A RCM program for the filtration plant and investigation of bearing failure at Elkem Bremanger

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Norsk tittel: Utføre en RCM analyse for vedlikehold av filter anlegget og utforske lager havari hos Elkem Bremanger

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Preface

This thesis is part of the department of Mechanical and Marine Engineering bachelor at the western Norway University of Applied Sciences in Bergen, Norway. The report is a completion of our bachelor's degree in industrial engineering.

The thesis was given by Elkem Bremanger and written in collaboration with them, the report has been based on disciplines that we have faced during this bachelordegree. A special thanks goes to Johnny Røys, Operation and maintenance manager at Elkem Bremanger. We are thankful for the collaboration, the material that has been provided, guidance and the opportunity to visit and work at Elkem's plant. Otherwise, we would like to thank the mechanics and operators at Elkem's filtration plant for discussions and sharing their knowledge with us.

We would also like to thank our Internal supervisor, Prof. Dr. Maneesh Singh for all the guidance he as provided us during our work with this thesis, for sharing his knowledge and discussions regarding the RCM process.

Abstract

The Bachelor thesis focuses on maintenance and how RCM can contribute to reliable and efficient maintenance. The thesis is written for Elkem Bremanger with focus on their filtration plant. Elkem Bremanger is a metalwork that manufactures, processes, and distributes silicon products. In the production of silicon, the process of filtrating the exhausts is an essential part of the production. Therefore, it was desirable for Elkem to optimize their maintenance program for the plant, simultaneously there was an interest in doing a deeper study in a repeated bearing failure.

The report starts with a review of general maintenance, followed by a theoretical introduction of RCM. Through a detailed study of the plant, its processes and equipment, enough knowledge was acquired to perform a RCM analysis. With this the steps in the RCM were reviewed, where the function failures, failure mode, FMECA and analysis of the proposed maintenance tasks were the focus. The goal of the analysis was to be able to draw up a maintenance plan that could reduce the likelihood of the failure modes or the effect of the consequence.

Hopefully, the company and plant will benefit from the maintenance plan that has now been prepared in this report. The report is a good basis for further work especially regarding data collection and how this data can be used in the future, where it will contribute to a better analysis.

Following the presentation of the maintenance plan, theory, technical information, and the actual problem that is faced with frequent bearing failures is presented. The data is then reviewed, and an FMECA and RCA was carried out with the focus on pollution as the cause. Due to lack of data, a subjective approach was used. And on this basis, it is concluded that contamination is the main cause of the bearing failures.

The report is then summarized with a review and discussion of challenges and issues that arose during the assignment. It also discusses the possible improvements and measures that can contribute to a better result of the bachelor thesis and future projects.

Sammendrag

Bacheloroppgaven dreier seg om vedlikehold hvor fokuset er på RCM og hvordan dette kan bidra til et pålitelig og effektivt vedlikehold. Oppgaven er skrevet for Elkem Bremanger og omhandler deres filtrerings anlegg. Elkem Bremanger er et metallverk som produserer, foredler og distribuerer silisium produkter. Ved produksjon av silisium er anlegget som renser avgassene en vesentlig del av prosessen. For Elkem var det derfor ønskelig å optimalisere vedlikeholdsprogrammet til anlegget, samtidig som det ble gjort en dypere undersøkelse i et gjentatt lagerhavari.

Rapporten starter med en gjennomgang av generelt vedlikehold etterfulgt av en teoretisk innføring av RCM. Gjennom en detaljert studie av anlegget, prosessene og utstyret ble det tilegnet nok kunnskap til å gjennomføre en RCM analyse. Med dette så ble stegene i RCM analysen gjennomgått hvor funksjons feiler, feil modus, FMECA og analyse av vedlikeholdsoppgaver var i fokus. Målet ved analysen var å kunne utarbeide en vedlikeholdsplan som kunne redusere sannsynligheten for feil eller konsekvensen av feilen.

Forhåpentligvis vil bedriften og anlegget få nytte av vedlikeholdsplanen som nå har blitt utarbeidet i denne rapporten. Anlegget har nå et godt grunnlag for videre arbeid spesielt med tanke på data innsamling og hvordan denne dataen kan bli brukt framover, der vil rapporten kunne bidra til en bedre analyse.

Etter fremleggelse av vedlikeholdsplanen, blir det så lagt fram teori, teknisk informasjon og selve problemstillingen man står over ved hyppige lager havari. Deretter blir dataen gjennomgått, og det blir utført en FMECA og RCA av lageret med hovedfokus på forurensing som årsak. På grunn av mangelfull data blir det brukt en subjektiv framgangsmåte og med dette som grunnlag blir det konkludert at forurensing er hovedårsaken til lager havariene.

Rapporten avrundes deretter med en gjennomgang og diskusjon om utfordringer og problemstillinger som har oppstått under prosjektet. Det blir også drøftet hvilke mulige forbedringer og tiltak som kan bedre resultatene i rapporten og framtidige prosjekter.

Table of contents

List of Figures

List of Tables

Definitions and Abbreviations

Likelihood - The probability of an event happening

Risk – The combination of the consequence of an event happening, and the likelihood of it happening.

Failure - ''termination of the ability of an item to perform a required function [1].''

Failure mode - ''A single event, which causes a functional failure [2].''

Criticality - ''numerical index of the severity of a failure or a fault combined with the probability or frequency of its occurrence [1].''

Overhaul - '' Comprehensive set of preventive maintenance actions carried out, in order to maintain the required level of performance of an item [1].''

Down time - ''time interval throughout which an item is in a down state [1].''

Item - ''part, component, device, subsystem, functional unit, equipment or system that can be indicidually described and considered [1].''

Reliability - ''Ability of an item to perform a required function under given conditions for a given time interval [1].''

Function – ''What the owner or user of a physical asset or system wants it to do [2].''

Functional failure - ''A state in which a physical asset or system is unable to perform a specific function to a desired level of performance [2].''

Failure effects - ''What happens when a failure mode occurs [2].''

Failure mechanism – ''physical, chemical or other processes which may lead or have led to failure [1].''

N/A – Abbrevation for not available

DE – Acronym for drive end

NDE – Acronym for non drive end

SOP – Standard operational procedure

RCM – Acronym for Reliability-centered maintenance.

FFA – Acronym for functional failure analysis.

MTTF – Acronym for mean time to failure.

MTTR – Acronym for mean time to repair.

MTBF – Acronym for mean time between failure.

FMECA – Acronym for failure mode, effects, and criticality analysis.

MSI – Acronym for maintenance significant item.

COF – Acronym for consequence of failure.

RPN – Acronym for risk priority number. RPN is a value of the product of severity, likelihood, and detection.

RPM – Acronym for revolutions per minute**.**

HS&E – Acronym for health, safety, and environment.

P&ID – Acronym for piping and instrumentation diagram.

1. Introduction

This chapter introduces the background of the thesis, the objective, information about Elkem, scope, limitations, and the structure of the thesis.

1.1 Background

Maintenance plans are often based on the manufacturers recomnendations and regulations, that also guide the overall industry [3]. This can resolve in companies doing to much maintenance, both by intervals and changing parts to frequently. On the other hand, when companies design and develop their own systems and process plants the outcome can be the opposite. Especially if there is put little time and resources in developing and overseeing the need for maintenance in their plant. The authors of this report are both students at Western Norway University of applied sciences Bergen, where both are studying Industrial engineering. In addition to this the authors have certificate of apprenticeship as industrial mechanics.

RCM is a maintenance philosophy that was developed and used in the aviation industry since the early 70s. It mainly focuses on the systems functions and aims for the equipment to continue “to do whatever its user want it do”, instead of focusing on its condition [4]. For this reason, RCM requires deep understanding of the system, its processes, and sub-processes and how each failure affect safety, environment, cost, and operations. With RCM focusing on cost effective maintenance, removing unnecessary maintenance actions [3], the safety and environmental integrity, and higher availability of the assets [4].

The smoke filtration plant at Elkem Bremanger has been chosen as the subject of this study because of its essential role in the metal industri. Due to strict regulation both internal and by the government failures of equipment in such a plant can result in considerable environmental incidents. Failures of a vast variety of equipment can also lead to economic losses, safety, and production.

1.2 Elkem ASA

Elkem was established in 1904 and has since become one of the world's leading companies in the production of metals and materials. Elkem's production chain ranges from raw materials such as quartz to silicon, to downstream silicon specialties, as well as special ferrosilicon alloys and carbon materials. Elkem is divided into four business areas: silicones, silicon materials, foundry products and carbon. Elkem has 27 production sites and a large network of sales offices and agents all over the world. Today, over 6,300 employees in Elkem provide a solid foundation for technology development, R&D activities and optimization [5].

1.3 Elkem Bremanger AS

Elkem Bremanger is a subsidiary of Elkem ASA, which is a world-leading company in the field of silicon technology. The foundry plant located in Svelgen in Bremanger municipality was started as an ironwork in 1928. Bremanger Smelteverk became part of Elkem when Christiania Spigerverk became part of the Elkem Group in 1972, and today they are named Elkem Bremanger. The main product for Elkem Bremanger is ferrosilicon and silicon metal, and they manufacture metallurgic silicon-based products for the world market. An example is Silgrain which is a unique product from their proprietary chemical purification technology, and it is used in in the electronic and solar industry. Elkem Bremanger consists of approximately 200 employees [6].

Figure 1. 1: Elkem Bremanger

1.4 Objective

Aim of the project is to develop RCM based maintenance program for the filtration plant at Elkem and investigate the cause of bearing failure at their paddle conveyor.

RCM aims to identify the failure modes that create a risk to the operation according to the operating context described from the company. This is established and mapped through the RCM steps, which in turn create the basis for selecting maintenance task that can reduce the likelihood of the failure occurring. Subsequently, proposed task will be recommended and adapted the company's current maintenance plan.

1.5 Scope and limitations

The plant filtrate particles in motion and with high temperatures, the aerodynamic and thermodynamic in this plant require more time to be studied and understood than available. Due to the limitations of resources and time, the analysis of the filtration plant will be limited to the process between the coarse separator and the redler, including both. It will focus mainly on the general mechanic functions and failure modes within these processes. The lack of quantitative data such as maintenance intervals, maintenance task and failures that are not specified and collected will also be a limitation for this thesis.

Especially since finding the cause of bearing failure at the paddle conveyor demands certain and specified data for the correct conclusion. Quantitative data that are missing and needed for this thesis will then be based on the opinions of the operators, experienced professionals at Elkem and the authors. This will be gathered through meetings and interviews between the authors and Elkem's professionals throughout this thesis.

1.6 Structure of the thesis

Chapter 2 is the theoretical background of this thesis, and it starts with an introduction to maintenance in general. Then a brief history of RCM will be presented followed by the RCM concept and philosophy. In Chapter 3, the authors will introduce the theoretically method and steps in the RCM, and how to implement this in practice. The data gathering, results and the final decision worksheet will be registered and presented in Chapter 4. In Chapter 5 the analysis regarding the bearing failure will be presented including technical information, procedures, the analysis itself and suggestions to the problem. The limitations and challenges faced in this thesis will be discussed in Chapter 6 as well as recommendations for further work. Then the conclusion will be presented in Chapter 7.

2 Maintenance theory

This chapter will work as an introduction to maintenance and its history. It will define different kinds of maintenance and the concept of reliability centered maintenance.

2.1 Introduction to maintenance

Maintenance is any action done to keep an asset in a condition that makes it perform as it is supposed to. The acceptable performance of a machine must be defined by its designed output, and how big of a deviation from this the management are willing to accept. To keep this at a satisfying level it must be performed maintenance tasks to keep the asset in good condition. Therefore, maintenance is key to keep any system operational. Literature on the subject has showed that historically businesses have not recognized maintenance as something that brings value to the company. Instead of maintaining the integrity of the assets, it has been normal to let assets fail and then use resources to fix or replace the given asset. Modern solutions have been focusing on increasing the performance and value of a system by carrying out maintenance tasks before failure to decrease or completely remove down time – and thereby make it valuable to carry out maintenance before failure [7].

Since businesses has started to value maintenance, it has become more usual to have a maintenance program for its systems. This is done to make sure that assets do not fail pre-maturely, avoid downtime for production or services and reduce costs. Even though the idea of maintenance is simple, there is several ways and tools to use when building a maintenance strategy. Maintenance can be divided in to the main categories: corrective maintenance, preventive maintenance and predictive maintenance [7].

2.2 Corrective maintenance

Corrective maintenance is when there is carried out a maintenance action right before or after an asset has failed. Also known as ‘’fix when broken’’. This has been the usual way of doing maintenance in many industries for decades. Today, this method is used more often when an asset has minor effects on the systems output or performance. It is also used when it is more cost efficient to fix or replace it once it has failed, than doing preventive or predictivemaintenance [7].

2.3 Preventive maintenance

Preventive maintenance is when there is a routine replacement or overhaul of assets with intervals based on running time or calendar time. The maintenance task should be carried out when interval says so, no matter what condition the asset is in. [7].

2.4 Predictive maintenance

Predictive maintenance is when maintenance is carried out based on the actual condition of the asset. The maintenance is carried out when there is a tell-tale about a failure that is evident and occuring. One can use human senses to look for tell-tales or analyse performance data. By using technology, one can monitor an assets condition by installing measuring instruments that gather data which again can be analysed to undestand the condition of the asset. Installation of sensors, doing analysis of oils, using acoustic or ultrasonic-sound tests etc. is rather expensive, and many companies does not have the resources dedicated to maintenance to use this strategy. A preventive maintenance task it is often based on time intervals, this can result in replacement or overhaul of a perfectly fine and functional asset. By doing this, time and resources are spent on unnecessary maintenance tasks. By using predictive maintenance there will only be carried out maintanance tasks when it is necessary. [7].

2.5 Reliability-centered maintenance

Reliability-centered maintenance (RCM) was originally developed by F.S. Nowlan and H.F. Heap and published by the U.S. Department of defence in 1978. The objective of the report was to increase the safety and reliability of the equipment within the commercial aviation industry. Since then, the RCM process defined by Nowlan and Heap has been revised and utilized in almost every industrialized country and in all kinds of industries [2].

RCM is a maintenance strategy which objective is to develop a program that maximizes the effects of maintenance actions whilst eliminating non-necessary actions. A RCM analysis focuses on how the different functions within a system or equipment can fail, and thereby analyzes and prioritizes them based on safety and economic reasoning. Instead of replacing or overhauling every part in a system set by a given time interval, a RCM program will focus on the functions necessary to keep the system operational. It is getting more desirable to use condition-based maintenance since it is one of the most effective ways of doing maintenance actions, the challenge is the high investment cost. With a base in a RCM analysis it is easier to see where it is worth to make an investment, and by this maximize the invested rescources.

According to JA1011 [2], there is no specific way on how to complete a RCM analysis. JA1011 describes the basic principles and the minimum criteria required to complete a RCM analysis. Following this, it is reasonable to claim that a RCM analysis is a tool rather than a fixed procedure on how to make a maintenance plan. The objective is to find the most cost-effective way of keeping the system running. A RCM analysis basically provides answers to the following seven questions[2].

1. What are the functions and associated desired standards of performance of the asset in its present operational context(functions)?
2. In what ways can it fail to fulfil its functions (functional failures)?
3. What causes each functional failure (failure modes)?
4. What happens when each failure occurs (failure effects)?
5. In what way does each failure matter (failure consequences)?

6. What should be done to predict or prevent each failure (proactive tasks and task intervals)?
7. What should be done if a suitable proactive task cannot be found (default actions)?

According to Rausand, a preventive maintenannce task is effective if it provides a reduced expected loss relatted to HS&E, production availability and/or material damage [3]. By using RCM there can be developed a maintenance program that is based on the arguments compiled by the analysis. The analysis will contain both qualitative arguments and quantitative data to find the best solutions. The maintenance program will focus on replacing or overhauling parts that are rated with a high criticality, instead of replacing every part of an equipment or system. In this way, material and personnel costs that occurs when replacing parts that are not likely to fail will be avoided. The goal of the analysis is not to eliminate all corrective maintenance actions, but to find which assets that are more cost efficient to run-to-failure instead of using resources on replacing or overhauling them. By doing this, the risk of having maintenance-induced failures will decrease. The objective is not to prevent all failures, but the ones that are critical and where it is cost efficent doing it. It is important to understand that a preventive maintenance program will never make up for a system or asset that have a poor design, inadequate build quality or bad maintenance practices [3].

3 Method

This chapter describes the theory and methodology used to analyse and find the results in the RCM analysis.

The RCM analysis will be based on the steps suggested by Rausand [3], but it will be adjusted for this thesis. Within each step of the RCM it will be used different sources to describe the approach that have been used. This has been done to adapt the analysis for Elkems situation.

1. Study preparation.
2. System selection and definition.
3. Functional failure analysis.
4. Data collection and analysis.
5. Failure mode effects and criticality analysis.
6. Critical failure mode selection,
7. RCM decision worksheet.

3.1 Study preparation

For the first step it will be established a study group that will have the responsibility to complete the RCM analysis. The group will decide what the objective should be, which system/equipment it should analyze and the limitations of the analysis. It is important that the group includes the company's legislative requirements, policies and acceptance criteria with respect to HS&E [3].

To make a thorough analysis it is important to gather as much information as possible about the system and equipments that is chosen. Documents or other information that describes how the system works or how it should perform is helpful to understand and define when it is not performing as it should. This can be anything from operating and maintenance manuals to piping and instrumentation diagrams(P&ID). If there is any information missing in form of documentation, it should not be used resources on creating them unless it is considered important for the outcome of the analysis [8].

3.2 System selection and definition

The system selected should always have the potential to improve and benefit from a maintenance program. Within this, it should be decided if it is necessary to look at the whole system, sub-system or a single equipment. It is possible to break any system down to a sub-system, sub-sub-systems and equipment. The lowest possible asset within a system will be an analysis item. An analysis item must have a minimum of one failure mode for it to be evaluated. This includes the supporting equipment to the analysis item – it is only needed to analyze the supporting equipment's failure causes that are related to the analysis items failure modes. When analyzing the items, it should be kept within the highest practical indenture level to reduce uncertainty around performance standards [3].

3.3 Functional failure analysis

In this step there will be a mapping of the different functions that can fail within the chosen system. The objective of this analysis is to expose and rate each functional failure, which will decide if it is necessary to undergo further analysis. These failures may lead to a complete performance loss or reduced to a level that is not acceptable. Every functional failure will be evaluated according to how critical it is regarding the four categories: safety of personell(S), environment(E), production availability(A) and material costs(C). The functional failures in this analysis will be based on the functions of each sub-system and the items related to them.[3].

The criticality will be rated as low, medium, or high. For a subject to undergo further analysis, a minimum of one of these four categories must be considered as medium or high criticality [3].

3.4 Data collection and analysis

All relevant data regarding maintenance, operations and performance should be gathered and sorted out during this step. By analysing the data and estimating mean time to failure(MTTF), mean time to repair(MTTR) and failure rate function, an understanding on how to optimize the time intervals between maintenance tasks will be established [3].

Historical data about failure, performance, maintenance, operating costs, performed maintenance, maintenance programs, consequences etc. are often registered and systemized by those who use the systems. If this data is inadequate, reaching out to external sources may be a possibility to get the necessary data to analyse the system. Examples of external sources can be vendors, manufacturers or users of similar systems [8].

3.5 FMECA

Failure mode, effects, and criticality analysis (FMECA) is a tool used to break down how a certain asset can fail and what the effects will be. There is no defined way of how to create a FMECA work sheet. Some work sheets might be very detailed in certain cases, and vice versa. The FMECA should be adapted to the system and data available. The objective is to find the different ways a MSI can fail, why it fails, what are the effects, what are the consequences of the effects, how critical it is and how often one should do a maintenance task to take care of the integrity of the assets [3].

The FMECA used in this report is based on the functional failures for each sub-system, not the failures of each item. Instead of looking at each item in the whole sub-system and analysing all the ways it can fail, it is focused on how it can fail and cause a functional failure for the sub-system. In this way, the focus of the analyzis will only be on the failures that will make an impact on the integrity of the sub-system and its ability to perform its intended function. By doing this, maintenance tasks of non-essential failures regarding the sub-systems performance and thus the systems performance, will not be included.

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:													
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				

Table 3. 1: Failure mode, effects, and criticality analysis

Item

This column will list the different MSI’s found in the critical item selection. Each item will be related to one or several of the sub-systems functional failures.

Functional failure

This column will list the different functional failures that were found in the functional failure analysis and rated as critical. It is important to understand that the functional failure is not the functional failure of the item, but it is the sub-systems loss of function when the item analysed has a failure mode.

Failure mode

The failure mode is directly linked to the item’s event when a failure occurs. This describes how the item might fail. All of the failure modes listed should result in a functional failure, or a reduction in performance for the sub-system, this is to avoid focusing on all of the possible ways the item can fail in insignificant ways.

Failure cause

The failure cause is related to the underlying reason why the failure mode most likely have happened. This can be due to circumstances surrounding design, use, installation, manufacturing, specification or maintenance induced failures [1].

COF

Consequence of failure is rated from 1 – 5, where 1 is the lowest and 5 is the highest, with respect to the categories safety of personell(S), environment(E), production availability(A) and material costs(C). In the FMECA the COF is related to the items and its failure modes, not the result of the functional failure.

	Criteria for environmental consequences			
	Environment	Air pollution	Sea pollution	Land pollution
5	Catastrophic	Great air pollution with long-lasting conseqeunces	Great sea pollution with long-lasting consequences	Fire in plant with long-lasting consequences
4	Extensive impact	Exhaust pollution >12 hours	Microsilica pollution < 10 ton	Small fire - great pollution of microsilica in surroundings
3	Major impact	Exhaust pollution >4 hours	Oil/fuel leakage	Release of microsilica/slurry
2	Serious impact	Sound pollution/gas leakage	Leakage of slurry	Leakage of corse particles in plant
1	Minor impact	negligible/short impact in air	negligible/short imapct at sea	negligible/short impact at land

Table 3. 2: COF environmental matrix

	Criteria for operational & economic consequences			
	Assets loss	Cost	Filtration plant	Unplanned down time
5	Total loss	> 1 mill NOK	Total stop in production ability, failed equipment	> 10 days
4	Extensive loss	500 000 - 1 mill NOK	Extensive damage to equipment and loss of production	2 - 10 days
3	Major loss	100 000 - 500 000 NOK	Loss of production availability	1 day
2	Serious loss	10 000 -100 000 NOK	Partially production loss	> 12 hours
1	Minor loss	< 10 000 NOK	Minor equipment damage	1 - 12 hours

Table 3. 3 COF production availability and cost matrix

Failure effects

The failure effects describe what happens within the system when a failure mode occurs.

Likelihood (Like.)

The likelihood is rated from 1 – 5, where 1 is the lowest and 5 is the highest. This is an indicator of how likely it is that a failure mode will happen based on the experience and history of Elkem.

	Likelihood class
5	Happens every week
4	Happens on a monthly basis
3	Experienced several times/year in this facility
2	Has happened in this facility
1	Not experienced in this facility

Table 3. 4: Likelihood matrix

Detection (Det.)

The detection is rated from 1 – 5, where 1 is the easies to detect and 5 is the hardest to detect. When failure with a high consequence occurs, it is critical to take into consideration how much time it takes to detect this failure. This is factored into the RPN.

	Detection
5	Not able to detect by inspection
4	Poor chance for detection by visual inspection
3	Failure can be detected by visual inspection
2	It is very likely to be detected soon after it occurs
1	Failure is momentarily detected when it occurs

Table 3. 5: Detection matrix

RPN

RPN (risk index scoring) is a value given the product of severity, likelihood, and detection.

Severity = Safety x Environment x Availability x Economic

RPN = Severity x Likelihood x Detection

						Likelihood class				
						1	2	3	4	5
		Safety	Environment	Production availability	Costs	Most unlikely	Unlikely	Likely	Very likely	Most likely
Consequence class	5	Multiple fatalities	Catastrophic	Total loss	> 1 mil NOK	5	10	15	20	25
	4	Fatality	Extensive impact	Extensive loss	500 000 - 1 mil NOK	4	8	12	16	20
	3	Repatriation	Major impact	Major loss	100 000 - 500 000 NOK	3	6	9	12	15
	2	Lost time	Serious impact	Serious loss	10 000 - 100 000 NOK	2	4	6	8	10
	1	No lost time	Minor impact	Minor loss	< 10 000 NOK	1	2	3	4	5

Table 3. 6: Risk matrix

3.6 Critical failure mode selection

In the RCM process assets need to be ranked or prioritized to find the significant items that should be further addressed in the analysis. There are different approaches of addressing the criticality of the items and how they are rated. When the significant items are ranked by importance the different failure modes for these items should also be ranked after its criticality. Items that end up being classified as significant items should be ranked in order of importance before the analysis of maintenance tasks is carried out. [4].

The analysis or ranking of these failure modes can be done in a quantitative or qualitative analysis. If there is enough data revolving the failure modes at hand a quantitative analysis should be performed. Data that are used in such an analysis should be revised and thoroughly checked by professionals with understanding of the equipment and the plants processes. Data collected over a long period of time with good specification will give a precise analysis. In such analysis where there is little or no data available a qualitative analysis could be carried out. This should also be carried out by professionals with knowledge regarding the equipment, processes, and the company’s standards. In these cases where you do not have data and information available, a qualitative method can be used to rank the equipment and assets.

RPN (risk index scoring) is a method for indexing severity, detection, and likelihood, in cases where there are little or no data, the rate of severity and the likelihood are often based on a subjective assessment. The RPN value consist of the product between severity, detection, and likelihood, where the severity value is the product between safety, environment, availability, and cost. In this thesis every failure mode in the FMECA will be assigned values for severity, likelihood, and detection, implemented in close cooperation with Elkem. The RPN will then be calculated and every failure mode will be given an RPN value and ranked from high to low [9].

The numbering of severity, likelihood and detection is done using parameters set by the authors of this thesis and professionals at Elkem. Adjusted to the plant, its processes and equipment these parameters will give a guideline on ranking each failure mode. When the analysis is completed the failure modes with the highest RNP value will be picked for further maintenance actions to reduce the risk. There should always be an RPN interval for deciding which RPN value is high enough for further actions. The severity of a failure mode should always remain constant whatever maintenance task is taken, when trying to reduce the risk through maintenance actions the focus should be on reducing the likelihood and detectability.

3.7 RCM decision worksheet

Based on the RPN value, the most critical failure modes will be chosen for further work to determine how maintenance should be performed. To find out what type of maintenance tasks, time intervals and who should preform it, the RCM II decision worksheet described by Moubray will be used [4].

RCM DECISION WORKSHEET	Plant: Elkem System: Filtration plant												
Item Failure mode	Consequence evaluation				H1 S1 O1 N1	H2 S2 O1 N2	H3 S3 O3 N3	Default action			Proposed task	Initial interval	Can be done by
	H	S	E	O				H4	H5	S4			

Table 3. 7: Maintenance decision worksheet

The worksheet is filled out using a diagram that is made up of simple questions that can only be answered yes or no. By using this diagram there will be developed a systematic approach that results in a recommendation on how to approach the various failure modes. The recommendation will lead to one of the previously described types of maintenance or a redesign of the equipment.

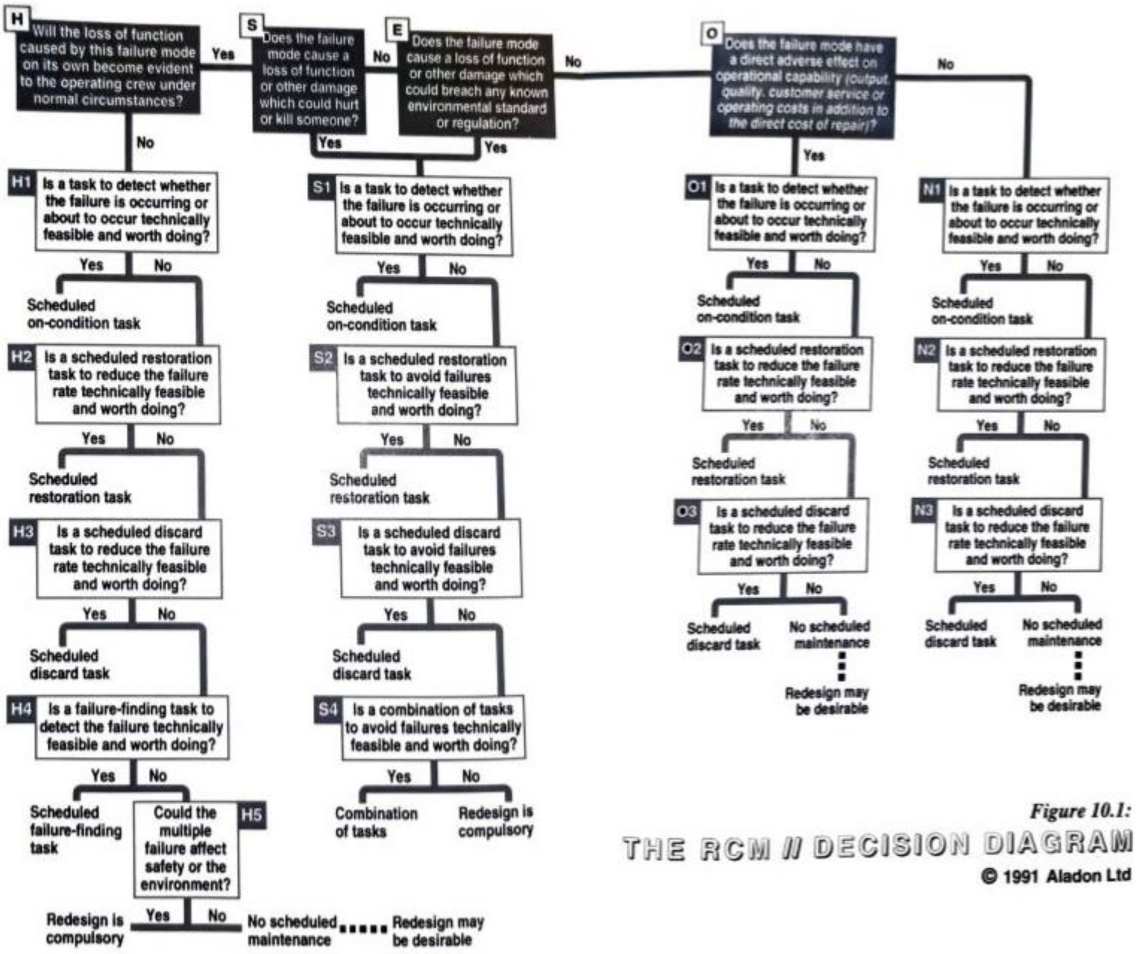


Figure 3. 1: Maintenance decision diagram [4]

When the diagram has led to a recommendation, a proposed task is then described which is based on the method the diagram has recommended. This description should be detailed enough for the person performing the maintenance task to understand how to carry out the procedure, and that it is not open for interpretation. If the recommendation is a change of design, it should describe how todays design are causing challenges [4].

Example of non-sufficient detailed description: Check the coupling.

Example of sufficiently detailed description: Check that the bolts on the coupling are tight.

The maintenance tasks can be done by anyone who has the competence and confidence to carry out the proposed task. It is not necessary to allocate over-competent personnel to carry out tasks where there is no need for it [4].

3.7.1 Theory and definitions for decision diagram

In this chapter it will be explained how to implement the decision worksheet and diagram in practice.

When analysing the sub-systems and items it is desirable to end up with a proactive maintenance task that can be carried out to increase the assets integrity. Moubray uses the terms scheduled restoration, scheduled discard, and on-condition tasks within proactive maintenance. For the task to be carried out it must be technically feasible and be worth doing. If there is no proactive task to be found, or it is not regarded as worth doing or technically feasible, a default action must take place [4].

Scheduled restoration tasks (proactive)

A scheduled restoration task is a restoration action of a component, item, or sub-system right before its running time reaches the pre-determined age limit. The restoration should be done no matter what condition the given asset is in when the running time reaches its limit [4].

When setting the time interval, one should use reliable historical data to decide how long it should take between restorations. Data might not always be available and the use of models that predicts its deterioration patterns as well as qualitative arguments have to be used [4].

For a scheduled restoration task to be rated as technically feasible the item must at one point show a rapid increase in the conditional probability of failure. Most items must survive to this point and the restoration resets the items resistance to failure. If the failure of an asset has environmental or safety consequences the asset must maintain its integrity longer than the restoration interval to avoid unwanted environmental or health and safety consequences [4].

The downside of using a scheduled restoration approach is that there often will be a restoration long before the asset needs a restoration. Because of this it is important to consider if the costs of replacing the asset with a given interval is cheaper than letting the asset run to failure. If this is the case, it is more reasonable to let it run to failure. This can only be done if there is no substantial environmental or health and safety consequences of the failure. Scheduled restorations will often lead to downtime and stop in the operation, unless there is an alternative asset or system that can keep the operation going. Most systems does not run around the clock and there will be natural openings to do the task, but if the operation have to stop it must be taken in to consideration if the costs of production loss is worth it [4].

Scheduled discard tasks (proactive)

A scheduled discard task is a complete replacement of a component, item, or sub-system right before its running time reaches a pre-determined age limit. The task should be done no matter what condition the given asset is in when the age limit reaches its end. The method and arguments are basically the same for discards tasks and restoration tasks, considering technically feasibility [4].

Deciding the age-limit is done using the same method as for the scheduled restoration tasks. Implementation must be relevant to the health and safety consequences that are related to the failure analysed. If there is a health and safety consequence, one should set the interval based on what Moubray defines as Safe-life limits. This limit should prevent all failures. Naturally, this method excludes all assets that has a probability of failure due to infant mortality [4].

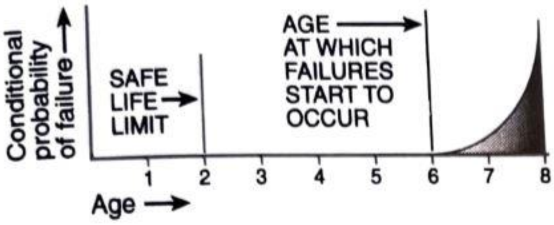


Figure 3. 2: Safe-life limit model [4]

If there is no health and safety consequences to consider, it will be more relevant to think of the discard as an economic-life limit. The age-limit will then be based on what will be the most cost-effective. By using deterioration patterns and historical data it is possible to set a reasonable age-limit for the asset. Costs of operational downtime during the discard task must be more reasonable than the costs of a run to failure [4].

On-condition tasks (proactive)

An on-condition maintenance task is based on a tell-tale that a failure is occurring or that it is about to occur. This makes it possible to carry out maintenance on assets that is deteriorating instead of just assuming that it is deteriorating because of its age. The graph in figure 3.4 shows the condition of an asset over time. Point P is where it is possible to detect a failure occurring, this point is dependent on what kind of techniques used to detect tell-tales and what kind of asset it is [4].

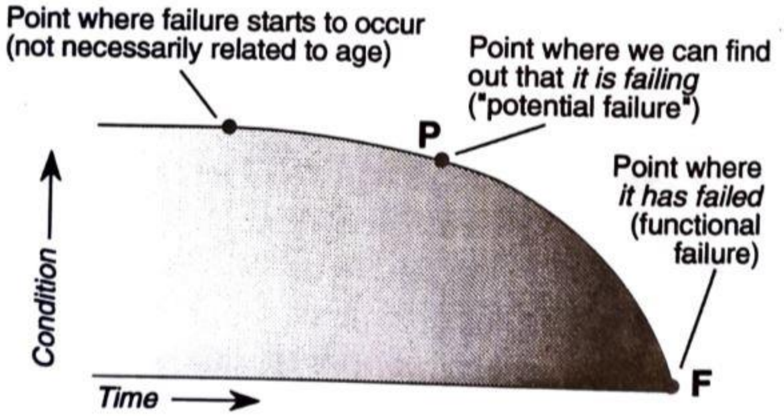


Figure 3. 3: Failure curve with a tell-tale(P) [4]

For on-condition maintenance to work, there must be a tell-tale and an inspection interval that is set regarding to a few important factors. If the inspection interval is to short, there will be a use of resources on inspection that is not necessary. If the inspection interval is too long, it is possible that the tell-tale has developed into a failure between inspections. Therefore, the inspection interval is key to success. It will be important to use data, models, or experience to determine how much time, or stress, there will be on an asset from the tell-tale to failure. When the P-F interval is assumed, the inspection interval should be determined based on this. Then it should be adjusted according to how much time is needed to complete the maintenance task. The Nett P-F interval is the time between actual detection of the tell-tale to failure. If the Nett P-F interval is to short, there will not be enough time from inspection to failure to carry out the necessary maintenance task. If the maintenance task needs the operation to shut down it should be considered shortening the inspection interval. There should be enough time to discover the tell-tale, as well as implementing the maintenance tasks. This is to avoid stopping the operation and lose production availability. This is only necessary if an unwanted stop in operation is more expensive or dangerous than keeping the operation running with an asset that does not perform as it should. It is also important to remember that a failure seldom has a set P-F interval. This can differentiate by large amounts of time, and the time interval should be set to the shorter ones instead of the long ones [4].

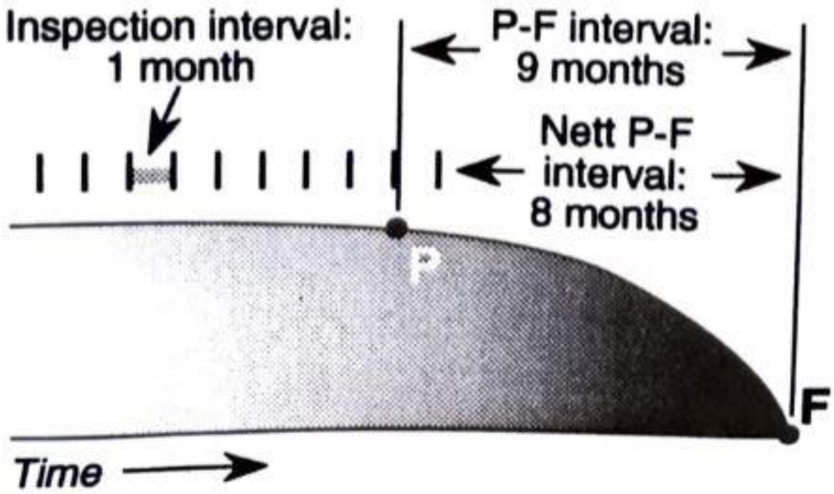


Figure 3. 4: P-F interval [4]

According to Moubray [4], these are the four arguments for an on-conditional task to be technically feasible:

- It is possible to define a clear potential failure condition
- The P-F interval is reasonably consistent
- It is practical to monitor the item at intervals less than the P-F interval
- The Nett P-F interval is long enough to be of some use (in other words, long enough for action to be taken or reduce or eliminate the consequences of the functional failure)

The practical part of doing an inspection can be done in many ways. Moubray describes the four major categories as:

- Condition monitoring

Condition monitoring is the approach of using equipment that is meant to monitor the condition of the assets. This can be done by installing sensors that reveals change in vibrations, temperatures, particles etc. Using condition monitoring takes away the need for a physical inspection and gives very precise data to work with. Sensors work around the clock and makes it possible to reveal a potential failure as soon as there is a tell-tale. The cons of condition monitoring are the cost of installation, and that it can be more advanced than necessary [4].

- Variations in product quality

By setting a standard of what quality the manufactured goods should be, the end-product can be monitored and deviations that might indicate that your assets are starting to fail can be found [4].

- Primary effects monitoring

By monitoring the production numbers like speed, pressure, flow rate, temperatures, power, effect etc. deviations can be found. There must be a record of what different gauges should measure when performance is optimal, and how much of a deviation that is acceptable [4].

- Inspection based on the human senses

Inspection by humans have its pros and cons. The cons are that every experience is subjective and human errors can happen. The pros are that a person can reveal several symptoms at once, it is easy to implement, and it can be at a low cost. Humans are not as sensitive as a sensor, and it may lead to a shorter interval between detection and failure. Therefore, when using this method, it should be a shorter time between inspection intervals. A standardized way of carrying out the inspection and what to look for should be made to minimize human errors [4].

For an on-condition maintenance task to be worth doing the failure has to be evident. A hidden failure often has hidden function and hidden consequences. Which makes it hard to do inspections and to find the potential occurring failure. The exception is when a hidden failure has consequences that eventually evolve into a very critical consequence. If there is a significant health and safety consequence associated with the failure, condition-based maintenance should be used provided there is a safe period between detection of the occuring failure and the actual failure. Other than this, it must be more cost effective to carry out inspections and perform maintenance, than the cost of fixing the failure and the operating costs of the downtime [4].

No scheduled action (default action)

No scheduled maintenance is a strategy where the item runs to failure and then it is repaired or replaced. This is only done if there is a hidden failure where the result of the consequences does not affect the environment or health and safety. It should also be done when there are no cost-effective preventive maintenance tasks found for a failure [4].

Redesign (default action)

When implementing a maintenance-program, the last choice of actions is to redesign the system. A redesign is expensive, challenging and time consuming and there is no guaranty that there will be an increase in the systems integrity when completed. A redesign will only be recommended when there are no other maintenance tasks available or if there are failures that have environmental or health and safety consequences that can not be avoided by doing maintenance [4].

Failure finding task (default actions)

A failure finding task is used when there is a hidden failure that is not found. This is often used to check for hidden failures that does not have any noticeable consequences. Naturally, the consequences must be low enough to accept that the asset will be in a failed state for a given time. The task should not increase the risk of multiple failures and it has to be practical to carry out the task at the required intervals. A failure finding task is regarded as worth doing if it results in a lowered probability of failure of multiple failures [4].

4 Analysis

In this chapter all of the investigation and its results of the RCM analysis will be carried out.

4.1 Study preparation

The study group consist of the two authors of this thesis and the head supervisor of maintenance at Elkem Bremanger. Communication between the three parts has happened mostly by e-mail and phone calls due to its long distance between HVL and Elkem Bremanger. The two authors have also spent time at the process plant to get a better understanding of the system as well as meetings and discussions with personell working at Elkem Bremanger. To start the analysis, it was important to gather as much thecnical information as possible. Documents and other information that describes how the system works or how it should perform was important when starting the analysis.

Figure 4. 1: The filtration system seen from above

All information regarding the filtration process used in this bachelor thesis is explained by personell working at Elkem Bremanger. The operation and maintenance manager has provided the study group with information on the process, technical drawings, and data regarding maintenance history.

4.2 System selection and definition

In this chapter there will be a description of the system, the sub-systems and their items and the limitations.

4.2.1 The operating context

The facility addressed in this bachelor thesis is a filtration process plant at Elkem Bremanger. The plant consists of several processes which in turn have sub-processes. The various parts and equipment in this process are manufactured by different suppliers, but are assembled to suit the power, production and working environment of Elkem's furnaces.

According to Elkem Bremanger's department managers, the facility's functionality and specifications are specifically adapted to each of the furnaces. Therefore, in this bachelor thesis, the plant's process, sub-processes, and equipment have been carefully reviewed in collaboration with Elkem's department managers and operators.

4.2.2 The filtration process

The furnaces run continuously and so does the filtration plant. The smoke that is formed during the melting process has a temperature of about 400 degrees celsius when it leaves the furnace. When the smoke reaches the coarse separator, the temperature is about 200 degrees Celsius. Temperature plays a role in the wear and tear of the equipment in the plant, but so does the amount of smoke that continuously passes through the plant. According to Elkem Bremanger, between 35-60 tons of microsillica is produced every day.

The smoke filtration process consists of 3 filters that belong to each of the furnaces at Elkem Bremanger. Each filter is adapted to their respective furnace for capacity, but all filters have the same function.

Figure 4. 2 Sub-system – pipes & ducts

The transportation of smoke goes through pipes from the furnace up to the filter using centrifugal fans. Furnace 2 has two main fans, furnace 4 also has two main fans, while furnace 5 has three. All the fans are alike and has the same capacity.

When dust and gas arrive at the process plant, it enters two separation processes. In the first process, they separate the coarse particles through a coarse separator. The coarse particles consist of raw materials and particles that exceed 45 µm. This is categorized as waste and landfilled. Figure 4.3 shows the pipline leading into the coarse separator.

Figure 4. 3: Sub-system - coarse separator

The smoke will then be driven further into the filtration process by the main fans. There is one main fan per coarse separator. Figure 4.4 shows the main fan.

Figure 4. 4: Sub-system – main fan

The smoke then goes into the filters. The filters consist of a total of 12 chambers for furnace 5, 9 chambers for furnace 4 and 6 chambers for furnace 2, each chamber having 160 filter bags. Figure 4.5 shows the bottom of the chamber.

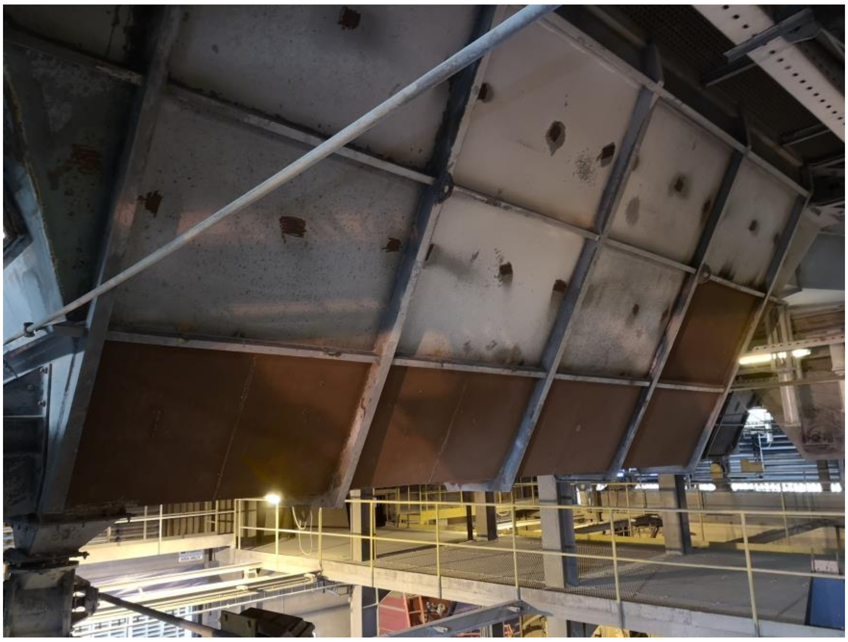


Figure 4. 5: Sub-system – filter

The process separates the microsillica from the gas, by pressing the gas through Gore-Tex filter bags. The gas will go trough the filter bags while the microsillica particles will get collected in the chambers. There will constantly be an overpressure inside the chambers produced by the fans which is essential for pressuring gas through the filter bags. When the 160 filter bags are getting clogged by microsillica the pressure inside the chamber will rise and the dampers leading gas inside the filter will close. When the filters are clogged, it creates a severe pressure on the Gore-Tex bags. In this stage the filter bags need cleaning which is done by creating a under pressure. When the inlet dampers are closed the dampers leading a under pressure stream is opened. The under pressure is created by the flush fan and leads the microsillica to fall out of the Gore-Tex bag and down in the chamber.

Figure 4. 6: Sub-system – flush fan

The microsillica is then transported by a paddle conveyor inside the bottom of the chamber and into a cell feeder. The cell feeder is driven by a chain connected to the paddle conveyor, which then feeds microsillica to the redler. The redler will convey microsillica to the dust sender that distribute microsillica for sale and further treatment of the product.

Figure 4. 7: Sub-system - redler

In principle, all systems and equipment can benefit from an RCM analysis [3]. However, when implementing the RCM to a plant, the process can be limited due to resources. Therefore, it is always crucial to decide which system and processes shall be prioritized. This filtration plant is a system with several underlying sub-systems. In this analysis it is chosen to analyze the complete system from the coarse separator to the redler. Even though the system includes several functions and items it is believed the result of the analysis will be best when the whole system is taken into consideration. Thus, the filtration system is divided into 6 different hierarchy considering their main functions in the plant.

When analyzing the complete filtration system, the function and performance expectations of each assembly are easier to assess, and the failure consequences are foreseeable. Therefore, the hierarchy will be separated into six different levels each focusing on the respective system as: Coarse separator, main fan, flush fan, filter, redler and the duct and pipes in the plant.

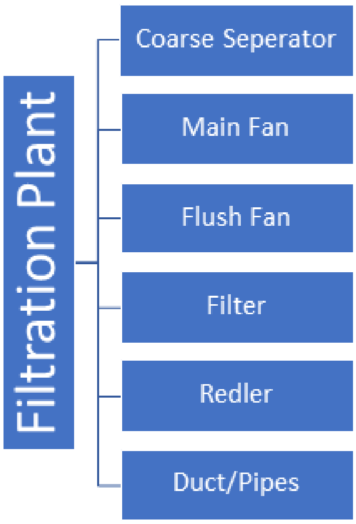


Figure 4. 8 Filtration system hierarchy

The identification of the primary and secondary functions together with the performance for each system will be the next step. This will provide the necessary framework for further analysis.

4.2.3 Identifications of system functions and items

The identification of how a system can fail is crucial for any RCM analysis, to be able to determine this the system function and expected performance must first be defined. Having determined which systems that are going to be analyzed, their primary and secondary functions have been defined as the following:

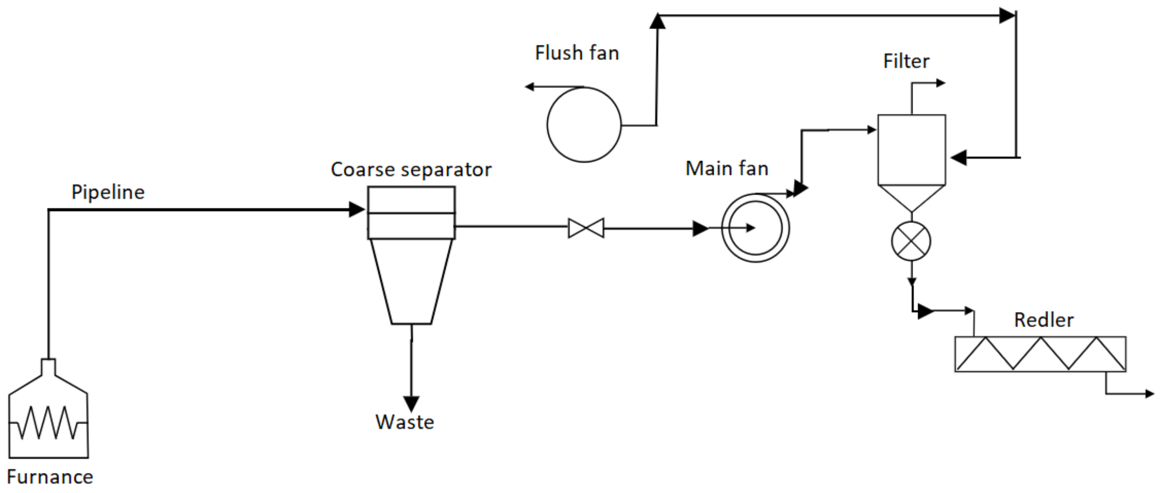


Figure 4. 9: Flowsheet of the filtration plant

Duct & Pipes

The sub-system that is considered duct/pipes is spread from the start of the process and all the way to the filter. The duct/pipes are the sub-system that connects all of the other sub-systems. Since it mostly consists of piping, and a few functional items, it is considered the most basic sub-system. In figure 4.10 the ducts and pipes have been marked in red. The figure shows how it connects the different sub-systems.

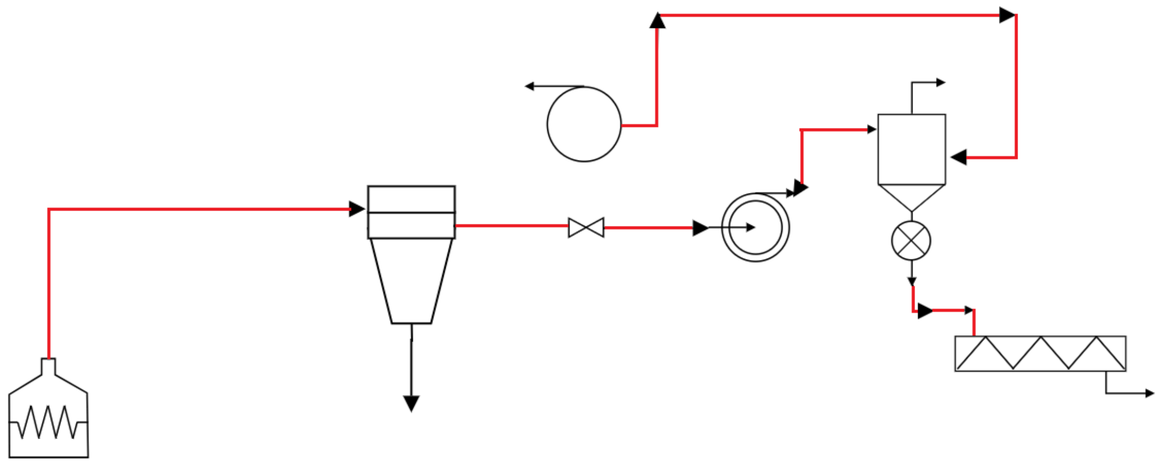


Figure 4. 10: Flowsheet ducts & pipes

The sub-systems functions:

1. Contain gas
2. Lead gasses from one system to the next

The functional failures:

1. Leakage
2. Flow restriction

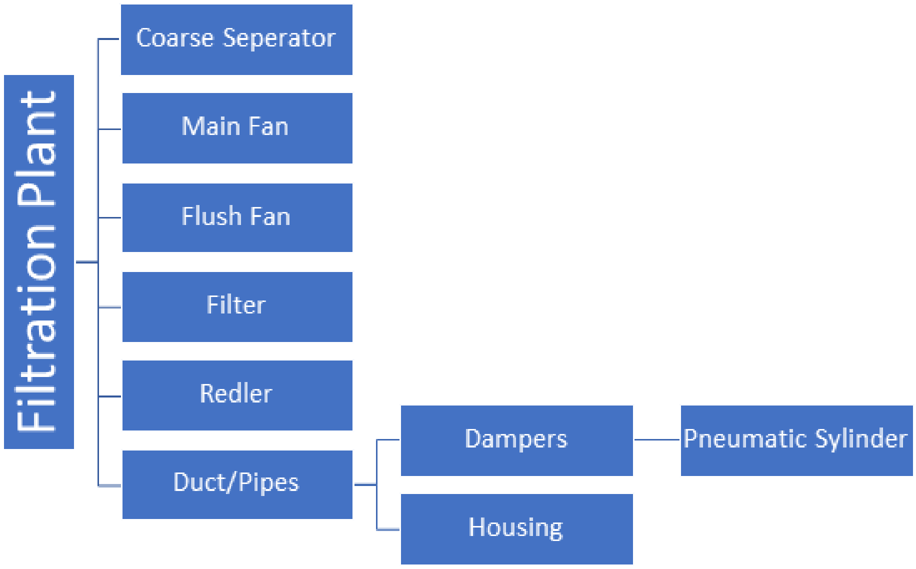


Figure 4. 11: Hierarchy ducts & pipes

Coarse separator

The coarse separator is the first process the exhaust gas will be subjected to. The coarse separator is not a very complex sub-system, but vital for the filtration process and the production of microsillica.

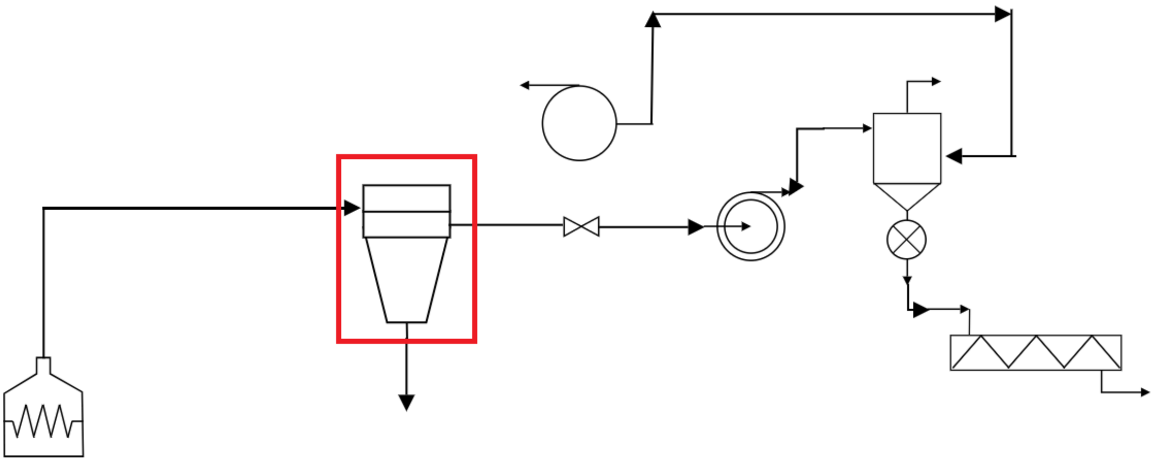


Figure 4. 12: Flowsheet coarse separator

The sub-systems functions:

1. To separate particles larger than 45
2. To contain all particles within the separator

The functional failures:

1. Fails to separate particles >45µm.
2. Leakage.

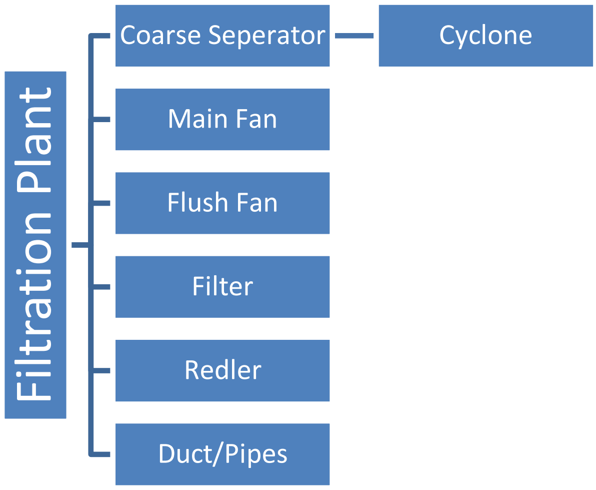


Figure 4. 13: Hierarchy coarse separator

Main fan

Without the main fan no smoke will be driven through the filtration plant, and the production of microsilica will not be possible. Even though it has only one primary functions, it is one of the more complex sub-systems due to its many items.

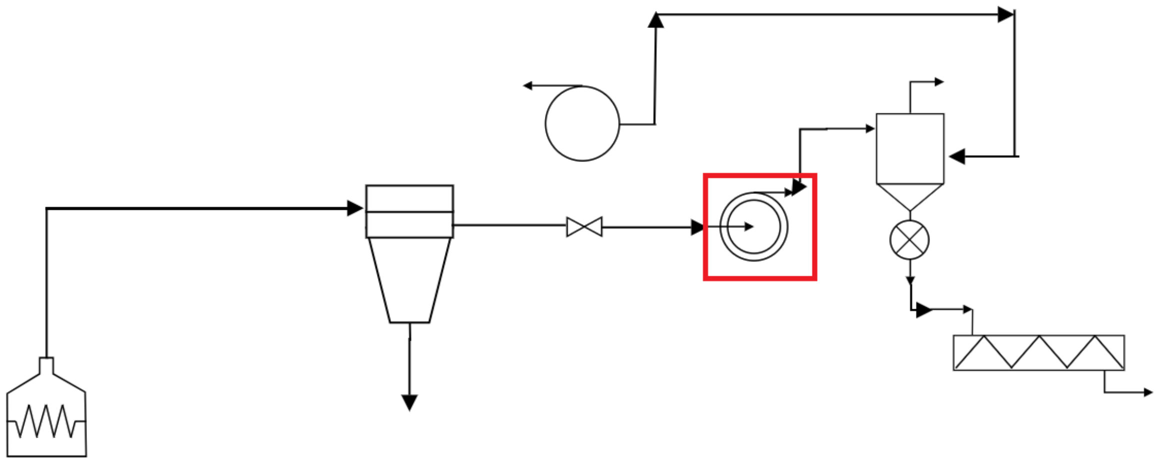


Figure 4. 14: Flowsheet main fan

The sub-systems functions:

1. To carry all gas and dust from the furnace to the filtration plant
2. Deliver pressure to the filters

The functional failure:

1. Fails to create suction/pressure

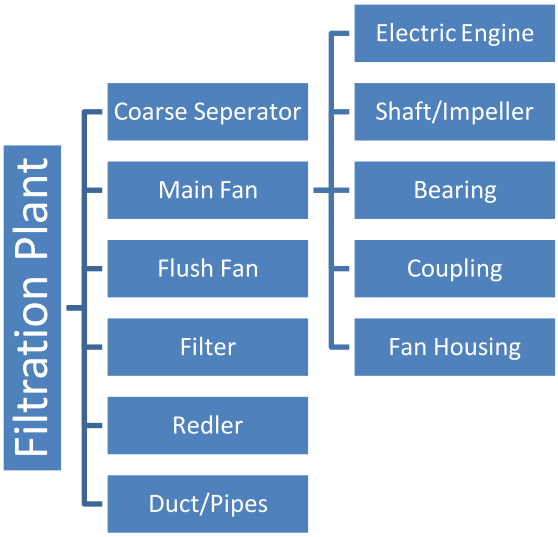


Figure 4. 15: Hierarchy main fan

Flush fan

The flush fan only has one function, to create an underpressure in the filter.

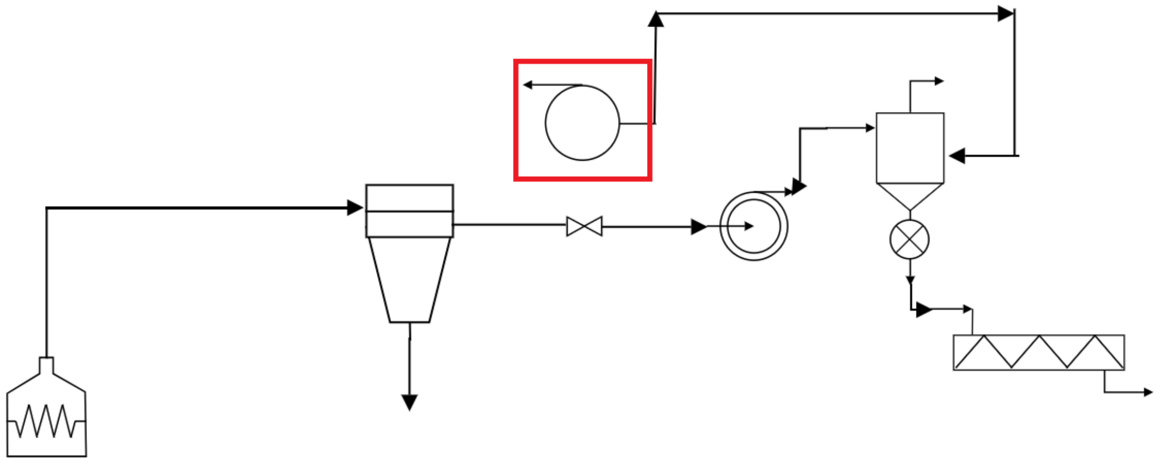


Figure 4. 16: Flowsheet flush fan

The sub-systems function:

1. To create under pressure inside the filter

Functional failure:

1. Fail to create suction

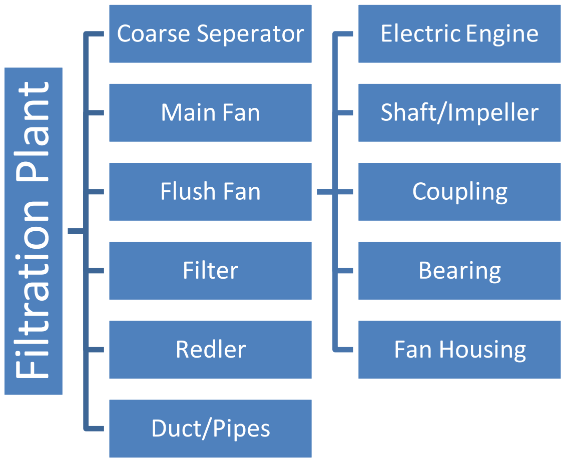


Figure 4. 17: Hierarchy flush fan

Filter

The filter is the most important sub-system regarding value adding processes. It has several parts and functions that are considered important. The filter is also subjected to a lot of maintenance tasks because of its many itmes and wear when processing microsillica.

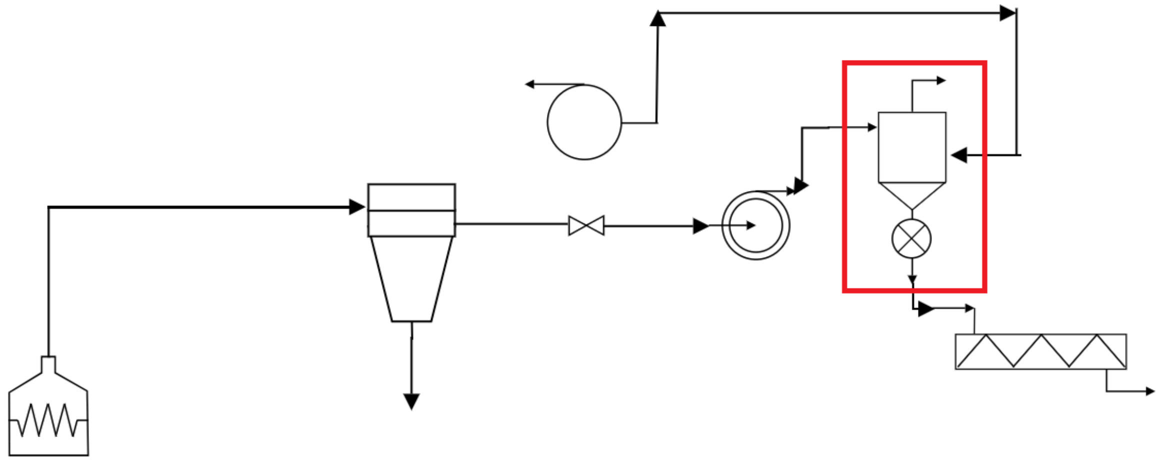


Figure 4. 18: Flowsheet filter

The sub-systems functions:

1. Filtrate the gas
2. Contain all the microsillica
3. Transport the microsillica to the redler

The functional failures:

1. Fails to filter
2. Leakage
3. Fails to convey microsilica

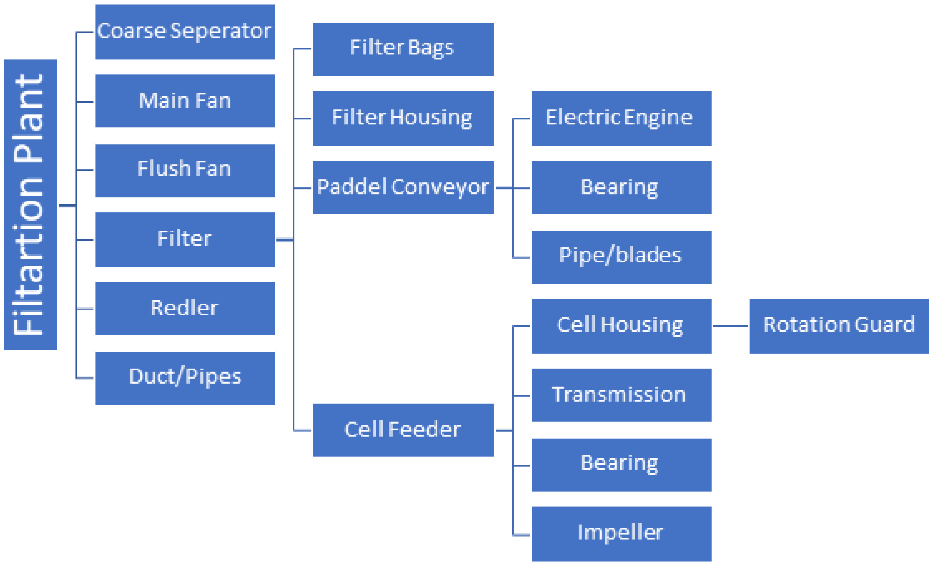


Figure 4. 19: Hierarchy filter

Redler

The redler transports the microsilica from the filter to further processing, and it is the last sub-system in our analysis.

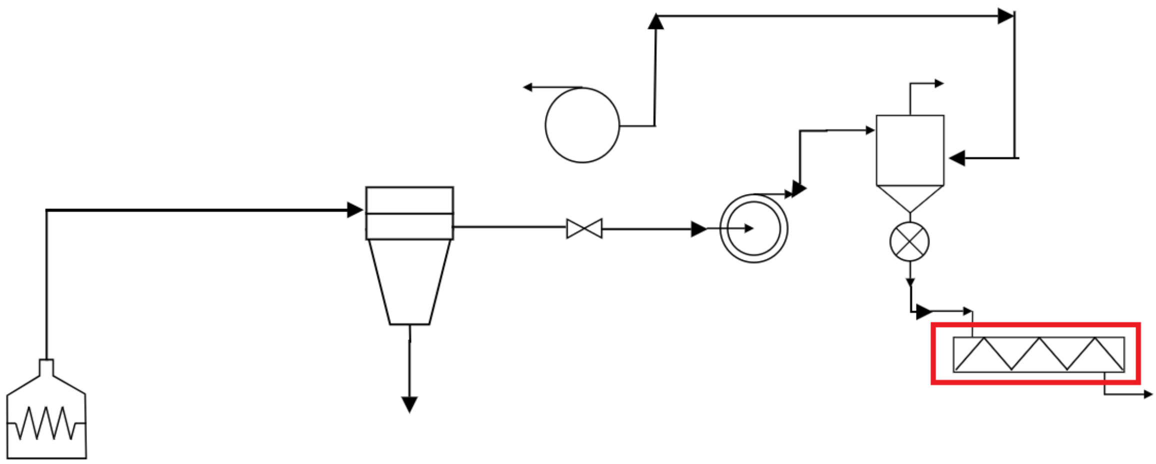


Figure 4. 20: Flowsheet redler

The sub-systems functions:

1. Transport the microsillica to the dust-sender
2. Contain the microsillica

The functional failures:

1. Fails to convey microsilica
2. Leakage

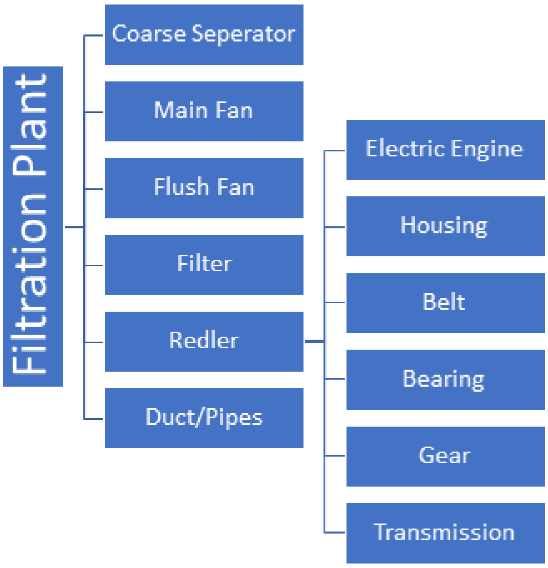


Figure 4. 21: Hierarchy redler

Further into this analysis both the system function, functional failures and failure modes will be recorded in the FFA and the FMECA worksheets

4.3 Functional Failure Analysis

The functional failure analysis has been carried out based on the functions necessary to filtrate microsilica from the gas, and the items that are related to the functions. The filtration process has been divided into six sub-systems. The process is not very complicated, and the system is built on very basic sub-sytems and items. The filtration plant has few primary functions, and thereby few functional failures. As shown in the table below, all of the functions and functional failures have been listed with a criticality rating regarding safety of personell(S), environmental impact(E), production availability(A) and costs (C).

Functional failure analysis				Criticality			
Sub-system	Sub-system functions	Sub-system functional failures	Items	S	E	A	C
Duct/pipes	Contain gas	Leakage	Pipe				
	Lead gas	Flow restriction	Pipe				
		Flow restriction	Dampers				
Coarse separator	Separate particles	Fails to separate particles >45µm	Cyclone				
	Contain gas	Leakage	Cyclone				
Main fan	Extract and carry smoke through plant Deliver pressure to filter	Fails to create suction/pressure	Electrical engine				
		Fails to create suction/pressure	Shaft/impeller				
		Fails to create suction/pressure	Bearing				
		Fails to create suction/pressure	Coupling				
		Leakage	Fan housing				
Flush fan	Create underpressure inside the filter	Fails to create suction	Electrical engine				
		Fails to create suction	Shaft/impeller				
		Fails to create suction	Coupling				
		Fails to create suction	Bearing				
		Leakage	Fan housing				
Filter	Filtrate the gas	Fails to filter	Filter bags				
	Contain all the microsilica	Leakage	Filter housing				
	Transport the microsilica to the redler	Fails to convey the microsilica	Electrical engine				
		Fails to convey the microsilica	Bearing				
		Fails to convey the microsilica	Pipe/blades				
		Fails to convey the microsilica	Cell housing				
		Fails to convey the microsilica	Bearing (cell feeder)				
		Fails to convey the microsilica	Transmission				
		Fails to convey the microsilica	Impeller				
Redler	Transport the microsilica	Fails to convey the microsilica	Electrical engine				
		Fails to convey the microsilica	Bearing				
		Fails to convey the microsilica	Belt				
		Fails to convey the microsilica	Transmission				
	Contain microsilica	Leakage	Housing				

Table 4. 1: Functional failure analysis

To undergo further analysis, at least one of the criticality factors must have been rated as medium or higher. All of the functional failures, except leakage fom the redler, is rated with a medium or higher criticality for atleast one of these factors. Due to this, all the sub-systems will be analysed further. Instead of looking at the functions, the focus will be on the functional failures found in this step.

4.4 Data collection and analysis

The data and information that are available for this analysis are technical drawings, data sheets, production data, maintenance history etc. In this chapter the maintenance history will be looked into. The objective is to get a better understanding of the maintenance action carried out in the filtration plant at Elkem Bremanger and use it in our analysis of the system.

Elkem Bremanger registers completed maintenance tasks and inspections in an excel sheet. In this excel sheet there is sixteen cloumns that is filled providing information on what sub-system the error regards, description of failure, maintenance reaction, dates, responsible person, work order number etc. Instead of using Elkems's worksheet, it has been created a new one to filter out unnecssary data like work project number, reported by (name), person responsible, equipment number, cost centre etc. All of the data was then sorted into different sheets regarding the equipment description. The equipment description is described by Elkem and is almost the same as the sub-systems described in this report. In the new sheet, there was added two new columns which is related to this report. The added columns are functional failures and failure mode. The reason for this is to relate the maintenance data to the functional failures and failure modes described in this report, and to use that information to calculate MTBF. Some of the information in the sheet is based on quantitative measurements from sensors, but this data is not directly registered in the sheet. This means that the maintenance data is based on qualitative observations reported by operators or supervisors.

3500031092	BR163000 - VDL EL Silgrai		20180527	20180531	BR282521	HOVEDVIFTE 1, OVN 5	282500	520 - KVU Corr unpl.m	90	No error/other needs	Hovudvifte 1 tippa	Justert trykk på smøre	BRESMY	BRETFL	1
3500031087	BR163000 - VDL EL Silgrai		20180526	20180531	BR282521	HOVEDVIFTE 1, OVN 5	282500	520 - KVU Corr unpl.m	90	No error/other needs	Vifte 1 tippa	Tippa på vibrasjon/ter	BRESMY	BRETFL	1
3500020607	BR260000 - VDL FeSi/Four		20170121	20170121	BR282521	HOVEDVIFTE 1, OVN 5	282500	520 - KVU Corr unpl.m	90	Other error/process relate	Starthjelp på hovedvifte	Starthjelp på vifte1 ma	BREFBU	BREJRO	1
3500018019	BR260000 - VDL FeSi/Four		20161007	20161007	BR282521	HOVEDVIFTE 1, OVN 5	282500	520 - KVU Corr unpl.m	90	Instrumental error	vifte åpne ikkje	Feil på magnetventil v	BRERST	BRESRO	1
3505120	BR263000 - VDL EL FeSi/F		20150105	20150102	BR282521	HOVEDVIFTE 1, OVN 5	282500	520 - KVU Corr unpl.m	90	Other error/process relate	Oljepumpe på hovudvifte 1 stopp	Kontrollert motor og n	BRESMIA	BREGMY	1
3500042524	BR360000 - VDL Ovn 5 / Ku		20200205	20200212	BR282521	HOVEDVIFTE 1, OVN 5	282500	510 - KVP Corr.plan	85		Montre rekvrk og gangbru runtt fur	Montert ny gangveg m	BREBKJ	BREBKJ	1
3500040378	BR360000 - VDL Ovn 5 / Ku	BROVN5-HRN	20191001	20191231	BR282521	HOVEDVIFTE 1, OVN 5	282500	900 - Project	85		Lagerbytte på hovedvifte 1	24/10-19: Skaffe doku	BREJRO	BREJRO	1
3500039935	BR360000 - VDL Ovn 5 / Ku		20190906	20190930	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	85		Rive olje rør og aggregat til houvu	Rive	BRERSV	BRERSV	1
3500039272	BR360000 - VDL Ovn 5 / Ku		20190719	20190722	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	85	Mechanical error	høy vibrasjonsverdi, blitt registrert	19/07-2019	EXTBREMG	BREEST	1
3500038153	BR360000 - VDL Ovn 5 / Ku		20190521	20190523	BR282521	HOVEDVIFTE 1, OVN 5	282500	510 - KVP Corr.plan	85	No error/other needs	Kontroll av lagerbolter og inspeks	inspeksjon,låse opp.	BREJRO	BREJRO	1
3500037805	BR360000 - VDL Ovn 5 / Ku		20190515	20190508	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	85	Mechanical error	Økning lagertemp og økning i lagervibrasjoner		BRESRI	BREOFJ	1
3500037948	BR360000 - VDL Ovn 5 / Ku		20190509	20190509	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	85	Mechanical error	tømme lager for greas	tømme lager for freas	EXTBREMG	BREOFJ	1
3500035911	BR360000 - VDL Ovn 5 / Ku		20190123	20190123	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	90	No error/other needs	Sjekke/dra til bolter på lagerhus c	Sjekka bolter. Alle fine	BRESRI	BREOFJ	1
3500034461	BR360000 - VDL Ovn 5 / Ku		20181113	20181123	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	90	Material malfunction	Reingjere evakueringskanal for g	.	BREJRO	BREJRO	1
3500033910	BR360000 - VDL Ovn 5 / Ku		20181016	20181017	BR282521	HOVEDVIFTE 1, OVN 5	282500	500 - FVT Prev.maint	90	No error/other needs	Kontroll og etterstramming av fun	Sjekka alle bolter. dei	BREJRO	BREJRO	1
3500033562	BR360000 - VDL Ovn 5 / Ku		20181002	20181003	BR282521	HOVEDVIFTE 1, OVN 5	282500	510 - KVP Corr.plan	90	Mechanical error	Tømme lagerhus for grease og ir	Tømme lagerhus for (	BREJRO	BREJRO	1

Table 4. 2: The original data from Elkem

Entry date	Requested fi	Equipment	Maintenance	Failure cause	Error description	Functional failure	Failure mode	Work done line 1
20180527	20180531	HOVEDVIFTE	Corrective	No error/other needs	Hovudvifte 1 tippa	No suction/pressure	No rotation due to activated engine protector	Justert trykk på smøreolje
20180526	20180531	HOVEDVIFTE	Corrective	No error/other needs	Vifte 1 tippa	No suction/pressure	No rotation due to activated engine protector	Tippa på vibrasjon/temp. Fann ikkje noko gale, starta
20170121	20170121	HOVEDVIFTE	Corrective	Other error/process related error	Starthjelp på hovedvifte	Misc		Starthjelp på vifte1 maipulert ledeskinne flagg
20161007	20161007	HOVEDVIFTE	Corrective	Instrumental error	vifte åpne ikkje	N/A - No suction/pressure	N/A	Feil på magnetventil ved hydraulikkanlegg,åpne vift
20150105	20150102	HOVEDVIFTE	Corrective	Other error/process related error	Oljepumpe på hovudvifte 1 stoppet.	N/A - No suction/pressure	N/A	Kontrollert motor og målt. Ingen feil. Starta opp igjen
20200205	20200212	HOVEDVIFTE	Corrective		Montre rekvrk og gangbru runtt fundament	Misc		Montert ny gangveg med rekkverk rundt fundament
20191001	20191231	HOVEDVIFTE	Project		Lagerbytte på hovedvifte 1	No suction/pressure	No rotation due to bearing failure	24/10-19: Skaffe dokumentasjon på anlegget og låsin
20190906	20190930	HOVEDVIFTE	Preventive		Rive olje rør og aggregat til houvud vifte 1, 2, 3 ovn 5	Misc		Rive
20190719	20190722	HOVEDVIFTE	Preventive	Mechanical error	høy vibrasjonsverdi, blitt registrert helt opp i 19mm/s	Misc		19/07-2019
20190521	20190523	HOVEDVIFTE	Corrective	No error/other needs	Kontroll av lagerbolter og inspeksjon innvendig av viftehj	Misc		inspeksjon,låse opp.
20190515	20190508	HOVEDVIFTE	Preventive	Mechanical error	Økning lagertemp og økning i lagervibrasjoner	No suction/pressure	No rotation due to activated engine protector	
20190509	20190509	HOVEDVIFTE	Preventive	Mechanical error	tømme lager for greas	Misc		tømme lager for freas
20190123	20190123	HOVEDVIFTE	Preventive	No error/other needs	Sjekke/dra til bolter på lagerhus og lagerhustopp.	Misc		Sjekka bolter. Alle fine

Table 4. 3: Data after sorting and simplifying it

4.4.1 Challenges

Out of the sixteen columns in the original sheet, fourteen of them have a standardized way of register information. This leaves two columns with unstandardized data, ‘’error description’’ and ‘’work done line 1’’. This can be a problem because there can be a reoccurring failure which can be described in different ways every time it is registered. When a description is not standardized, it is hard to analyse the data and gather the information that can identify a certain problem. Sorting out the different maintenance problems will also be a challenge and it makes the related data somewhat useless. If there is ten different descriptions of one problem, which makes it hard to confirm that it is actually just one problem, the data can not be used to calculate the MTBF since the description is of ten different problems instead of one reoccurring problem.

The added functional failure and failure mode columns are based on the already unclear and inadequate data in the error description. It is hard to draw conclusions and find certain relations when the data is this unclear, and therefore it will not be used to find failure modes or functional failures. Even if it was possible to find clear relations between the error descriptions and functional failures, it would not necessary give a realistic picture of the situation due to the lack of maintenance records done during the five-year period this has been registered.

4.4.2 Data analysed

The column previously named order type, now named maintenance, was standardized by Elkem Bremanger, and was used to categorize if maintenance actions carried out was preventive or corrective tasks. This information gives an insight of what kind of maintenance that has been carried out at the filtration plant. There has been registered 249 maintenance tasks that are rated as preventive or corrective maintenance, which is enough data to get realistic picture of the situation.

Sub-system	Corrective maintenance	Preventive maintenance	Total	Corrective % of total
Duct/pipes	13	2	15	86,66666667
Coarse separator I	10	1	11	90,90909091
Coarse separator II	7	1	8	87,5
Coarse separator III	15	1	16	93,75
Coarse separator total	32	3	35	91,42857143
Main fan 1	22	11	33	66,66666667
Main fan 2	12	6	18	66,66666667
Main fan 3	9	5	14	64,28571429
Main fan total	43	22	65	66,15384615
Flush fan 1	6	1	7	85,71428571
Flush fan 2	2	3	5	40
Flush fan total	8	4	12	66,66666667
Filter 2	21	10	31	67,74193548
Filter 4	6	3	9	66,66666667
Filter 6	3	1	4	75
Filter 8	4	1	5	80
Filter 10	4	0	4	100
Filter 12	16	3	19	84,21052632
Filter 13	9	2	11	81,81818182
Filter 14	2	0	2	100
Filter 15	4	0	4	100
Filter 16	0	1	1	0
Filter 17	15	6	21	71,42857143
Filter 18	3	2	5	60
Filter total	87	29	116	75
Reddler 1	2	0	2	100
Reddler 2	3	1	4	75
Redler total	5	1	6	83,33333333

Table 4. 4: Maintenance types carried out in the different sub-systems

Absolute numbers for sub-systems			
CM	PM	Total	Corrective % of total
188	61	249	75,50200803

Table 4. 5: The absolute numbers for maintenance done across all sub-systems

According to the data available, there has been a total of 249 maintenance actions carried out on the defined sub-systems the last 5 years. When looking at the numbers for all the sub-systems combined almost 75% of the maintenance is of a corrective manner. Since it is not possible to relate the maintenance to the functional failures, it is impossible to draw conclusions regarding operational integrity. But often when carry out a corrective maintenance task there has been a failure, and this results in loss of operational integrity.

Both the main fan and flush fan has the lowest corrective maintenance percentage of all sub-systems, this might be due to its criticality and that Elkem Bremanger prioritizes them by doing preventive maintenance or inspections more often to these systems compared to the rest. On the other side of the scale, the coarse separators are the sub-systems with the highest corrective maintenance. It is hard to do preventive maintenance on the coarse separators, which might be the reason why they have the highest corrective maintenance percentage.

Elkem Bremanger does have periods of stop in production, these periods should be used to carry out preventive or predictive maintenance to secure operational integrity. Considering that three quarters of all maintenance registered is corrective, an assumsion can be made that a lot of those corrective maintenance actions can be turned in to preventive or predective tasks during the systems natural periods of down time.

4.5 FMECA

In the failure mode, effects, and criticality analysis the itmes that were picked in the critical item selection will be further analyzed. Each sub-system will get its analysis, but only with respect too the items deemed critical. The worksheet will give an overview of the failure modes related to the items and the function failures, and the risk they pose.

4.5.1 Duct/pipes

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Duct/pipes												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Duct/pipes	Leakage	Cracks/hole due to corrosion	Use	Wear, unpredictable	N/A	2	2	1	1	Loss of microsilica - welding or replace piping	4	2	32
	Leakage	Not airtight connections	Installation/Use	Random failure	N/A	2	2	1	1	Loss of microsilica - replace gaskets/tighten bolts	3	3	36
	Flow restriction	Build up of particles	Use	Random failure	N/A	1	1	2	2	Reduces flow of gas - production shut down to clean	2	3	24
Dampers	Flow restriction	Cylinder fails to open damper	Design/Use	Wear, unpredictable	N/A	1	1	2	2	Blocks of all flow of gas - cylinder must be replaced/fixed	4	1	16

Table 4. 6: FMECA for ducts & pipes

4.5.2 Coarse separator

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Coarse separator												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Cyclone	Fails to separate	Seperation opening inside cyclone worn out	Use	Wear, Predictable	115 000	1	1	3	3	Bigger particles continues on to main fan - production shutdown and replacement of coarse separator	2	3	54
	Leakage	Cracks/holes due to corrosion	Use	Wear, Unpredictable	N/A	2	2	1	1	Loss of microsilica - Continous welding and patching up holes	3	2	24
	Leakage	Cracks/holes due to errosion	Use	Wear, Unpredictable	N/A	2	2	1	1	Loss of microsilica - Continous welding and patching up holes	3	2	24

Table 4. 7: FMECA for coarse separator

4.5.3 Main fan

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Main fan												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Electric engine	No suction/pressure	No rotation due to loss of power	Design/Use	Random failure	N/A	1	3	3	2	Fails to operate - investigate electrical system	2	1	36
	No suction/pressure	No rotation due to activated engine protector	Design/Use	Random failure	N/A	1	1	2	1	Fails to operate - investigate/deactivate engine protector	3	1	6
	No suction/pressure	No rotation due to engine failure	Design/Use	Age	44 000	1	4	4	4	Fails to operate - Replace/overhaul engine	2	1	128
Shaft/impeller	No suction/pressure	No rotation due to broken shaft	Use/Design	Wear/Tear, unpredictable	90 000	2	4	4	4	Fails to transfer power - disassemble fan and replace shaft	1	1	128
	No suction/pressure	No suction/pressure due to broken impeller	Use/Design	Wear/Tear, unpredictable	90 000	2	4	4	4	Fails to create suction/pressure - replace impeller	1	1	128
Bearing	No suction/pressure	No rotation due to bearing failure	Installation/Use/Design	Wear, predictable	44 000	2	3	3	3	Fails to operate - replace bearing	3	1	162
	No suction/pressure	Reduced RPM due to occuring bearing failure	Installation/Use/Design	Wear, predictable	< 44 000	1	3	3	2	Reduced operational performance - replace bearing	3	2	108
Coupling	No suction/pressure	No rotation due to broken coupling	Installation/Use/Design	Random failure	90 000	2	3	3	2	Fails to transfer power - replace coupling	2	1	72
	No suction/pressure	Reduced RPM due to misaligned coupling	Installation/Use/Design	Random failure	N/A	1	2	2	2	Fails to perform optimal - Must realign coupling	2	2	32
Fan housing	Leakage	Cracks/holes due to corotion	Use	Wear, predictable	90 000	2	1	1	2	Reduced suction - welding and patching up holes	2	3	24
	Leakage	Cracks/holes due to errosion	Use	Wear, predictable	90 000	2	1	1	2	Reduced suction - welding and patching up holes	2	3	24

Table 4. 8: FMECA for main fan

4.5.4 Flush fan

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Flush fan												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Electric engine	Fails to create suction	No rotation due to loss of power	Design/Use	Random failure	N/A	1	2	2	2	Fails to operate - investigate electrical system	3	1	24
	Fails to create suction	No rotation due to activated engine protector	Design/Use	Random failure	N/A	1	1	1	1	Fails to operate - investigate/deactivate engine protector	3	1	3
	Fails to create suction	No rotation due to engine failure	Design/Use	Age	87 000	1	3	3	3	Fails to operate - replace/overhaul engine	2	1	54
Shaft/impeller	Fails to create suction	No rotation due to broken shaft	Use/Design	Wear/Tear, unpredictable	105 000	2	3	3	2	Fails to transfer power - disassemble fan and replace shaft	1	1	36
	Fails to create suction	No rotation due to broken impeller	Use/Design	Wear/Tear, unpredictable	105 000	2	3	4	3	Fails to create suction - replace impeller	1	1	72
Bearing	Fails to create suction	No rotation due to bearing failure	Installation/Use/Design	Wear, predicatble	44 000	2	2	3	2	Fails to operate - replace bearing	3	1	72
	Fails to create suction	Reduced RPM due to occuring bearing failure	Installation/Use/Design	Wear, predicatble	< 44 000	1	2	2	2	Reduces operational performance - replace bearing	3	2	48
Coupling	Fails to create suction	No rotation due to broken coupling	Installation/Use/Design	Random failure	75 000	1	3	3	2	Fails to transfer power - replace coupling	2	1	36
	Fails to create suction	Reduced RPM due to misaligned coupling	Installation/Use/Design	Random failure	N/A	1	2	2	2	Fails to preform optimal - realign coupling	2	2	32
Fan housing	Leakage	Cracks/holes due to corrotion	Use	Wear, predicatble	90 000	2	1	1	2	Reduced suction - welding and patching up holes	2	3	24
	Leakage	Cracks/holes due to errosion	Use	Wear, predicatble	90 000	2	1	1	2	Reduced suction - welding and patching up holes	2	3	24

Table 4. 9: FMECA for flush fan

4.5.5 Filter

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Filter												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Filter bags	Fails to filter	Does not release gas due to clogging	Use	Age, Predictable	38 000	2	1	1	1	Pressure build up - investigate reasons for clogging	4	3	24
	Fails to filter	Due to hole in filter bag	Use	Wear, Unpredictable	N/A	2	2	1	1	Loss of microsilica - filter bag must be replaced	4	3	48
	Fails to filter	Due to not airtight connection	Installation/Use	Random failure	N/A	2	2	1	1	Loss of microsilica - connection must be investigated	4	2	32
Filter housing	Leakage	Cracks/holes due to corrosion	Use	Wear, Predictable	125 000	2	2	1	2	Loss of microsilica - continous welding and patching up	3	2	48
	Leakage	Cracks/holes due to errosion	Use	Wear, Predictable	125 000	2	2	1	2	Loss of microsilica - continous welding and patching up	3	2	48
Electrical engine	Fails to convey microsilica	No rotation due to loss of power	Design/Use	Random failure	N/A	1	1	2	1	Flow of microsilica stops - investigatie electrical system	3	1	6
	Fails to convey microsilica	No rotation due to active engine protector	Design/Use	Random failure	N/A	1	1	1	1	Flow of microsilica stops - investigate/deactivate engine protector	4	1	4
	Fails to convey microsilica	No rotation due to engine failure	Design/Use	Age, Predictable	43 800	2	1	3	2	Flow of microsilica stops - replace/overhaul engine	2	1	24
Bearing	Fails to convey microsilica	No rotation due to bearing failure	Installation/Use/Design	Wear/Tear, Unpredictable	N/A	2	1	3	2	Flow of microsilica stops - replace bearing	3	1	36
	Fails to convey microsilica	Reduced RPM due to bearing failure	Installation/Use/Design	Wear/Tear, Unpredictable	N/A	1	1	3	2	Flow of microsilica is reduced - replace bearing	3	2	36
Pipe/blades	Fails to convey microsilica	Fails to rotate due to broken pipe	Use	Wear/Tear, Unpredictable	N/A	1	1	3	2	Fails to transfer microsillica - replace pipe	2	1	12
	Fails to convey microsilica	Fails to convey microsilica due to broken blades	Use	Wear/Tear, Unpredictable	N/A	1	1	2	1	Reduced operational performance - replace blades	3	3	18
Cell housing (cell feeder)	Fails to contain microsilica	Leakage due to broken gasket	Use/Installation	Age, Unpredictable	10 000	2	1	2	1	Loss of microsilica - replace gasket	3	2	24
Bearing (cell feeder)	Fails to convey microsilica	No rotation due to bearing failure	Installation/Use/Design	Wear, Predictable	10 000	2	1	2	2	Flow of microsilica stops - replace bearing	3	1	24
	Fails to convey microsilica	Reduced RPM due to bearing failure	Installation/Use/Design	Wear, Predictable	< 10 000	1	1	2	1	Flow of microsilica is reduced - replace bearing	3	2	12
Transmission (cell feeder)	Fails to convey microsilica	No rotation due to broken chain	Use/Design	Random failure	N/A	2	1	1	1	Fails to transfer power - replace chain	4	1	8
	Fails to convey microsilica	No rotation due to broken gears	Use/Design	Wear/Tear, Unpredictable	N/A	2	1	2	1	Fails to transfer power - replace or fasten gears	3	1	12
Impeller (cell feeder)	Fails to convey microsilica	Due to broken impeller	Use/design	Wear/Tear, predictable	10 000	1	1	3	2	Reduced operational performance - replace impeller	2	1	12

Table 4. 10: FMECA for filter

4.5.6 Redler

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS													
Plant:	Elkem												
System:	Filtration plant												
Sub-system:	Redler												
Item	Functional failure	Failure mode	Failure cause	Failure development	MTBF (Hours)	COF				Failure effects	Like.	Det.	RPN
						S	E	A	C				
Electric enginge	Fails to convey microsilica	No rotation due to loss of power	Design/Use	Random failure	N/A	1	1	2	1	Stop in production flow - investigate electrical system	3	1	6
	Fails to convey microsilica	No rotation due to activated engine protector	Design/Use	Random failure	N/A	1	1	1	1	Stop in production flow - investigate/deactivate engine protector	4	1	4
	Fails to convey microsilica	No rotation due to engine failure	Design/Use	Age	43 800	1	1	3	2	Stop in production flow - replace/overhaul engine	2	1	12
Bearing	Fails to convey microsilica	No rotation due to bearing failure	Installation/Use/Design	Wear, Unpredictable	26 000	2	1	2	2	Stop in production flow - replace bearing	3	1	24
	Fails to convey microsilica	Reduced RPM due to occuring bearing failure	Installation/Use/Design	Wear, Unpredictable	< 26 000	1	1	2	1	Reduced operational performance - replace bearing	3	2	12
Belt	Fails to convey microsilica	Belt does not rotate due to tear	Use	Random failure	N/A	2	1	2	2	Stop in production flow - investigate belt	3	1	24
	Fails to convey microsilica	Belt rotates without conveying microsilica	Use/Design	Wear, Unpredictable	30 000	1	1	3	2	Stop in production flow - investigate belt	2	3	36
Transmission	Fails to convey microsilica	Does not transform power due to broken chain	Design/Use	Random failure	N/A	2	1	2	1	Stop in production flow - replace chain	3	1	12
	Fails to convey microsilica	Does not transform power due to broken gears	Design/Use/Installation	Wear, Unpredictable	26 000	2	1	3	2	Stop in production flow - replace gears	2	1	24

Table 4. 11: FMECA for redler

4.6 Critical failure mode selection

In this thesis six sub-systems have been thorough investigated through FMECA, where 52 failure modes have been analyzed. These failure modes where then evaluated by its consequence regarding safety, environment, availability, and cost. In close cooperation with professionals at Elkem Bremanger these failure modes where evaluated also by their likelihood and detection. In the evaluation process there was made parameters regarding safety, environment, availability, cost, likelihood, and detection to ease the process. These parameters where worked out together with Elkem to be adjusted with their plant, its processes and Elkem's internal standards.

In this thesis the RPN value covers the total severity of safety, environment, availability, and cost combined. Represented in the last column of the FMECA worksheet. The failure modes with the highest RPN value will then be taken into further actions to develop a possible maintenance task. Together with Elkem Bremanger there was put a lower limit to when the RPN value was high enough for further actions, all failure modes with a higher RPN value than 40 should be taken into further actions. In total there was found 14 failure modes with RPN value 40 or higher, where the highest had a value of 162. All failure modes that were taken into consideration is listed in table 4.12.

Item	Functional failure	Failure mode	COF				Sub-system	Like.	Det.	RPN
			S	E	A	C				
Bearing	No suction/pressure	No rotation due to bearing failure	2	3	3	3	Main fan	3	1	162
Electric engine	No suction/pressure	No rotation due to engine failure	1	4	4	4	Main fan	2	1	128
Shaft/impeller	No suction/pressure	No rotation due to broken shaft	2	4	4	4	Main fan	1	1	128
Shaft/impeller	No suction/pressure	No suction/pressure due to broken impeller	2	4	4	4	Main fan	1	1	128
Bearing	No suction/pressure	Reduced RPM due to occuring bearing failure	1	3	3	2	Main fan	3	2	108
Shaft/impeller	Fails to create suction	No rotation due to broken impeller	2	3	4	3	Flush fan	1	1	72
Bearing	Fails to create suction	No rotation due to bearing failure	2	2	3	2	Flush fan	3	1	72
Coupling	No suction/pressure	No rotation due to broken coupling	2	3	3	2	Main fan	2	1	72
Cyclone	Fails to separate	Seperation opening inside cyclone worn out	1	1	3	3	Coarse separator	2	3	54
Electric engine	Fails to create suction	No rotation due to engine failure	1	3	3	3	Flush fan	2	1	54
Filter bags	Fails to filter	Due to hole in filter bag	2	2	1	1	Filter	4	3	48
Filter housing	Leakage	Cracks/holes due to corrosion	2	2	1	2	Filter	3	2	48
Filter housing	Leakage	Cracks/holes due to errosion	2	2	1	2	Filter	3	2	48
Bearing	Fails to create suction	Reduced RPM due to occuring bearing failure	1	2	2	2	Flush fan	3	2	48

Table 4. 12: Critical failure modes

4.7 RCM decision diagram

All of the critical failre modes with a RPN over 40 was processed and handled by using the decision diagram and worksheet. This led to a suggested type of maintenance task to be carried out and several proposed ways to handle the failure modes. It is important to notice that in addition to this it will still be necessary to follow the manufacturers instruction on how to maintain items. For example, it will be important to follow the lubrication specification and refill intervals on the bearings. Most of the failure modes have been handed a scheduled on-condition task, this is due to the criticality of the failure modes and how much there is to gain by using resources on these failure modes. The proposed tasks, initial interval, and description of who can carry out the tasks is listed in table 4.13.

4.7.1 Implementing the proposed tasks

As the suggestions and plan has been worked out, the next step is to implement the proposed task. First of all, the people surrounding the operation or maintenance of these sub-systemes should be informed and teached the principles and thoughts of the analysis and its results. This is to make sure that everyone acknowledges the strategy.

The condition monitoring equipment should be procured and installed as soon as possible. The physical installation of the sensors and the computers that will monitor and record the results will take time to be ready. In the meantime, there should be arranged training that will teach the operators and other personnel how the inspections and data should be read, interpreted, and stored.

RCM DECISION WORKSHEET	Plant: Elkem System: Filtration plant													
Item Failure mode	Consequence evaluation				H1 S1 O1 N1	H2 S2 O1 N2	H3 S3 O3 N3	Default action			Type of maintenance task to be carried out	Proposed task	Initial interval	Can be done by
	H	S	E	O				H4	H5	S4				
Bearing (MF) No rotation due to bearing failure	Y	N	Y		Y						Scheduled on-condition task	Condition monitoring by vibration and temperature sensors	Continously	Operators
Electrical engine (MF) No rotation due to engine failure	Y	N	Y		Y						Scheduled on-condition task	Condition monitoring by vibration end temperature sensors	Continously	Operators
Shaft/impeller (MF) No rotation due to broken shaft	Y	N	Y		Y						Scheduled on-condition task	1. Condition monitoring by vibration sensors 2. Visual inspection - check manually for wear & tear	1. Continously 2. Every 6 months	1. Operators 2. Trained personnel
Shaft/impeller (MF) No suction/pressure due to broken impeller	Y	N	Y		Y						Scheduled on-condition task	1. Condition monitoring by vibration and temperature sensors 2. Visual inspection - check manually for cracks, wear and tear on impeller 3. NDT of welds and critical areas	1. Continously 2. Every 6 months 3. Every 24 months	1. Operators 2. Trained personnel 3. Cerified personnel
Bearing (MF) Reduced RPM due to occuring bearing failure	Y	N	Y		Y						Scheduled on-condition task	Condition monitoring by vibration and temperature sensors	Continously	Operators
Shaft/impeller (FF) No rotation due to broken impeller	Y	N	Y		Y						Scheduled on-condition task	1. Condition monitoring by vibration sensors 2. Visual inspection - check manually for wear & tears 3. NDT of welds and critical areas	1. Continously 2. Every 6 months 3. Every 24 months	1. Operators 2. Trained personnel 3. Certified personnel
Bearing (FF) No rotation due to bearing failure	Y	N	N	Y	Y						Scheduled on-condition task	Condition monitoring by vibration and temperature sensors	Continously	Operators
Coupling (MF) No rotation due to broken coupling	Y	N	Y		Y						Scheduled on-condition task	Visual inspection - inspect the general condition of coupling, bolts and rubber element	Every 6 months	Trained personnel
Cyclone (CS) Seperation opening inside cyclone worn out	Y	N	N	Y	Y						Scheduled on-condition task	Visual inspection - check thickness of plates and welds	Every 6 months	Trained personnel
Electrical engine (FF) No rotation due to engine failure	Y	N	N	Y	Y						Scheduled on-condition task	1. Condition monitoring by vibration sensors, temperature and effect 2. Visual inspection - check manually for wear & tears or other damage	1. Continously 2. Every 6 months	1. Operators 2. Trained personnel
Filter bags (F) Leakage due to hole in filter bag	Y	N	N	N	N	N	N				No sheduled maintenance	Remove filter bag, block flange and report to supervisor	N/A	Operators
Filter housing (F) Cracks/holes due to corrosion	N	Y			Y						Scheduled on-condition task	1. Visual inspection - check welds and plates for cracks or holes and report to supervisor 2. NDT - check welds and thickness of plates with ultrasound and report to supervisor	1. Every 6 months 2. Every 24 months	1. Trained personnel 2. Certified personnel
Filter housing (F) Cracks/holes due to errosion	N	Y			Y						Scheduled on-condition task	1. Visual inspection - check welds and plates for cracks or holes and report to supervisor 2. NDT - check welds and thickness of plates with ultrasound and report to supervisor	1. Every 6 months 2. Every 24 months	1. Trained personnel 2. Certified personnel
Bearing (FF) Reduced RPM due to bearing failure	Y	N	N	Y	Y						Scheduled on-condition task	Condition monitoring by vibration and temperature sensors	Continously	Operators

Table 4. 13: RCM Decision worksheet

5. Investigation of bearing failure

In recent years Elkem have had a challenge with rapid bearing failure regarding their paddle conveyor at the filtration plant. These bearings are included in this thesis and has undergone Critical items selection and FMECA, considering their low RPN they were not taken into further maintenance actions. Both Elkem Bremanger and the authors of this report are in an agreement that the bearings are not critical based on safety, environment, availability, or cost. Looking at one paddle conveyor at a specific chamber there are little or no consequence, because of the relative low cost of changing two bearings. There are however economic consequences regarding the short bearing lifetime combined with the amount of beairngs in the plant.

As mentioned earlier in this report the filtration plant consists of 27 filters and the total amount of paddle conveyor bearings will then be 54 for the entire plant. The predicted bearing life has been calculated to approximately 4,8 years or 42 000 hours. This is calculation was done by Elkem's professionals together with the bearing supplier SKF.

Elkem Bremanger has provided us with data regarding MTBF and bearing specifications. The data provided regarding MTBF for these failures varies between 2 years and as low as 2 months. The gathered data concerning failure cause and failure mechanism is often imprecise or not specified. Therefore, the data will mostly be used to determine intervals between each bearing failure. Further investigation will be based on subjective opinions between the authors of this report and professionals at Elkem this being mechanics, operators and their maintenance leader.

5.1 Technical information

This chapter will provide technical information on the bearing arrangement.

5.1.1 Bearings

The paddle conveyor assembly inside the microsillica chambers uses two different bearings, one for the drive side (DE) and another for the none drive side (NDE). These bearings have an estimated service life of 4,8 years; however, this service life varies greatly in today's situation.

The DE bearing used is a SKF 2217 K, self-aligning ball bearing. These bearing consist of two rows of balls with two deep grooves in the inner ring. These bearings are insensitive to angular misalignment of the shaft relative to the housing, which can occur due to shaft deflection as shown in figure 5.1. In general, these bearings handle static and dynamic misalignment just like spherical roller bearing, like the ones used for NDE. As these bearings are not under high speed it is not as crucial, but they can resist high speed performance due to lower friction than other roller bearings, which allows them to stay cooler [10].

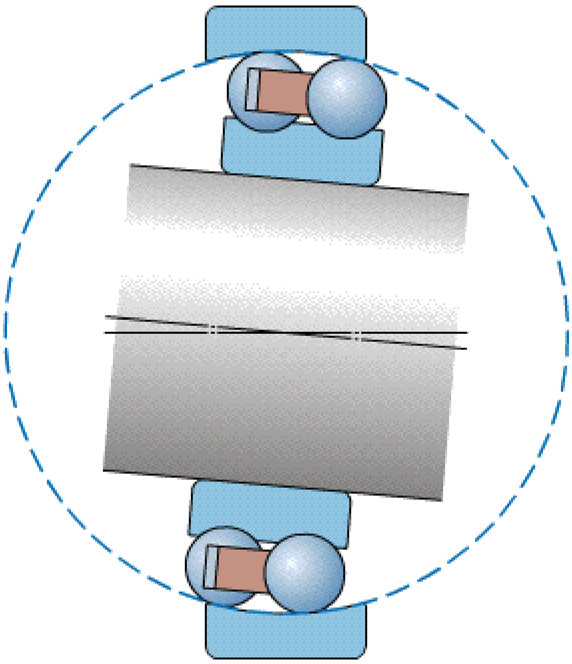


Figure 5. 1: Angular misalignment for bearing [10]

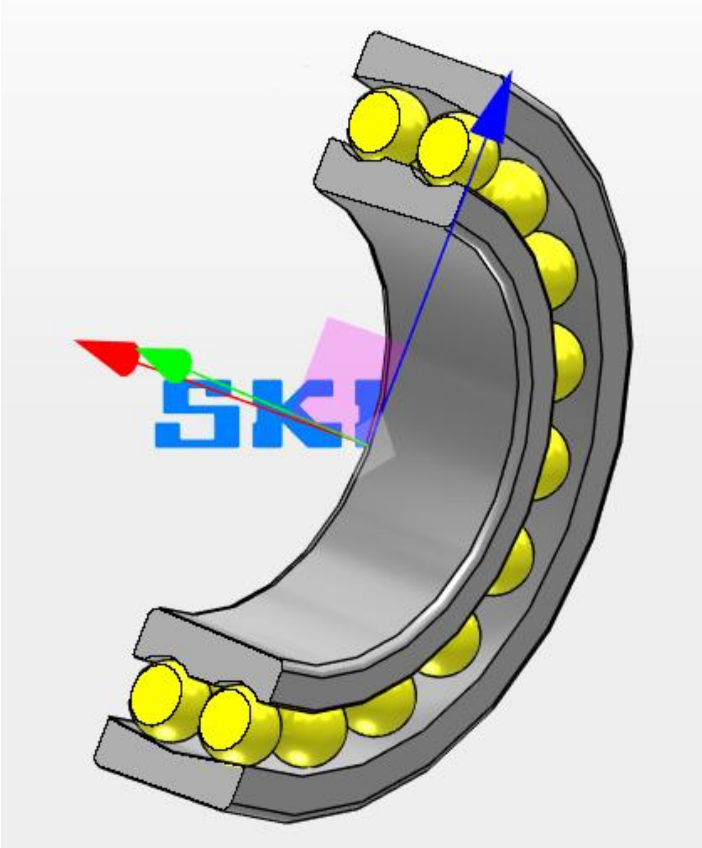


Figure 5. 2: SKF 2217 K self-aligning ball bearing

The NDE bearing used is a SKF NU 2217, single row cylindrical roller bearing. They provide low friction and a high axial load carrying capacity. Due to their profile they are also less sensitive to misalignment and shaft deflection. The components of the cylindrical roller bearings are interchangeable, which should facilitate mounting and dismounting. The NU design bearings have two integral flanges on the outer ring and no flanges on the inner ring. An added benefit of this bearing is the accommodations of axial displacement of the shaft relative to the housing in both directions [11].

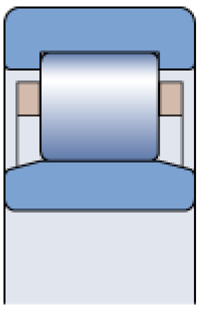


Figure 5. 3: SKF NU 2215, single row cylindrical roller bearing [11]

Figure 5. 4 SKF NU 2217, single row cylindrical roller bearing [11]

5.1.2 Housing

Both the bearings have the same bearing housing, which is a SKF SNL 517. These housing are made from cast iron and lubricated by grease or oil, which is Mobilux EP2 grease in this case. These are also among the most used housings SKF supply, which makes them great for quality and economy. According to the supplier the incorporated bearings these housings use, achieve the maximum service life with minimal maintenance [12].

SNL housings has an efficient relubrication system, with an integrated flange that guides grease from the fitting directly to the bearing, which in theory should reduce grease consumption and disposal cost.

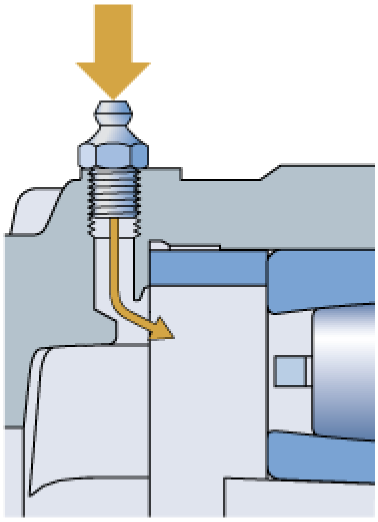


Figure 5. 5: Lubrication channel [12]

Assemblies were the shaft do not go all the way through the housing should have an end cover that fits into the seal groove in the housing. Applications where temperatures exceed 110°C steel end covers should be used [12].

Figure 5. 6: Bearing house [12]

5.1.3 Seal

There is a varity of sealing methods used for sealing the bearing inside the housing, and one of the most common one is SKF TSNA – 517L**,** which is used at this assembly. The main TSNA bearing seal which is a four-lip seal consisting of four separate lips which are radially spilt. With the seal being made from a thermoplastic polyester elastomer. For this specific shaft, these seals have a permissible angular misalignment of approximately 0,5°. They should also handle some axial movement relative to the housing. From SKF specification table these seals should be very suitable for dust, coarse particles, and fine particles.

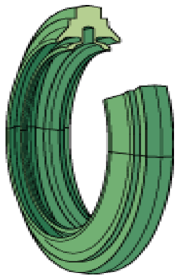


Figure 5. 7 TSNA Bearing seal [13]

5.1.4 Grease

Elkem use Mobil Mobilux EP2 as their main grease, which is a lithium based general purpose grease. This grease is used during initial installation and preventative maintenance of the bearings. According to Mobil's spec sheet this grease should operate within a temperature range of -20 to 130C, but they may also be used at a higher range given that the lubrication frequency is increased. Their grease range is designed to provide extra protection against wear, rusting and water washout. As specific application of Mobilux EP2 it is recommended for applications for antifriction and plain bearings, bushing and pins under normal operating conditions [14].

5.2 Procedures

Today Elkem Bremanger has specific procedures regarding maintenance, replacements, and inspections. These are general procedures where they have a visual inspection weekly concerning the seals and checking for leaks. These preventative maintenance procedures also include greasing both DE and NDE with 5 grams of the mentioned Mobilux EP2 grease. Besides this there are no other current preventative maintenance procedures.

Furthermore, they have developed a standard practice for replacing the cloth and bearings for both sides of the chambers. Listing the required safety equipment and tools needed for the work. As well as giving a specific step by step instruction for how the bearing replacement should be done, which is listed below for both NDE and DE.

5.2.1 Drive end

Tasks before chamber stop:

- Checking that the correct parts are accounted for.
- Type out work permit.
- Stop chamber and disconnect alarm for the chamber
- Lock chamber from process room
- Disable safety switch and attach lock
- Test start the chamber

Tasks during chamber stop

Disassembly:

- Releasing motor and attach the motors forward mounts to the rear mounts of the bracket
- Disconnect the axle connection (Taper lock) and release it from the axle – *measure distance on the axle pre-disassembly*
- Disconnect drive gear from axle and release it from the axle – *measure distance on the axle pre-disassembly*
- Disassemble the top of the bearing housing
- Detach the cloth from the chamber wall
- Use a pully to lift the axle
- Disassemble the nut holding the bearing in place, pulling the bearing off – *measure distance on the axle pre-disassembly*
- Remove bottom section of the bearing housing

Assembly:

- Mount the new cloth and graphite seal
- Mount bottom section of bearing housing
- Assemble bearing and necessary spacers before tightening the nut
- Mount the top section of the bearing housing and fill it with grease
- Mount drive gear and connection motor
- Remount motor
- Clean up the area, gather tools and old parts. Old parts are to be recycled, and tools put in designated area
- Remove lock

Tasks after chamber stop

- Sign for completed work and have operator sign for received equipment
- Remove sign notifying mechanical work
- Visual inspection of chamber after cloth and bearing change. Check to see if everything is in the right condition.

5.2.2 Non drive end

Tasks before chamber stop

- Checking that the correct parts are accounted for.
- Type out work permit.
- Stop chamber and disconnect alarm for the chamber
- Lock chamber from process room
- Disable safety switch and attach lock
- Test start the chamber

Tasks during chamber stop

Disassembly:

- Remove to top section of the bearing housing
- Remove the cloth from the chamber wall
- Lift the axle and dismount the bearing and housing – *lift by a point on the chamber wall*
- Heat the bearing and remove it from the axle – *might have to use a puller*
- Remove cloth, spring, and graphite seal

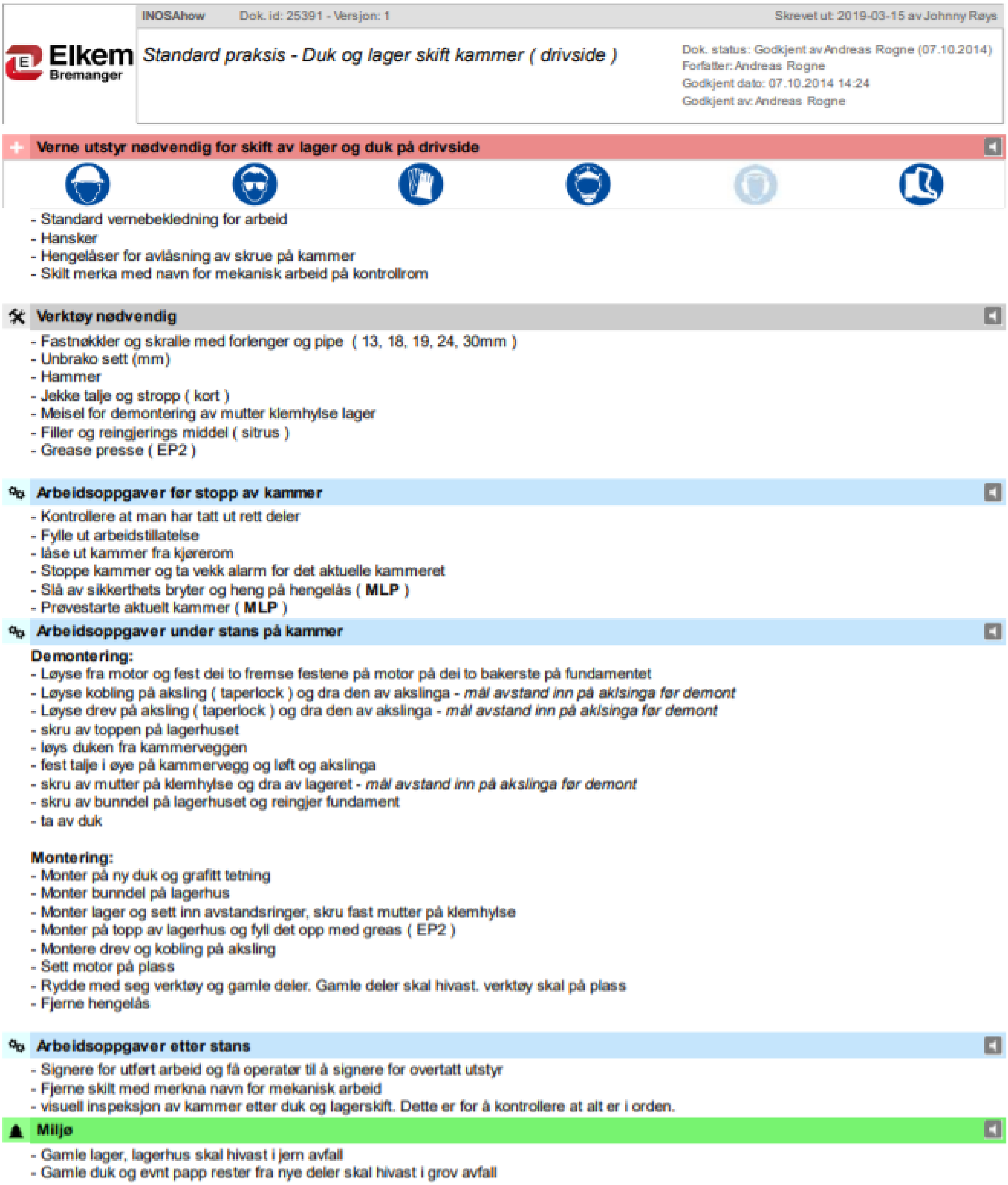
Assembly:

- Install new cloth and graphite seal
- Compress spring and lock it compressed, before mounting it on the axle
- Mount bearing housing seal on the axle
- Heat bearing sleeve and mount it on the axle – *must be cooled before mounting the bearing*
- Mount the bearing and lower the axle
- Mount the top section of the bearing housing and fill with grease
- Clean up the area, gathering tools and old parts
- Remove lock and turn on safety switch

Tasks after chamber stop

- Sign for completed work and have operator sign for received equipment
- Remove sign notifying mechanical work
- Visual inspection of chamber after cloth and bearing change. Check to see if everything is in the right condition.

5.2.3 SOP



INOSAhow Dok. id: 25391 - Versjon: 1 Skrevet ut: 2019-03-15 av Johnny Røys

Elkem Bremanger

Standard praksis - Duk og lager skift kammer (drivside)

Dok. status: Godkjent av Andreas Rogne (07.10.2014)
Forfatter: Andreas Rogne
Godkjent dato: 07.10.2014 14:24
Godkjent av: Andreas Rogne

Verne utstyr nødvendig for skift av lager og duk på drivside

- Standard vernebekledning for arbeid
- Hansker
- Hengeláser for avlåsning av skrue på kammer
- Skilt merka med navn for mekanisk arbeid på kontrollrom

Verktøy nødvendig

- Fastnøkkler og skralle med forlenger og pipe (13, 18, 19, 24, 30mm)
- Unbrako sett (mm)
- Hammer
- Jekke talje og stropp (kort)
- Meisel for demontering av mutter klemhylse lager
- Filler og reingjerings middel (sitrus)
- Grease presse (EP2)

Arbeidsoppgaver før stopp av kammer

- Kontrollere at man har tatt ut rett deler
- Fylle ut arbeidstillatelse
- låse ut kammer fra kjørerom
- Stoppe kammer og ta vekk alarm for det aktuelle kammeret
- Slå av sikkerthets bryter og heng på hengelås (**MLP**)
- Prøvestarte aktuelt kammer (**MLP**)

Arbeidsoppgaver under stans på kammer

Demontering:
- Løyse fra motor og fest dei to fremse festene på motor på dei to bakerste på fundamentet
- Løyse kobling på aksling (taperlock) og dra den av akslinga - *mål avstand inn på aklsinga før demont*
- Løyse drev på aksling (taperlock) og dra den av akslinga - *mål avstand inn på aklsinga før demont*
- skru av toppen på lagerhuset
- løys duken fra kammerveggen
- fest talje i øye på kammervegg og løft og akslinga
- skru av mutter på klemhylse og dra av lageret - *mål avstand inn på akslinga før demont*
- skru av bunndel på lagerhuset og reingjer fundament
- ta av duk

Montering:
- Monter på ny duk og grafitt tetning
- Monter bunndel på lagerhus
- Monter lager og sett inn avstandsringer, skru fast mutter på klemhylse
- Monter på topp av lagerhus og fyll det opp med greas (EP2)
- Montere drev og kobling på aksling
- Sett motor på plass
- Rydde med seg verktøy og gamle deler. Gamle deler skal hivast. verktøy skal på plass
- Fjerne hengelås

Arbeidsoppgaver etter stans

- Signere for utført arbeid og få operatør til å signere for overtatt utstyr
- Fjerne skilt med merkna navn for mekanisk arbeid
- visuell inspeksjon av kammer etter duk og lagerskift. Dette er for å kontrollere at alt er i orden.

Miljø

- Gamle lager, lagerhus skal hivast i jern avfall
- Gamle duk og evnt papp rester fra nye deler skal hivast i grov avfall

Figure 5. 8: SOP

In this subsection the SOP will be evaluated and possible improvements that can increase the lifetime of the bearings. Elkem's SOP's are satisfactory, but there are some general points that could be improved to increase the lifetime of the bearings. Both the SOP's (NDE and DE) have been evaluated and the results have been compared to the RCA and FMECA analyzes that are shown later in this chapter.

When comparing the FMECA for the bearing assembly and the SOP, there are mainly three causes during the installation of new bearings that could lead to a failure in the future. The first cause comes from pollution during the installation. During the installation, the bearings are exposed and vulnerable to pollution caused by the environmental condition in and around the filters. This could be a factor that could potentially act as a catalyst for a future breakdown. Incorrect mounting of the bearing itself could be a factor regarding the short lifetime. The bearing could be mounted too lose or tightened too much on the clamping sleeve. This could be an effect of challenging working conditions when changing bearings. The third possible cause could be miss alignment. Specification regarding installation provided from the supplier SKF, says that the angular tolerance between seal and bearing housing cannot exceed 0.5 degrees relative to shaft. Where this could lead to leaks into the bearing housing which again could lead to a future breakdown.

Regarding these causes for potential failure, there is suggested some improvements to the SOP's that can help prevent failure occruing. The SOP's used today does not specify any cleaning procedure during installation. By implementing a standard cleaning procedure before and during installation the chances for contamination of the bearing assembly can be reduced. The cleaning procedure could include vacuuming and removing as much dust as possible in overhangs and surfaces around the mounting site.

There is also a possibility to pre-assemble the bearing on the shaft in a workshop where the environment would be sterile and the chances for a correct assembly is higher. Considering the shaft is attached only by 6 bolts, the time used to dismantle the shaft and put it back together will have little impact on the total downtime. However, the pre-assembly itself and the procedure for mounting bearings on shafts in a sterile environment could lead to more downtime and use of resources.

The SOP has no procedure on how to mount and tighten the bearing on the drive side, SKF has assembly instructions on how many revolutions needed to tighten the bearing with the correct torque. The main problem here is that the environment and the workspace in the installation site make it difficult to mount the bearings with the right torque, even with a reference to how much to tighten it. If the bearing is tightened to much there will be less clearance between the balls and the inner ring, creating higher friction and increasing the forces in the bearing. If the bearing is too loose a greater clearance is achieved, creating movement which makes the balls absorb the forces through strokes.

A solution to this could be as mentioned earlier, to assemble the complete bearing lineup in a workshop. Here the environment would be sterile, and it would be possible to achieve a satisfactory assembly. Another option could be to create special tools for tightening the bearing when it is mounted inside the bearing housing.

The last possible cause in the installation is the misalignment between the bearing housing and the shaft, which causes a non-uniform pressure on the seal. This will lead to faster worn out seals and contamination of the bearing. A solution to this problem could be to create a mounting bracket for the bearing housings and use a measuring tool to measure that the misalignment is within the tolerance of 0.5 degrees. This will be a small investment considering that the layout is similar on all 27 chambers.

5.3 Rolling bearings: failures, causes and countermeasures

Bearings are often an essential part of a bigger system and a necessary part to keep the system in operation. Broken bearings lead to downtime and replacement can be expensive, therefore it is desirable to keep the lifetime of the bearings to the longest operation time possible. The lifetime of a bearing is usually expressed as a period or a given number of revolutions before failure. The inner ring, outer ring and rolling element often fail because of rolling fatigue caused by repeated stress.

To find the failure mechanisms and causes of the bearing failure it is necessary to do a systematic investigation of the broken bearing. When a bearing failure is realized, there should be done an investigation to determine the causes and mechanisms for the failure. When a bearing failure is under investigation it is important to comprehensively investigate not only the bearing itself, but also the shaft, housing, seal, and lubricant used. To find the causes of failure it is important to have the right knowledge and experience with bearings and lubricants combined with a good understanding of the equipment. In addition to this, it is important to consider the installation procedures and the operational condition of the bearing.

5.3.1 Finding the failure cause

A failure cause is the circumstances that has made it possible for a failure mechanism to happen. Often the failure happens due to normal wear and age. But considering the high frequency of bearing failures at Elkem Bremanger, it is reasonable to assume there is other causes that leads to failure.

To determine the failure causes it is important to accurately find the time of when a failure occurs. This way the research of the failure cause can be limited. When using table 5.1, it is possible to assume what the cause of bearing failure is. By using this method, the cause of failure can be determined being design, manufacturing or by the end customer. Finding the failure cause will not directly explain the bearing failures, but it will tell if it is due to its design, manufacturing faults or wrong use.

Table 1–1 Time of Breakage Occurrence and Causes

Causes / Time of fracture occurrence	Inappropriate use of bearings	Faulty design of shaft, housing or other installation aspects or improper processing	Improper lubricant, lubrication method or sealing device	Defect in bearings	Mis-mounting of bearings	Defect in sealing device, contamination of water, dust or other foreign matters, or shortage of lubricant
(1) Fracture occurring immediately after bearings were mounted or within a short time after mounting	○	○	○	○	○	
(2) Fracture occurring immediately after overhaul			○		○	
(3) Fracture occurring immediately after lubricant was supplied			○			
(4) Fracture occurring immediately after repair or removal of shaft, housing or other parts		○	○		○	
(5) Fracture occurring during normal operation			○		○	○

Table 5. 1: Time of breakage and occurrence and causes [15]

The optimal solution would be to use condition monitoring techniques to investigate the failure development. If there is enough data or monitoring of the bearing's temperature, noise, rotating torque and vibration, operational abnormalities can be discovered in an early stage. At Elkem Bremanger there are over 50 bearings and little monitoring, which makes it difficult to discover abnormalities in an early stage. However, it might be possible to detect by hands-on inspection checks. Table 5.2 shows different tell-tales and possible causes and coutnermeasures.

Table 1–2 Abnormal Operations, their Causes and Countermeasures

Abnormal operation		Causes	Countermeasures (supplementary countermeasures)
Increase in temperature		1. Excessively tight bearing internal clearance 2. Creep on bearing ring	Replace with a new bearing. (Correct bearing internal clearance and interference.) Replace with a new bearing. (Correct interference.)
		3. Excessively heavy load 4. Improper centering in mounting	Remounting (Correct load by adjusting housing.) Remounting (Correct centering, or widen mounting clearance.)
		5. Defect in bearing 6. Improper volume of lubricant	Replace with a new bearing. (Take proper countermeasures, after inspecting the causes.) Correct lubricant volume.
		7. Improper lubricant 8. Improper lubrication method	Change to proper lubricant. Correct lubrication method by remounting or replacement with new parts.
		9. Oil seal – Excessive interference – Shortage of lubricant – Improper oil seal 10. Abnormal contact with labyrinth seal or other parts	Correct interference by installing new seal or changing seal type. Supply lubricant. Correct oil seal type or sealing method. Remounting or modify parts.
Excessively loud noise or foreign noise	Noise at uniform intervals	1. Flaws including scratches, brinelling, etc. 2. Electric pitting	Repair bearings or replace with new ones. (Care should be taken in handling bearings.) Repair bearings or replace with new ones. (Prevent electricity from passing through bearings by modifying their design.)
		3. Cracking of inner or outer ring(s) 4. Flaking of raceway surface 5. Receway surface roughened by foreign matter(s)	Replace with a new bearing. Replace with a new bearing. Repair bearings or replace with new ones.
	High-pitched metallic noise	1. Excessively narrow internal clearance 2. Shortage of lubricant 3. Sliding of rolling element	Replace with a new bearing or widen internal clearance. Supply lubricant. Change to proper lubricant or decrease operational clearance.
	Noise at nonuniform intervals	1. Contamination by foreign matter(s) 2. Contact with another rolling part	Change to proper lubricant. Remounting or modify parts.
		3. Flaw or flaking on rolling element 4. Wear of cage	Replace with a new bearing. Replace with a new bearing.
Excessively high vibration		1. Contamination by foreign matter(s) 2. Excessively wide clearance 3. Flaw on raceway surface or rolling contact surface	Change to proper lubricant. Remounting bearing or replace with a new one. Replace with a new bearing.
Excessively large rotational torque		1. Improper mounting 2. Improper sealing device 3. Improper lubricant	Remounting (Widen internal clearance. Care should be taken with centering.) Remounting (Reduce interference of oil seal.) Decrease lubricant volume. (Care should be taken not to supply an excessive amount of lubricant.)

Table 5. 2: Abnormal operations, their causes and countermeasures [15]

5.3.2 Finding the failure mechanism

During the examination of the broken bearings it is important to carefully inspect every part of the bearing to find symptoms that may indicate what kind of failure mechanisms has led to the failure. A failure mechanism might be erosion due to contamination, whilst the failure cause can be wrong type of seal used. A wrong seal will not be the direct cause of failure, but it will be the preliminary reason for a failure mechanism to arise.

To find the failure mechanisms, there should be a standardized inspection carried out by trained personnel when there is a bearing failure. All parts in the bearing arrangement must be inspected and analysed. Symptoms must be interpreted and registered in a systematic and standardized way to be able to find reoccurring patterns. Symptoms are well documented and [15] catalogue might be helpful to diagnose different symptoms and tell-tales.

5.4 Data collection

This has been covered in chapter 4.4 earlier in this thesis. Elkem Bremanger uses the same excel sheet for all maintenance data recorded. This means that the same problem occurs when analysing the bearing failure data as for the rest of the maintenance. Therefore, there should be put resources in standardization and specifications of data gathered. This would ease the process of finding patterns and telltales for the reoccurring failures that might develope.

5.5 Case study with focus on contamination

In this chapter there will be a further investigation to the contamination of bearing and bearing house inside the filtration plant. Bearings that are exposed to contamination may get a reduced service life and the likelihood of unexpected failure increases. Contamination becomes a challenge considering that Elkem's product consists of fine particles of microsillica, the particles produced have an average size of 0,15 micrometres. When dealing with such small particles it is challenging to keep it clean and avoid contamination during installation and operation.

5.5.1 FMECA

By undergoing an analysis of every item in the assembly, the failure cause and mechanism can be found. As mentioned previously, the failure causes could be divided into three groups, this could make it easier

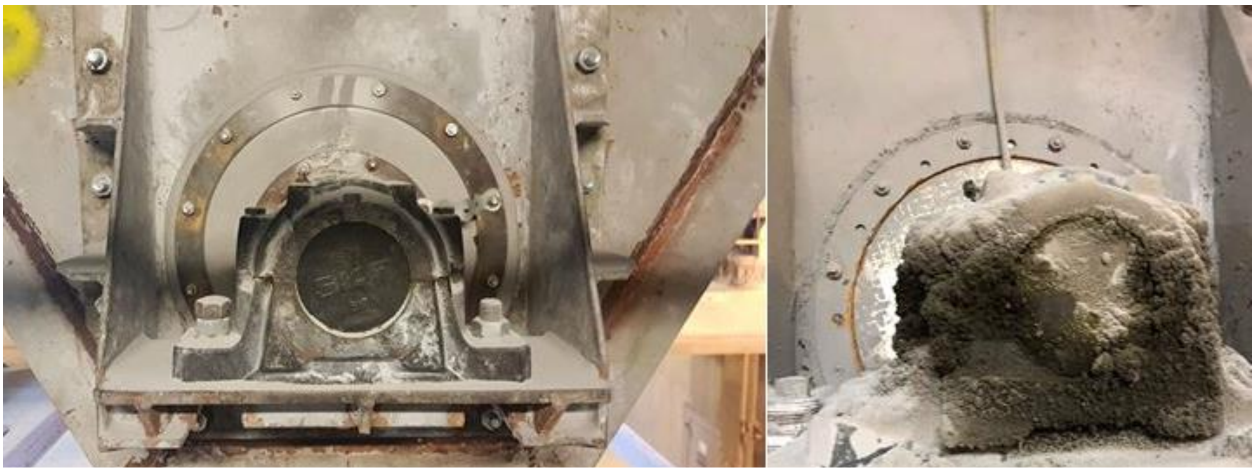


Figure 5. 9: Clean vs dirty bearing house

to separate the different failure causes and result in the right failure mechanism. By entering this data into the FMECA spreadsheet, the failure mode, cause, and reason can be displayed. This information could then contribute to find the mechanism of each failure and be resolved by maintenance actions. The FMECA for the bearing assembly is shown below.

FMECA for bearing arrangement on filter

FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS							
Plant:	Elkem						
System:	Filtration plant						
Sub-sub-system:	Bearing arrangement						
Item	Function	Failure mode	Failure cause	Reason	Local effect	System effect	Detection method
Bearing house	House the bearing. Keeping it in place and alligned.	Fails to keep bearing in place	Design	Wrong dimensions	Bearing house failure	Production stop	Trip device and rotation sensor
			Manufacturing	Weakness in construction			
			Use	Ageing, abnormal load, wrong installation			
Bearing	To allow rotation between to fixed parts	Loss of rotation	Design	Wrong type of bearing used	Bearing failure	Production stop	Trip device and rotation sensor
			Manufacturing	Weakness in construction			
			Use	Wrong installation, ageing, abnormal load, lack of grease, wrong grease			
Seals	Seal of bearing from outside environment	Contamination	Design	Wrong seal	Contamination of grease which leads to bearing failure	Production stop	Visual
			Manufacturing	Weakness in construction			
			Use	Wrong installation, eccentric shaft			
Cover	Cover of bearing from outside	Contamination	Design	Wrong cover	Contamination of grease which leads to bearing failure	Production stop	Visual
			Manufacturing	Weakness in construction			
			Use	Ageing, wrong installation			
Bushing	Replaceable metal hollow shaft	Out worn	Design	Wrong material, wrong tollerance	Loss of placement, chipping, loss of bearing support	Production stop	Trip device and rotation sensor
			Manufacturing	Weakness in construction			
			Use	Wrong installation, ageing			
Shaft	Transferring the power and rotation of the screw	Can not transfer power and rotation	Design	Wrong material, wrong dimension	Loss of placement, chipping, loss of bearing support	Production stop	Trip device and rotation sensor
			Manufacturing	Weakness in construction			
			Use	Wrong installation, ageing			

Table 5. 3: FMECA for bearing arrangement

5.5.2 Contamination as the failure mechanism

In this case there is a lack of certain and specified data, which is not satisfactory for basing any evaluation or choice for further actions. Therefore, the following actions and evaluation is worked out between the authors of this report and Elkem Bremangers professionals. Further work will be based on assumptions and subjective opinions together with the data that is of use.

Elkem is suspecting that contamination by microsillica is the failure mechanism to most of bearing failures. This is based on experience by the operators and mechanics that have been changing bearings over the resent years. This is a reasonable assumption to make considering how small the particles are and how much microsillica there is in the environment. Even though the different failure mechanisms might be a result of contamination, one does not know the failure cause.

Figure 5. 10: Bearing house full of contaminated grease

Choice of bearing

The choice of bearing and bearing house is a result of calculations and recommendation by the manufacturer. Looking into this there is no reason that the bearings should fail due to the rpm, the forces it endures or any abnormal load it could be exposed to. This is an assumption taken together with the employees from Elkem Bremanger.

Bearings are not exposed to bad production batches

Considering the amount of bearing failure occurring in the plant, it will be assumed that none of the components are exposed to bad production batches or weaknesses. Meaning that failures are not expected to come from manufacturing. This is an assumption taken together with the employees from Elkem Bremanger.

Grease

According to the manufacturer’s recommendation Elkem is using the right grease for their bearings. Elkem has a preventive maintenance program that ensure correct amount of refill every second month.

5.5.3 Root Cause Analysis

By mapping possible reasons for bearing contamination there will be obtained an overview that makes it easier to identify the problem. Assuming that the design and manufacturing as mentioned, is not causing contamination. The causes listed below may explain how the bearings get contaminated.

Leakage due to wrong seal

The sealing used in this assembly may not be the best option possible. Particles of microsillica is extremely small, and this may lead to contamination because of it breaches the sealing mechanism. When the microsillica comes in contact with the seal it will create friction and wear on the seal, which over time may cause the sealings to fail.

Bad execution of installation

Bad execution of installation can lead to contamination. This can happen in two ways.

- Contamination happens during the installation. Extreme conditions make it hard to avoid microsillica settling within the bearing house before it is closed.
- Incorrect instalment, leading to misalignment between the bearing house and shaft, which again leads to non-uniform pressure on the seal.

Ageing

This case is based on bearings never reaching their supposed lifetime, but there will still be some expected wear and tear during the lifetime. Normal operation combined with the fine particles might lead to severe abrasive conditions which again leads to leakage and contamination.

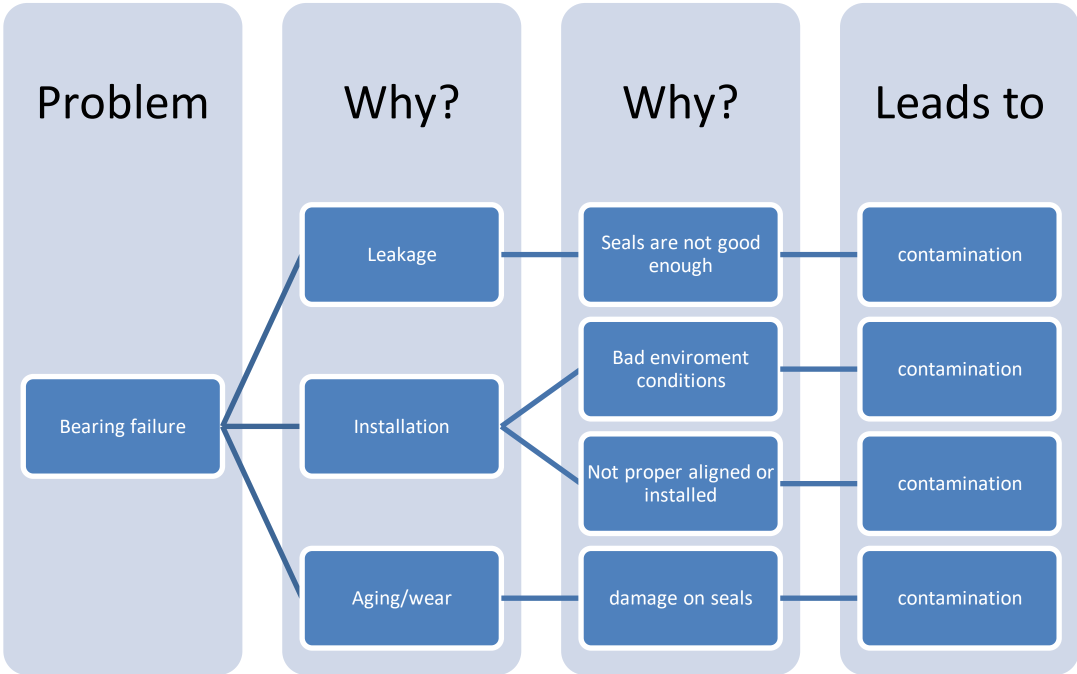


Figure 5. 11: RCA bearing failure

As seen in figure 5.11 the sealing mechanism is essential for avoiding contaminated bearings, which eventually will lead to a bearing failure. To find the root cause of this contamination there is done further investigation to why the sealings fail.

Damaged seal

It is advised to implement an inspection routine of every seal and define its state when a bearing failure occurs. By doing this the degradation of the seal will become evident and an evaluation can be done. Evaluation of this information will provide a good basis for determining whether damaged seals is the cause of bearing failure.

Figure 5. 12: A worn out seal next to a new one

Installation

Making sure the SOP for bearing installation is followed through correctly should eliminate any chance of misalignment. It must be stressed that cleanliness during mounting of the bearing is extremely important.

Wrong seal

If the two former possible causes have been eliminated and there still is a problem with contamination, a new sealing or sealing method should be implemented. It should be provided data and information to the sealing manufacturer to see if there exists a better solution that fits this plant and its processes.

5.6 Suggestions

After several meetings and discussion with Elkem there has been worked out several suggestions for improvement regarding contamination that leads to bearing failure.

Covers can be placed around the bearings and by having overpressure inside the box it will prevent microsillica to enter the bearings. This solution should work well if installation of bearings is kept as clean as possible. In this solution there will be an economical investment regarding the production of the boxes and the air supply. Where air supply is already installed for other purposes, leaving installation of a reduction valve on the box.

There is also a possibility to change the lubrication method and use oil-lubricated bearings. This will give a continuous lubrication of new oil and contaminated oil will be changed continuous with new filtered oil. However, there is great costs associated with rebuilding and implementation of oil aggregates. It is also a risk related to leaks in the oil lubrication system, and a leakage of oil in this environment is highly unwanted.

Replacing the current seals with seals more suitable to the wear and environment. SKF has the same type of TSNA L seals in materials that withstand abrasive wear in a much higher rate than the seals that are used today. Changing seals may extend the lifetime for the seals and therefore the lifetime for the bearings.

Another possible solution can be to replace the bearings with closed bearings. Then a three-barrier solution is achieved that can resist contamination even if the particles enter the bearing house. The bearing itself is lubricant free, meaning it has its own lubrication inside the closed seals. If particles then contaminate the bearing house, the bearings which has its own seals will withstand the particles. In this case, bearings on both sides must be replaced with BS2-2217-2RS / VT143 [16]. Since this bearing is wider, the spacer rings in the drive side housing must be changed to FRB 8.5 / 150 [13], while those on the non-drive side must be removed so that spherical bearing can move axially. The bearing houses can then almost be completely filled with grease since the speed is as low as 45 rpm.

Figure 5. 13: SKF BS2-2217-2RS / VT143 [16]

6. Discussions and recommendations

6.1 RCM

One of the most important aspects of the RCM process is having a good understanding of how the plant and its processes work, as well as having a good understanding of the function of each item. The importance is reflected when making decisions based on the functions that affect the system. In this thesis the filtration plant has been evaluated and a lot of time has been spent understanding the process and what is required for all components to perform their function. A good effect of an RCM analysis is that the plant is carefully studied which leads to increased competence for all participants, but it can also point out important aspects for extern personnel.

Essentially, the goal is to achieve a cost-effective maintenance with a focus on safety, the environment, availability, and costs. Listed below are some of the outcomes that contributed to this.

Identify critical items and their processes

When implementing RCM, the goal is to utilize components lifetime by performing maintenance. By identifying critical equipment an overview of which items are critical and important to the process is created. In the RCM analysis carried out here, the impeller of the main fan was weighed as a critical item with special regards to environment, production, and cost. Therefore, it was chosen to perform NDT testing during inspection, to detect ongoing failures and potentially prevent sudden breakdown.

Data collection

All decisions are ultimately based on quantitative or qualitative data. Data that provides information on maintenance, failure modes or mechanisms can be major contributor in a decision or conclusion. The data collected may also provide useful information for the operators understanding of the plant and be used for similar cases in other processes in the company.

Safety

Safety for people, the environment and equipment are one of Elkem Bremanger's main priorities, as well as the focus of RCM. Equipment and processes that have a high risk associated with HS&E are carefully investigated to avoid the occurrence of failures. The result of this assessment will lead to a safe operation, focusing on the condition of the critical equipment. In this assignment, a major focus was placed on both the main and the flush fans, which could pose a threat to the environment in the event of a failure. It was therefore recommended that vibration and temperature measurements was performed continuously, while a detailed assessment of the equipment is carried out through NDT and visual inspections.

Non-critical items

As stated earlier, the goal is to achieve a safe and cost-effective operation through maintenance. And through the mapping of non-critical items, there will be established an overview of which items that are not critical to safety, the environment, availability, or costs. This equipment can then be chosen for non-scheduled maintenance. This saves both time and money on unnecessary maintenance and frees up resources which then can be spent on critical processes and equipment. In this thesis it was found that it is not necessary or economically justifiable to carry out preventive maintenance on the bearings associated with the paddle conveyor on the filter.

Mentioned above are some of the benefits of conducting an RCM analysis of a plant or a process. Another positive outcome will be the increase of knowledge of operators and professionals working at the facility by including them in such a process. Of course, there are many more benefits, but it is also important to see RCM as a continuous improvement process. It is mentioned in SAE JA 1011 that one can obtain erroneous and imprecise RCM analyzes, depending on the data collected for the analysis. Plant conditions, environmental and safety requirements can change. A periodic review of both the maintenance strategy and the RCM framework can achieve continuous improvement in the maintenance work.

6.2 Bearings

In the second part of the report, an analysis was prepared to give insight into the possible failure causes that could cause the bearing to fail long before its lifetime. The data collected and provided to us during this analysis was in many cases incomplete or unspecified, leading to an uncertain analysis. An FMECA and RCA were conducted to identify possible causes that could result in a failure. With the information available and in collaboration with Elkem, a subjective approach was used. Based on a combination of the data available and the experience of Elkem's employees.

Measures were presented both for data collection, installation and inspection routines that could help find the cause of failure. All parts of the assembely were evaluated in collaboration with the supplier and Elkem, and the bearing, bearing housing, grease and seals was of the correct choice.

After reviewing the information and discussions, it was established that contamination was most likely the reason for the rapid bearing failure. Even though there was not enough data to be certain there was enough information to back the assumption that bearings fail because of the heavily contaminated environment.

By the end of the report there was not enough reliable documentation to be certain of how contamination and other causes contribute to this failure. Showing the importance of their routines regarding installation, maintenance and how they collect the data. By focusing on the general aspect of data gathering, procedures it was enlightend how this information could be used to prevent these failures.

6.3 Challenges and limitations

Performing an RCM analysis can yield good results on the plant, processes, and equipment under evaluation. But such analysis will rarely go without challenges and limitations. The analysis requires good cooperation between the people involved. When working in teams there will be multiple meetings, discussions, exchange of information and other expertises. This can be demanding because of geographical distances between the company and the personell that implement the analysis, it is also often a challenge for everyone to be present at the same time. This year has also been particularly demanding due to the corona pandemic which has made meetings and gatherings difficult. In this theis, much of the information and discussions have been done by phone or e-mail, as well as visiting the plant at Elkem Bremanger. During the stay most of the technical documentation was reviewed and discussions regarding function, performance, COF, failure modes, effects as well as challenges regarding their maintenance tasks.

A limitation that was experienced throughout this thesis was the lack of specified data and logged maintenance routines. This applied to both the RCM analysis, but especially when it came to the root cause analysis regarding bearing failure. The bearing failure had occurred many times but there was not enough detailed data regarding the failures. It then becomes difficult to make any evaluations or recommendations based on a quantitative method since nothing could be determined for sure.

The process of implementing a RCM analysis can be challenging by itself, which was experienced in this thesis with more than one of the aspects. In the very start at the system breakdown and definition, it became challenging to decide the correct level for breaking down the process and its components. For example, when an electrical motor fails the cause of failure could come from a low-level component such as the brushes inside the motor. If every item were broken down in such low level, there would be thousands of components in this thesis, making it extremely hard and time consuming to analyze.

Another challenge that was experienced was defining every item in the FMECA by their risk regarding safety, environment, availability, and cost. Not only does it require a lot of understanding for every single item under evaluation, but also the company's internal guidelines. When ranking every failure mode there is always a worst-case scenario and a best-case scenario when it occurs, which leads to a challenging decision. For example, when a bearing failure at the main fan occurs, will it pose any risk for the safety of personell? If the failure leads to the bearing house breaking apart it could, if it happens before the trip switch stops the fan and there are people close by. The probability for the bearing house to break, and at the same time people are close to the fan is however extremely small.

The most challenging part of the root cause analysis regarding the bearing failures was the lack of data and determining how detailed the analysis should be. Describing failure modes, causes and mechanisms was limited by the data, but it was also hard to know how deep you should go to find the root cause of the failure. When in theory the root cause analysis could continue almost forever.

6.4 Results

The result of the RCM analysis is shown in table 4.13, which is the RCM decision worksheet. This shows the recommended maintenance task for all the critical items that were chosen for further evaluation. The analysis covers the coarse separator to the redler, where all subsystems in between are discussed in detail. This worksheet is the product of the main steps in the RCM analysis that were chosen for this project.

Table 3.2, 3.3 and 3.6 is covering the risk analysis that has been done in the FMECA, these tables were used to determine the value of risk and the consequence regarding safety, environment, availability, and cost for each of the items included in the FMECA.

In table 4.1 the functional failure analysis is shown, describing which functional failures that could occur in each sub subsystem. It also gives an overview over which items the sub-system contains. Which is further explained in the hierarchy of every sub-process.

There is established an FMECA worksheet for every sub-system in this thesis, which is the foundation for the proposed maintenance task presented. The FMECA gives information about the plant, sub-process and which item that are under investigation. It then gives valuable data regarding the functional failure, failure mode, failure cause, etc. This data is then turned into valuable information that is used to determine further work on the specific item.

When the bearing failure analysis was implemented, there was not enough documented and reliable data on how the contamination or other causes contribute to the bearing failure. Establishing the importance of routines, installation and how data are collected. In Chapter 4.4 there is established a proposed task for how Elkem Bremanger could gather data that would be sufficient in determining the root cause of failure in the future. Based on subjective opinions between the authors and professional at Elkem Bremanger there was in Chapter 5.6 presented possible suggestion that could help increase the lifetime of the bearing.

6.5 Recommendations for further work

Although the RCM process has been applied and a maintenance program has been recommended for the processes in the filtration plant, the outcome could still be improved. RCM analyzes often tend to be imprecise because of lack of data and information regarding parameters, failure modes, MTBF, etc. Therefore, there should be a continuous work regarding the RCM to always develop the analysis. I this thesis there are most likely some incorrect outcomes because of the lack of precise data.

The outcome of the bearing failure analysis was mostly based on qualitative information leaving us with an imprecise result. While the suggestions made from the analysis most likely will give good results regarding the lifetime of the bearing, there could be done further work to accomplish a better result and solution. Some recommended actions for further work regarding the RCM and the bearing failure is listed below:

Implement a standard practice for logging and collecting data in the process plant. This should include the likes of failure modes, mechanisms, intervals and MTBF. By collecting data that is precise and determined, the process of turning the data into valuable information will be easier and benefit the maintenance work in the future.

The bearing failure analysis will be a good fundament for further work, when there is gathered enough data to make decisions based on a quantitative method, the process should continue. The analysis could also be a fundament for other similar issues where the root cause has to be resolved in other to make a decision.

To ensure reliability and progress, both the FMECA and the data used in this analysis should be renewed and overlooked continuously. And by using the experience from this analysis combined with monitoring, data gathering and the experience from the operators and mechanics the result should improve over time.

7. Conclusion

The objective for this thesis was to develop a RCM based maintenance program for the filtration plant at Elkem Bremanger and to find the root cause of the bearing failure at their paddle conveyors. Both approaches have been described theoretically and then been applied to the filtration plant and the bearings at Elkem Bremanger. The RCM process started with studying the plant, its processes, and different components. Understanding how the plant and its processes are built up and how they work is one of the most essential parts in the RCM. With this knowledge there was established system definitions, system breakdown, risk valuation, FMECA, critical failure selection and at the end the maintenance actions were recommended.

There is a strong belief that the selected maintenance program for the filtration plant will help preserve good maintenance routines, were the lifetime of the asset is utilized and waste of resources are reduced. Still the RCM should not be expected to be flawless and perfect, there may be functional failures, failure modes or other factors that have been overlooked. Therefore, the RCM should be renewed and overlooked at a regular interval.

The root cause analysis of the bearing failure started with a closer look to the assembly, environment, and the general working conditions for the bearings. The technical information was evaluated together with the procedures and the data available. The lack of reliable and precise data made the analysis difficult and it could not be done in a quantitative method. Therefore, some suggestions were made that could make both the collection and the data more suitable for future decisions. Based on a subjective approach there was made an FMECA that lead to a study where contamination was the cause of the bearing failure. Even though we cannot be certain, we believe that the root cause is contamination and that this leads to a shorter lifetime than expected.

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