correlated with failure.
- The group recommend implementing the supplied computer program to evaluate ordering quantum of spare parts. As shown in greater extend in the report there is a considerable sum to be saved from low- to high cost components, based on the correct number of components in each order.
- If reliability data is needed, you need to demand it when ordering equipment. It is challenging to get a hold of such data after the order is completed.

By implementing these bullet points, the group strongly believe that it will increase availability and decrease costs related to spare parts.

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Appendix

Appendix A: Preventative maintenance plan

<table>
<tr><td rowspan="6">KLS Logistikk</td><td colspan="3">FOREBYGGENDE VEDLIKEHOLDS PLAN</td></tr>
<tr><td>Benevnelse   :   Tankvogn FFB semi</td><td>Mek:</td><td></td></tr>
<tr><td>Tekn. plass nr :</td><td>Nedetid :</td><td></td></tr>
<tr><td>Revisjon: 1   Revisjon dato: 12/1-2016</td><td>Ressursbehov:</td><td></td></tr>
<tr><td></td><td>Tegninger :</td><td></td></tr>
<tr><td>Utført dato:</td><td></td><td></td></tr>
</table>

Description	Short text task description	Etter hver fylling	Daglig	Ukentlig	Månedlig	3M	6M	12M	24M	36M	120M	Utført	Kommentar
Slangeklemmer	Sjekk plassering av festeskruene og ettertrekk ved behov.	O											
Slangeklemmer	Visuell inspeksjon som en del av før-avgang sjekk	O											
Slangeklemmer	Visuell inspeksjon av luftveiene mellom individuelle tank kamre.	O											
Slanger	Kontroller slanger for skader		O										
Slanger	Kontroller at slangeklemmer sitter som de skal		O										
Slanger	Innenfor og utenfor rengjøring		O										
Oksyd uttak	Visuell sjekk av bunnventiler		O										
Oksyd uttak	Material hoses Materielle slanger		O										
Oksydslanger	Sjekk slangene for skader		O										
Oksydslanger	Kontroller slangeklemmer for fast sitte		O										
Material utmating	Sjekk tilstand					M	M						
Material utmating	Sjekk lekkasje tetthet, blindplugg					M	M						
Fluidiseringssytem	Visuell kontroll av fluidiseringsduk.						M						

Appendix B: Pricelist from Feldbinder

Winsen	-- Angebot --

Hydro Aluminium AS

N052267-N052269 / Delivery time: on stock

Pos	Artikel-Nr.	Menge	MA	Einzelpreis	Gesamtpreis	
10	1002653	1,000	STK	447,55	447,55	
	Pinch valve		Rabatt	0,00 %		
	DN 125					
20	1073250	1,000	STK	120,45	120,45	
	Safety valve		Rabatt	0,00 %		
	1,5" 2bar					
30	010583	1,000	STK	38,80	38,80	
	Storz coupling DN 125		Rabatt	0,00 %		
	5" female					
40	1058745	1,000	STK	197,65	197,65	
	aeration pad Euro III		Rabatt	0,00 %		
	DN800/200					
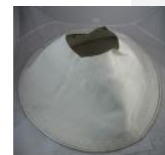
Appendix C: Instruction Manual, Safety valve

6.4 Safety valve

The safety valve illustration 6.3 (7) is an important protective device. It limits the excess pressure (working pressure) in the silo tank to a maximum of 2.00 bar, thus preventing the tank bursting.

Important information about testing the safety valve function can be found on „Safety valve" on page 158. The precise working pressure can be found on the type plate.

The current internal tank pressure illustration 6.3 (5) and the pressure in the air line (2) can be read on the pressure gauges.

Connectable safety valve

Another safety valve illustration 6.4 (1) can be mounted as optional equipment on the air manifold. It responds at a reduced pressure of 0.90 bar and can be activated or deactivated with a shut-off valve.

Connect the valve using the shut-off valve for transporting a light, dusty load, for example, that needs a reduced working pressure when it is being evacuated. In this case, the operating pressure is set and limited to 0.90 bar.
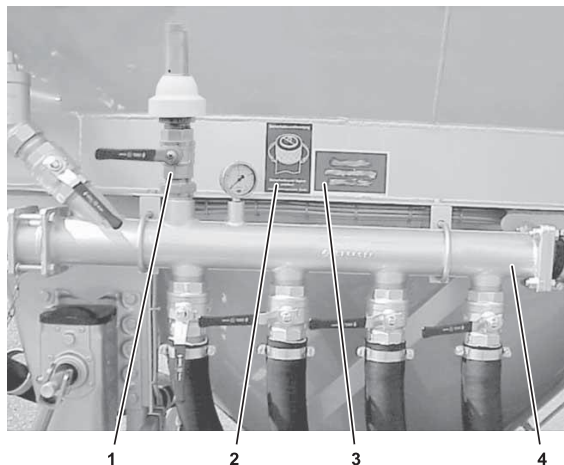

Illustration 6.4 Connectible safety valve (optional equipment)

1 Connectable safety valve
2 Adhesive sign "Safety valve maintenance"
3 Adhesive sign "Compressed air supply max. 2.00 bar"
4 Air manifold

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IV

Appendix D: Instruction Manual, Pinch Valve

6.10 Central material line and material discharge

Illustration 6.18 Central material line

1 Central material line

2 Non-return valve

3 Hose for control air of pinch valve

4 Shut-off valve in the material line (pinch valve)

The central material line goes from the individual discharges of the silo tank to the material coupling from which the load is being discharged. The lines of the individual chambers or discharges join into one line.

It is possible that the material lines do not merge into a manifold, but are led out individually to the side of the silo vehicle. In such a case, the material hose must be connected to the material coupling of the outlet to be discharged.

Shut-off valves (ball valves, butterfly valves, pinch valves) can be fitted in the line sections of the central material line. With these shut off controls, you can decide which chamber or discharge vessel is to be discharged.

Like the drop bottoms, the mechanical butterfly valves can be activated with a lever via a Cardan shaft, which is led out to the side of the silo tank.

Material discharge and material hose

The central material line (1) ends at material discharge. The material hose for transferring the load can be connected to this. Before discharging, open the material outlet using the butterfly valve and close it again after discharging the tank.

The material hoses supplied by Feldbinder are made of a conductive material and meet the safety standards concerning potential equalisation.

You can control the discharge process using the stop valves on the air manifold. In doing so, also use injected air via the ring nozzle, see also „Discharging with compressed air" on page 150. Never use the butterfly valve in the material line to control the discharging of the silo tank.

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V

A sight glass can be fixed in front of the material discharge. This allows you to check whether the load is flowing smoothly.
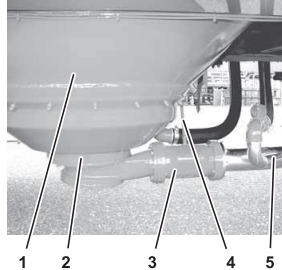
Illustration 6.19 Pinch valve in manifold

1   Material discharge (cone)

2   Discharge vessel

3   Pinch valve

4   Control line for pinch valve

5   Central material line with injected air supply

When the material line is fitted with pinch valves (3), its proper function is guaranteed only if sufficient pressure is built up in the tank for operating air. The control air is fed to the pinch valve via the control line (4). In case of pressure failure, the pinch valve can still be opened.

The control of the pinch valves is carried out via valves (1) and (2) shown in illustration 6.20 which are located on a special panel. For more information on the operation, see section „Discharging with compressed air" on page 150.

Illustration 6.20 Pinch valve control, example of a two-chamber silo tank

1   Control valve of the rear pinch valve (open/close)

2   Control valve of the front pinch valve (open/close)

In current vehicles, the switch positions for "open" and "close" are marked with the following pictogram:

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VI

Appendix E: Exchange rate; Norske Bank

VALUTAKURS FOR EURO (EUR)
NOK PR. 1 EUR

Oppdatert: 22. april 14:33

VELG VALUTA

EURO (EUR) - 9,2443

22. APR	21. APR	SISTE MND
9,2443	9,2015	

Skriv inn beløp:

1 EUR = **9,24** NOK *

Appendix F: Decision Logic form

Decide Maintenancetype and Interval														
Department:								Number:		Maintenance unit:				
Failure mode	Decision Logic							Maintenance activity description		O/S	Int	U	Sparepart(s)	Availability	C
	1	2	3	4	5	6	Code								
Comment:															

Appendix G: OREDA data

The OREDA project was founded in 1981. The main object of the OREDA project is to improve safety and cost-effectiveness in design and operation of oil and gas exploration and production rigs. This is done by collecting maintenance and operational data, and by exchanging reliability, availability, maintenance and safety data between the companies.

Many companies went together to make this database. We have used data from OREDA 4th Edition (2002) and the participating company are: ENI/AGIP, BP, ExxonMobile, Norsk Hydro, Phillips Petroleum Norway, Statoil, Shell and TotalFinaElf.

How we used the OREDA data

We have chosen to use the upper value of the failure rate data. This is mainly due to the oxide in the system, this white powder (oxide) is very fine and has a grinding effect on the internal of the tanker. And since it is so fine, it will find small cracks in the equipment and stay there to cause problems operating the equipment later on.

Why we chose OREDA data

OREDA data is from the offshore sector and therefore all the data is taken in this climate. And this environment is not exactly the same as the environment at Hydro Karmøy, but since we lack data from the producer/manufacturer of the equipment, we have in collaboration with Leif Tore Larsen chosen to go for OREDA data. The tools we use will still work if producer/manufacturer provides reliability data.

Following explanations are gathered from OREDA handbook

Taxonomy number and item

The taxonomy number is an identification of the item.

Population

Total number of items in this database

Installations

Total number of platforms covered by the data.

Aggregated time in service

Calendar time and operational time are presented as the basis for failure rate estimates. Note that the operational time in many cases are based on estimates by the collector, while calendar time is given with high certainty.

Number of demands

The accumulated number of demands for the total population is given when available. In most cases these numbers are estimates and not accurate measurements.

Failure mode

Description of different failure modes.

Number of failures

Total number of failures.

Failure rates

The failure rate columns present estimates of the failure rate for each failure mode. The following entries are included:

Mean: An estimate of the average failure rate of the specified failure mode, obtained by using the OREDA estimator

Lower,Upper: A 90% uncertainty interval for the failure rate

SD: A standard deviation indicating the variation between the multiple samples.

n/t: The total number of failures divided by the total time in service.

All the entries are measured per 10^6 hours and refer either to calendar time* or operational time †

Active repair time (hours)

This column contains the average calendar time (hours) required to repair and return the item to a state where it is ready to resume its functions. Active repair time is the time when actual repair work is done. It doesn't include time to shut down the unit, wait for spare parts, start-up after repair etc.

Repair (manhours)

The repair column presents three values of the repair time. The mean value is the average number of man-hours recorded to repair the failure and restore the function. The min and max values are the lowest and highest number of man-hours for the repair of the item.

Comments

When available the failure probability is given in the comment section.

## Appendix H: OREDA data; Safety valve

Merknad [kH3]: Snu denne

Taxononomy no	4.3.7	Item				Control and Safety
		Equipment			Valves	
		PSV - Conventional				

Population 170	Installations 2	Aggregated time in service (10^6 hours)				No of demands
		Calendar time *	5.1485	Operational time†	4.8847	

Failure mode	No of failures	Failure rate (per 10^6 hours)					Active rep.hrs	Repair (manhours)		
		Lower	Mean	Upper	SD	n/τ		Min	Mean	Max
Critical	**23***	**0,42**	**3,84**	**10,15**	**3,21**	**4,47**	**6,3**	**5,0**	**6,3**	**11,0**
	23†	**0,45**	**4,05**	**10,70**	**3,39**	**4,71**				
Fail to close on demand	3*	0,09	0,57	1,38	0,42	0,58	6,0	6,0	6,0	6,0
	3†	0,10	0,60	1,46	0,44	0,61				
Fail to open on demand	14*	0,32	2,46	6,29	1,96	2,72	6,5	5,0	6,5	11,0
	14†	0,33	2,59	6,63	2,06	2,87				
Valve leakage in closed position	6*	0,17	1,11	2,74	0,84	1,17	6,0	6,0	6,0	6,0
	6†	0,18	1,17	2,89	0,88	1,23				
Degraded	**65***	**7,43**	**11,94**	**17,31**	**3,03**	**12,63**	**6,6**	**4,0**	**6,6**	**16,0**
	65†	**7,80**	**12,57**	**18,27**	**3,21**	**13,31**				
Spurious operation	65*	7,43	11,94	17,31	3,03	12,63	6,6	4,0	6,6	16,0
	65†	7,80	12,57	18,27	3,21	13,31				
Incipient	**99†**	**4,11**	**15,29**	**32,29**	**8,93**	**19,23**	**6,6**	**2,0**	**6,6**	**14,0**
	99*	**4,32**	**16,11**	**34,04**	**9,42**	**20,57**				
Valve leakage in closed position	99†	4,11	15,29	32,29	8,93	19,23	6,6	2,0	6,6	14,0
	99*	4,32	16,11	34,04	9,42	20,27				
All modes	**187†**	**2,06**	**23,99**	**66,77**	**21,72**	**36,32**	**6,5**	**2,0**	**6,5**	**16,0**
	187*	**2,17**	**25,28**	**70,38**	**22,90**	**38,28**				

HØGSKOLEN STORD/HAUGESUND

Availability increase: A model in maintenance optimization for spare parts at Hydro Karmøy

HYDRO

Appendix I: OREDA data; Pinch valve

Taxononomy no	4.4.11	Item						Control and Safety Equipment
		Valves						Shut-Off
Population 67	**Installations** 5	Aggregated time in service (10^6 hours)					**No of demands**	
		Calendar time *	1.3664		Operational time†	1.3404		

Failure mode	No of failures	Failure rate (per 10^6 hours)					Active rep.hrs	Repair (manhours)		
		Lower	Mean	Upper	SD	n/τ		Min	Mean	Max
Critical	**11***	**3,86**	**7,34**	**11,74**	**2,43**	**8,05**	**14,0**	**2,0**	**14,5**	**37,0**
	11†	**3,93**	**7,49**	**11,96**	**2,47**	**8,21**				
Fail to close on demand	6*	0,35	3,54	9,62	3,09	4,39	14,2	2,0	13,2	37,0
	6†	0,36	3,61	9,80	3,15	4,48				
Fail to open on demand	5*	0,29	3,06	8,36	2,69	3,66	13,8	10,0	16,2	26,0
	5†	0,30	3,12	8,49	2,73	3,73				
Degraded	**18***	**0,39**	**19,70**	**61,13**	**21,63**	**13,17**	**24,0**	**2,0**	**13,6**	**70,0**
	18†	**0,40**	**20,38**	**63,26**	**22,39**	**13,43**				
Abnormal instrument reading	1*	0,01	0,94	3,12	1,14	0,73	-	6,0	6,0	6,0
	1†	0,01	0,95	3,07	1,11	0,75				
External leakage - Process medium	2*	0,00	4,04	17,18	6,62	1,46	-	2,0	2,0	2,0
	2†	0,00	4,21	17,80	6,84	1,49				
External leakage - Utility medium	5*	0,29	3,06	8,36	2,69	3,66	27,3	7,0	22,5	62,0
	5†	0,30	3,12	8,49	2,73	3,73				
Internal leakage	2*	0,01	1,47	5,58	2,06	1,46	12,0	4,0	9,5	15,0
	2†	0,01	1,49	5,58	2,06	1,49				
Other	4*	0,01	8,58	35,97	13,76	2,93	-	2,0	2,0	2,0
	4†	0,01	8,96	37,28	14,21	2,98				
Spurious operation	1*	0,01	0,63	2,02	0,73	0,73	14,0	14,0	14,0	14,0
	1†	0,01	0,64	2,06	0,75	0,75				
Structural deficiency	1*	0,00	1,78	7,79	3,04	0,73	-	6,0	6,0	6,0
	1*	0,00	1,85	8,08	3,15	0,75				
Unknown	1†	0,01	0,63	2,02	0,73	0,73	2,0	2,0	2,0	2,0
	1*	0,01	0,64	2,06	0,75	0,75				
Valve leakage in closed position	1†	0,01	0,63	2,02	0,73	0,73	58,0	70,0	70,0	70,0
	1*	0,01	0,64	2,06	0,75	0,75				
Incipient	**7†**	**0,82**	**3,97**	**9,07**	**2,64**	**5,12**	**7,3**	**2,0**	**7,3**	**29,0**
	7*	**0,76**	**4,02**	**9,38**	**2,77**	**5,22**				
Abnormal instrument reading	7†	0,82	3,97	9,07	2,64	5,12	7,3	2,0	7,3	29,0
	7*	0,76	4,02	9,38	2,77	5,22				
Unknown	**2†**	**0,09**	**1,22**	**3,46**	**1,14**	**1,46**	**40,0**	**51,0**	**57,5**	**64,0**
	2*	**0,09**	**1,24**	**3,54**	**1,16**	**1,49**				
Unknown	2†	0,09	1,22	3,46	1,14	1,46	40,0	51,0	57,5	64,0
	2*	0,09	1,24	3,54	1,16	1,49				
All modes	**38†**	**3,60**	**26,65**	**67,54**	**20,93**	**27,81**	**17,0**	**2,0**	**15,1**	**70,0**
	38*	**3,54**	**27,39**	**70,00**	**21,78**	**28,35**				

Appendix F: Boundary valve

This simple drawing shows the boundaries for the OREDA data.
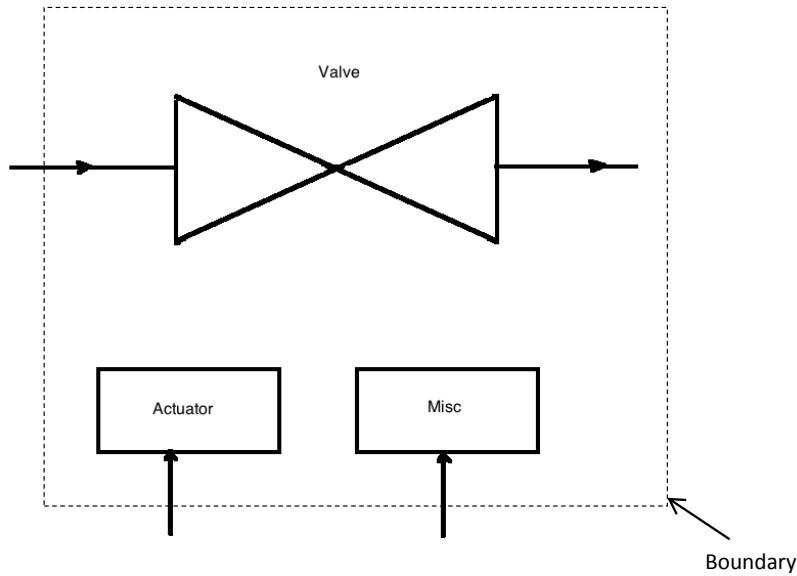
Equipment unit	Valve			
Subunit	**Actuator**	**Pipe**	**Valve**	**Miscellaneous**
Maintainable items	Spring Seals Case	Fitting Flange Header Fastener/bolts	Valve body Valve seals	Other