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MASTER'S THESIS

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Writer: Leif André Larsen Hansen	……………………………… (Writer's signature)
Faculty supervisor: Professor Tore Markeset External supervisor(s): David Vestvik, Oceaneering Asset Integrity	
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Abstract

The purpose of this master thesis is to develop data-driven mathematical models to “simulate” an equipment lifecycle over a period of time to reveal the associated effects like survival curve and hazard rate. The failure frequency or the hazard rate is input to a cost/benefit analysis with cost of failure and cost of maintenance to find the optimal maintenance interval. Furthermore a baseline preventive maintenance program made with Reliability Centred Maintenance methodology is compared with the PM-program optimized with use of the data-driven methodology.

The model is tested and used with a sample size of 100, random sampled over a period of 10 years and uses OREDA failure mode dataset with Mean failure rates as input. Survival Analysis is developed with use of Lifelines resulting into estimated survival (reliability) function with and the Kaplan Meier estimate and estimated Hazard rate with the Nelson Aalen estimate.

The study shows potentials of cost savings using data-driven modelling; however the most beneficial is that the data-driven modelling results into a decision basis for cost/benefit analysis for optimizing maintenance. Decision basis support like chance of asset survival for a given time interval, MTTF (Mean Time To Failure) and hazard rate.

Last but not least recommendations for further work are discussed.

PREFACE

This thesis is written as the last step to complete Master of Science in Technology and Operations Management at University of Stavanger. It has been a privilege to write this thesis in co-operation with my assignor, Oceaneering Asset Integrity in Stavanger and Trondheim, Norway. We have started with some experience concept data, but eventually learnt more on the analysis and modelling subject to give a better decision support.

First I would like to thank my tutor, David Vestvik, Maintenance Specialist, at Oceaneering Asset Integrity in Stavanger, for continuous help and guidance.

Secondly I would thank my tutor, Professor Tore Markeset, Dr. Ing and Head, Dept. of Industrial Economics, Risk Management and Planning, at University of Stavanger, for help to getting started and continuous follow up.

Thirdly I would thank Haaken Ahnfelt, PhD and Asset Management Specialist, and Daulet Moldabayev, Asset Integrity Engineer both at Oceaneering Asset Integrity in Trondheim for their input and continuous help especially on the analysis and modelling part.

Finally I would like to thank my family in my partner Marit Irene for showing me support and greatness in taking all my responsibilities at home in this period, and also thank my daughter Era Isabell for showing patience.

Sincerely,
Leif André L. Hansen

Table of Contents

1. Introduction

This chapter introduces the background of the thesis and the aim of the research. Furthermore delimitations are explained and thesis outline is presented.

1.1 Background

Maintenance is a one of largest contributors within the operating cost. Maintenance contributes with increased add-on value by life extension and risk reduction to ensuring safe and reliable operations.

According to a graphical overview *Investment and operating costs* from Norsk Petroleum (2016) [see appendix A], the maintenance spending of oil and gas companies on the Norwegian continental shelf (NCS) in 2013 is record high at 19.2 Billion NOK, which represents about 30% of the operating costs. Companies are realizing the importance of maintenance. To improve maintenance management effectiveness and efficiency, several service companies likes of Oceaneering have established that provided knowledge and technology based services within integrity management.

With the high activity level on the NCS in recent years resulted in steep growth in investment and operating costs. The sudden drop of oil prices in 2014 forced the chain of companies in the oil and gas industry to be reversed, to adapt to the lower cost and lower activity level. Companies now work hard to improve profitability by operating more efficiently and reducing costs. This has led transition and rethinking on the agenda.

Christer (1999) and Péres (1996) referred in Rausand, M. & Høyland, A. (2004, p. 362) states that maintenance management traditionally has been a reverse engineering activity, where the decision process has been highly correlated with the technical and mechanical education of the maintenance staff and their own practical experience. And that the technical experience is essential, but should not be the only basis for maintenance related decisions.

Choose the “best” maintenance task at the “best” possible time is a complex task. Depend on current state of the item, future factors like the consequences of this choice for the long term exploitation of the item.

Christer (1999) and Scarf (1997) referred in Rausand, M. & Høyland, A. (2004, p. 362) additionally recommends to establish mathematical models that can be used to assess the impacts of maintenance decisions. This approach seems to give promising results but has not yet been sufficiently developed in an industrial context.

Oceaneering Asset Integrity (OAI) within the Integrity Management department is currently using RCM methodology for maintenance planning. Today the maintenance planning is based on assumptions built on subjective experience from previous work and inherited best practices in the maintenance concepts and strategies. OAI is looking for a confirmation of effects and methods by use of data-driven maintenance planning and mathematical models to develop that seems to give promising results for both customer and company itself. It will provide an objective result for an informed decision making, integrity assurance and maximizes the return of efforts. By using mathematical/stochastic models it may be possible to “simulate” maintenance strategies and to reveal the associated effects and maintenance costs and operational performance. The simulation may, in some cases, be used to determine the best maintenance strategy to implement.

1.2 Problem Description

The main objective of this thesis is to study effects and quantitative methods by use of data-driven planning on preventive maintenance programs built with use of reliability centred maintenance methodology with respect to LCC (Life Cycle Cost) in order to optimize integrity management within the oil and gas industry.

What types of equipment will this data-driven mathematical/stochastic models work with?

What are the differences in maintenance planning using RCM methodology versus data-driven?

How to find a mathematical/stochastic model to “simulate” maintenance strategies and to reveal the associated effects and maintenance costs and operational performance?

1.3 Aim of the Research

This master’s thesis aims at doing performance based assessment of maintenance management related functions within the oil and gas industry. The purpose with this thesis is to study the effects and quantitative methods within the oil and gas industry by use of data-driven maintenance planning with respect to LCC (Life Cycle Cost) in order to optimize integrity management with regards to minimizing cost and reducing downtime, without compromising risk.

1.4 Limitations

The limitations of this thesis are:

1. Limited systems, equipment and maintenance packing have been considered in this thesis.
    - Systems:
        - Utility system 7xx SFI. These systems can be seen as equal systems between an offshore platform and a rig
    - Equipment:
        - Large heavy machinery: Main engine failure modes ~10 to 20
        - Small: Pump, Electrical Motor, including belonging equipment as Valves, Transmitter within shutdown limits.
    - Packing or bundling:
        - Functional-based package versus round jobs
        - EX-check on safety critical equipment as round jobs
2. The consequences considered in this thesis are based on the failure mode “loss of function”. Consequences based on failure mode “does not work as intended” failure of equipment are not considered.
3. Consequences related to HSE, cost and production are considered in this thesis. However, cost and production cost are fixed.
4. Data sample is from Norwegian Oil and gas industry NCS and OREDA. It does not cover all industries.

Exploit the effects of selecting different types of maintenance strategies:

- Strategy 1 – Low focus on PM, plans with Run-to-failure strategy (cost of corrective maintenance) – High risk
- Strategy 2 – PM on almost everything – Low risk
- Strategy 3 – Plans made with failure rate and optimized interval. PM on an optimal level. Prolong intervals based on risk and cost effectiveness. Documented with regards on risk and cost. How much under the acceptance criteria is «accepted»? Example acceptance criteria of 5/200. While maintenance test history/records are saying 0-1 failure of 200. Can the maintenance interval be prolonged? And what is the “optimal” interval?

1.5 Scope of Work

The project shall look into the following:

Choose two to four datatypes to use in addition to regular planning variables:

- Maintenance planning cost
- Scheduling and work order levelling
- Plan size
- Spare part and spare part cost

Project tasks:

1. *Task-1: Decide attributes to be used*
2. *Task-2: Data collection. Are attributes obtainable?*
3. *Task-3: Create a baseline PM (Preventive Maintenance)-program*
4. *Task-4: Define and calculate KPI (Key Performance Indicators) for baseline PM-program*
5. *Task-5: Optimize PM using additional attributes and quantified methods*
6. *Task-6: Calculate KPI for optimized PM-program*

1.6 Delimitations

This project is limited to 34 weeks available for this master's thesis project. However, working 100 % at 37.5 hours/week there is less available productive hours than normal master thesis. Due to this limitation the study will not investigate in spare part, spare part cost with whole LCC costing. Quantitative data describing the failure rate will be gathered only within the limited systems and selected equipment.

1.7 Deliverables

Deliverables are maintenance optimization products with customer value for decision making assisted by mathematical methods on data-driven maintenance planning.

- PM-planning program with optimized maintenance and spare parts.
  - Scheduling
- Report with total impact cost maintenance cost.
  - Spare parts for maintenance purpose are only taken into consideration
  - Routine job is not taken into consideration
- Report with Workload analysis cost and PM schedule overview

1.8 Thesis Outline

The outline of the thesis is the chapter 1 the introduction part. Chapter 2 is theory used in this thesis, and chapter 3 explains the research method used for analysis, both chapters are preparatory parts. This section is followed by chapter 4, analysis of the optimization of the maintenance intervals and chapter 5 with discussion of the findings and future work. In chapter 6 the analysis and discussion part ends with conclusions and summary of the work. Finally there are supportive parts of references and appendix.

2. Theory

This chapter consist of a theoretical reference framework. Research and theoretical views pertinent for the thesis are presented.

The aim of the framework is to introduce maintenance and maintenance management.

2.1 Overview of Maintenance

Maintenance is a vast term and there are several various explanations and definitions of this it in use. For this thesis the definition from NORSOK Z-008 3rd edition (2011) is chosen:

> Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function. (p. 9)

2.2 Types of Maintenance

2.2.1 Preventive maintenance

Preventive maintenance, PM, is defined by NORSOK Z-008 (2011) maintenance performed at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the function of an item.

2.2.2 Corrective maintenance

According to NORSOK Z-008 (2011), corrective maintenance, CM, is maintenance carried out after a failure and set the item back into a state where it can perform its required function.

2.3 Maintenance Management

For this thesis the definition for maintenance management is from NORSOK Z-008 3rd edition (2011) is appropriate:

> All activities of the management that determine the maintenance objectives, strategies, and the responsibilities and implement them by means such as maintenance planning, maintenance control, and supervision, improvements of methods in the organisation including economical aspects (p. 9).

Maintenance stated in the activities regulation §45 (Norwegian Petroleum Safety Association [PSA], 2016):

> The responsible party shall ensure that facilities or parts thereof are maintained, so that they are capable of carrying out their intended functions in all phases of their lifetime.

Classification stated in the activities regulation §46 (Norwegian Petroleum Safety Association [PSA], 2016):

> Facilities' systems and equipment shall be classified as regards the health, safety and environment consequences of potential functional failures.

> For functional failures that can lead to serious consequences, the responsible party shall identify the various fault modes with associated failure causes and failure mechanisms, and predict the likelihood of failure for the individual fault mode.
> The classification shall be used as a basis in choosing maintenance activities and maintenance frequencies, in prioritising between different maintenance activities and in evaluating the need for spare parts.

Maintenance effectiveness and continuous improvement stated in the activities regulation §49 (Norwegian Petroleum Safety Association [PSA], 2016):

> The maintenance effectiveness shall be systematically evaluated based on registered performance and technical condition data for facilities or parts thereof.
> The evaluation shall be used for continuous improvement of the maintenance programme, cf. Section 23 of the Management Regulations.

Guideline:

> Maintenance effectiveness as mentioned in the first subsection, means the ratio between the requirements stipulated for performance and technical condition and the actual results.
>
> The standards NS-EN ISO 14224 and NS-EN ISO 20815, Appendix E, should be used when registering data as mentioned in the first subsection, including failure data and maintenance data.

2.4 Reliability Centred Maintenance

RCM definition from NORSOK Z-008 3rd edition (2011):

> Method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation (p. 10).

Woodhouse (2014, p. 39) claims that methods such as FMEA, RCM and other ‘risk-based maintenance’ approaches that treat each failure mode individually may miss important combinational effects, such as the fact that a new risk may be introduced by a proposed maintenance activity. He further states that the methods are reliability centred, aimed at predicting, preventing, correcting or mitigating functional failures and their consequences. So RCM is not good at revealing tasks aimed to slow down degradation rates and extend life (e.g. painting or lubrication), or to raise/recover operational efficiency (e.g. cleaning of heat exchangers) where there is no discrete point of the asset having 'failed'.

RCM identifies the ‘technically appropriate’ maintenance method, but not whether the solution is the most cost-effective option or what is the right amount of the activities (e.g. interval or timing).

Local Effect:

- Degraded Function
- Loss of Function
- No immediate Effect
- Unsafe Failure

“Hidden Failure is a failure that is not immediately evident to operations and maintenance personnel.” NORSOK Z-008 (2011)

2.5 Life Cycle Costing

The abbreviation LCC is used for Life Cycle Cost and Life Cycle Costing. Life Cycle Costing is an analysis tool for economic analysis and engineering analysis according to Markeset (2015, p. 139) in his slides about Introduction to Maintenance Engineering. He further states that results of an LCC analysis may be used as a decision basis for:

- Selecting equipment and production systems
- Optimizing cost and benefit for selection alternative production schemes
- Modifications of existing systems/machines/equipment
- Investments in new and improved technology
- Selecting machines/equipment from different suppliers

Life Cycle Cost (LCC) definition from ISO 15663-1:

> Discounted cumulative total of all costs incurred by a specified function or item of equipment over its life cycle (p. 3).

Life Cycle Costs are all costs related to acquisition and utilization of a product over a defined period of the product life cycle. Life Cycle Costing definition from ISO 15663-1:

> Process of evaluating the difference between the life cycle costs of two or more alternative options (p. 3).

Life Cycle Costing is also known as Cost Benefit Analysis (CBA).

Cost Type	*Cost Drivers*
Procurement Cost	
Operational Cost	• Operating personnel • Operator training • Operational facilities • Support and handling equipment • Energy/ utilities/ fuel
Maintenance Cost	• Maintenance personnel and support • Spare/ repair parts • Test and support equipment maintenance • Transition and handling • Maintenance training • Maintenance facilities • Technical Data • System/ product modification
Disposal Cost	

Table 1 - Mapping of Cost Drivers adapted from Markeset (2015, p. 142)

2.5.1 Maintenance Related Cost

Woodhouse (2014, p. 25) claims that the word ‘Optimized’ is overused, and often misused. But ‘Optimized’ is the correct term for the best value compromise between competing objectives – which is what management decisions seek to deliver.

“The optimum is the point where the total value (sum) of all costs, risks, performance losses etc. is at its lowest combined ‘cost’ to the business” Woodhouse (2014, p. 25). The optimum point is also illustrated as C_{MIN} in Figure 1.

Markeset (2015, p. 187) illustrates in figure 1 maintenance related cost over percentage level of preventive maintenance. The horizontal axis on the graph shows the percentage level of preventive maintenance. The vertical axis on the graph shows costs in \$. He further explains that maintenance related costs are here divided into types like basic (routine) services (C_{BS}) with activity groups like cleaning, greasing, lubricating, adjustment, etc. Predictive and Preventive maintenance (C_{PM}) are activities like inspection, condition monitoring, functional testing, overhauling. While Corrective maintenance (C_{CM}) are activities like replacement of parts or exchange of equipment. Failure consequence costs (C_{RISKEX}) are costs like HSE (Health, Safety and the Environment), Production / services, Material damage, and damage to reputation. Total maintenance costs C_{TOT} are summarized C_{PM} + C_{PM} + C_{CM} + C_{RISKEX}. Part of RCM goal is minimum maintenance costs, where C_{MIN} is the minimum of C_{TOT}.

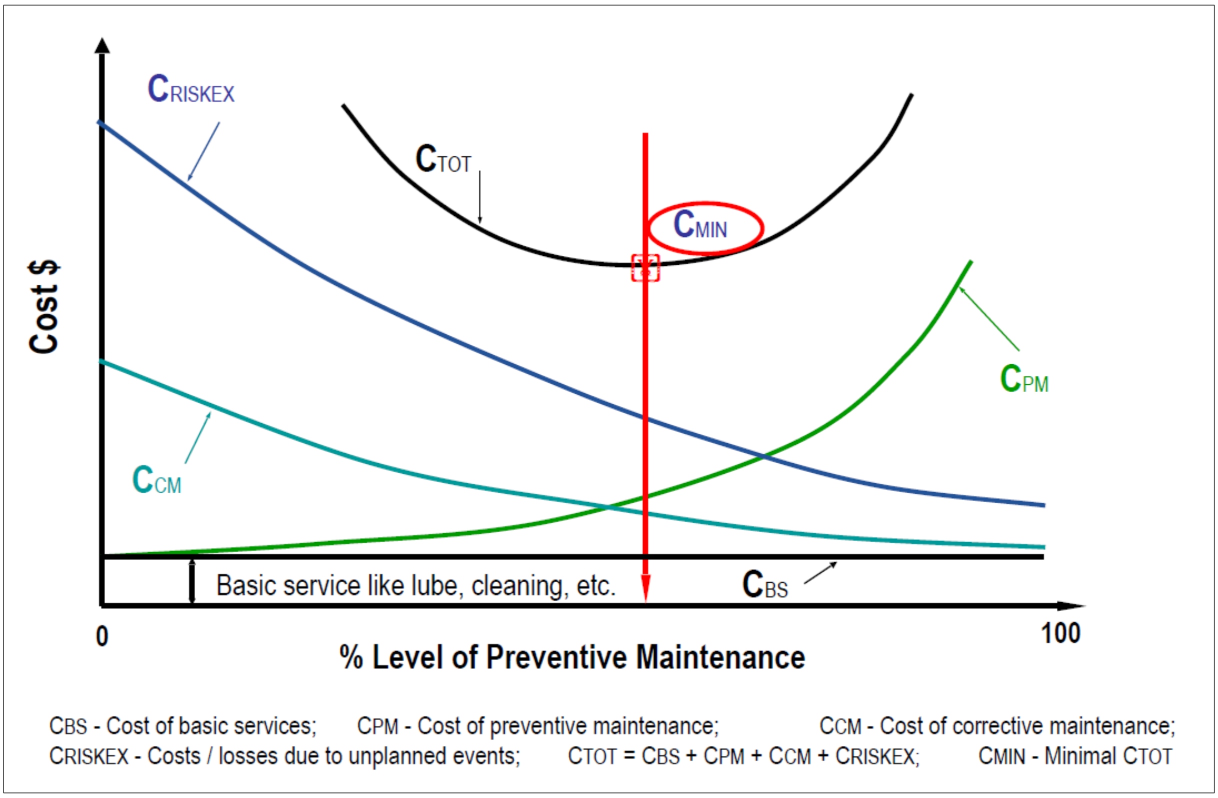


Figure 1 - Maintenance related costs (adapted from Markeset (2015, p. 188)

2.6 Technical Hierarchy

NORSOK Z-008 (2011, p.16) states that the technical hierarchy is a corner stone in maintenance management. Also that it describes the technical structure of the installation by giving functional locations unique identifiers. The technical hierarchy provides an overview of equipment units that belong together technically, and shows the physical relationship between main equipment, instruments, valves, etc. The technical hierarchy should be established at an early phase to give an overview of all the tags/equipment and how they are related. The purpose of the technical hierarchy is as follows:

- show technical interdependencies of the installation;
- retrieval of tags, equipment and spare parts;
- retrieval of documents and drawings;
- retrieval of historical maintenance data from CMMS;
- planning of operations (e.g. relationships due to shutdown etc.);
- cost allocation and retrieval;
- planning and organization of the maintenance programme;
- planning of corrective work.

2.7 Consequence Classification

Functional based Norsok Standard Z-008

Definition from NORSOK Z-008 3rd edition (2011):

> Quantitative analysis of events and failures and assignment of the consequences of these. (p. 7)

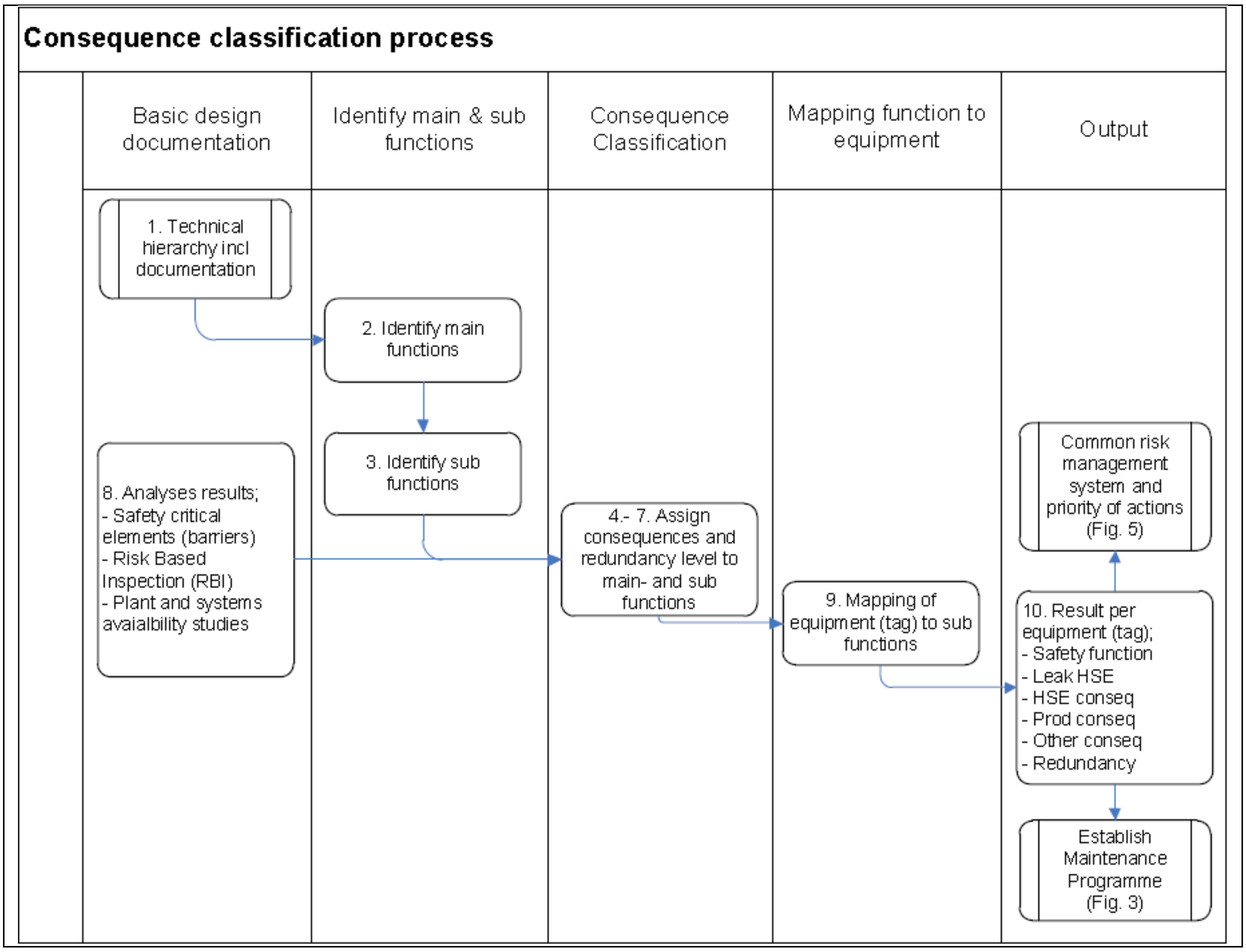


Figure 2 - Consequence classification process, adapted from NORSOK Z-008 (2011) (p.18)

Consequence classification work process described stepwise NORSOK Z-008 (2001):

Table 2 - Consequence classification work process, NORSOK Z-008 (2011) (p.18)

No	***Step***	***Activity***
1	Technical hierarchy	The established technical hierarchy including documentation is used to identify systems and equipment which is subject to consequence classification.
2	Identify MFs	- Each plant system should be divided into a number of MFs covering the entire system. - The MFs are characterized by being the principal tasks in the process such as heat exchanging, pumping, separation, power generation, compressing, distributing, storing, etc. Annex A gives an overview of typical MFs for an oil and gas production plant. - Each MF is given a unique designation consisting of a number (if appropriate a tag number) and a name that describes the task and the process.
3	Identify sub functions	- MFs are split into sub functions. In order to simplify the consequence assessment, the sub function level can be standardized for typical process equipment with pre-defined terms. See Annex B. - The standard list of sub functions has to be supplemented with other sub functions relevant for the system configuration.
4	Assign MF redundancy	- MF redundancy shall be specified, see Table 3 for example of redundancy definitions. - In case of safety systems or protective functions with redundancy due to functional reliability or regulatory requirements, the redundancy effect should not be counted for.
5	Assign MF consequences	- The entire MF failure consequence is assessed in terms of the state where the MF no longer is able to perform its required functions. - Assuming that other adjacent functions and equipment are operating normally - In this assessment any redundancy within the function is disregarded, as the redundancy will be treated separately. - Other mitigating actions are not considered at this stage, i.e. like spares, manning, and tools. - The most serious, but nevertheless realistic effects of a function fault shall be identified according to set risk criteria. See Clause 4.
6	Assign sub function redundancy	- If there is redundancy within a sub function, the number of parallel units and capacity per unit shall be stipulated, see Table 3 for example of redundancy definitions.
7	Assign sub function consequences	- The consequence on system/plant of a fault in a sub function is assessed with respect to HSE, production and cost according to the same principles as outlined for MF.
8	Input from other analyses	- Structures/pipelines and risers: These systems are not covered by this NORSOK standard, but the same classification systematic is proposed used. - Containment: For the tags/systems that are containment related, results from the RBI analysis are used to set the safety/environmental consequence of failure (leakage HSE). - Safety functions: Dedicated safety functions shall be identified via a risk assessment where performance requirements are defined such as reliability and survivability. In the classification process these systems are mapped to the tag hierarchy for readily identification in the CMMS system. The functional requirements are carried forward to the maintenance program to maintain these functions, primarily in the form of functional testing.
9	Equipment mapping to function	- The equipment (identified by its tag numbers, see Clause 6) carrying out the sub functions shall be assigned to the respective sub functions. - If equipment performs more than one sub function (e.g. some instrument loops), it should be assigned to the most critical sub function. - All equipment (identified by its tag number) will inherit the same description, consequence classification and redundancy as the sub function of which they are a part. See Annex C for an example.
10	Result per equipment	- Consequence analysis should be documented according to 7.4 and the key data stored in CMMS readily available.

Redundancy of equipment

Table 3 - Example of redundancy definition, adapted from NORSOK Z-008 (2011) (p.34)

Red	***Redundancy degree definition***
A	No redundancy i.e. the entire system is required to avoid any loss of function.
B	One parallel unit can suffer a fault without influencing the function.
C	Two or more parallel units can suffer a fault at the same time without influencing the function

2.7.1 Failure Modes (OREDA)

Severity class types definition from OREDA (2009)

Critical failure:

> *A failure which causes immediate and complete loss of an equipment unit's capability of providing its output (p. 43).*

Degraded failures:

> *A failure which is not critical, but it prevents an equipment unit from providing its output within specifications. Such a failure would usually, but not necessarily, be gradual or partial, and may develop into a critical failure in time (p.43).*

Incipient failures:

> *A failure which does not immediately cause loss of a unit's capability of providing its output, but which, if not attended to, could result in a critical or degraded failure in the near future (p.43).*

2.7.2 Failure Patterns

The six failure patterns

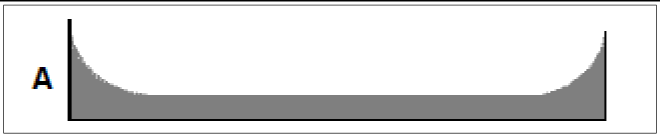
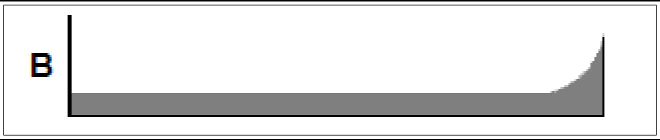
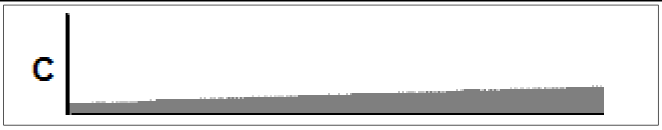
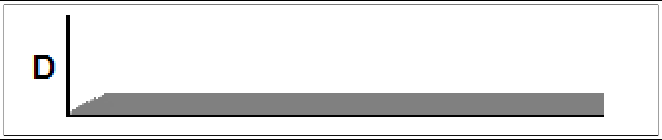
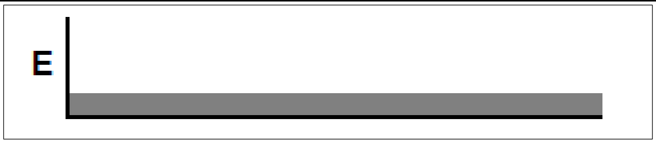
	Failure Pattern A - 'Bathtub' • Combination of 'infant mortality', 'random' and 'wear out' failure
	Failure Pattern B – 'Wear Out' • Age related failures • Linear process of deterioration
	Failure Pattern C – 'Fatigue' • Steadily increasing probability of failure
	Failure Pattern D – 'Initial Break-in period' • Wear and tear in repetitive cycles
	Failure Pattern E – 'Random' • Random failures • The conditional probability of failure is constant
	Failure Pattern F - 'Infant Mortality' • Declines with age

Figure 3 - The six failure patterns Moubray (p.235)

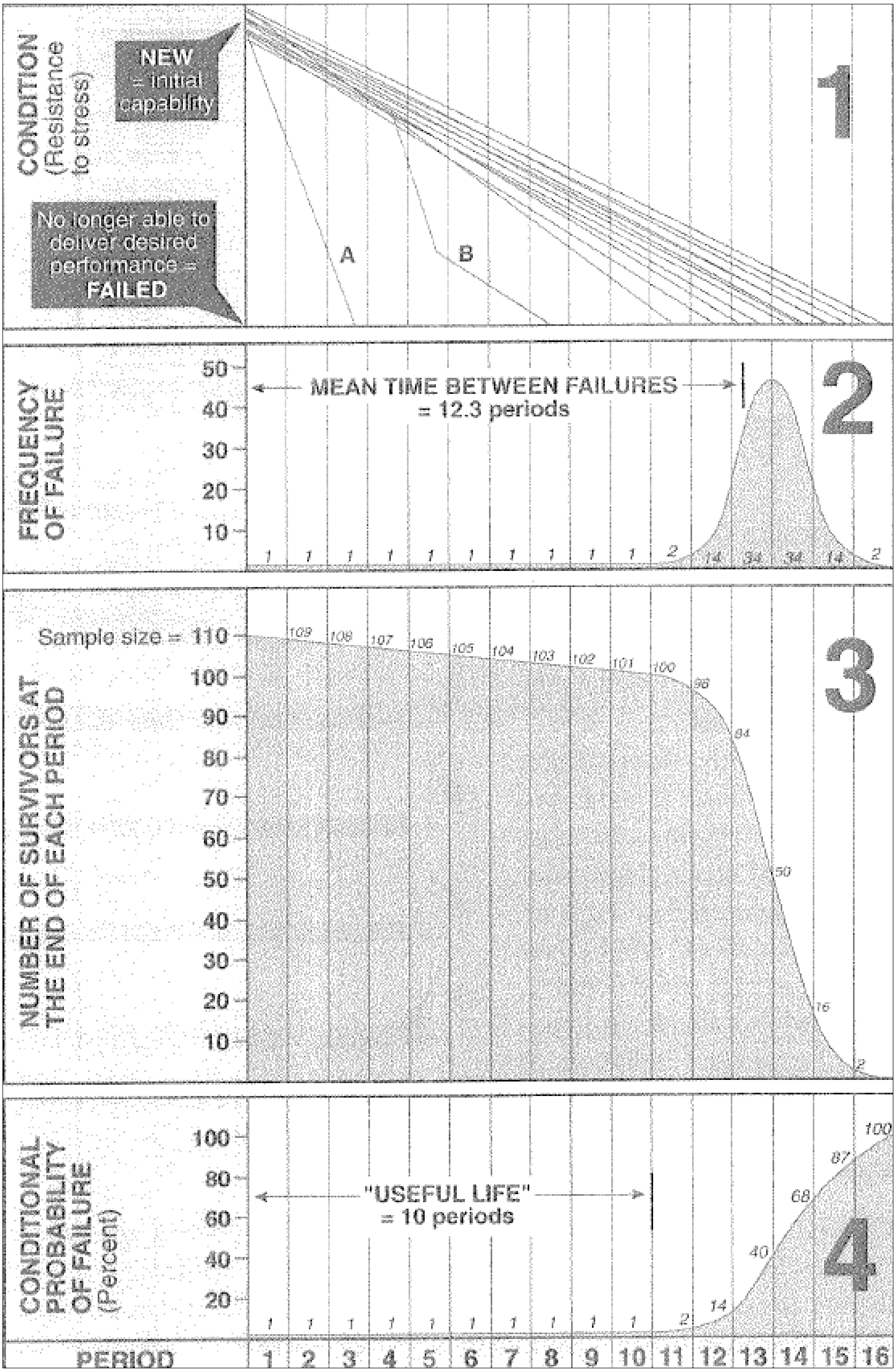


Figure 4 - Failure Pattern B (Moubray, p.236)

2.8 Generic maintenance concept

NORSOK Z-008 (2011) describes that a GMC (Generic Maintenance Concept) is a set of maintenance activities, strategies and maintenance details:

- Activity group,
- Activity type,
- Shut down required,
- Frequency of maintenance activities,
- Man hours required for activity

The GMC should be defined by a structured RCM analysis where failure modes and failure causes are identified.

OCEANEERING

Maintenance Concept, Corporate
Customer, (Installation)

Rev. No.:A1
Rev. Date:2012-12-21
Approved by: Ola Nordmann

Equipment group:	**RO-EM-AC-10**
Equipment Group Description:	**Electric Motor, Alternating Current**
Concept note:	**Applies for AC electric motors independent of voltage and design.**
Concept responsible:	**E-Electrical**

Activity Information										Interval for respective consequence				Work load	
Object	**R**	**M**	**Activity No.**	**Activity Group**	**Activity Description**	**D**	**A**	**S**	**Duration (HRS)**	**Unit**	**High**	**Medium**	**Low**	**Resource x time**	**Total man hours**
Motor															
		P	RO-EM-AC-10-02A	02 NEAR VISUAL CHECK	Near visual heck of motor for damage, noise, vibration and cleanliness.	E	N	N	0,25	M	3	6	*	ELECx0,25	0,25
	2	P	RO-EM-AC-10-51A	51 LUBRICATION	Lubrication of electric motor as per OEM.	E	N	Y	0.25	M	6	12	*	ELECx0,25	0,25
	1	P	RO-EM-AC-10-15A	15 MEASUREMENT	Megger test stator windings.	E	Y	Y	0.5	M	12	12	12	ELECx0.5	0.5

R) Note:

1	Ref: ABS Part 5, Survey After Construction
2	Where applicable. Roundabout job

Failure Mode Catalogue Profile	RO-EM-AC-A		Electric Motor, AC							
Preventive Activity(s)	**Object**	**Failure Mode ID**	**Failure Mode**	**Failure Cause**	**Failure Mechanism**	**Frequency (yrs/failure)**	**Analysis Reference**	**Local Effect**	**Local Effect Comment**	**Hidden Failure**
RO-EM-AC-10-02A	Electric motor	RO-EM-AC-A-SPO-A	SPO Spurious operation	Wear	Wear	5-10 Years	Goliat project	Loss of function	Regulating wrong	V
RO-EM-AC-10-02A RO-EM-AC-10-15A	Electric motor	RO-EM-AC-A-FTS-A	FTS Failure to start on demand	Protection trip due to overcurrent, overload & short circuit	General electrical failure	5-10 Years	OREDA	Loss of function	Unable to start	-
RO-EM-AC-10-15A	Electric motor	RO-EM-AC-A-LOO-A	LOO Low output	Voltage unbalance	General electrical failure	> 20 Years	OREDA	Degraded Function	Driven unit is not working	-
RO-EM-AC-10-51A	Bearing	RO-EM-AC-A-EXL-A	EXL External Leakage	Bearing friction, lubrication	Vibration	5-10 Years	OREDA	Degraded Function	Vibration will soon cause overheat	-
RO-EM-AC-10-15A	Stator	RO-EM-AC-A-STD-A	STD Structural deficiency	Winding failure	Vibration	5-10 Years	OREDA	Degraded Function	Winding become loose and mechanically damages insulation	-
RO-EM-AC-10-02A RO-EM-AC-10-51A	Bearing	RO-EM-AC-A-VIB-A	VIB Vibration	Bearing fracture/fault	Vibration	2-5 Years	Oceaneering	Degraded Function		-
RO-EM-AC-10-02A RO-EM-AC-10-51A	Bearing	RO-EM-AC-A-OHE-A	OHE Overheating	Bearing fracture/fault	General material failure	5-10 Years	Goliat project	Unsafe failure		V
RO-EM-AC-10-02A RO-EM-AC-10-51A	Bearing	RO-EM-AC-A-FRO-A	FRO Failure to rotate	Mechanical damage	General material failure	5-10 Years	Goliat project	Loss of function		V

Figure 5 - example of Maintenance concept, adapted from Oceaneering procedure for Maintenance concept

2.8.1 Maintenance concept information

Key to presentation of formats

Where the formats of coding elements are described in this document, the following shall apply:

Table 4 - Coding elements

A	An alpha character A-Z
N	A numeric character 0-9
Z	Either an alpha or a numeric character

Numbering form for MC (maintenance concepts):

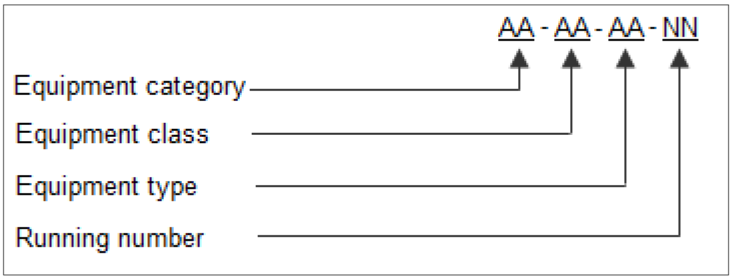


Figure 6 - Concept codes

Oceaneering procedure for MC describes MC by following equipment class from ISO 14224 Annex A and combinations with equipment type coding from NORSOK Z-DP-002 (1996) normally used as basis for ENS (Engineering Numbering Systems).

Example of RO-EM-AC-10:

- Equipment category: RO - Rotating
- Equipment class: EM – Electrical Motors
- Equipment type: AC – Alternating Current
- Running number: 10

- *Concept note* describes the scope and validity of the MC.
- *Concept responsible* is the main responsible department or discipline for the MC content.

2.8.2 Maintenance activity information

MCA (Maintenance concept activities) use the similar coding as its MC, in addition to an activity group, and activity sequence letter.

Numbering form for MCA:

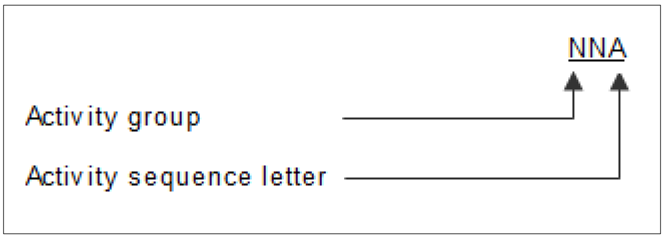


Figure 7 - Activity codes

Example of RO-EM-AC-10-02A:

- Description of concept – See above.
- Activity group: 02 (Close visual check). Activity group is inherited coding from RC/AGR era.
- Activity sequence letter: A. The activity sequence letter is to differ between same activity groups within a maintenance concept.

- Activity description is a short description of what is going to be performed in the maintenance activity.
- D-Department/Discipline; The responsible department/discipline for the activity.
- A-Authority requirement; Is the activity an authority requirement? Yes/No

- S-Shutdown requirement; Does the equipment need to be shut down to perform the maintenance activity? Yes/No
- Duration; The duration of performing the maintenance activity.
    - The duration is without planning, collecting tools and cleaning up after the work is performed. That information will be added when packing the maintenance program.
- Intervals
    - The numbers of interval alternatives for a maintenance activity is determined by the number of consequence categories. The example in Figure 2 has an interval for high, medium and low.
- Work load:
    - If work load is part of the project scope, make sure to have client personnel verify/update the duration of each activity, and what resource/discipline is executing the activities with actual working time for each resource/discipline per activity

2.8.3 Failure mode coding

FM (Failure modes) uses the similar coding as its MC, in addition to failure mode code, and failure mode sequence letter.

Numbering form for FM:

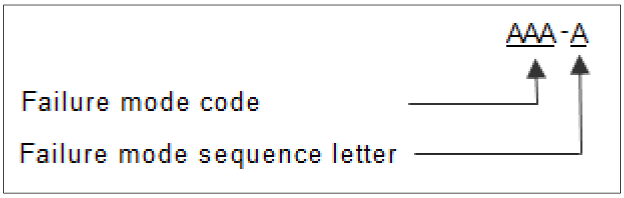


Figure 8 - Failure mode codes

Example of RO-EM-AC-10-02A-LOO-A:

- Description of MC and MCA – See above.
- Failure mode: LOO (Low output). Failure modes are according to ISO 14224.
- Activity sequence letter: A. The failure mode sequence letter is to differ between same failure modes within a maintenance concept.

2.9 Establish Maintenance Program

Work flow for establishing PM (preventive maintenance) program

Table 5 - Maintenance program process NORSOK Z-008 (2011) (p.20)

No	***Step***	***Activity***
1	Grouping and classification	Input to the process is the technical hierarchy and a functional grouping and functional classification of the plant in question. See Clause 8.
2	Safety functions	If the equipment is defined as a safety function, there should exist a Performance Standard and a safety requirement specification defining basic requirements including testing frequency for hidden failures. For safety functions with given availability requirements, there exists models for how to estimate testing time, see OLF 070 or IEC 61508. Further, for many safety systems there will exist additional maintenance tasks to be done like cleaning, lubrication, etc. which should be described in generic concepts for this equipment group. These data and tasks are then input to the PM programme.
3	Generic concepts	The next step in the process is to determine if there exist generic concepts for the equipment. If that is the case, the applicability and relevance of the concept should be checked as well as if there exist specific PM requirements from authority or company.
4	Adjustment of GMCs	The generic concepts should be evaluated for the actual case considering the production value of the plant (deferred production) and repair capacity (man-power, spares and tools) at hand to handle the most common failures. Any local adjustments should be in addition to the generic concept.
5	Risk analysis/ Assignment of maintenance activities	In case no GMC is applicable or the purpose of the study requires more in-depth evaluations, it is recommended that an RCM/RBI/SIL analysis is carried out according to IEC 60300-3-11 and DNV RP- G-101. Identification of relevant failure modes and estimation of failure probability should primarily be based on operational experience of the actual equipment, and alternatively on generic failure data from similar operations. Again, the task will involve both safety assessment and cost benefit to determine the maintenance tasks, as well as including authority/company requirements. See 9.3 for unsafe failure modes.
	Cost benefit analysis	Defining intervals are to a large extent based on engineering judgement The engineering judgement should be based on a form of cost-benefit assessment including the following factors: • consequences of function or sub-function failures and functional redundancy; • probability of function or sub-function failures and its function of time or frequency of PM activities; • detectability of failure and failure mechanisms, including the time available to make necessary mitigating actions to avoid critical function or sub-function failure; • cost of alternative preventive activities.
6	Developing generic maintenance concepts	The above RCM/RBI/SIL analysis can be transformed to a GMC for later use on similar equipment. Additional experience related to use of the concepts should be included.
7	Low consequence items	For equipment's classified with low consequence of failure, a planned corrective maintenance strategy may be selected (run to failure). However, a minimum set of activities to prolong lifetime may also be considered. See 9.3 for unsafe failure modes.
8	Establish maintenance programme	Finally, all the maintenance tasks should be packed and scheduled considering plant production plans, resources requirements, turnaround schedule, etc. to derive to the final maintenance plan.

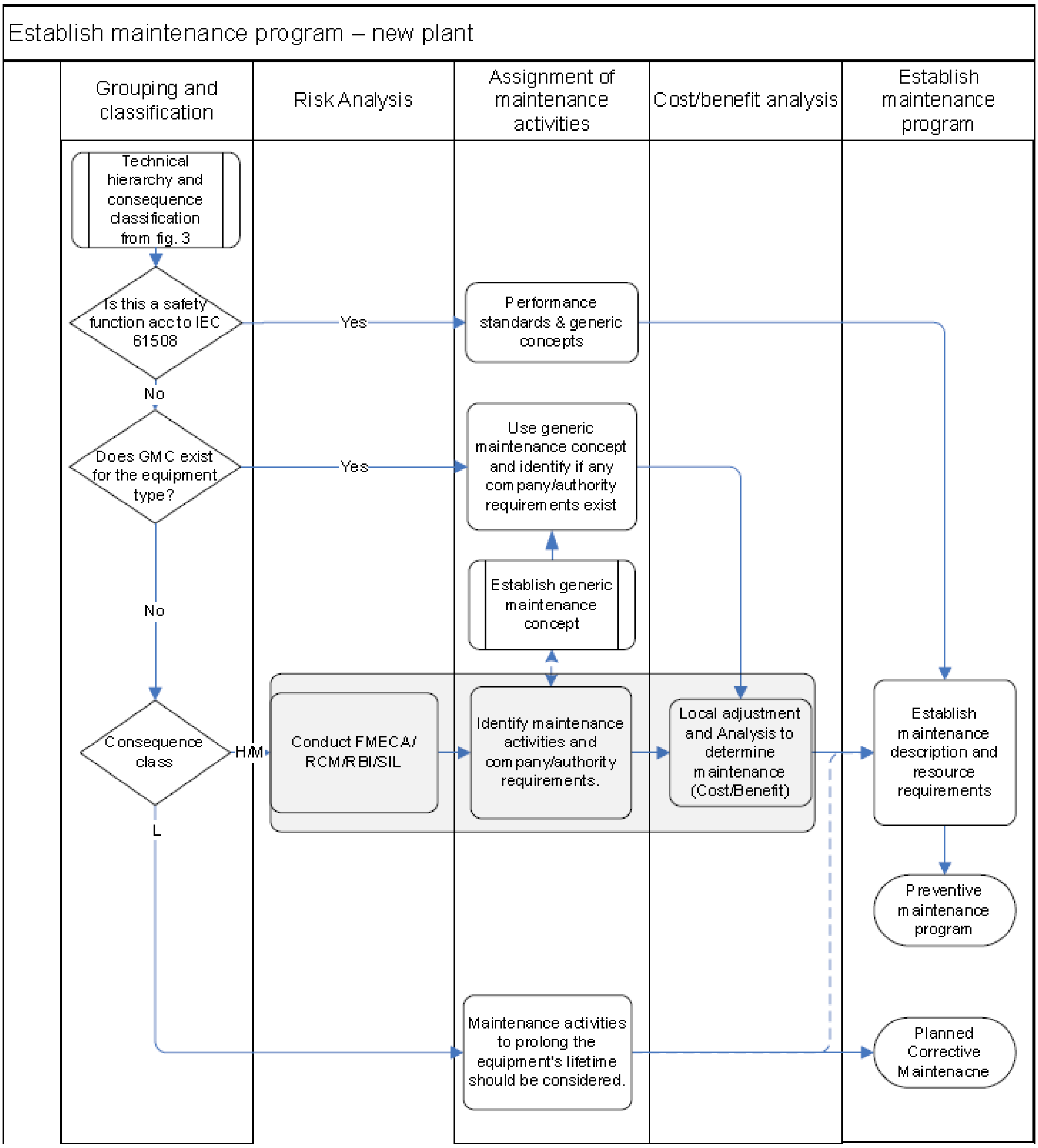


Figure 9 - Establishing maintenance programme, adapted from NORSOK Z-008 (2011) (p.21)

2.9.1 Update maintenance programme

NORSOK Z-008 (2011, p.23) states that a maintenance program needs updating at regular intervals. The triggers for such updating can be one or more of the following:

- the observed failure rate is significantly different from what was expected, i.e.:
    - higher failure rate is observed requiring a change in maintenance strategy or frequency – or replacement of the unit;
    - lower failure rate, or no observed damage at PM may point towards extension of intervals or omitting certain tasks.
- the operational environment has changed causing different consequence and probability:
    - less or more production;
    - change in product composition.
- cost of maintenance different from expected;
- new technology that could make the maintenance more efficient (like new methods for condition monitoring) is available;
- updated regulations;
- information from vendor;
- modifications.

The evaluation should be based on historical data and experience. A process diagram to update a maintenance program is shown in Figure 10. If it is a safety system, an evaluation of number of failures per tests versus PS requirements should be performed. If there is a significant change in the safety system performance stated in the PS, this information should be feedback to the overall risk assessment for the plant.

For non-safety systems a cost-benefit analysis based on experience should be performed. Based on this evaluation maintenance program and GMC (if relevant) should be updated, and implemented in the maintenance plan.

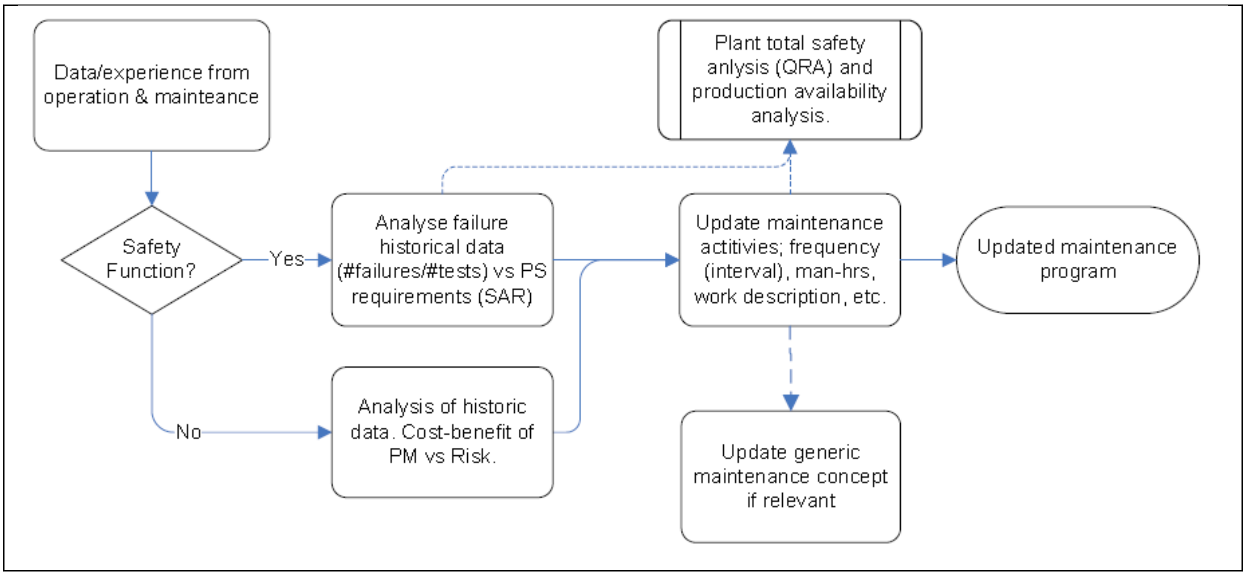


Figure 10 - Process for updating maintenance program, adapted from NORSOK Z-008 (2011) (p.23)

2.10 Survival analysis

«Traditionally, survival analysis was developed to measure lifespans of individuals» Lifelines (2016).

2.10.1 Estimating the Survival function using Kaplan-Meier

To estimate the survival function, the Kaplan-Meier Estimate, defined as:

$$\hat{S}(t) = \prod_{t_i<t} \frac{n_i - d_i}{n_i} \tag{1}$$

Where d_i are the number of death events at time *t* and n_i is the number of subjects at risk of death just prior to time *t*.

Kaplan-Meier estimator is seen to be equal to the empirical survivor function $R_n(t)$.

2.10.2 Estimating hazard rates using Nelson-Aalen

The survival curve visualizes the lifetime data; however it is not the only way. The hazard function λ(t) of a population, the Kaplan-Meier estimate cannot be transformed. Fortunately, there is a estimator of the cumulative hazard function:

$$\Lambda(t) = \int_0^t \lambda(z)dz \tag{2}$$

The estimator for this quantity is called Nelson Aalen estimator, and is defined as:

$$\widehat{\Lambda}(t) = \sum_{t_i \leq t} \frac{d_i}{n_i} \tag{3}$$

Where d_i is the number of death events at time *t* and n_i is the number of exposed individuals.

3. Methodology

This chapter consist of different aspects of the research tasks and the research process of the thesis explained in steps. It will also discuss the quality of methods used and criticism of these methods.

3.1 Research process

The process of data pre-processing, failure rate analysis, modelling, cost estimation, time to next activity and preventive maintenance scheduler steps is the framework of the methodology is shown in Figure 11 - Model design mockup.

Step 1 – Equipment boundaries and description:

Equipment boundaries are set for the selected equipment. In order to limit the scope of equipment included in the assessment and the analysis. Equipment is selected from a technical hierarchy. Equipment's function is described with its consequence classification. Tags are assessed with maintenance concepts with its maintenance activities in order to create a baseline PM program in next step.

Step 2 – Establish baseline PM program:

In this step, the preventive maintenance activities are selected for each tag based on the tag-concept linkage and following the process of establishing maintenance program from Figure 9. The input parameters from the activities are interval, man hours, shut down required. The output of tag-activities is bundled into suitable sizes of maintenance plans.

Step 3 – Identify failure modes and failure frequency:

From the equipment description a mapping to OREDA equipment taxonomy codes is described. The equipment description is then used as reference in the data gathering process. This step contains to gather, clean and structure the input data for each major failure mode used for analysis and modelling stage. This step includes gathering the parameters failure frequency and corrective man hours.

Step 4 – Failure rate analysis and modelling stage:

Failure rate analysis is done as random sampling of events. The sample failure events from normal distribution with input data from MTTF and SD as 'st_dev' for each failure mode per equipment. The parameter 'st_dev' controls the time interval where failure events take place. About 99 % of the failure events will take place in the interval (MTTF-3*st_dev, MTTF+3*st_dev). Sample size is 100, and time period range is set to 10 years. Failure rate is then estimated from the random sample. In modelling survival function (reliability) is plotted with input from the failure rate with use of Lifelines and Kaplan Meier Fitter functionality. Hazard rate is plotted with the input from the failure rate with use of Lifelines and Nelson Aalen Fitter functionality, and converted to a cumulative hazard rate with confidence interval of 95%. (See Appendix D)

Step 5 – Cost estimation:

Decision basis for cost estimation is decided by cost of failure and cost of maintenance both with input for an overall cost or total impact. Also input from the modelling is the hazard rate for each failure mode. The hazard rate is used to calculate the cost of failure. Cost of failure is estimated input parameters like cost of spares and other, corrective man hours and downtime. The output and result from the cost estimation is a report on cost (see 'optimizing PM interval' reports in analysis chapter) to find the optimal maintenance interval, which is found by the minimum total impact (see Figure 1). A sensitivity analysis is in addition for a decision range between the minimum value from highest total impact and the minimum value for the lowest total impact (see ‘sensitivity analysis’ reports in analysis chapter). A recommended interval is chosen based on the decision basis from the cost estimation (lowest possible total impact) in combination with the survival function (highest possible survival percentage) to find the “best” maintenance interval.

Step 6 – Time to next activity (Optimize maintenance interval):

Compare the effects of the maintenance intervals from baseline pm with the recommended interval for bundling based on the optimal interval. A workload table is suitable for presenting the differences in intervals and workload (see example in Table 60) for each case.

Step 7 – Optimized PM plan:

The whole bundling and levelling process is completed in this step. Until this step the recommended interval is input for each package or maintenance plan. From this step it is resulting to a recommended schedule dates for the maintenance plans (see example in **Error! Reference source not found.**). This will also give an overview of total cost impact for each period (year).

The model overview:

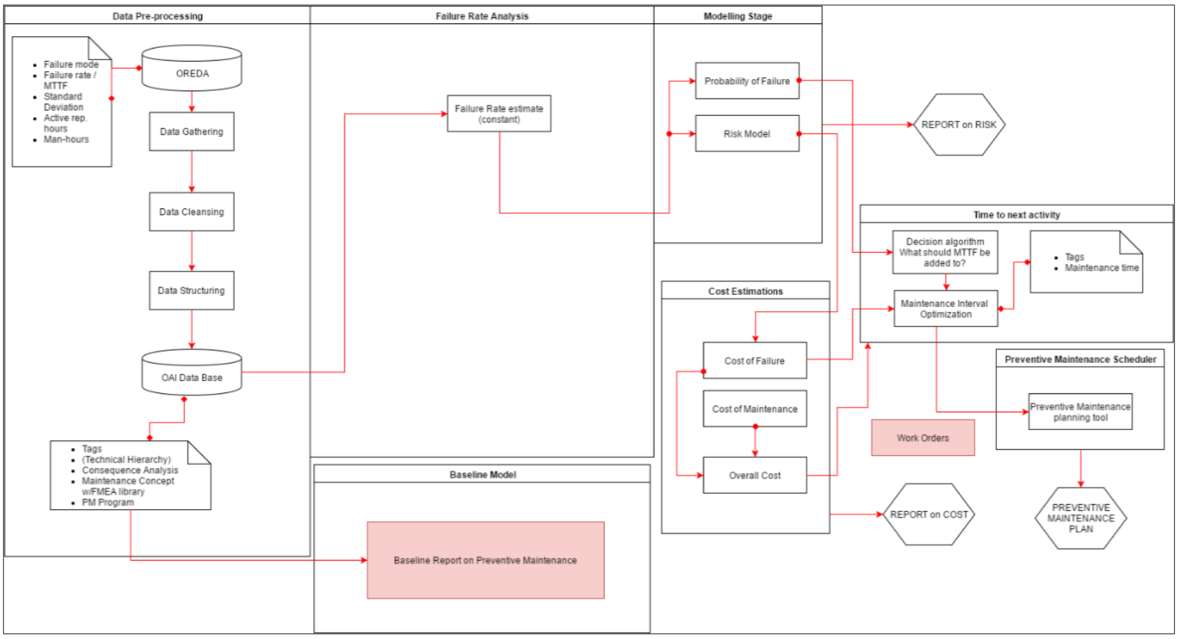


Figure 11 - Model design mockup

3.1.1 Preparatory part

Equipment boundaries are set and mapping of equipment towards OREDA taxonomy codes are described in Table 6 - Description of Equipment.

Table 6 - Description of Equipment

Cases	***Equipment***	***Description***	***OREDA source***
Pump package	ME-HE-PL	Heat Exchanger	Taxonomy 3.1.1
	RO-PU-CE	Pumps, centrifugal	Taxonomy 1.3.1
	RO-EM-DC	Electric Motors, General	Taxonomy 2.2
	SC-VA-CV	Control Valve w/actuator	Taxonomy 4.4.10
	SC-ID-IL	Instrument loop, electronic	Taxonomy 4.2
	SC-ID-SL	Switch loop	Taxonomy 4.2
Fire and gas detectors	SC-FG-DG	Detector, gas HC	Taxonomy 4.1.4
Main engine	RO-CE-DE	Engine, diesel	Taxonomy 1.4.1

Technical hierarchy

Pump package boundary is selected from one engine high temperature cooling system.

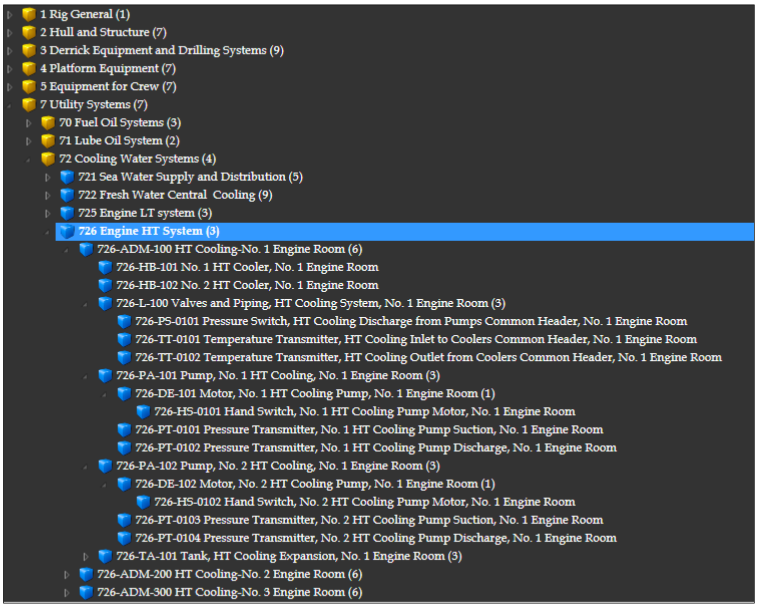


Figure 12 - Technical Hierarchy - HT Pump package, adapted from KAMFER

Fire and gas detectors package boundary is selected from gas detectors in Hull location.

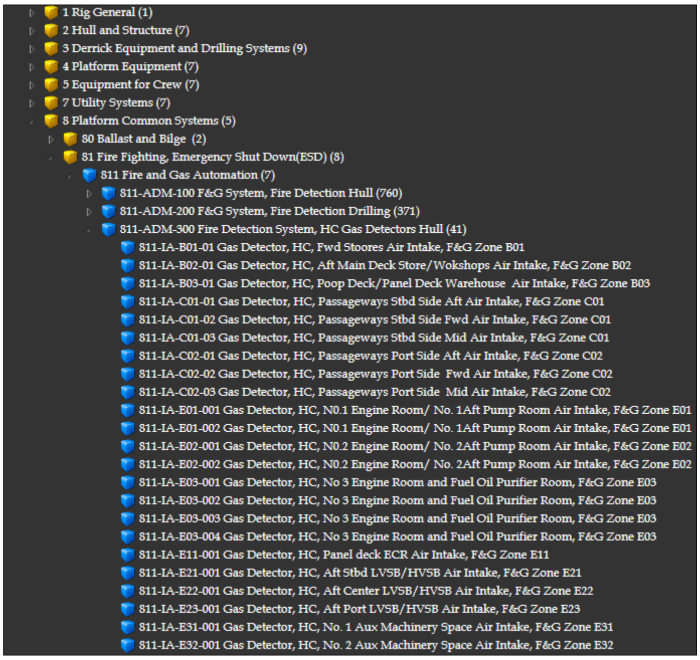


Figure 13 - Technical Hierarchy - Detector, Gas, HC, adapted from KAMFER

Main engine package boundary is selected from main power generation.

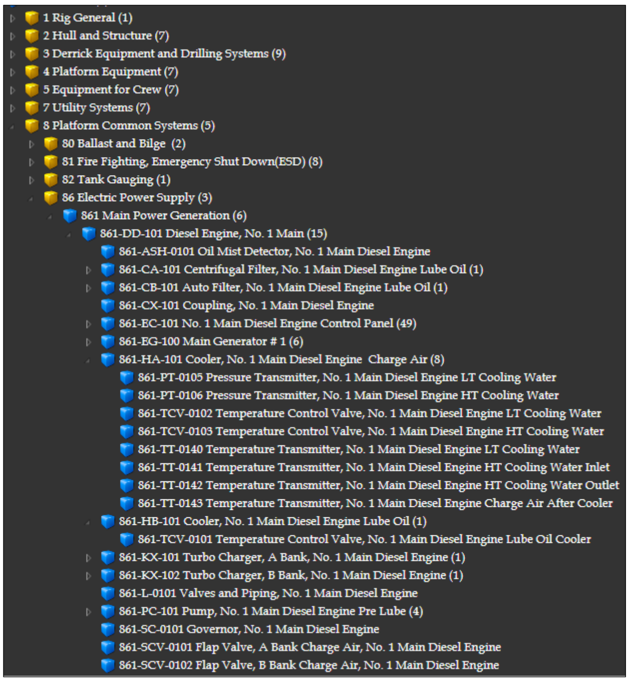


Figure 14 - Technical Hierarchy – Main engine, adapted from KAMFER

Consequence Classification of main functions and belonging sub-functions is done according to NORSOK Z-008 guidelines and inheritance rules. Only relevant functions for equipment are listed in table below.

Description of column headings for

Table 7 and

Table 8:

- No: Identification numbering of the main- and sub functions.
- Desc: Description of the main- and sub functions. Main functions describe what the equipment function is.
- R: Redundancy (see Table 3)
- P: Parallel units
- C: Capacity
- CS: Consequence Safety (3: High, 2: Medium, 1: Low)
- CP: Consequence Production (3: High, 2: Medium, 1: Low)
- CC: Consequence Cost (3: High, 2: Medium, 1: Low)
- SystemEffect: System effect if failure loss of function
- InstEffect: Installation effect if failure loss of function

Table 7 – Equipment consequence classification of functions

Equipment	***No***	***Desc***	***SystemEffect***	***InstEffect***
ME-HE-PL	72106 MAIN	SEAWATER HEAT EXCHANGING OF HT AND LT ENGINE COOLING	Loss of cooling for main engines. Mechanical failures (leakage, growth, clogging) most common.	Critical for HSE and operation, loss of cooling for engines. May have impact on additional repair cost, expensive parts.
RO-EM-DC, RO-PU-CE	72602 MAIN	PUMPING FRESH WATER ENGINE ROOM LOW TEMPERATURE	Loss of high temp. cooling water supply for engines. Electrical and mechanical failures most common.	Critical for HSE and operation, loss of cooling for engines. May have impact on additional repair cost, expensive parts.
SC-ID-IL, SC-ID-SL, SC-VA-CV	72602 CONTROL	CONTROLLING	Regulation/control is not working.	Loss of main function.
RO-CE-DE	86101 MAIN	GENERATING POWER	Loss of driving engines for electric power generators. Electrical, instrument and mechanical failures most common.	Critical for HSE and operation, lose power to thrusters, drift out of position, out of DP3 class. Loss of power for drilling, stop in operation. High additional repair cost.
	86101 CONTROL	CONTROLLING	Regulation/control is not working.	Loss of main function.
SC-FG-DG	81105 MAIN	DETECTING HC GAS	HC detection stops working or is unavailable. Unable to detect HC with F&G system. Instrument failures most common.	Critical for HSE, render safety critical systems inoperable. No immediate impact on operation or additional repair cost.

Table 8 - Equipment consequence classification of functions (2)

Equipment	No	R	P	C	CS	CP	CC
ME-HE-PL	72106MAIN	B	2	100	3	3	1
RO-EM-DC, RO-PU-CE	72602MAIN	B	2	100	3	3	2
SC-ID-IL, SC-ID-SL, SC-VA-CV	72602CONTROL	B	2	100	3	3	2
RO-CE-DE	86101MAIN	B	6	20	3	3	3
	86101CONTROL	B	6	20	3	3	3
SC-FG-DG	81105MAIN	A	1	100	3	1	1

Planning variables chosen:

- Optimum Maintenance Interval:
    - Failure rate
    - Interval
    - Consequence
- Maintenance planning cost:
    - Man hours (Workload)
    - Duration
        - Shutdown (Yes/No)
    - Consequence
- Spare part and spare part cost:
    - Spare part cost
        - Purchase
        - Transportation
        - Storing
- Life Cycle Cost:
    - Operation and maintenance

3.1.2 Data Collection

OREDA failure data are gathered for each equipment class for each failure mode. According to (Vestvik 2012) the methodology of calculating total failure rate by considering all failure severities in sum is to find the failure rate including incipient failures, not only the critical failures. Preventive maintenance on some type of equipment should be performed before the failure becomes critical.

Total mean failure rate (λ_{Total}) per 10^6 hours is calculated for each failure mode by using the sum of severities of mean failure rate for each degree of failure in critical, degraded and incipient by:

$$\lambda_{Total} = \frac{n_C + n_D + n_I}{Time\ (10^6)} \quad (4)$$

Where n_C, n_D, and n_I is mean failure rate of critical failures, -degraded failures, and -incipient failures respectively.

Degree of each failure severities is calculated by mean failure rate of each severity divided to total mean failure rate times 100, by:

$$Degree_{Critical} = \frac{\lambda_C}{\lambda_{Total}} \times 100 \quad (5)$$

$$Degree_{Degraded} = \frac{\lambda_D}{\lambda_{Total}} \times 100 \quad (6)$$

$$Degree_{Incipient} = \frac{\lambda_I}{\lambda_{Total}} \times 100 \tag{7}$$

SD (standard deviation) is selected for each failure mode and each severity class and then summarized as SD weighted based on D (degree) of severity failure rate:

$$SD_w = \frac{SD_c * D_C}{100} + \frac{SD_D * D_D}{100} + \frac{SD_I * D_I}{100} \tag{8}$$

MARH (Mean active reparation hours) is selected for each failure mode and each severity class and then summarized as active rep. hours weighted based on D (degree) of severity failure rate:

$$Active\ rep.hours_w = \frac{MARH_C * D_C}{100} + \frac{MARH_D * D_D}{100} + \frac{MARH_I * D_I}{100} \tag{9}$$

MH (Man hours) is selected for each failure mode and each severity class and then summarized as Man hours weighted based on D (degree) of severity failure rate for both Mean- and Max Man-hours:

$$Man\ hours_w = \frac{MH_C * D_C}{100} + \frac{MH_D * D_D}{100} + \frac{MH_I * D_I}{100} \tag{10}$$

MTTF years is calculated from 1 divided by λ_{Total} per 10^6 hours, and to obtain in years this is divided by 8760 hours by:

$$MTTF\ years = \frac{1}{\frac{\frac{\lambda_{Total}}{10^6\ hrs}}{8760\ hrs}} \tag{11}$$

SD years is calculated from 1 divided by SD_W per 10^6 hrs, and to obtain in years this is divided by 8760 hours by:

$$SD\ years = \frac{1}{\frac{\frac{SD_w}{10^6\ hrs}}{8760\ hrs}} \tag{12}$$

Failure Modes are selected by major failure modes and mapped to individual maintenance concept and activities to prevent and counteract a failure to occur.

Table 9 - Failure rate, SD and degree of critical, degraded and incipient failure rate from OREDA (2009)

Equipment	***Failure Mode***	λ_{Total} ***(10^6 hours)***	***SD_w***	***C***	***D***	***I***
ME-HE-PL	External Leakage - Process medium	23,15	20,18	100,00	0,00	0,00
RO-EM-DC	Failure to start on demand	6,18	4,06	84,79	15,21	0,00
	Low Output	9,17	5,32	92,48	7,52	0,00
	Overheating	0,75	0,97	100,00	0,00	0,00
	Parameter Deviation	6,92	4,19	20,66	57,37	21,97
	Spurious Stop	4,32	3,05	100,00	0,00	0,00
	Structural Deficiency	3,51	4,58	44,16	55,84	0,00
	Vibration	4,06	1,02	14,53	66,26	19,21
RO-PU-CE	Erratic Output	6,47	14,18	5,87	94,13	0,00
	External Leakage - Process medium	10,91	10,71	45,19	21,54	33,27
	External Leakage - Utility medium	32,05	34,79	16,69	70,05	13,26
	Failure to start on demand	4,53	5,26	100,00	0,00	0,00
	High Output	2,41	5,89	100,00	0,00	0,00
	Internal leakage	6,41	5,51	8,42	70,98	20,59
	Low Output	5,39	1,77	28,20	66,79	5,01
	Parameter Deviation	4,55	3,34	35,16	6,37	58,46
	Spurious Stop	9,06	19,51	100,00	0,00	0,00
	Structural Deficiency	6,07	11,53	48,93	36,08	14,99
	Vibration	14,36	13,90	40,60	57,31	2,09
SC-VA-CV	External Leakage - Process medium	0,38	0,40	0,00	100,00	0,00
	External Leakage - Utility medium	0,38	0,40	0,00	100,00	0,00
	Fail to close on demand	0,38	0,40	100,00	0,00	0,00
	Fail to open on demand	1,14	0,51	66,67	33,33	0,00
	Fail to regulate	1,14	0,69	100,00	0,00	0,00
	Valve leakage in closed position	1,52	0,49	25,00	50,00	25,00
	Low Output	4,39	1,66	0,00	91,34	8,66
	Plugged/Choked	0,76	0,57	0,00	100,00	0,00
SC-ID-IL	Abnormal output - Low	0,29	0,29	100,00	0,00	0,00
	Fail to function on demand	1,76	0,72	100,00	0,00	0,00
	Spurious Operation	1,47	0,66	100,00	0,00	0,00
SC-ID-SL	Abnormal output - Low	0,29	0,29	100,00	0,00	0,00
	Fail to function on demand	1,76	0,72	100,00	0,00	0,00
	Spurious Operation	1,47	0,66	100,00	0,00	0,00
RO-CE-DE	External Leakage - Utility medium	29,35	17,28	8,38	67,60	24,02
	Fail to start on demand	27,23	30,40	66,36	15,61	18,03
	Internal leakage	9,81	6,23	0,00	100,00	0,00
	Low Output	4,73	7,46	0,00	82,88	17,12
	Noise	5,19	5,42	18,11	66,28	15,61
	Overheating	3,66	5,42	0,00	50,27	49,73
	Spurious Stop	2,37	1,92	65,82	34,18	0,00
	Structural Deficiency	9,4	7,19	0,00	73,94	26,06
	Vibration	2,21	3,66	0,00	100,00	0,00
SC-FG-DG	Erratic Output	2,93	2,66	0,00	100,00	0,00
	Fail to function on demand	1,05	0,91	100,00	0,00	0,00
	No Output	0,29	0,48	100,00	0,00	0,00
	Spurious high alarm level	1,04	0,41	100,00	0,00	0,00
	Spurious low alarm level	0,62	0,39	80,65	19,35	0,00
	Spurious Operation	1,6	0,62	100,00	0,00	0,00
	High Output	0,58	0,54	0,00	100,00	0,00
	Low Output	0,38	0,48	0,00	100,00	0,00

Table 10 - Active rep. hrs, man-hours and degree of critical, degraded and incipient failure rate from OREDA (2009)

Equipment	Failure Mode	Active rep. hrs	Man-hours$_w$ mean	Man-hours$_w$ max
ME-HE-PL	External Leakage - Process medium	0,0	6*	12*
RO-EM-DC	Failure to start on demand	23,4	25,5	37,7
	Low Output	15,1	20,9	44,9
	Overheating	3,0	3,0	4
	Parameter Deviation	3,8	6,2	20,6
	Spurious Stop	16,0	23,0	129,0
	Structural Deficiency	12,6	20,3	72,3
	Vibration	3,9	8,6	11,7
RO-PU-CE	Erratic Output	18,7	37,3	44,8
	External Leakage - Process medium	16,8	25,7	133,2
	External Leakage - Utility medium	11,6	18,0	148,3
	Failure to start on demand	7,8	30,0	336,0
	High Output	0,0	3,3	6,0
	Internal leakage	11,9	21,9	81,3
	Low Output	9,9	21,3	94,0
	Parameter Deviation	11,0	19,2	73,4
	Spurious Stop	13,0	17,0	248,0
	Structural Deficiency	11,4	21,3	67,6
	Vibration	14,7	57,7	243,2
SC-VA-CV	External Leakage - Process medium	2,0	2,0	2,0
	External Leakage - Utility medium	4,0	4,0	4,0
	Fail to close on demand	2,0	2,0	2,0
	Fail to open on demand	1,4	1,4	1,5
	Fail to regulate	2,7	2,7	4,0
	Valve leakage in closed position	7,5	7,5	9,0
	Low Output	5,7	5,7	12,0
	Plugged/Choked	2,0	0,0	0,0
SC-ID-IL	Abnormal output - Low	4,0	4,0	4,0
	Fail to function on demand	3,3	3,3	8,0
	Spurious Operation	2,2	2,2	3,0
SC-ID-SL	Abnormal output - Low	4,0	4,0	4,0
	Fail to function on demand	3,3	3,3	8,0
	Spurious Operation	2,2	2,2	3,0
RO-CE-DE	External Leakage - Utility medium	18,2	27	103,1
	Fail to start on demand	14,2	8,8	64,4
	Internal leakage	25,0	22	68,0
	Low Output	7,2	10	16,5
	Noise	8,2	12	16,4
	Overheating	13,5	36	25,6
	Spurious Stop	64,0	12	116,0
	Structural Deficiency	13,9	34	169,6
	Vibration	40,0	64	120,0
SC-FG-DG	Erratic Output	3,7	3,0	11,0
	Fail to function on demand	3,8	4,3	10,0
	No Output	2,5	4,5	8,0
	Spurious high alarm level	2,3	2,3	8,0
	Spurious low alarm level	2,6	2,6	4,8
	Spurious Operation	2,7	5,6	41,0
	High Output	2,3	2,3	4,0
	Low Output	4,7	6,7	13,0

Table 11 – MTTF years, SD years

Equipment	Failure Mode		MTTF years	SD years
ME-HE-PL	ELP	External Leakage - Process medium	4,93	5,66
RO-EM-DC	FTS	Failure to start on demand	18,47	28,15
	LOO	Low Output	12,45	21,45
	OHE	Overheating	152,21	117,69
	PDE	Parameter Deviation	16,50	27,26
	UST	Spurious Stop	26,42	37,43
	STD	Structural Deficiency	32,52	24,90
	VIB	Vibration	28,12	112,10
RO-PU-CE	ERO	Erratic Output	17,64	8,05
	ELP	External Leakage - Process medium	10,46	10,66
	ELU	External Leakage - Utility medium	3,56	3,28
	FTS	Failure to start on demand	25,20	21,70
	HIO	High Output	47,37	19,38
	INL	Internal leakage	17,81	20,73
	LOO	Low Output	21,18	64,67
	PDE	Parameter Deviation	25,09	34,14
	UST	Spurious Stop	12,60	5,85
	STD	Structural Deficiency	18,81	9,90
	VIB	Vibration	7,95	8,21
SC-VA-CV	ELP	External Leakage - Process medium	300,41	285,39
	ELU	External Leakage - Utility medium	300,41	285,39
	FTC	Fail to close on demand	300,41	285,39
	FTO	Fail to open on demand	100,14	222,38
	FTR	Fail to regulate	100,14	165,44
	LCP	Valve leakage in closed position	75,10	235,37
	LOO	Low Output	26,00	68,75
	PLU	Plugged/Choked	150,20	200,27
SC-ID-IL	AOL	Abnormal output - Low	393,64	393,64
	FTF	Fail to function on demand	64,86	158,55
	SPO	Spurious Operation	77,66	172,96
SC-ID-SL	AOL	Abnormal output - Low	393,64	393,64
	FTF	Fail to function on demand	64,86	158,55
	SPO	Spurious Operation	77,66	172,96
RO-CE-DE	ELU	External Leakage - Utility medium	3,89	6,61
	FTS	Fail to start on demand	4,19	3,76
	INL	Internal leakage	11,64	18,32
	LOO	Low Output	24,13	15,31
	NOO	Noise	22,00	21,07
	OHE	Overheating	31,19	21,07
	UST	Spurious Stop	48,17	59,31
	STD	Structural Deficiency	12,14	15,87
	VIB	Vibration	51,65	31,19
SC-FG-DG	ERO	Erratic Output	38,96	42,92
	FTF	Fail to function on demand	108,72	125,45
	NOO	No Output	393,64	237,82
	SHH	Spurious high alarm level	109,76	278,43
	SLL	Spurious low alarm level	184,12	292,71
	SPO	Spurious Operation	71,35	184,12
	HIO	High Output	196,82	211,40
	LOO	Low Output	300,41	237,82

3.1.3 Analysis of Data

The RCM activity to failure mode decision logic documents and shows the decisions each failure mode has been given during assessing of failure modes.

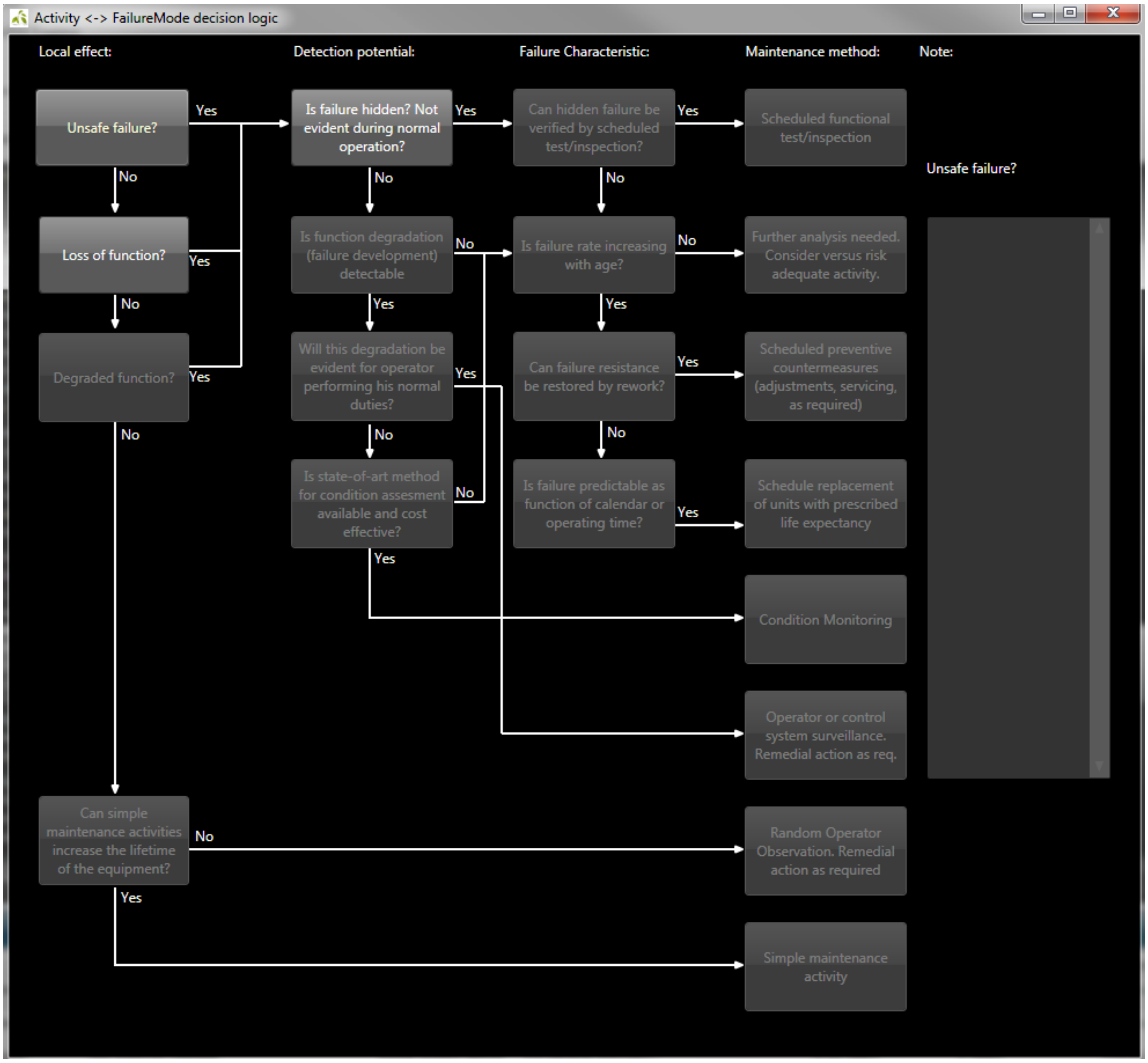


Figure 15 - RCM Activity <-> Failure Mode decision logic (OII KAMFER 7)

Table 12 - Failure mechanisms, failure effects, and failure management decision path and –policy ME-HE-PL and RO-EM-DC

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
ME-HE-PL	ELP	General Mechanical Failure	Yes	Unsafe Failure	No	11, 21,22, 32,33, 43	Schedule preventive countermeasures (adjustments, servicing, as required)
RO-EM-DC	FTS	General electrical failure	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	LOO	General electrical failure	No	Degraded Function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	OHE	General material failure	Yes	Unsafe Failure	No	11, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	PDE	General electrical failure	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	UST	Short circuiting	Yes	Unsafe Failure	No	11, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	STD	Vibration	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	VIB	Vibration	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.

Table 13 - Failure mechanisms, failure effects, and failure management decision path and –policy RO-PU-CE

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
RO-PU-CE	ERO	Corrosion	No	Degraded function	No	13, 21,22,32, 33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	ELP	General Mechanical Failure	Yes	Unsafe Failure	No	11, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	ELU	General Mechanical Failure	Yes	Unsafe Failure	No	11, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	FTS	Leakage	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	HIO	General Mechanical Failure	No	Degraded Function	Yes	13, 21, 31, 41	Scheduled functional test/inspection
	INL	Leakage	No	Loss of Function	No	12, 21,22, 31, 33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	LOO	Blockage/ plugged	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	PDE	Blockage/ plugged	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	UST	General instrument failure	No	Loss of function	No	12, 21, 31, 41	Scheduled functional test/inspection
	STD	General Mechanical Failure	No	Degraded Function	No	13, 21,22, 32, 33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	VIB	Clearance/ alignment failure	No	Loss of function	No	12, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)

Table 14 - Failure mechanisms, failure effects, and failure management decision path and –policy SC-VA-CV

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
SC-VA-CV	ELP	Looseness	Yes	Unsafe Failure	No	11, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	ELU	General Mechanical Failure	Yes	Unsafe Failure	No	11, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	FTC	Blockage/ plugged	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	FTO	General instrument failure	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	FTR	Blockage/ plugged	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	LCP	General material failure	Yes	Unsafe Failure	No	13, 21, 31, 41	Scheduled functional test/inspection
	LOO	Blockage/ plugged	No	Degraded Function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	PLU	Blockage/ plugged	No	Loss of function	No	12, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.

Table 15 - Failure mechanisms, failure effects, and failure management decision path and –policy SC-ID-IL and SC-ID-SL

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
SC-ID-IL	AOL	Out of adjustment	No	Degraded function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	FTF	Faulty signal/ indication/alarm	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	SPO	Faulty signal/ indication/alarm	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
SC-ID-SL	AOL	Out of adjustment	No	Degraded function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	FTF	Faulty signal/ indication/alarm	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	SPO	Faulty signal/ indication/alarm	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection

Table 16 - Failure mechanisms, failure effects, and failure management decision path and –policy SC-FG-DG

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
SC-FG-DG	ERO	Out of adjustment	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	FTF	General instrument failure	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	NOO	No signal/ indication/ alarm	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	SHH	Out of adjustment	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	SLL	Out of adjustment	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	SPO	Contamination	No	Degraded Function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	HIO	Out of adjustment	No	Loss of Function	Yes	12,21, 31, 41	Scheduled functional test/inspection
	LOO	Out of adjustment	No	Loss of Function	Yes	12, 21, 31, 41	Scheduled functional test/inspection

Table 17 - Failure mechanisms, failure effects, and failure management decision path and –policy RO-CE-DE

Equipment	***FM***	***Failure Mechanisms***	***UF***	***Local Effect***	***HF***	***FMa Decision path***	***FMa Policy***
RO-CE-DE	ELU	Leakage	Yes	Unsafe Failure	No	11, 21,22, 32,33, 43	Schedule preventive countermeasures (adjustments, servicing, as required)
	FTS	General Mechanical Failure	No	Loss of function	Yes	12, 21, 31, 41	Scheduled functional test/inspection
	INL	General electrical failure	No	Loss of Function	No	12, 21,22, 31,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	LOO	General material failure	No	Degraded Function	No	13, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	NOO	General Mechanical Failure	No	Loss of Function	No	12, 21,22, 31,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	OHE	General Mechanical Failure	Yes	Unsafe Failure	No	11, 21,22,23, 46	Operator or control system surveillance. Remedial action as req.
	UST	Blockage/ plugged	No	Loss of function	No	12, 21, 31, 41	Scheduled functional test/inspection
	STD	General Mechanical Failure	No	Degraded Function	No	13, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)
	VIB	General Mechanical Failure	No	Loss of function	No	12, 21,22, 32,33, 43	Scheduled functional preventive countermeasures (adjusting, servicing, as required)

Maintenance Concepts and Maintenance Activities

- A: Authority- or concern requirement Yes/No
- S: Shut down of equipment Yes/No
- D: Duration in hours

Table 18 - Equipment maintenance activity <-> failure modes

Equipment	***Maint. activity***	***Failure Modes***	***Description of maintenance***	***A***	***S***	***Initial Interval***	***D***	***Qty of Men***	***Total WL***
ME-HE-PL	41A	ELP	HEAT EXCHANGER, CLEANING	N	Y	06	6	1x3, 1x3	12
RO-EM-DC	15A	FTS, LOO	ELECTRIC MOTOR, MEGGERTEST	Y	Y	12	0,5	1	0,5
	51A	STD, VIB	ELECTRIC MOTOR, LUBRICATION	N	Y	03	0,3	1	0,3
RO-PU-CE	21A	HIO, LOO, PDE	CENTRIFUGAL PUMP, FUNCTION TEST	N	N	12	0,5	1	0,5
	51A	VIB	CENTRIFUGAL PUMP, LUBRICATION	N	Y	01	1	1x2	2
	53A	STD	CENTRIFUGAL PUMP, OIL CHANGE	N	Y	12	1	1x3	3
SC-ID-IL	31A	AOL, FTF, SPO	TRANSMITTER, FUNCTION TEST	Y	N	12	0,5	1	0,5
SC-ID-SL	02A	AOL, FTF, SPO	SWITCH, FUNCTION TEST	N	N	06	0,3	1	0,3
SC-VA-CV	02A	ELP, ELU, FTC, FTO, LCP, LOO	VALVE, FUNCTION TEST	N	N	12	0,3	1x0,3	0,3
RO-CE-DE	02A	STD, VIB	MAIN ENGINE, 8000H INSPECTION	N	Y	12	15	2x1, 1	45
	02B	UST	THERMOSTATIC VALVE, NEAR VISUAL CHECK	N	N	18	2	1	2
	02C	STD, VIB	DIESEL ENGINE, BEARING NEAR VISUAL CHECK	N	Y	36	168	2x1, 1, 2x1	672
	02D	STD, VIB	DIESEL ENGINE, BEARING CHECK (SMALL END)	N	Y	48	24	2x1, 1	48
	21B	(STP)	FLAP VALVE, FUNCTION TEST	Y	Y	03	1	2x1	2
	34A	NOI, VIB	MAIN ENGINE, RETIGHTENING	N	Y	12	4	2x1, 1	12
	41A	LOO	CHARGE AIR COOLER, CLEANING	N	Y	06	24	2x1, 2x1	96
	62A	UST	MAIN ENGINE CENTRIFUGAL FILTER, REPLACE	N	Y	01	1	1, 1	1,5
	71A	VIB	DIESEL ENGINE, OVERHAUL	N	Y	24	336	3x1, 2x1, 2x1	2016
	71B	FTS, UST	FUEL INJECTORS, OVERHAUL	N	Y	03	8	2x1	16
SC-FG-DG	21A	ERO, FTF, NOO	GAS DETECTORS HC, FUNCTION TEST	Y	N	03	0,25	1	0,5

3.1.4 Baseline Model for Analysis

Baseline preventive maintenance program is created from the basis of MC-tag linkage, and the activities MC consist of. Workload overview:

Table 19 - Baseline PM program Workload

Case	***Equipment***	***Totals in 10 years***	***Total per year***	***Amount of tags***	***MHRS per equipment per year***
Pump package	ME-HE-PL	960	96	4	24
	RO-EM-DC	68	6,8	4	1,7
	RO-PU-CE	1.110	110	4	27,5
	SC-ID-IL	70	7,0	14	0,5
	SC-ID-SL	12	1,2	2	0,6
	SC-VA-CV	12	1,2	4	0,3
Main engine	RO-CE-DE	15.840	1584	1	1584,3
Fire and gas detector	SC-FG-DG	460	46	23	2
		18.530	1.853		

Baseline PM program schedule made with a rate assumed NOK 500. Cost numbers in millions NOK. WL: Workload in hours. N: Amount of tags. Y0 = Year 0, Y1 = Year 1…

Table 20 - Baseline PM program Schedule for Pump package

Task name	***WL***	***N***	***Y0***	***Y1***	***Y2***	***Y3***	***Y4***	***Y5***	***Y6***	***Y7***	***Y8***	***Y9***	***Y10***
HEAT EXCHANGER, CLEANING	12	4	2	2	2	2	2	2	2	2	2	2	2
ELECTRIC MOTOR, MEGGERTEST	0,5	4	1	1	1	1	1	1	1	1	1	1	1
ELECTRIC MOTOR, LUBRICATION	0,3	4	4	4	4	4	4	4	4	4	4	4	4
CENTRIFUGAL PUMP, FUNCTION TEST	0,5	4	1	1	1	1	1	1	1	1	1	1	1
CENTRIFUGAL PUMP, LUBRICATION	2	4	12	12	12	12	12	12	12	12	12	12	12
CENTRIFUGAL PUMP, OIL CHANGE	3	4	1	1	1	1	1	1	1	1	1	1	1
TRANSMITTER, FUNCTION TEST	0,5	14	1	1	1	1	1	1	1	1	1	1	1
SWITCH, FUNCTION TEST	0,3	2	2	2	2	2	2	2	2	2	2	2	2
VALVE, FUNCTION TEST	0,3	4	1	1	1	1	1	1	1	1	1	1	1
Schedule totals													
Planned maintenance cost			0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1

Table 21 - Baseline PM program Schedule for Main engine

Task name	***WL***	***N***	***Y0***	***Y1***	***Y2***	***Y3***	***Y4***	***Y5***	***Y6***	***Y7***	***Y8***	***Y9***	***Y10***
MAIN ENGINE, INSPECTION	45	1	1	1	1	1	1	1	1	1	1	1	1
THERMOSTATIC VALVE, NEAR VISUAL CHECK	2	3	1	0	1	0	1	0	1	0	1	0	1
DIESEL ENGINE, BEARING NEAR VISUAL CHECK	672	1	0	0	1	0	0	1	0	0	1	0	0
DIESEL ENGINE, BEARING CHECK (SMALL END)	48	1	0	0	0	1	0	0	0	1	0	0	0
MAIN ENGINE, RETIGHTENING	12	2	1	1	1	1	1	1	1	1	1	1	1
CHARGE AIR COOLER, CLEANING	96	1	4	4	4	4	4	4	4	4	4	4	4
MAIN ENGINE CENTRIFUGAL FILTER, REPLACE	1,5	1	12	12	12	12	12	12	12	12	12	12	12
DIESEL ENGINE OVERHAUL	2016	1	0	1	0	1	0	1	0	1	0	1	0
FUEL INJECTORS OVERHAUL	16	1	4	4	4	4	4	4	4	4	4	4	4
Schedule totals													
Planned maintenance cost		0,4	1,4	0,7	1,4	0,4	1,7	0,4	1,4	0,8	0,8	1,4	0,4

3.2 Research Quality

The data gathering is done in separate stages. Equipment, technical hierarchy (see Figure 12, Figure 13, Figure 14), consequence classification (see

Table 7), maintenance concept (Table 12, Table 18), baseline PM-data are all collected from OAI experience database. Equipment failure data is for the specific equipment taxonomy (as per Table 6) collected from OREDA (2009) into Table 9. That results into MTTF and SD basis (see Table 11) for Failure rate analysis and modelling.

3.3 Methodology criticism

The selection of equipment for the pre-processing work, analysis and modelling, cost estimations, bundling of PM program and selection of theory is mainly based on experience and expert judgement. The creation of failure rate analysis and modelling stage is cooperation with mathematicians within OAI expertise. The relevancy of these choices has been controlled through meetings with supervisors at OAI.

It should be mentioned that the study intended to analyse notifications and real failure reporting for a given offshore installation on NCA, but with issues of confidentiality and limitations to sensitive information, instead a study on OREDA failure data was chosen. The study with OREDA data may not give the intended results, but the intention, ideas and method should be highlighted with this work.

4. Analysis and Results

4.1 Data Pre-processing for Analysis

4.1.1 Data Required for Analysis

Data required for analysis is essential. Information specific for equipment or Functional Locations:

- Equipment Type, Description
- Tag Number (identification)
- Tag Description
- Location
- System
- Failure consequence parameters (HSE, Cost, Production..)
- Maintenance strategy or maintenance concept

Chosen datatypes to use in addition to regular planning variables:

- Optimum Maintenance Interval
- Maintenance planning cost
- Spare part and spare part cost
- Life Cycle Cost

4.1.2 Data Gathering for Analysis

Data required for analysis

Pump package (Related WO: R-102044, MainTag: 726-PA-101)
- Pump
- Motor, El
- Control valves
- Sensors (Transmitter, Switch)

Fire and Gas detectors (Related WO: R-100114)
- Gas detector HC

Main Engine (Related WO: R-100127)
- Main engine

4.2 Analysis of Field data

Analysis of field data is done with the use of Python and coding on Survival analysis in Appendix D.

4.2.1 Failure Rate Analysis

OREDA input with MTTF and SD is random sampled and normal distributed with a sample size of 100.

Random sample and use of Lifelines simulates survivors and failures in 10 years of duration. These results in survival curves with Kaplan Meier estimate, hazard rate with Nelson Aalen estimate, and estimated MTTF. Analysis results in estimated MTTF and with estimated SD:

Table 22 - Failure rate estimations from analysis

Equipment	Failure Mode	MTTF Years Estimated	SD Years Estimated
ME-HE-PL	ELP	5,92	3,13
RO-EM-DC	FTS	6,33	3,01
	LOO	4,51	3,40
	OHE	0,91	0,00
	PDE	5,99	2,37
	STD	5,15	2,93
	UST	5,97	3,66
	VIB	4,75	4,17
RO-PU-CE	ELP	5,52	2,99
	ELU	4,11	2,58
	ERO	7,13	2,78
	FTS	5,18	2,79
	HIO	-	-
	INL	7,00	2,75
	LOO	3,29	2,13
	PDE	4,51	3,11
	STD	6,70	2,04
	UST	7,17	2,22
	VIB	5,39	2,80
SC-VA-CV	ELP	5	-
	ELU	3,83	0
	FTC	-	-
	FTO	1,33	0
	FTR	6,25	-
	LCP	9,75	0
	LOO	6,15	2,83
	PLU	-	-
SC-ID-IL	AOL	-	-
	FTF	3,91	2,33
	SPO	6,66	3,10
SC-ID-SL	AOL	8,33	0
	FTF	6,81	2,80
	SPO	3,08	2,91
RO-CE-DE	ELU	5,54	2,84
	FTS	4,49	2,84
	INL	4,76	3,28
	LOO	5,05	3,07
	NOI	5,22	3,28
	OHE	4,50	2,44
	STD	6,20	2,63
	UST	5,39	2,51
	VIB	2,53	0,76
SC-FG-DG	ERO	750	322
	FTF	7,58	3,33
	HIO	808	379
	LOO	-	-
	NOO	-	-
	SHH	1068	463
	SLL	-	-
	SPO	908	601

4.2.2 Data-Modelling

Lifelines (see Appendix D) with survivors and failures is then used as input to Kaplan Meier fitter resulting in survival function, and Nelson Aalen fitter resulting in hazard rate.

4.2.3 Results from Data-Modelling

Survival curves with Kaplan Meier fitter.

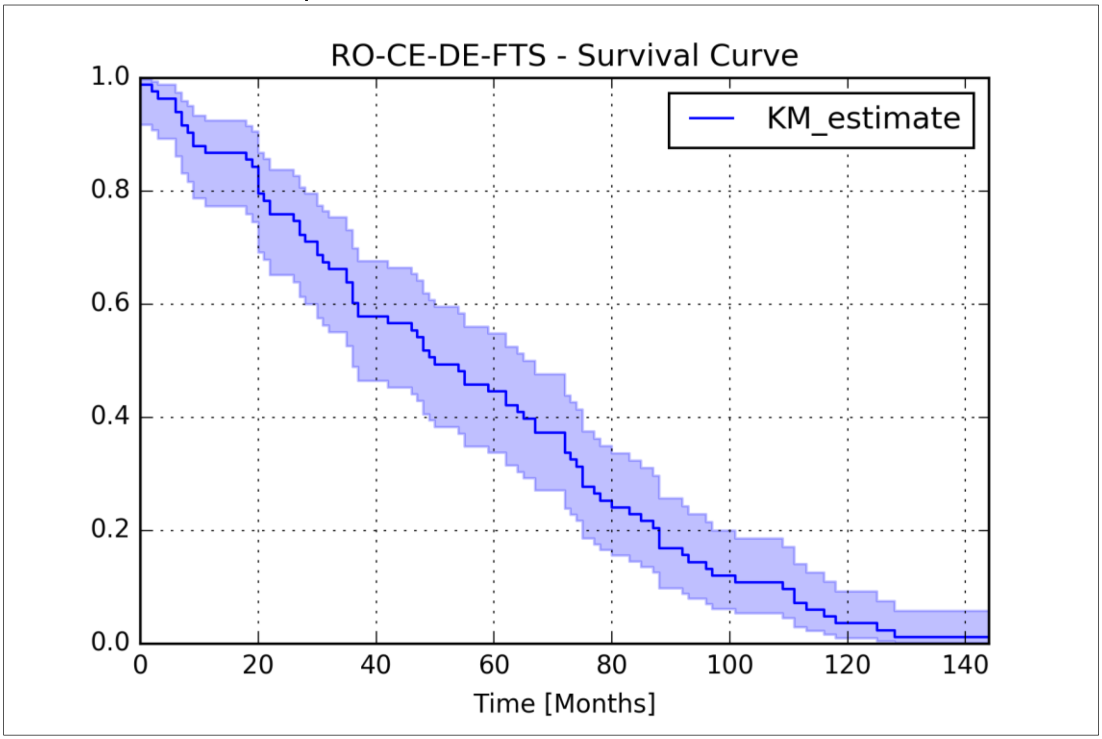


Figure 16 - Example of Survival curve with Kaplan Meier estimate from analysis

Report on Risk, Hazard rate from NelsonAalenFitter function.

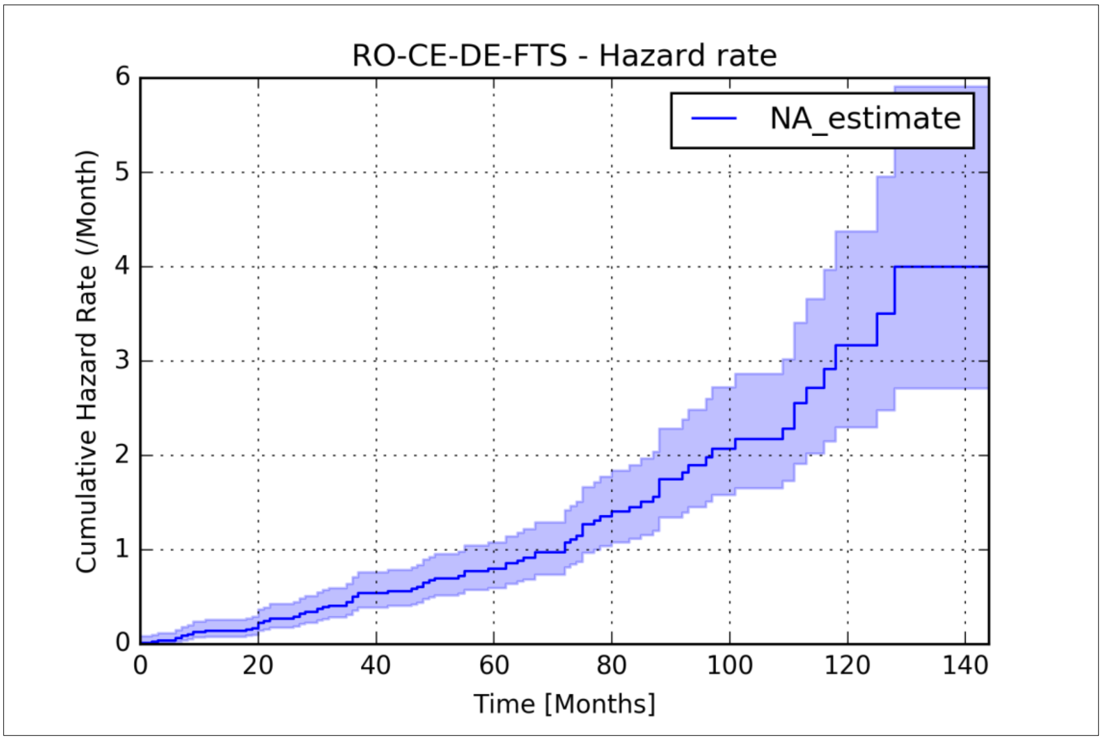


Figure 17 - Hazard rate with Nelson Aalen estimate from Analysis

4.2.4 Cost Estimations – Report on Cost

Preventive maintenance cost is calculated with following input and attributes:

DI (Downtime impact) is calculated if shutdown is required, and calculated by downtime duration times downtime cost. (Downtime cost is assumed to be 10000 NOK):

$$DI = \text{ } Downtime\ duration\ \times Downtime\ cost \tag{13}$$

CoSO (Cost of spares and other) for PM are individually assumed.

PMAC (Preventive Maintenance Activity Cost) is calculated by man hours input from maintenance concept activities time the rate that is assumed to be 500 NOK per hour.

$$PMAC = \text{ } Man\ hours\ \times rate \tag{14}$$

PM_{Cost} (Preventive Maintenance cost) is calculated by sum of DI, CoSO and MAC:

$$PM_{Cost} = \sum DI + CoSO + PMAC \tag{15}$$

PM_{Cost} per month is calculated by PM_{Cost} times the period (10 years) divided by the interval (for each interval):

$$PM_{Cost}\ per\ month = \frac{PM_{Cost} \times period\ (120\ month)}{Interval} \tag{16}$$

Corrective maintenance and consequences of failure is calculated with following input and attributes:

- Hazard rate λ_{months} is the Nelson Aalen estimate cumulated per month, assumed to be equal to the integral as if it was a continuous function.
- CoSO2 (Cost of spares and other 2) for CM is assumed to be 30000 NOK due to unplanned maintenance is more unpredictable and spares might not be in storage.
- CMAC (Corrective Maintenance Activity Cost) is calculated by man hours input from OREDA failure mode input times repair rate assumed to be 500 NOK per hour.

$$CMAC = \text{ } Man\ hours\ (OREDA) \times repair\ rate \tag{17}$$

CM_{Cost} is calculated by sum of CoSO2 and CMAC:

$$CM_{Cost} = \sum CoSO2 + PMAC \tag{18}$$

CM_{Cost} per month is calculated by Hazard rate in months times CM_{Cost}.

$$CM_{Cost}\ per\ month = \text{ } \lambda_{months}(t) \times CM_{Cost} \tag{19}$$

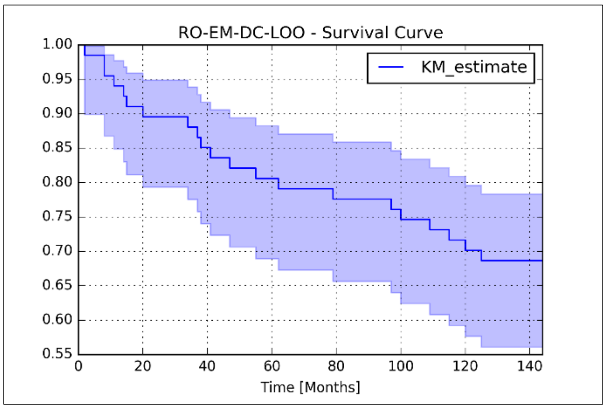
Optimize PM using additional attributes and quantified methods. Input for report on cost optimizing report is set on individual activity basis. See each input table for details.

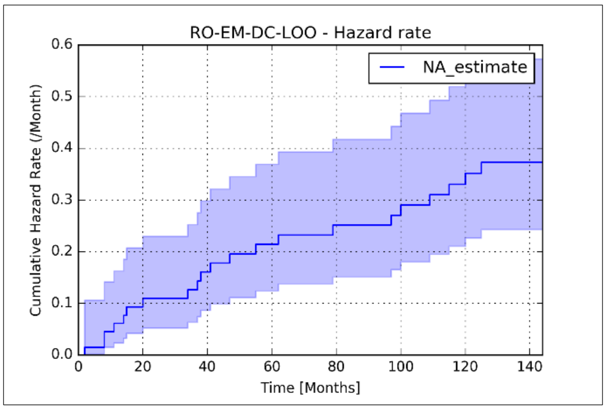
4.2.5 Optimizing PM Interval – Pump package

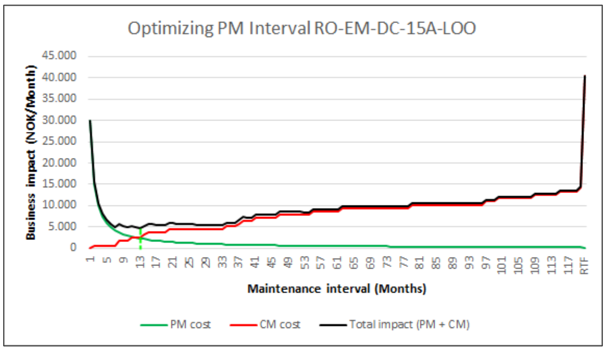
Table 23 - Input data MCA: RO-EM-DC-15A, ELECTRIC MOTOR, MEGGERTEST

PM Cost	CM Cost
• Downtime cost is not taken into consideration, due to equipment redundancy B. • CoSO = 0 NOK • Man hours = 0,5 hour(s) • Rate = 500 NOK • PMAC = 250 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 20,9 hour(s) • Max Man hours = 44,9 hour(s) • Repair rate = 500 NOK • CMAC = 40.450 NOK

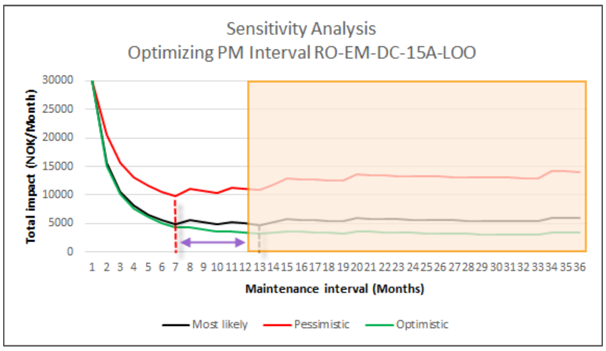
Table 24 - Optimization RO-EM-DC-15A, ELECTRIC MOTOR, MEGGERTEST







Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
3	10000	604	10604
6	5000	604	5604
12	2500	2471	4971
13	2308	2471	4779
18	1667	3765	5432
24	1250	4429	5679
30	1000	4429	5429
36	833	5103	5936
RTF	0	40450	40450

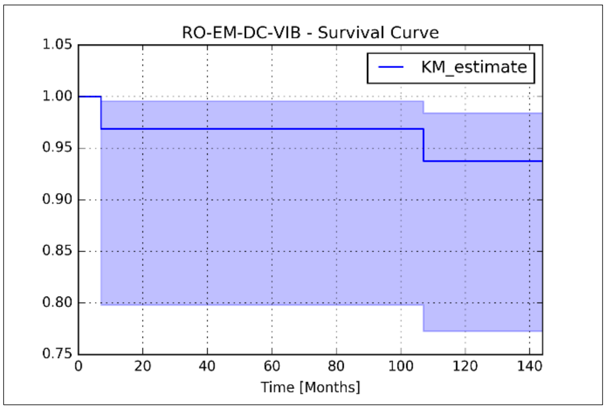


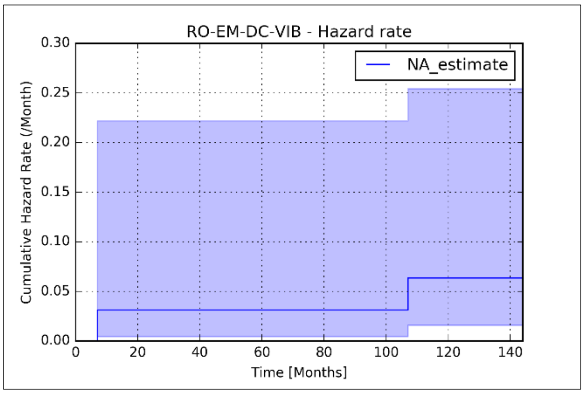
Results of PM optimization showing optimal maintenance interval for activity is 13 month(s). The recommended maintenance interval (taking authority requirements and data uncertainty into account) is 12 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 6069 NOK/Month. Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 7 month(s) to max 12 month(s). According to Survival function it is 94% chance of asset survival to reach (selected) interval of 12 Month(s).

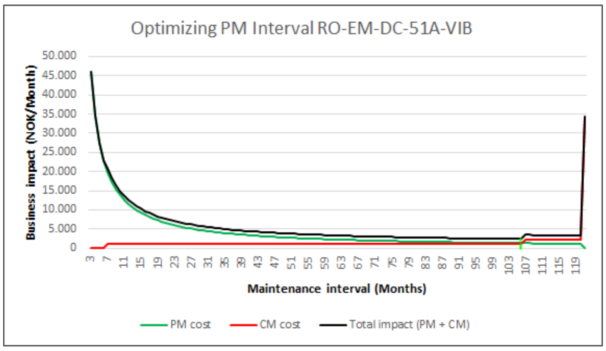
Table 25 - Input data MCA: RO-EM-DC-51A, ELECTRIC MOTOR, LUBRICATION

PM Cost	***CM Cost***
• Downtime cost is not taken into consideration, due to equipment redundancy B. • CoSO = 1.000 NOK • Man hours = 0,3 hour(s) • Rate = 500 NOK • PMAC = 3.150 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 8,6 hour(s) • Max Man hours = 11,7 hour(s) • Repair rate = 500 NOK • CMAC = 34.300 NOK

Table 26 - Optimization RO-EM-DC-51A, ELECTRIC MOTOR, LUBRICATION







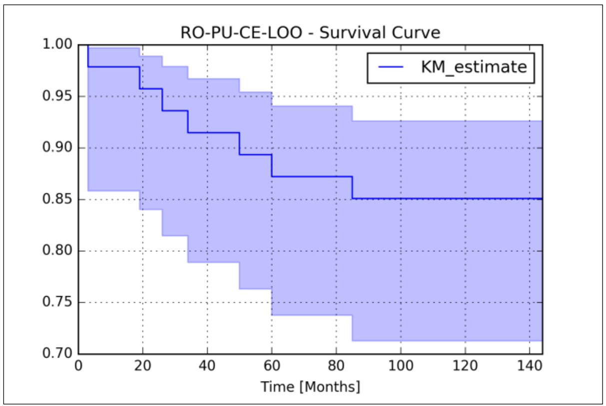
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
3	46000	0	46000
4	34500	0	34500
5	27600	0	27600
6	23000	0	23000
12	11500	1072	12572
24	5750	1072	6822
48	2875	1072	3947
72	1917	1072	2989
96	1438	1072	2509
106	1302	1072	2374
120	1150	2178	3328
RTF	0	34300	34300

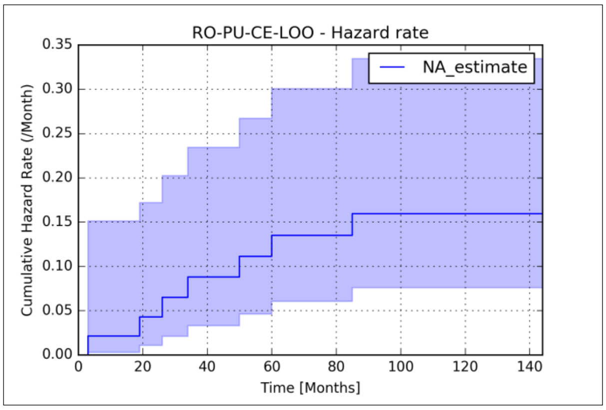
Results of PM optimization showing optimal maintenance interval for activity is 106 month(s). The recommended maintenance interval (taking packing and data uncertainty into account) is 6 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month. Current interval (3) and Run-to-failure (RTF) options.
According to Survival function it is 100% chance of asset survival to reach (selected) interval of 6 Month(s).

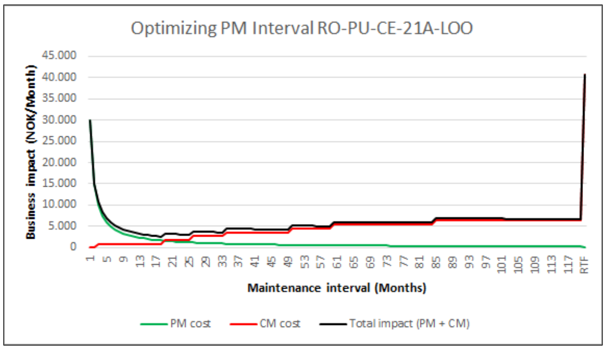
Table 27 - Input data MCA: RO-PU-CE-21A, CENTRIFUGAL PUMP, FUNCTION TEST

PM Cost	***CM Cost***
• Downtime cost is not taken into consideration, due to equipment redundancy B. • Man hours = 0,5 hour(s) • Rate = 500 NOK • PMAC = 250 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 21,3 hour(s) • Max Man hours = 94,0 hour(s) • Repair rate = 500 NOK • CMAC = 40.650 NOK

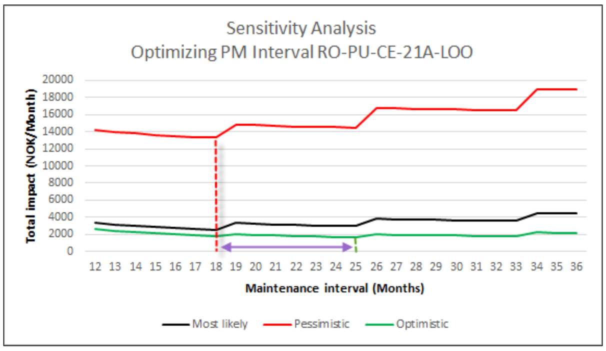
Table 28 - Optimization RO-PU-CE-21A, CENTRIFUGAL PUMP, FUNCTION TEST







Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
3	10000	865	10865
6	5000	865	5865
9	3333	865	4198
12	2500	865	3365
15	2000	865	2865
18	1667	865	2532
21	1429	1749	3177
24	1250	1749	2999
RTF	0	40650	40650

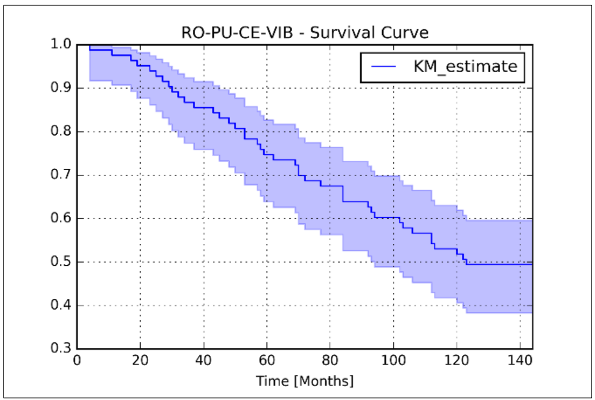


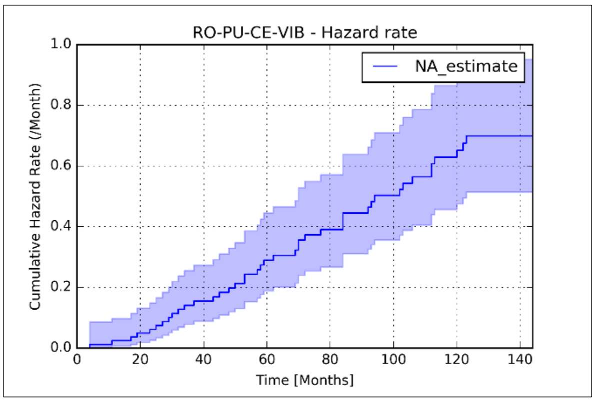
Results of PM optimization showing optimal maintenance interval for activity is 18 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 18 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 10771 NOK/Month. Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 18 month(s) to max 25 month(s).
According to Survival function it is 97,8% chance of asset survival to reach (selected) interval of 18 Month(s).

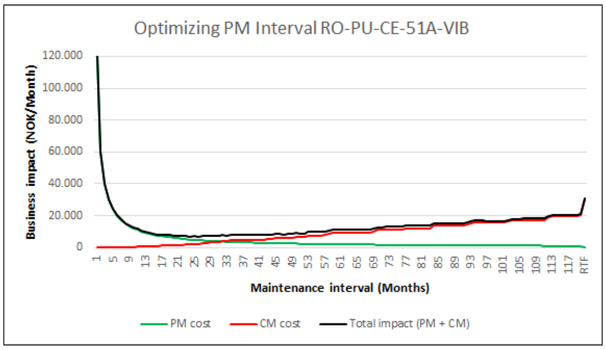
Table 29 - Input data MCA: RO-PU-CE-51A, CENTRIFUGAL PUMP, LUBRICATION

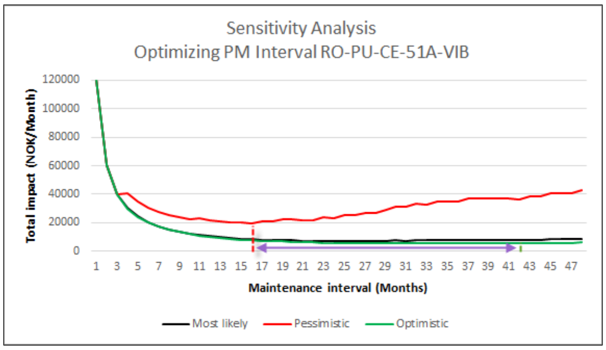
PM Cost	***CM Cost***
• CoSO not taken into consideration. A few grease pumps will not cost much. • Man hours = 2 hour(s) • Rate = 500 NOK • PMAC = 1.000 NOK	• CoSO2 = 2.000 NOK (Replace bearing) • Mean Man hours = 57,7 hour(s) • Max Man hours = 243,2 hour(s) • Repair rate = 500 NOK • CMAC = 30.850 NOK

Table 30 - Optimization RO-PU-CE-51A, CENTRIFUGAL PUMP, LUBRICATION









Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
1	120000	0	120000
3	40000	0	40000
6	20000	372	20372
9	13333	372	13705
12	10000	748	10748
15	8000	748	8748
18	6667	1129	7795
21	5714	1514	7229
24	5000	1905	6905
27	4444	2701	7146
30	4000	3518	7518
33	3636	3935	7572
36	3333	4358	7691
RTF	0	30850	30850

Results of PM optimization showing optimal maintenance interval for activity is 24 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 3 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month. Current interval (1) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 16 month(s) to max 42 month(s).
According to Survival function it is 100% chance of asset survival to reach (selected) interval of 3 Month(s).

Table 31 - Input data MCA: RO-PU-CE-53A, CENTRIFUGAL PUMP, OIL CHANGE

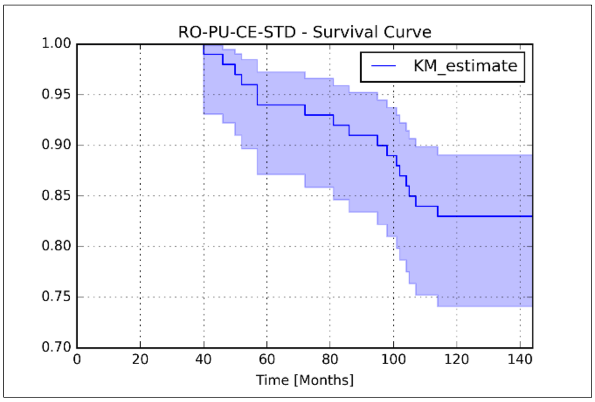
PM Cost

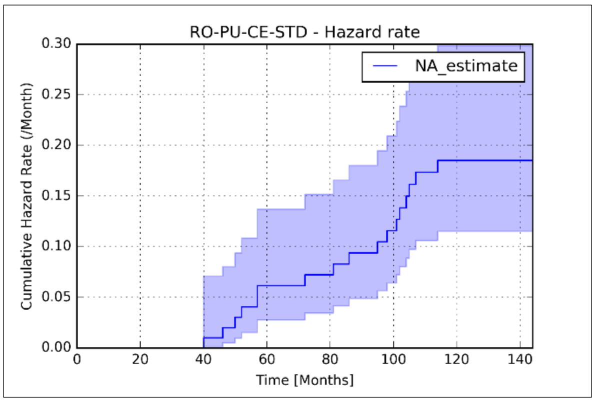
- Downtime cost is not taken into consideration, due to equipment redundancy B.
- CoSO = 500 NOK (Oil)
- Man hours = 3 hour(s)
- Rate = 500 NOK
- PMAC = 2.000 NOK

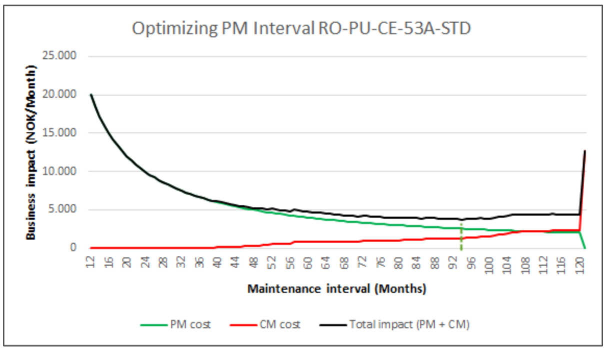
CM Cost

- CoSO2 = 2.000 NOK (Replace bearing)
- Mean Man hours = 21,3 hour(s)
- Max Man hours = 67,6 hour(s)
- Repair rate = 500 NOK
- CMAC = 12.650 NOK

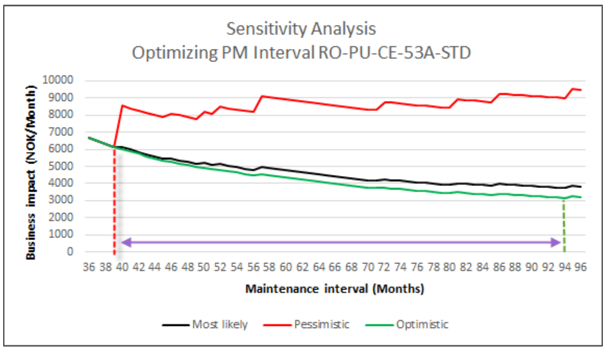
Table 32 - Optimization RO-PU-CE-53A, CENTRIFUGAL PUMP, OIL CHANGE







Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
12	20000	0	20000
24	10000	0	10000
36	6667	0	6667
48	5000	254	5254
60	4000	779	4779
72	3333	913	4247
84	2857	1049	3906
94	2553	1187	3740
96	2500	1326	3826
108	2222	2194	4416
120	2000	2344	4344
RTF	0	12650	12650

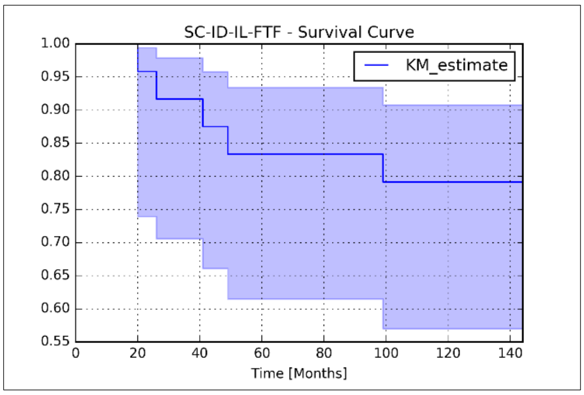


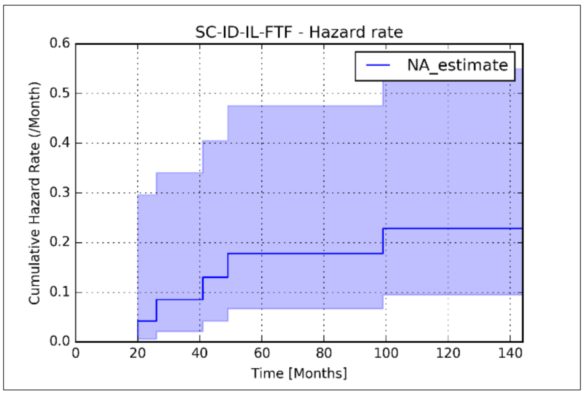
Results of PM optimization showing optimal maintenance interval for activity is 94 month(s). The recommended maintenance interval (taking oil deterioration and -degradation and data uncertainty into account) is 12 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month. Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 39 month(s) to max 94 month(s). According to Survival function it is 100% chance of asset survival to reach (selected) interval of 12 Month(s).

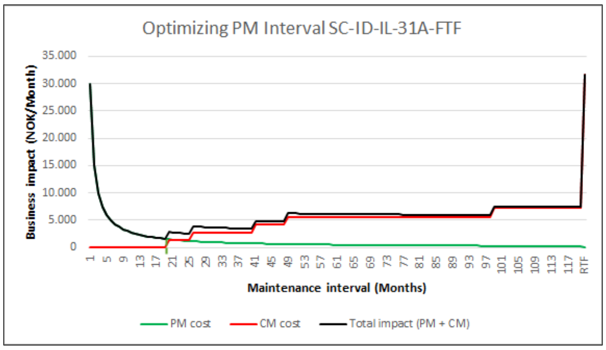
Table 33 - Input data MCA: SC-ID-IL-31A, TRANSMITTER, FUNCTIONAL TEST

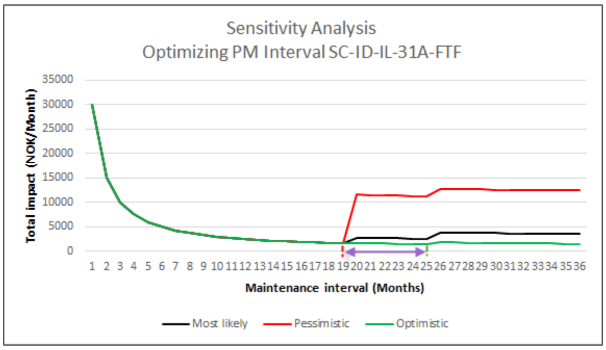
PM Cost	***CM Cost***
• Man hours = 0,5 hour(s) • Rate = 500 NOK • PMAC = 250 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 3,3 hour(s) • Max Man hours = 8 • Repair rate = 500 NOK • CMAC = 31.650 NOK

Table 34 - Optimization SC-ID-IL-31A, TRANSMITTER, FUNCTIONAL TEST









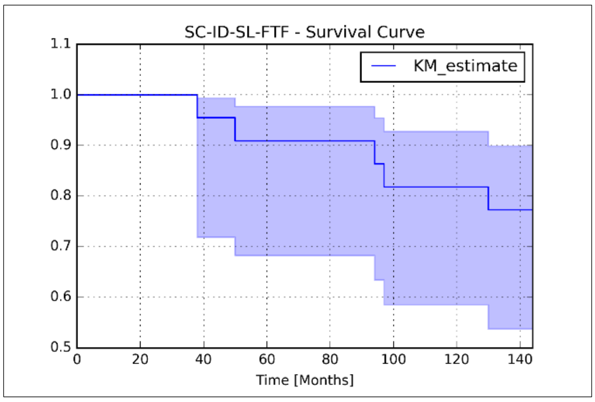
Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
3	10000	0	10000
6	5000	0	5000
9	3333	0	3333
12	2500	0	2500
15	2000	0	2000
18	1667	0	1667
19	1579	0	1579
20	1500	1319	2819
24	1250	1319	2569
30	1000	2695	3695
36	833	2695	3528
RTF	0	31100	31100

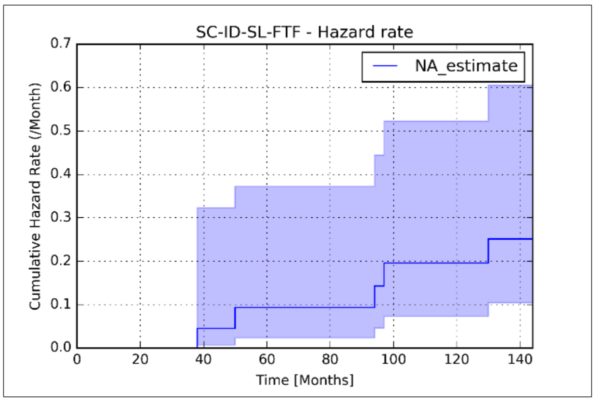
Results of PM optimization showing optimal maintenance interval for activity is 19 month(s). The recommended maintenance interval (taking packing and data uncertainty into account) is 18 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month. Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 19 month(s) to max 25 month(s). According to Survival function it is 100% chance of asset survival to reach (selected) interval of 18 Month(s).

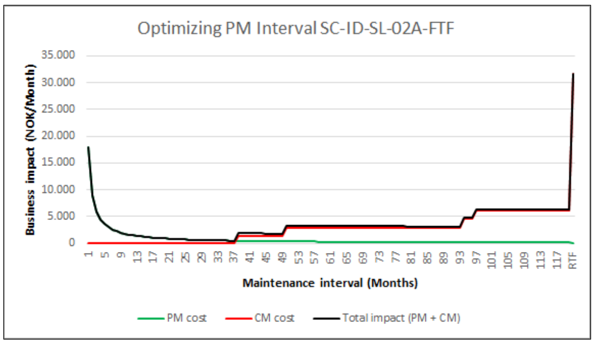
Table 35 - Input data MCA: SC-ID-SL-02A, SWITCH LOOP, FUNCTIONAL TEST

PM Cost	***CM Cost***
• Man hours = 0,3 hour(s) • Rate = 500 NOK • PMAC = 150 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 3,3 hour(s) • Max Man hours = 8 • Repair rate = 500 NOK • CMAC = 31.650 NOK

Table 36 - Optimization SC-ID-SL-02A, SWITCH LOOP, FUNCTIONAL TEST







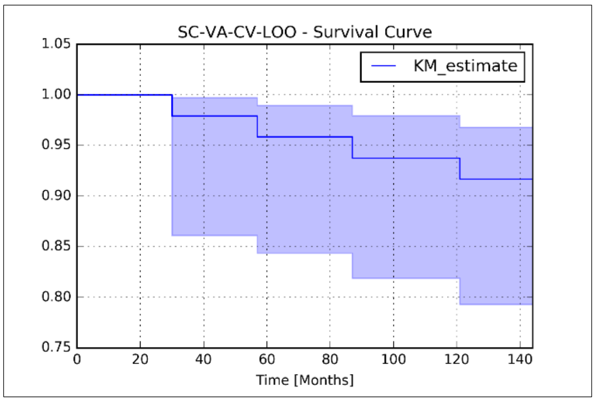
Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
1	18000	0	18000
6	3000	0	3000
12	1500	0	1500
18	1000	0	1000
24	750	0	750
30	600	0	600
36	500	0	500
37	486	0	486
38	474	1439	1912
42	429	1439	1867
48	375	1439	1814
RTF	0	31650	31650

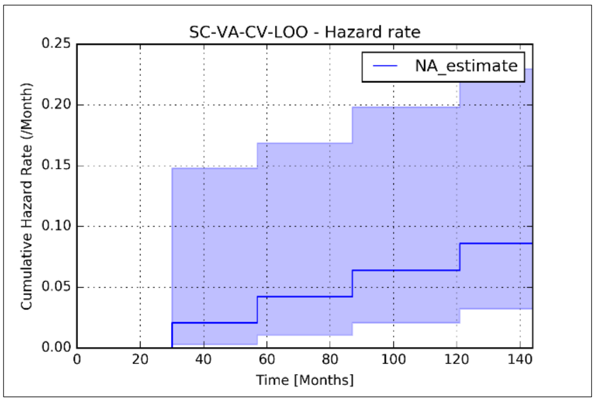
Results of PM optimization showing optimal maintenance interval for activity is 37 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 36 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month.
Current interval (6) and Run-to-failure (RTF) options.
According to Survival function it is 100% chance of asset survival to reach (selected) interval of 36 Month(s).

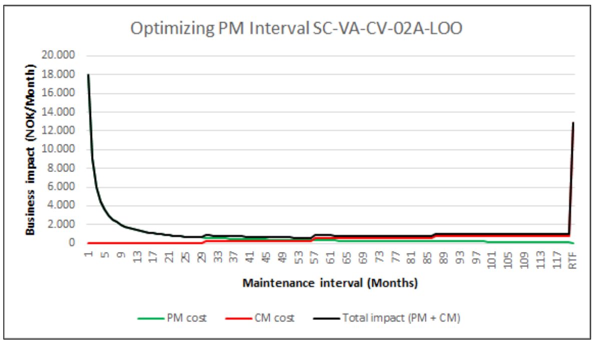
Table 37 - Input data MCA: SC-VA-CV-02A, CONTROL VALVE, FUNCTIONAL TEST

PM Cost	***CM Cost***
• Man hours = 0,3 hour(s) • Rate = 500 NOK • PMAC = 150 NOK	• CoSO2 = 10.000 NOK • Mean Man hours = 5,7 hour(s) • Max Man hours = 12 hour(s) • Repair rate = 500 NOK • CMAC = 12.850 NOK

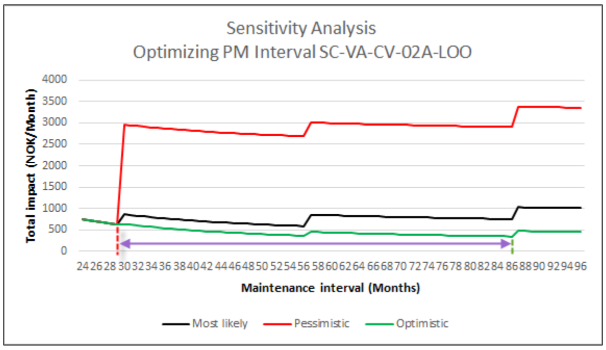
Table 38 - Optimization SC-VA-CV-02A, CONTROL VALVE, FUNCTIONAL TEST







Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
1	18000	0	18000
6	3000	0	3000
12	1500	0	1500
18	1000	0	1000
24	750	0	750
30	600	268	868
36	500	268	768
42	429	268	696
48	375	268	643
56	321	268	589
60	300	541	841
RTF	0	12850	12850



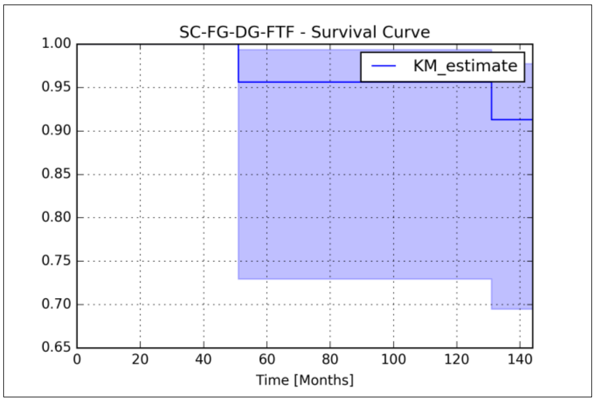
Results of PM optimization showing optimal maintenance interval for activity is 56 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 36 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 2.100 NOK/Month.
Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 29 month(s) to max 86 month(s).
According to Survival function it is 97,9% chance of asset survival to reach (selected) interval of 36 Month(s).

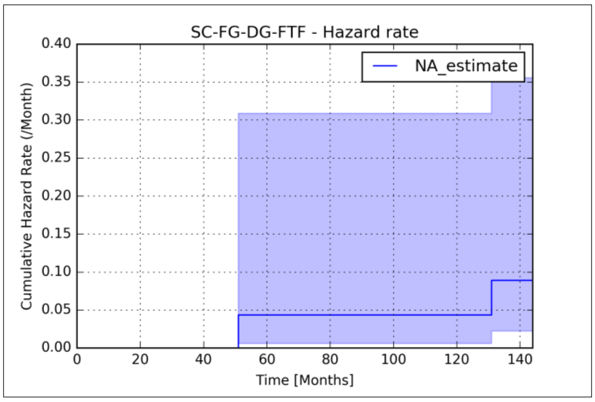
4.2.6 Optimizing PM Interval – Fire and gas detector

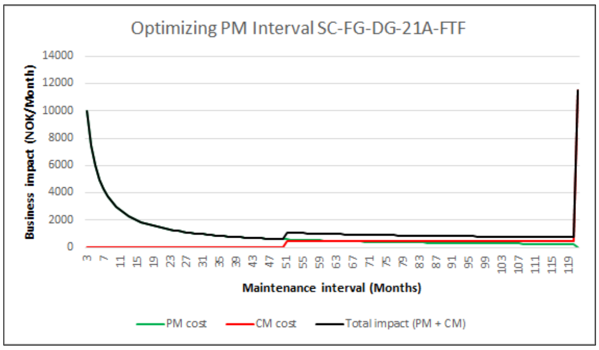
Table 39 - Input data MCA: SC-FG-DG-21A, DETECTOR GAS HC, FUNCTIONAL TEST

PM Cost	***CM Cost***
• Man hours = 0,5 hour(s) • Rate = 500 NOK • PMAC = 250 NOK	• CoSO2 = 10.000 NOK • Man hours = 3 hour(s) • Repair rate = 500 NOK • CMAC = 11.500 NOK

Table 40 - Optimization SC-DG-DG-21A, DETECTOR GAS HC, FUNCTIONAL TEST







Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
1	30000	0	30000
2	15000	0	15000
3	10000	0	10000
4	7500	0	7500
5	6000	0	6000
6	5000	0	5000
9	3333	0	3333
12	2500	0	2500
24	1250	0	1250
36	833	0	833
48	625	0	625
50	600	0	600
RTF	0	11500	11500

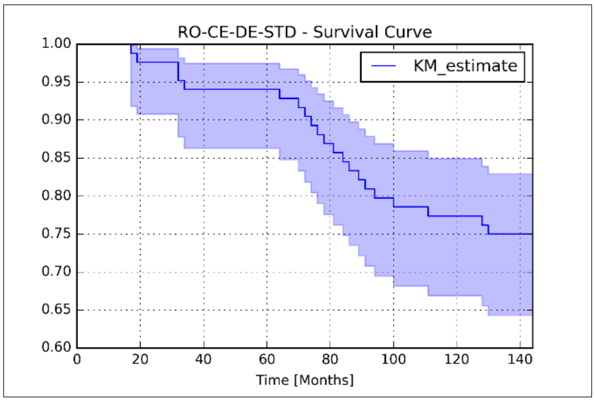
Results of PM optimization showing optimal maintenance interval for activity is 50 month(s). The recommended maintenance interval (taking performance standard of max 12 month(s) requirements into account) is 6 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 0 NOK/Month. Current interval (3) and Run-to-failure (RTF) options. According to Survival function it is 100% chance of asset survival to reach (selected) interval of 6 Month(s).

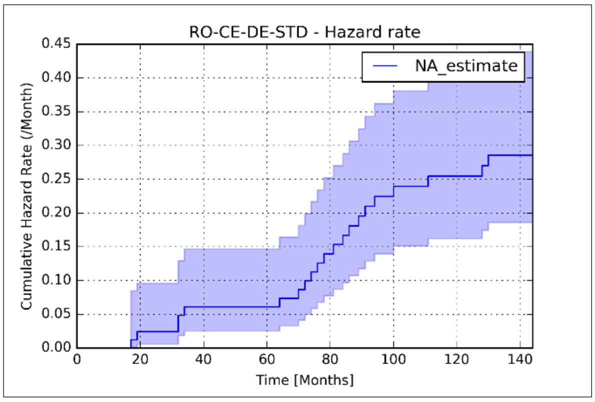
4.2.7 Optimizing PM Interval – Main engine

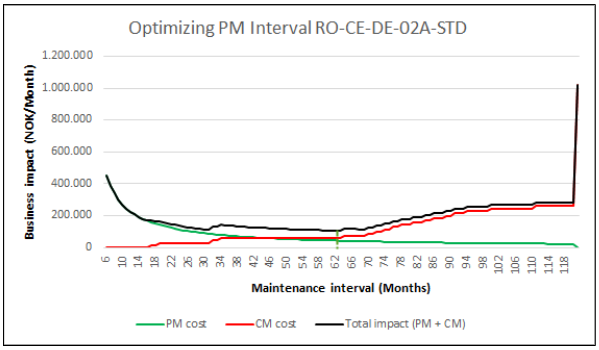
Table 41 - Input data MCA: RO-CE-DE-02A, MAIN ENGINE, 8000H INSPECTION

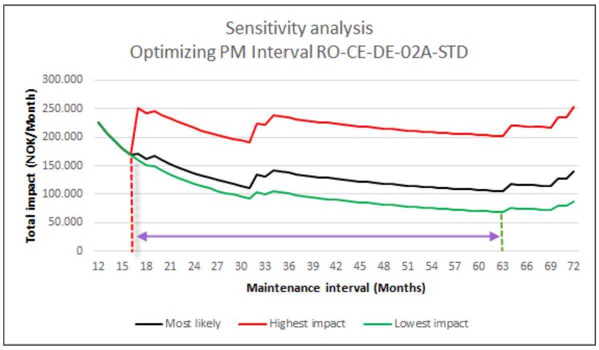
PM Cost	***CM Cost***
• Man hours = 45 hour(s) • Rate = 500 NOK • PMAC = 22.500 NOK	• CoSO2 = 1.000.000 NOK • Man hours = 45 hour(s)(uprated from 30,4 hours) • Repair rate = 500 NOK • CMAC = 1.022.500 NOK

Table 42 - Optimization RO-CE-DE-02A, MAIN ENGINE, 8000H INSPECTION









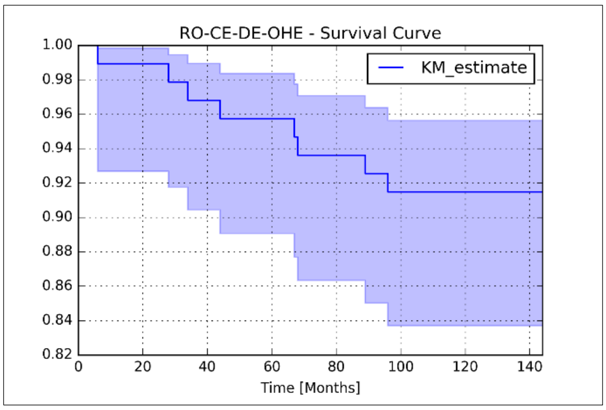
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
1	2700000	0	2700000
12	225000	0	225000
16	168750	0	168750
18	150000	12173	162173
24	112500	24492	136992
36	75000	62366	137366
48	56250	62366	118616
60	45000	62366	107366
63	42857	62366	105223
72	37500	101697	139197
84	32143	170810	202953
96	28125	229675	257800
108	25000	244936	269936
120	22500	260428	282928
RTF	0	1022500	1022500

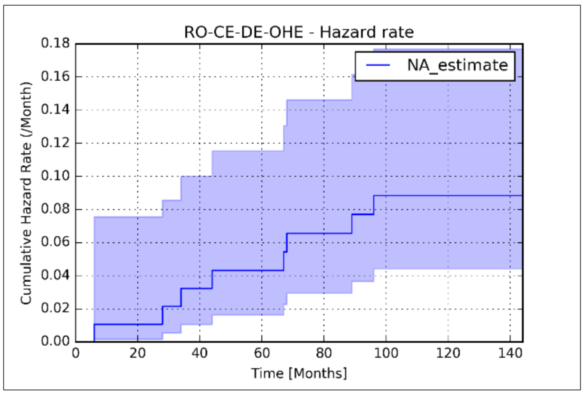
Results of PM optimization showing optimal maintenance interval for activity is 63 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 18 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 79.546 NOK/Month. Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 16 month(s) to max 63 month(s).
According to Survival function it is 98,8% chance of asset survival to reach (selected) interval of 18 Month(s).

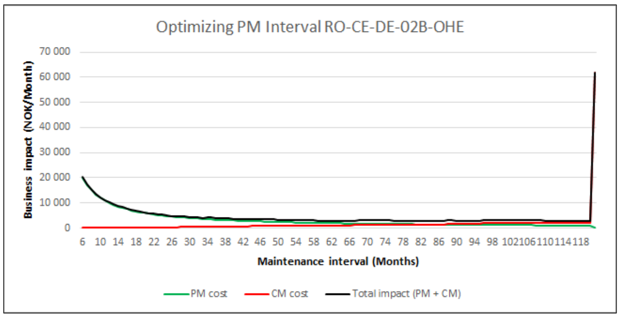
Table 43 - Input data MCA: RO-CE-DE-02B, THERMOSTATIC VALVE, NEAR VISUAL CHECK

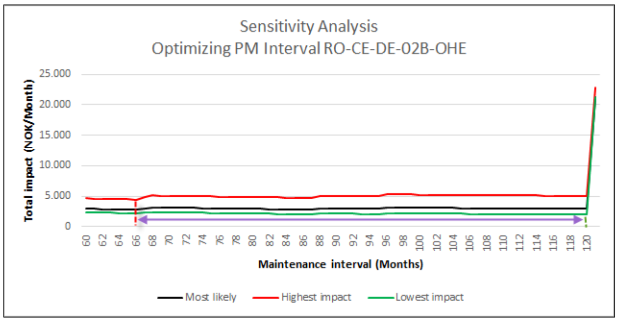
PM Cost	***CM Cost***
• Man hours = 2 hour(s) • Rate = 500 NOK • PMAC = 1.000 NOK	• CoSO2 = 10.000 NOK • Mean man hours = 22,6 hour(s) • Max man hours = 25,6 hour(s) • Repair rate = 500 NOK • CMAC = 21.300 NOK

Table 44 - Optimization RO-CE-DE-02B, THERMOSTATIC VALVE, NEAR VISUAL CHECK









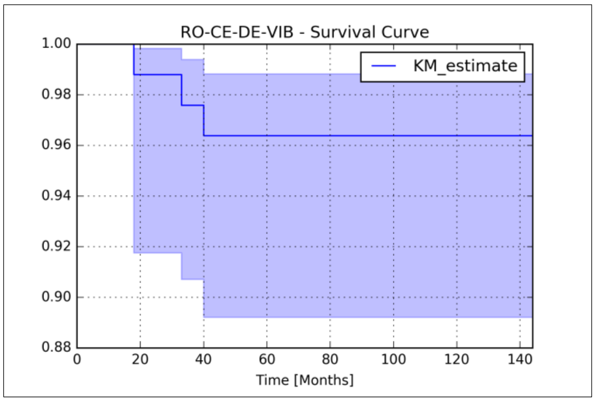
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
1	120000	0	120000
6	20000	439	20439
12	10000	439	10439
18	6667	439	7106
24	5000	439	5439
30	4000	883	4883
36	3333	1332	4666
42	2857	1332	4190
48	2500	1786	4286
54	2222	1786	4008
60	2000	1786	3786
66	1818	1786	3604
72	1667	2709	4376
RTF	0	41300	41300

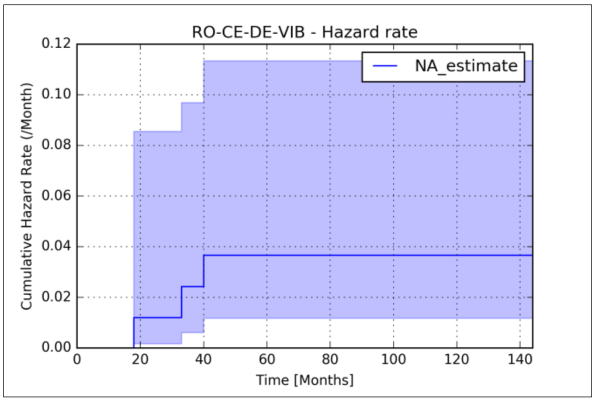
Results of PM optimization showing optimal maintenance interval for activity is 66 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 48 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 1.707 NOK/Month. Current interval (18) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 66 month(s) to max 120 month(s).
According to Survival function it is 95,7% chance of asset survival to reach (selected) interval of 48 Month(s).

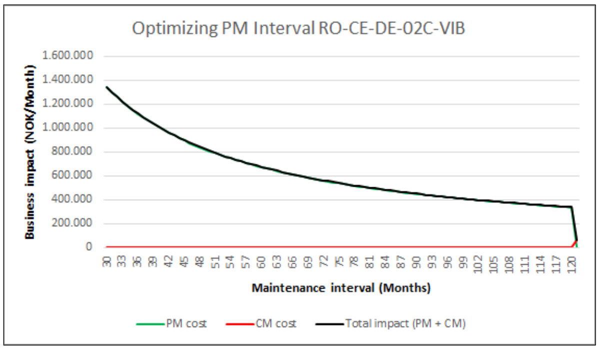
Table 45 - Input data MCA: RO-CE-DE-02C, DIESEL ENGINE, BEARING NEAR VISUAL CHECK

PM Cost	***CM Cost***
• Man hours = 672 hour(s) • Rate = 500 NOK • PMAC = 336.000 NOK	• CoSO2 = 1.000.000 NOK • Mean Man hours = 672 hour(s) (Uprated due to higher PM man hours than CM man hours from OREDA 64 hours) • Max man hours = 800 hours(s) (Uprated hours) • Repair rate = 500 NOK • CMAC = 1.336.000 NOK

Table 46 - Optimization RO-CE-DE-02C, DIESEL ENGINE, BEARING NEAR VISUAL CHECK







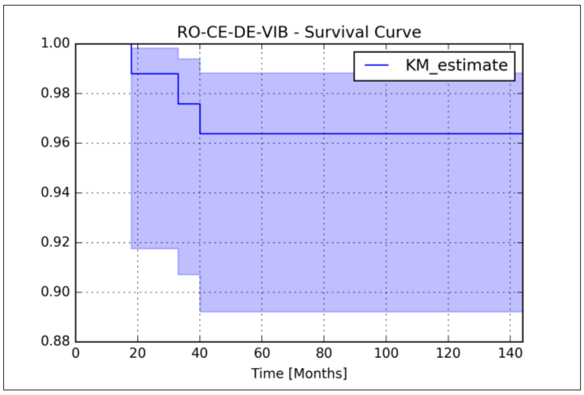
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
12	3360000	0	3360000
24	1680000	16096	1696096
36	1120000	32389	1152389
48	840000	48883	888883
60	672000	48883	720883
72	560000	48883	608883
84	480000	48883	528883
96	420000	48883	468883
108	373333	48883	422216
120	336000	48883	384883
RTF	0	1336000	1336000

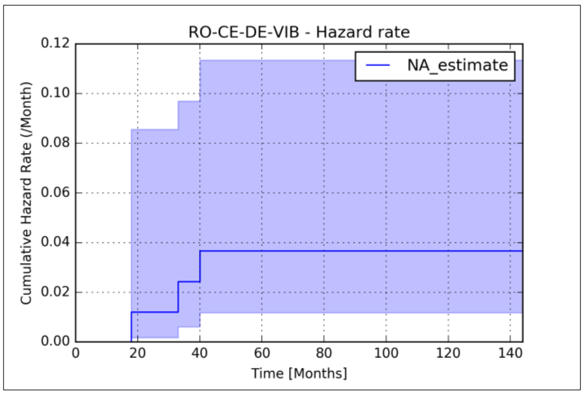
Results of PM optimization showing optimal maintenance interval for activity is 120 month(s). The recommended maintenance interval (taking packing and data uncertainty into account) is 36 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 103.365 NOK/Month.
Current interval (36) and Run-to-failure (RTF) options.
According to Survival function it is 97,6% chance of asset survival to reach interval of 36 Month(s).

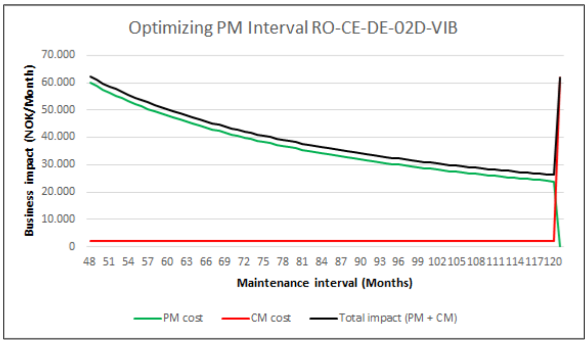
Table 47 - Input data MCA: RO-CE-DE-02D, DIESEL ENGINE, BEARING CHECK (SMALL END)

PM Cost	***CM Cost***
• Man hours = 48 hour(s) • Rate = 500 NOK • PMAC = 24.000 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 64 hour(s) • Max Man hours = 120 hour(s) • Repair rate = 500 NOK • CMAC = 62.000 NOK

Table 48 - Optimization RO-CE-DE-02D, DIESEL ENGINE, BEARING CHECK (SMALL END)







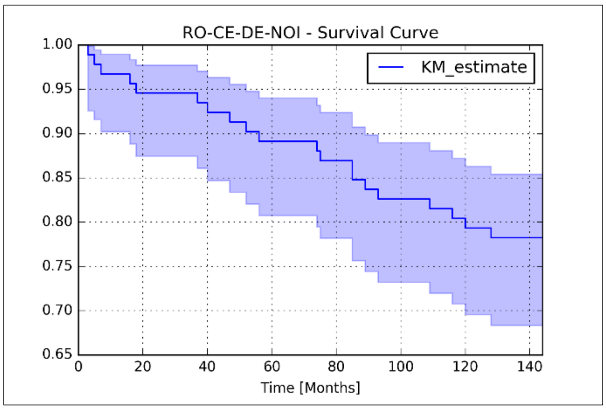
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
12	240000	0	240000
24	120000	747	120747
36	80000	1503	81503
48	60000	2269	62269
60	48000	2269	50269
72	40000	2269	42269
84	34286	2269	36554
96	30000	2269	32269
108	26667	2269	28935
120	24000	2269	26269
RTF	0	62000	62000

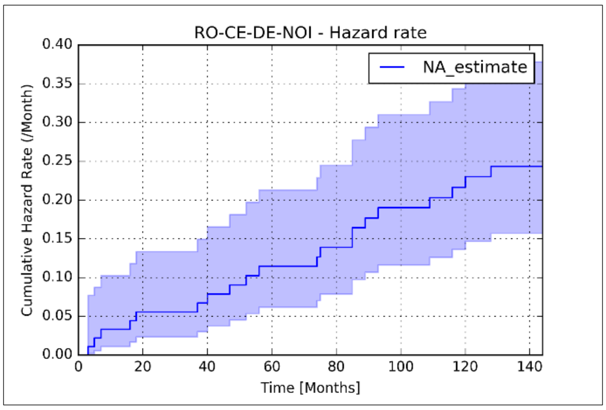
Results of PM optimization showing optimal maintenance interval for activity is 120 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 36 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 7.224 NOK/Month.
Current interval (48) and Run-to-failure (RTF) options.
According to Survival function it is 97,5% chance of asset survival to reach (selected) interval of 36 Month(s).

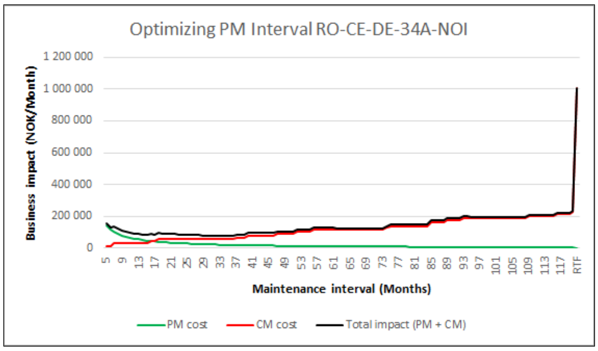
Table 49 - Input data MCA: RO-CE-DE-34A, MAIN ENGINE, RETIGHTENING

PM Cost	***CM Cost***
• Man hours = 12 hour(s) • Rate = 500 NOK • PMAC = 6.000 NOK	• $CoSO2$ = 1.000.000 NOK • Man hours = 9,8 hour(s) • Repair rate = 500 NOK • CMAC = 1.004.900 NOK

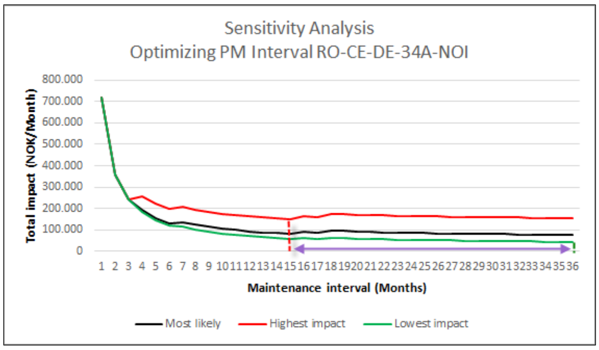
Table 50 - Optimization RO-CE-DE-34A, MAIN ENGINE, RETIGHTENING







Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
6	120000	10923	130923
12	60000	33131	93131
18	40000	55842	95842
24	30000	55842	85842
30	24000	55842	79842
36	20000	55842	75842
42	17143	79077	96220
48	15000	90899	105899
RTF	0	1004900	1004900

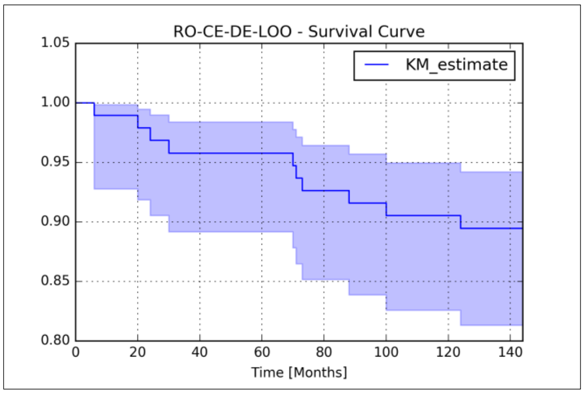


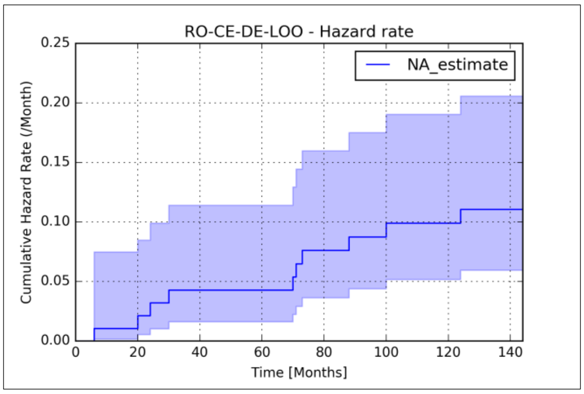
Results of PM optimization showing optimal maintenance interval for activity is 36 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 24 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 78.801 NOK/Month.
Current interval (12) and Run-to-failure (RTF) options. Results from sensitivity analysis showing range for decision of minimum 15 month(s) to max 36 month(s).
According to Survival function it is 94,5% chance of asset survival to reach (selected) interval of 24 Month(s).

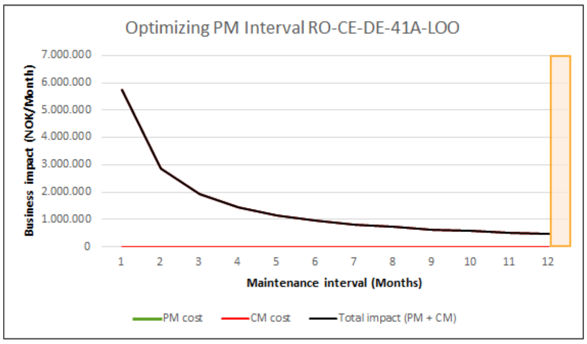
Table 51 - Input data MCA: RO-CE-DE-41A, CHARGE AIR COOLER, CLEANING

PM Cost	***CM Cost***
• Man hours = 96 hour(s) • Rate = 500 NOK • PMAC = 48.000 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 96 (Uprated from 12,4 hour(s)) • Max Man hours = 116 • Repair rate = 500 NOK • CMAC = 78.000 NOK

Table 52 - Optimization RO-CE-DE-41A, CHARGE AIR COOLER, CLEANING







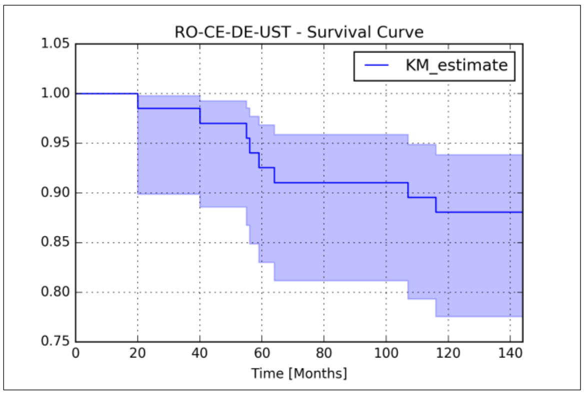
Maintenance interval Month(s)	PM cost NOK / Month	CM cost NOK / Month	Total cost impact NOK / Month
1	30000	0	30000
2	15000	0	15000
3	10000	0	10000
4	7500	0	7500
5	6000	0	6000
6	5000	0	5000
9	3333	0	3333
12	2500	0	2500
24	1250	0	1250
36	833	0	833
48	625	0	625
50	600	0	600
RTF	0	11500	11500

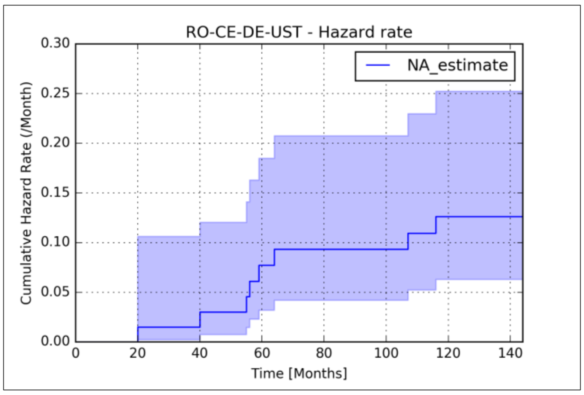
Results of PM optimization showing optimal maintenance interval for activity is 120M.
The recommended maintenance interval (taking OEM recommandation of max 12 month(s) requirements into account) is 12 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 5.758 NOK/Month. Current interval is (6).

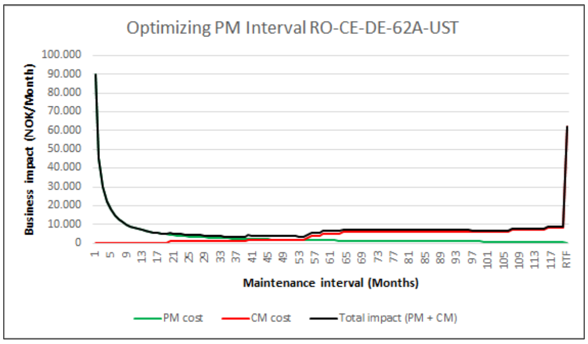
Table 53 - Input data MCA: RO-CE-DE-62A, MAIN ENGINE CENTRIFUGAL FILTER, REPLACE

PM Cost	***CM Cost***
• CoSO = 100 NOK (replace filter) • Man hours = 1,5 hour(s) • Rate = 500 NOK • PMAC = 750 NOK	• CoSO2 = 30.000 NOK • Mean Man hours = 67,9 hour(s) • Max Man hours = 116 hour(s) • Repair rate = 500 NOK • CMAC = 63.950 NOK

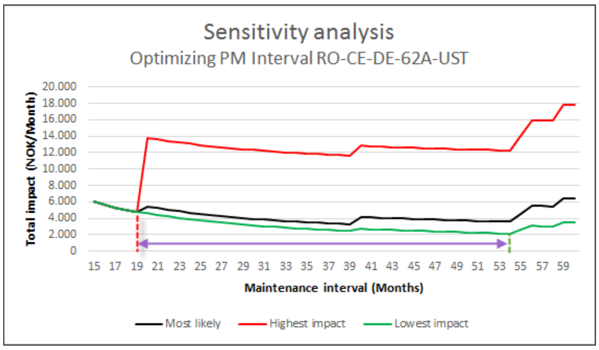
Table 54 - Optimization RO-CE-DE-62A, MAIN ENGINE CENTRIFUGAL FILTER, REPLACE







Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
1	90000	0	90000
6	15000	0	15000
12	7500	0	7500
18	5000	0	5000
24	3750	954	4704
30	3000	954	3954
36	2500	954	3454
39	2308	954	3262
42	2143	1923	4066
48	1875	1923	3798
RTF	0	63950	63950

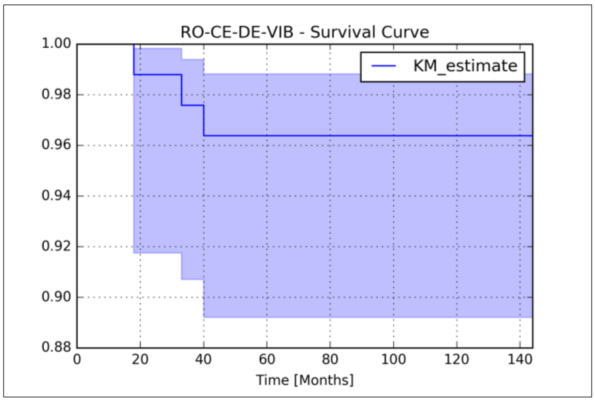


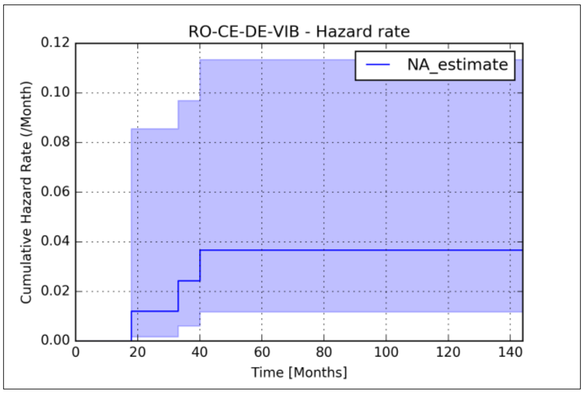
Results of PM optimization showing optimal maintenance interval for activity is 39 month(s).
The recommended maintenance interval (taking packing and data uncertainty into account) is 24 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 3.884 NOK/Month. Current interval (1) and Run-to-failure (RTF) options.
Results from sensitivity analysis showing range for decision of minimum 19 month(s) to max 54 month(s).
According to Survival function it is 98,5 % chance of asset survival to reach (selected) interval of 24 Month(s).

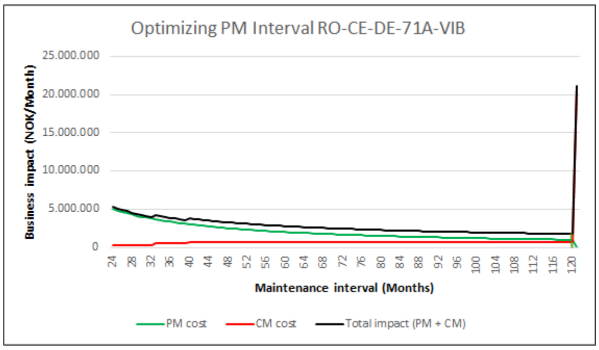
Table 55 - Input data MCA: RO-CE-DE-71A, DIESEL ENGINE OVERHAUL

PM Cost	***CM Cost***
• Man hours = 2016 hour(s) • Rate = 500 NOK • PMAC = 1.008.000 NOK	• CoSO2 = 20.000.000 NOK • Man hours = 2016 hour(s) (Uprated from 64 hour(s)) • Repair rate = 500 NOK • CMAC = 21.008.000 NOK

Table 56 - Optimization RO-CE-DE-71A, DIESEL ENGINE OVERHAUL







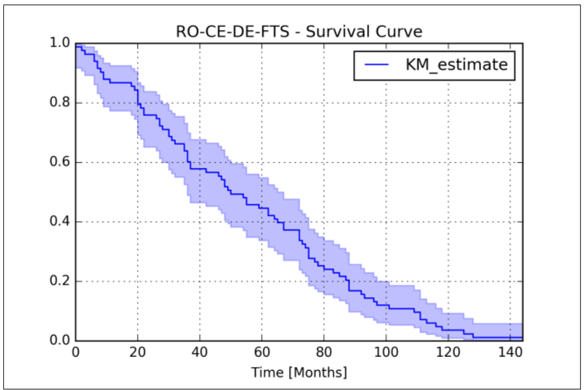
Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
12	10080000	0	10080000
24	5040000	253108	5293108
36	3360000	509304	3869304
48	2520000	768662	3288662
60	2016000	768662	2784662
72	1680000	768662	2448662
84	1440000	768662	2208662
96	1260000	768662	2028662
108	1120000	768662	1888662
120	1008000	768662	1776662
RTF	0	21008000	21008000

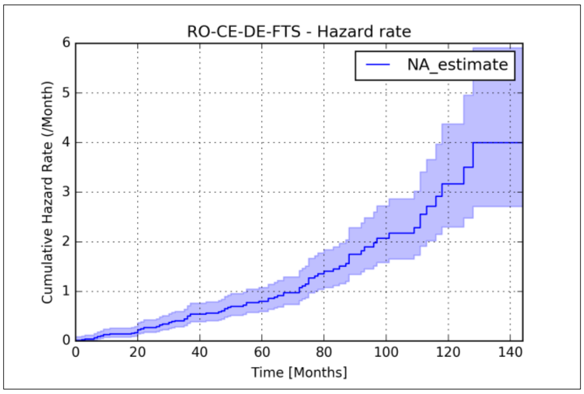
Results of PM optimization showing optimal maintenance interval for activity is 120. The recommended maintenance interval (taking packing and data uncertainty into account) is 36 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 1.541.557 NOK/Month. Current interval (24).
According to Survival function it is 98,8 % chance of asset survival to reach (selected) interval of 36 Month(s).

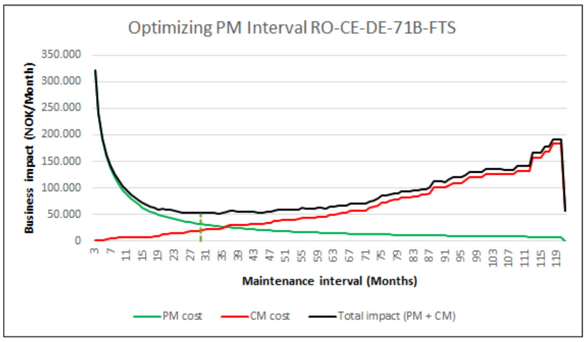
Table 57 - Input data MCA: RO-CE-DE-71B, FUEL INJECTORS OVERHAUL

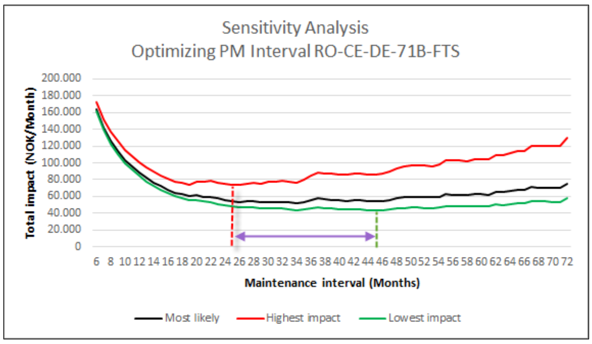
PM Cost	***CM Cost***
• Man hours = 16 hour(s) • Rate = 500 NOK • PMAC = 8.000 NOK	• CoSO2 = 50.000 NOK • Mean Man hours = 16 hour(s) (Uprated from 8,8 hours) • Max Man hours = 64 hour(s) • Repair rate = 500 NOK • CMAC = 58.000 NOK

Table 58 - Optimization RO-CE-DE-71B, FUEL INJECTORS OVERHAUL









Maintenance interval Month(s)	PM cost NOK / Month	CM costs NOK / Month	Total cost impact NOK / Month
3	320000	2122	322122
6	160000	3581	163581
12	80000	8193	88193
24	40000	15881	55881
34	28235	23690	51926
36	26667	29166	55833
48	20000	37820	57820
60	16000	46428	62428
72	13333	62344	75677
84	11429	84351	95780
96	10000	114967	124967
108	8889	126040	134929
120	8000	183787	191787
RTF	0	58000	58000

Results of PM optimization showing optimal maintenance interval for activity is 34 month(s). The recommended maintenance interval (taking packing and data uncertainty into account) is 24 month(s). The potential impact of data uncertainty (if recommended interval is selected) is 18.971 NOK/Month. Current interval (3) and Run-to-failure (RTF) options.
Results from sensitivity analysis showing range for decision of minimum 25 month(s) to max 45 month(s). According to Survival function it is 75,9 % chance of asset survival to reach (selected) interval of 24 Month(s).

4.3 Derivation of Results

PM program work load and schedule made with a rate assumed NOK 500.

Calculate Total Cost for optimized PM-program

Table 59 - Optimized PM program Workload

Case	***Equipment***	***Totals in 10 years***	***Total per year***	***Amount of tags***	***MHOUR(S) per equipment per year***
Pump package	ME-HE-PL	960	96	4	24
	RO-EM-DC	44	4,4	4	1,1
	RO-PU-CE	453	45,3	4	11,3
	SC-ID-IL	47	4,7	14	0,3
	SC-ID-SL	2	0,2	2	0,1
	SC-VA-CV	4	0,4	4	0,1
Main engine	RO-CE-DE	11.500	1.150	1	1150
Fire and gas detector	SC-FG-DG	230	23	23	1
	SUM	13.240	1.324		

Comparison of Total Cost of PM-program in workload:

Table 60 - Comparison of Baseline vs Optimized PM program

Case	***Equipment***	***Baseline totals in 10 years***	***Baseline Total Man hours per year***	***Optimized Total Man hours per year***	***Difference***	***Difference in percent***
Pump package	ME-HE-PL	960	96	96	0	0,0 %
	RO-EM-DC	68	6,8	4,4	-2,4	-35,3 %
	RO-PU-CE	1.110	110	45,3	-64,7	-58,8 %
	SC-ID-IL	70	7,0	4,7	-2,3	-33,3 %
	SC-ID-SL	12	1,2	0,2	-1	-83,3 %
	SC-VA-CV	12	1,2	0,4	-0,8	-66,7 %
Main engine	RO-CE-DE	15.840	1.584	1.150	-426,3	-27,0 %
Fire and gas detector	SC-FG-DG	460	46	23	-23	-50,0 %
	SUM	18.530	1.853	1.324	-520,5	-28,2 %

5. Discussion

This chapter gives an overall review of the thesis. Some aspects of findings are discussed. Moreover, the conclusions and future research are discussed.

5.1 Overall review of the project

Data collection

Why are OREDA short on some failure modes for some equipment types? For example, the equipment Heat exchanger, Plate has only failure mode: ELP (External leakage process medium). Failure modes like LOO (Low output) or PLU (Plugged) should have been documented. These failure modes would fit with the maintenance activity: 'cleaning'. Many failures and failure modes are maybe not documented in CMMS, because they are "hidden" in reporting in preventive maintenance orders. Thus, the incipient failure LOO (Low Output) on a heat exchanger is not registered in OREDA. Or it is also conceivable that the heat exchangers are maintained and cleaned at a regular basis? Which results that they are seldom plugged and/or has lower performance. To find the frequency of failure mode "LOO" one should check the PM-history for cleaning rates that will correspond to failure mode rate for Low output.

For the Main engine, the maintenance activities were based on the OEM manual. For each maintenance interval, many maintenance activities were combined into one activity that covered all the maintenance objects on the main engine. This was a challenging process to link to corresponding failure modes from OREDA. Should the large maintenance activities be divided for each maintenance object into separate maintenance activities? And would this result into a different result? For example, for Main engine the failure mode VIB (Vibration) does not have a maintenance object *bearing* in OREDA, however in the maintenance concept, the maintenance object *bearing* has several maintenance activities to check-, inspect- and lubrication of the bearing. Another example is oil change activity. There is often a PM-activity or routine job to make an oil change, but it is seldom reported as a failure if the oil is dirty because the equipment has not failed. However, should it be reported as incipient failure with failure mechanism as contaminated in the PM-program?

Modelling and analysis

During the random sampling, Normal distribution with derived MTTF and SD was used. The Normal (Gaussian) distribution is the most commonly used distribution in statistics.

Heuristically 99 percent of outputs of sampling lie between MTTF – 3 * SD and MTTF + 3 * SD. This explains the sensitivity of the analysis to the input data and parameters. It can be easily observed that for failure modes with large MTTF and SD values, results from the model are not as informative as with small MTTF and SD values. Could a different distribution be chosen?

Examples of alternative distributions for modelling are:

- The exponential distribution
- The binomial and geometric distributions
- The gamma distribution
- The Weibull distribution

The random sampling was done with a sample size of 100. This resulted in a larger data uncertainty in the 95 % confidence interval.

The models that are used have some limitations in terms of prediction. This can be seen for example from the fact that failure rates do not change after some period of time. The reason for this is that the time period for the study was limited to ten years. Therefore, in cases where the input data are large (MTTF, Standard deviation, failure times) the model will not be able to give a realistic output and the results should be treated/interpreted carefully.

The data analysis approach demands availability of a large amount of structured information. In these terms, the OREDA database is not good enough for developing data based models as the information it contains lacks quality.

Moreover, the models that are discussed in this work are merely simplistic and therefore they fit better for analysis of performance simplistic equipment, for example, equipment with one or few failure mode(s) and one maintenance activity such as functional test, inspection, ex-check, replace or exchange. Whereas complex equipment, with several failure modes and maintenance activities, require more sophisticated models and more descriptive data on its performance.

Another possible explanation could be due to not standardized reporting and lack of overview picture of the maintenance loop for the reporting.

To this end, it can be recommended that any failures is found on planned maintenance, should be registered in the same manner as a corrective failure as per ISO 14224.

Cost estimation and analysis

Several failure mechanisms can have linked to a maintenance activity. In this thesis, only the failure mechanism with the highest MTTF and combined with local effects of unsafe failure /loss of function was analysed at a time. This is due to the other failure modes being covered by the interval derived from the failure mechanisms with the highest MTTF. Would there be any difference to analyse all failure mechanisms for one maintenance activity versus the one with the highest MTTF?

Why is the optimal interval much longer than the initial or baseline maintenance interval? The failure mode VIB (Vibration) which the activity Lubrication and Overhaul activity is covering is not realistic in terms of the failure rate. Normal deterioration of bearings with none lubrication is assumed to be higher than analysis output. As mentioned in discussion in data collection the failures may also be “hidden” in the reporting in preventive maintenance orders, and due to the frequent replace some equipment may seldom failure and therefore not documented in OREDA.

Cost of spares and other was roughly estimated, and downtime cost was in these specific cases not taken into consideration, due to equipment redundancy and maintenance could be planned to have none downtime. Cost from consequence classification was not taken into consideration. To include consequence of failure for loss of function one must had calculated probability for redundant units had failed within the same period. Consequence classification often do not set value on the consequences of loss of function. The impacts are in the wording: “Potential for serious personnel injuries”, how to set a value on this? The contribution of impacts could be simplified as described in SALVO (p.68) by applying recognisable ranges of impact and scales of significance should be calibrated with a non-linearity scoring system that equates to a standardised value of, for example 1 point = 10.000 NOK. Example ranges of HSE impact would be like:

- No Potential for injuries=1;
- Potential for injuries requiring medical treatment=10;
- Potential for serious personnel injuries=100

Per NORSOK-Z008 both processes for establishing maintenance programme (see Figure 9) and for updating maintenance program (see Figure 10), a cost/benefit analysis does not fit for barrier elements/safety function. Because of barriers have reliability requirements, so cost/benefit is not relevant. However, other equipment with consequence medium or high should a local adjustment with a cost/benefit analysis be done to give a decision basis for better determine the “best” maintenance interval.

Results from comparison of WL from baseline PM with optimized PM (see Table 60), indicates in total potential savings of 520 man hours per year and 28 % out of these three cases. However, the largest contribution was the ~2000 man hour activity that was prolonged with 12 months, which resulted into savings of 426 NOK per year. The reason for main engine contributed for 85 percentages of the workload, were the small equipment selections of utility equipment and gas detectors. Large roundabout-jobs have potential for great savings and are less complicated to calculate, compared to large and complicated equipment. This is due to fewer failure mechanisms and hence fewer maintenance activities. In addition, most of these rounds are barrier activities, like Ex-check, fire and gas detecting, etc. where the reliability is prioritized. There may also be potential savings in how PM-program is bundled. This was not looked into how this effected, because of the small amount of equipment selection and time delimitation.

It is not recommended to extend the interval of maintenance activity that has a direct effect on the MTTF, such as Lubrication. By lubricating equipment, the degradation rate is prolonged. Removing such activities will increase the MTTF for other failure mechanisms.

5.2 Future Work

Modelling and analysis to assess the decision range of maintenance activity cost analysis establishes a good foundation for research of maintenance optimization. Further and more detailed work to be done in the following areas:

- *LCC including spare parts of individual equipment.* In this work, we did not consider the spare parts and the total cost of spare parts develop methodology on spare parts analysis,
    - Failure mode connection to spare parts similar to failure mode towards tags.
- Inspection of piping with use of mathematic corrosion rate.
- Bundling (preventive maintenance scheduler).

5.3 Challenges Encountered

Assigning consequence loss of function for failure modes from the generic consequence matrix to fit into cost analysis has proven to be challenging task.

6. Conclusion

This chapter gives conclusion and an overall summary of the thesis.

6.1 Overall summary of the Project

The most obvious conclusion was the discovery of the significance of the hazard rate affects the maintenance interval in cost analysis as one of the largest effects of data driven maintenance planning, … which agrees with the state “choose the “best” maintenance task at the “best” possible time is a complex task” in the thesis background.

What types of equipment will this data-driven mathematical/stochastic models work with?

The data-driven mathematical/stochastic models will work better with performance simplistic equipment, with few failure mode(s) and one or few maintenance activities. While larger and more performance complex equipment, such as Cranes or Main engines with many maintenance objects and many more failure modes within its boundary may require more effort and more descriptive data on its performance to analyse it well.

What are the differences in maintenance planning using RCM methodology versus data-driven?

The biggest differences are that the data-driven planning methodology can with an automated statistical model that simply can be fed with data, and in a short amount of time may result in predicting to what interval and when is it the most cost-effective to do maintenance with an updated status on the risk picture. While RCM methodology identifies the technically appropriate maintenance method, but not whether the solution is the most cost-effective option or what is the optimal interval of the activities or when it should be performed. Another difference according to Woodhouse (2014, p. 39) is that the RCM methods are, aimed at predicting, preventing, correcting or mitigating functional failures and their consequences. So, RCM is not good at revealing tasks aimed to slow down degradation rates and extend life (e.g. painting), or to raise/recover operational efficiency (e.g. cleaning of heat exchangers) where there is no discrete point of the asset having 'failed'.

Comparison of WL from baseline PM with optimized PM in results indicates savings up of 28 % in these three cases. However, the largest share was the activity with the highest work load (see Table 56) that may should have not be prolonged at all taken the data uncertainty into account.

How to find a mathematical/stochastic model to “simulate” maintenance strategies and to reveal the associated effects and maintenance costs and operational performance?

In this thesis, random sampling was chosen as a “simulation” model in combination with survival analysis using lifelines, and displaying the results for operational performance with the survival curves with use of Kaplan Meier estimate and furthermore displaying results of the Hazard rate with use of Nelson Aalen estimate. Hazard rate is then used to calculate the corrective maintenance cost or cost of failure. Last the survival curves is used to show asset survival chance at a given time.

7. References

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8. Appendices

8.1 APPENDIX A

8.1.1 OPERATING COSTS BY MAIN CATEGORY

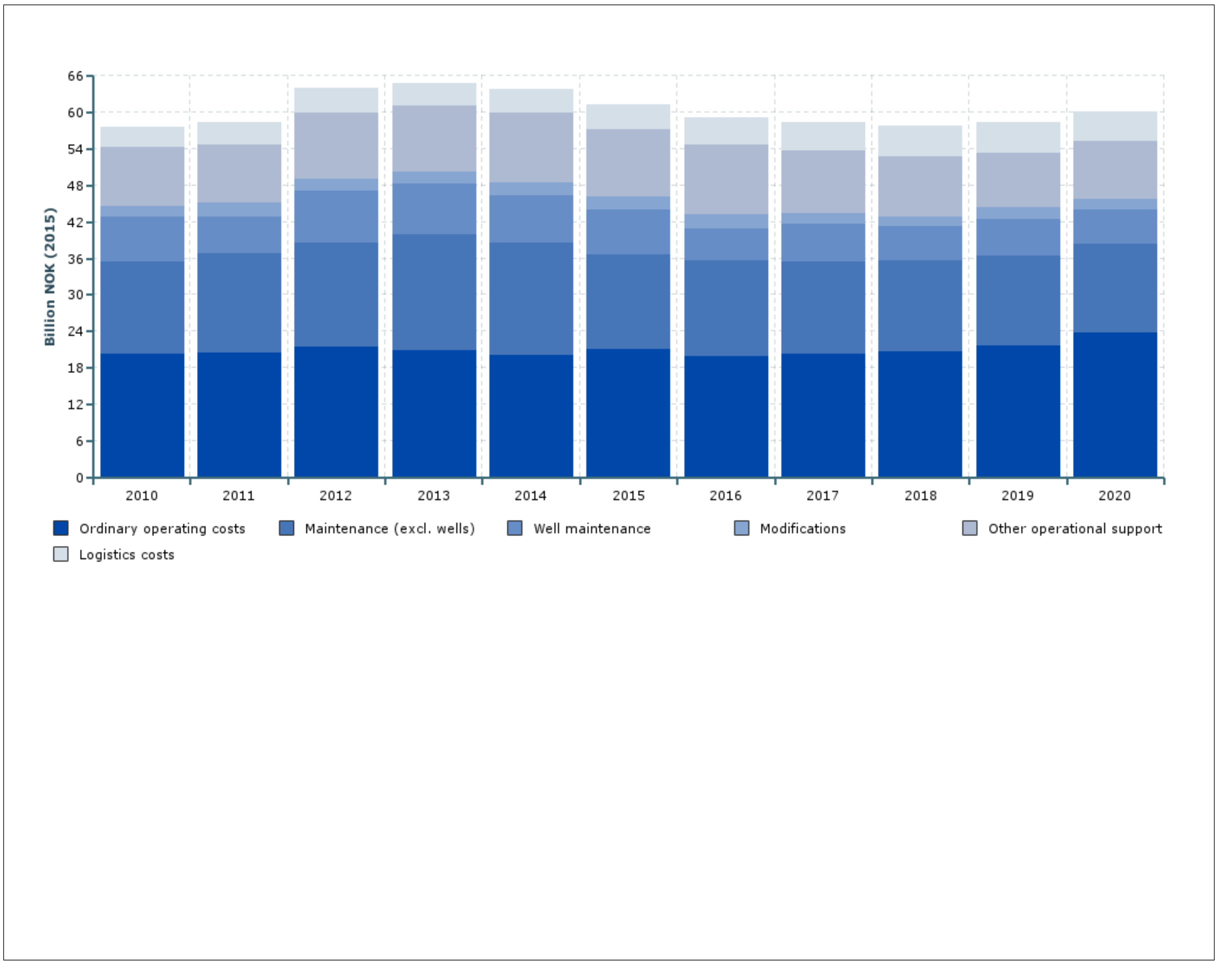

Figure A.1 – Operating costs by main category (Norsk petroleum 2016)

Source: http://www.norskpetroleum.no/en/economy/investments-operating-costs/

8.2 APPENDIX B

8.2.1 Simplifying consequence assessment of standard sub functions

Guidelines and inheritance rules for the standardised sub functions are shown in the table below.

Table B.1 - Consequence assessment of standardized sub functions, based on the MF consequence assessment. Adapted from NORSOK Z-008 (2011) (p.33)

Standard sub function	***Classification of loss of function*** **RED**	**HSE**	**PROD**	**COST**	***Comment***
Main task	MF	MF	MF	MF	
Pressure, relief	Configuration	H	L	L	RED: No redundancy for the failure mode ‘Fail to operate on demand’
Shut down, process	A	H	L	L	RED: No redundancy for the failure mode ‘Fail to operate on demand’
Shut down, equipment	MF	M	L	MF	
Controlling	MF	MF	MF	MF	
Monitoring	MF	M	L	L	
Local indication	MF	L	L	L	
Manual shutoff	MF	(MF)	(MF)	(MF)	

HSE/PROD/COST	See examples and definitions in APPENDIX C
H/M/L	Consequence “High”, “Medium” or “Low”
MF	Will inherit MFs values
RED	Redundancy, see definition in Table 3
( )	Reduce with one level from MF

8.3 APPENDIX C

The decision criteria for consequence classification are set and adapted according to company risk criteria for each class and agreed upon classification. As shown in consequence matrix in table below.

Table C.1 - Consequence matrix

Consequence	***HSE***	***Production***	***Other Cost***
H-High (3)	- Potential for serious injury - Environmental release - Loss of safety barrier operation	- Loss of drilling capability on rig	- Related cost over $150 000
M-Medium (2)	- Potensial for minor injury - Limited effect on safety systems	- Reduced drilling capability	- Related cost between $50 000-150 000
L-Low (1)	No potensial for: - Fire - Injuries - Environmental release	- No impact on drilling capacity	- Related cost under $50 000

8.4 APPENDIX D

Python script used for analysis and modelling with input from failure mode.

Table D.1 - Python – Risk estimation: Failure rate, Survival curves and Hazard rate

In [1]:	# Python imports import pandas as pd import numpy as np %matplotlib inline import matplotlib.pyplot as plt import matplotlib.ticker as ticker import matplotlib.dates as mdates import datetime import time import sys from os import makedirs from os.path import exists import scipy.stats as st import collections
In [2]:	input_data = pd.read_excel('Failure mode input.xlsx')
In [3]:	len(input_data)

In [4]:	for indx in range(52):
	#failure_mode = 'RO-PU-CE-HIO' # label to differenciate between files
	#mttf = 3.37 # years
	#st_dev = 1.38 # standard deviation: 99% of failures will be in the interval (mttf - 3*st_dev, mttf + 3*st_dev)
	
	failure_mode = input_data['Equipment-FM'][indx]
	mttf = input_data['MTTF Years'][indx]
	st_dev = input_data['SD Years'][indx]
	
	if not exists(failure_mode):
	    makedirs(failure_mode)
	
	sample_size = 100
	failure_times = st.norm.rvs(loc = mttf, scale = st_dev, size = sample_size)
	failure_times = failure_times[failure_times>0]
	failure_times = failure_times[failure_times< 100]
	
	x = np.linspace(1, 8, 100)
	normal_sf = 100*st.norm.sf(x, loc = mttf, scale = st_dev)
	
	#analysis period
	starttimes = [pd.to_datetime('2017-01-01')]*len(failure_times)
	ttf_in_days = [datetime.timedelta(days=int(ttf*365)) for ttf in failure_times]
	endtimes = []
	for i in range(len(starttimes)):
	  end_date = starttimes[i]+ttf_in_days[i]
	
	    endtimes.append(end_date)
	
	from lifelines.utils import datetimes_to_durations
	T,C = datetimes_to_durations(starttimes, endtimes, fill_date='2027-12-31', freq='M')
	
	### Estimating failure rate from random sample
	
	mttf_in_years = T[C==True].mean()/12 # mttf in years
	stdev_in_years = T[C==True].std()/12
	mttf_in_hours = mttf_in_years*8760

```
stdev_in_hours = stdev_in_years*8760
failure_rate_1M = 10**6/mttf_in_hours
print('MTTF in years = {:4.3f}, MTTF in hours = {:2.3f}.'.format(mttf_in_years, mttf_in_hours))
print('Standard deviation in years = {:4.3f}'.format(stdev_in_years))
print('Failure rate per 1M hours = {:5.3f}'.format(failure_rate_1M))

filename3 = 'FR_estimate'+failure_mode+'.xlsx'
FR_estimate = pd.DataFrame([mttf_in_years, stdev_in_years, mttf_in_hours, stdev_in_hours,
failure_rate_1M],
                          index = ['MTTF in years', 'Stdev in years', 'MTTF in hours', 'Stdev in hours',
                                   'Failure rate per 1Mh']).T
FR_estimate.to_excel(failure_mode+'/'+filename3)
#FR_estimate

from lifelines.plotting import plot_lifetimes
fig, ax = plt.subplots(figsize=(5,20))
plt.xlabel('Time [Months]')
plt.ylabel('Survival probability')
plt.title('Survivors and failures of '+failure_mode+' in period')
plot_lifetimes(T,C)
fig.savefig(failure_mode+'/'+'Survivors and failures of '+failure_mode+' in period.png', dpi = 300)

from lifelines import KaplanMeierFitter
kmf = KaplanMeierFitter()
kmf.fit(T, event_observed=C)

kmf.survival_function_.plot()
plt.grid()
plt.xlim(0,144)
plt.xlabel('Time [Months]')
kmf.plot()
plt.grid()
plt.xlim(0,144)
plt.xlabel('Time [Months]')
plt.title(''+failure_mode+' - Survival Curve')
plt.savefig(failure_mode+'/'+'Survival'+failure_mode+'.png', dpi = 300)

Survival_func = pd.DataFrame(kmf.survival_function_)

#Survival_func[Survival_func['KM_estimate']>0.5]

# upper and lower 95% confidence intervals
Survival_CI = pd.DataFrame(kmf.confidence_interval_)
#Survival_CI[Survival_CI['KM_estimate_lower_0.95']>0.5]

from lifelines import NelsonAalenFitter
naf = NelsonAalenFitter()
naf.fit(T,event_observed=C)
naf.plot()
plt.xlim(0,144)
plt.grid()
plt.xlabel('Time [Months]')
plt.ylabel('Cumulative Hazard Rate (/Month)')
plt.title(''+failure_mode+' - Hazard rate')
plt.savefig(failure_mode+'/'+'Hazard'+failure_mode+'.png', dpi = 300)

Hazard_func = naf.cumulative_hazard_

Hazard_CI = naf.confidence_interval_
```

```
### Exporting Kaplan-Meier survival (reliability) function and Nelson-Aalen hazard function to Excel

 filename1 = 'Survival_'+failure_mode+'.xlsx'
 filename2 = 'Hazard_'+failure_mode+'.xlsx'

 Surv_results = Survival_func.join(Survival_CI)
 Hazard_results = Hazard_func.join(Hazard_CI)

 Surv_results.to_excel(failure_mode+'/'+filename1)
 Hazard_results.to_excel(failure_mode+'/'+filename2)
```

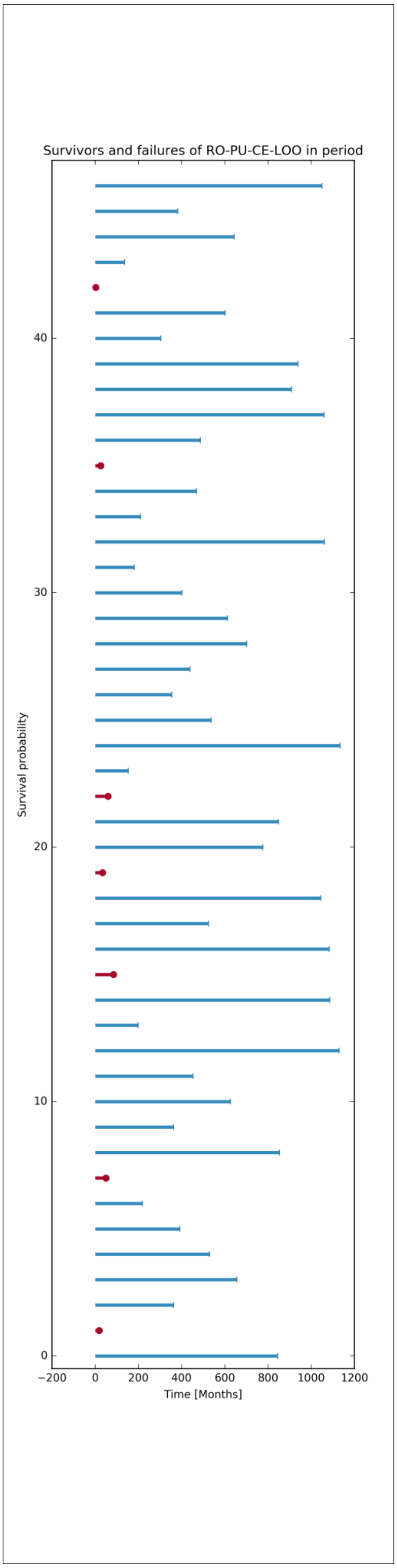

Figure D.1 - Survivors and failures with Lifelines

8.5 APPENDIX E

Work descriptions from Oceaneering Maintenance Concept Activities

8.5.1 Work Descriptions of Pump package

Table E.1 – Heat Exchanger - Plate Sea Water Cooled, Cleaning, ME-HE-PL-41A

Descaling/cleaning of heat exchanger: - Change duty stand by heat exchangers - Drain offline heat exchanger. - Descale and refill with water

Table E.2 - Electric Motor - General, Measurement, RO-EM-DC-15A

Megging of motor windings Megging of insulation inductance in motor windings. WARNING: Only approved/qualified personnel can perform this task according to existing instructions. WARNING: During Megging the termination cabinet shall be without voltage. (Supply shall be earthed) and switches taken out/Locked. MARK: When measuring insulation inductance, transient, high voltages, can be inducted even in equipment not directly connected to the measuring circuit. Therefore equipment that cant handle high voltages shall be protected before megging starts. - All cables for the motor must be disconnected from the feed. Cables not connected must be isolated from earthing. - Megger must be calibrated according to procedure specified by the vendor of the actual megger type. - Cable ends and megger must be cleaned so that there is no residue of dust, water, oil, grease, or other that can change the path of electrical flow. This can lead to incorrect indications of reduction of low insulating property of motor. - Activate megger and wait for stable readings. Follow the instruments manual. Record readings. - Ensure insulation inductance is greater than 1 Mohm.

Table E.3 – Electric Motor - General, Lubrication, RO-EM-DC-51A

Grease Lubrication as applicable: - Ensure that the grease nipple is clean and in good condition. - Lubricated with specified amount/type of grease as per OEM.

Table E.4 - Pump - Centrifugal, Amp Draw Test, RO-PU-CE-21A

Amp draw test under operational conditions.

Table E.5 - Pump - Centrifugal, Lubrication, RO-PU-CE-51A

Grease Lubrication 1. Sleeve bearings and inaccessible ball/roller -bearings w/ grease nipple: - Check The axial and radial clearances around the bearing where possible. - Ensure that the grease nipple is clean and in good condition. - Fill the bearing with specified amount/type of grease. Don't over-lubricate. - Clean the area. Register time, running time, and amount of grease added in CMMS. 2. Ball/roller -bearings with removable casings. - Ensure that the casings can be removed for cleaning. Remove necessary casings - Remove old grease where possible. Clean bearing with degreaser (As specified in manual), and compressed air. Make sure there is no ignition sources nearby while doing this job. - Check the condition, clearance and surface of the bearing. - Clean and check shaft seals. Replace if necessary. - Fill the bearing with specified amount/type of grease. Make sure to stuff the grease properly into the bearing. - Refit the removed casings. - Follow the operation manual on the tightening of bolts. - Clean the area. Register in CMMS. 3. Lubrication of equipment/shafts/bushings with sector/piston -movement. - Remove old, visible, external grease. - Make sure the grease nipple/cup is in good condition.

- Add correct amount/type of grease according to operation manual. - Where possible, move the shaft fully or partially while lubricating. - Remove excess grease, and register in CMMS.

Table E.6 - Pump - Centrifugal, Oil Change, RO-CE-DE-53A

Oil Change 1.0 OIL CHANGE Oil change of identical oils. If oil type is to be changed, special routines applies. Oil Change shall be implemented according to PM routines or if oil analysis identify deviations. 1.1 If an oil sampling is to be performed, this shall be done before draining and according to current routine 1.2 Use correct safety gear. 1.3 When changing oil on gears, the oil should be changed at normal running temperature. For other equipment the oil change can pe preformed without heating the system. 1.4 Drain used oil from the lowest point on the system. Usually from bottom plug in tank, or with dedicated pump. 1.5 When magnet plugs are installed in the sump/tank, these shall be taken out and controlled. Any particles that are discovered shall be sent to analysis. 1.6 If oil is extensively contaminated, the oilsump/systemtank shall be cleaned internally before refilling with new oil. The tank should be cleaned with warm system oil, e.g. by use of own filter unit. Flush from the top of the walls, down towards the bottom/sump. Drain the tank/sump and remove oil remains with Lint-free cloths. Avoid entering the tank. Make sure cloths are not forgotten. 1.7 Visually check the tank internally, with regards to functional defects. All filters that has been used in the system shall be changed when the oil is changed. Remember to also change the breathing/ filling filters. 1.8 All new oil shall be filtered into the tank/sump. This can be done with a filter unit, or with the systems own return filter. The filter unit must have been used for the same oil type, or eventually cleaned before use. Caution! When filling through the systems own filter, make sure the filter has sufficient filtration degree (corresponding to 3 micron absolut filtration). 1.9 Before restarting the unit, the filterunit should be connected to the reservoar, and a current filtering should be performed. The unit should not be started until adequate purity is achieved. 1.10 Remove spillage. 1.11 Update CMMS with maintenance history.

Table E.7 Instrument Loop - Electronic, Function Test, SC-ID-IL-31A

Verify calibration as per OEM.

Table E.8 - Switch Loop, Function Test, SC-ID-SL-02A

Check condition and verify switch function.

Table E.9 - Control Valve, Near Visual Check, SC-VA-CV-02A

Check and Lubrication of actuated valves. Confirm feedback to control room during test. Actuator - Visual inspection of exterior condition. Check for corrosion and surface protection) - Look for damage, loose parts etc. - Check for leaks. - Check hydraulic/pneumatic pipes/hoses - Check electrical cable connections/ limit switches. - Check, if possible, the movement of the actuator, and that it goes from open/close close/open. - Preserve movable parts with salt water protection where necessary.

8.5.2 Work Descriptions of Fire and gas detectors

Table E.10 - Detector - Gas, Function Test, SC-FG-DG-21A

Functional test of gas detectors as per OEM and regulatory bodies.

8.5.3 Work Descriptions of Main engine

Table E.11 - Main Engine, Near Visual Check, RO-CE-DE-02A

Major bearings: - Main bearings (Check 1st set. If not good, check all sets.) - Axial clearance check of thrust washer - Check big ends and small ends for connector rod bearings (Check 1st set. If not good, check all sets.) Resilient Mounts: - Inspect resilient mounts Crankshaft and gears: - Perform deflection check of crankshaft Control system: - Check clearance for RPM Pick-up - Check safety device Fuel system: - Inspection of one fuel injection pump - Inspect deflector (replace if needed) - Check plunger assembly - Check delivery valve

Table E.12 - Main Engine (Thermostatic Valve), Near Visual Check, RO-CE-DE-02B

Check of thermostatic valve for lube oil system and cooling water system

Table E.13 - Main Engine, Near Visual Check, RO-CE-DE-02C

- Check main bearings - Check connector rod bearings (big ends)

Table E.14 - Main Engine, Near Visual Check, RO-DE-DE-02D

- Check of connector rod bearings (small ends). - Clearance check of camshaft bearings.

Table E.15 - Main Engine, Tighten, RO-DE-DE-34A

Retighten major fasteners: - Nuts for cylinder head - Nuts for counter weight - Nuts for main bearing cap - Nuts for connecting rod - Nuts for camshaft - Nuts for timing gears - Bolts for engine block and base frame - Bolts for turbocharger Resilient Mount - retightening: - Bolt for base frame and resilient mount - Nut for resilient mount and foundation

Table E.16 - Main Engine (Turbo Charger), Cleaning, RO-CE-DE-41A

Clean charge air cooler as required per differential pressure measurement (maximum 8000H before cleaning).

Table E.17 - Main Engine (Centrifugal Filter), Replace, RO-CE-DE-62A

Clean and replace centrifugal filter for diesel engine

Table E.18 - Main Engine, Overhaul, RO-CE-DE-71A

Major bearings: - Clearance check of camshaft bearings (Check 1st set. If not good, check all sets). Cylinder unit and connection rod: - Intake/exhaust valve, seats and guide - Overhaul and regrind valve and seat - Inspect cylinder head cooling water space - Inspect indicator valve - Reconditioning of cylinder liner (Honing) - Inspect piston, piston pin, and piston rings - Measure big-end bore. Check clearance between piston pin and small end. Crankshaft and gears: - Clearance and backlash check for timing gears and pump driving gears Valve operating mechanism: - Check clearance on tappet roller shaft and bearing - Check clearance on rocker arms shaft and bearing

Table E.19 - Main Engine (Fuel Injectors), Overhaul, RO-CE-DE-71B

Overhaul of fuel injectors. Check and adjust opening pressure.