University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology/Marine and Subsea Technology	Spring semester,2012 Restricted access
Writer: David Halvorsen Vestvik	……………………………………………………………… (Writer's signature)

Faculty supervisor: Tore Markeset (UIS)

External supervisor: Ingvar Ringdal (Oceaneering Asset Integrity)

Title of thesis:
Development of FMEA/RCM methodology to be implemented in Generic Maintenance Concepts

Credits (ECTS):
30sp

Key words: RCM, Failure Modes, Regulations, NORSOK Z-008, Failure Mechanisms, OREDA, Mean Time to Failure, FMEA, FMECA, Technical hierarchy, Consequence Classification, Generic Maintenance Concepts	Pages: 62 + enclosure/other: 21 Stavanger, 14 June, 2012

Abstract

This master thesis has developed methods for how to interpret failure data and incorporate these into OIA's existing database. This also gave input to improvement of OIA's existing software Kamfer to develop more functionality to be able to document the work process of adding failure data to the existing Generic Maintenance Concepts. Further, this master thesis identified areas in the Oceaneering Asset Integrity (OAI)'s existing methodology that can be improved to be in compliance with regulatory requirements for establishing a preventive maintenance program.

The research was directed towards regulatory requirement for the Norwegian Continental Shelf, and any standards or writings with regards to FMEA/RCM processes and failure data. Pitfalls with regards to FMEA/RCM and failure data is that these areas of study are mainly for design of equipment and corporate risk assessments, so some interpretations has been done to be consistent both with regards to FMEA/RCM methodology and OIA's existing methodology.

Formulas for calculating failure rates from the Oreda failure data has been developed as part of the study.

Suggestions for optimizing a PM program based on historical data are also included.

Preface

This master thesis started out as an internal project in Oceaneering Asset Integrity (OAI) in the autumn 2011. The scope was to give input to a new FMEA or Failure Mode module in the new version of OAIs software tool, Kamfer 7, which is under development. The project participants were Ingvar Ringdal as Project Manager and I as an Asset Management Engineer.

With other projects consuming time the failure mode project fell behind of schedule. In December 2011 I proposed the project to be my scope for Master`s thesis. The proposal revived approval and Ingvar Ringdal agreed to be my External supervisor.

The major contents of the report are a main part, analysis results and recommendations. The main part focuses on RCM methodology, PSA regulations and standards. Additionally OAIs current methodology for delivering Asset Management services is studied to detect gaps against the regulations. The Oreda Reliability Handbook is studied to find a method for calculating Mean Time to Failure for maintenance purposes. Subsequently there is a discussion part where proposes structure of FMEA module and calculation of Oreda data. The final part contains the results and recommendations for further improvements.

I want to dedicate a great gratitude to Tore Markeset who agreed to be my faculty supervisor, especially since I presented the proposal for my Master`s thesis days before the deadline.

Additionally I want to thank Ingvar Ringdal for always answering questions and give guidance although he currently works from our Peth office in Australia.

To Oceaneering Asset Integrity and specially Eivind Jåsund, Jan Cato Vestvik and Gunnar Hilsen I want to thank for supporting me in my quest for a Master degree, both financially and permission with full salary.

Finally I want to give a great gratitude to my wife Naima and my 6 month old daughter Aya-Marie for coping with me in this period with full time work and studying.

Naima, I`m finally finished!

Stavanger, June 14 2012

David Halvorsen Vestvik

Abbreviations

The abbreviations used throughout this report are listed below:

CMMS	Computerized maintenance management systems
GMC	Generic Maintenance Concept
HSE	Health, Safety and Environment
MTTF	Mean Time To Failure
OAI	Oceaneering Asset Integrity
P&ID	Piping and Instrumentation diagram
PM	Preventive Maintenance
PSA	Petroleum Safety Authority Norway
RCM	Reliability Centred Maintenance

Table of Figures

List of Tables

Table of Contents

1 Introduction

1.1 Background

Oceaneering Asset Integrity (OAI) has built Preventive Maintenance Programs for the oil and gas industry since the 90`s.

In that period OAI has built up a database of generic maintenance concepts based on the various companies' best practice. The initial maintenance activities were based on failure modes. But with no new input or maintenance of the database, the failure modes disappeared from the maintenance strategies and are now mainly based on vendor maintenance manuals and maintenance experience.

After the new NORSOK Z-008 was issued, June 2011, the PSA focuses more on failure modes, cause and mechanism to determine the Preventive Maintenance activities.

As a response OAI started an internal project to implement failure modes as a module in OAI s new software KAMFER 7 which is under development. The failure mode module should be added to the new OAI Standard Generic Maintenance Concepts which were meant to contain the best maintenance practice from the different project data bases in KAMFER. After in initial phase where the building blocks were settled in terms of terminology and wanted structure, parts of the project were given as a master thesis. These parts were linked to finding a source of failure mode data and developing a methodology to establish Mean Time to Failure for the failure modes.

The OREDA Reliability Data Handbook has been chosen to serve as the fundament for the failure modes because of OREDAS generic approach and since it is the most reliable/only collection of failure data available. With supplement from other sources over time, the generic maintenance strategies will be in compliance with the PSA regulations.

The OREDA Reliability Data Handbook has previously been used by OAI to perform RAM analysis. But for maintenance purposes the data will not give any MTTF that can be basis for maintenance intervals without interpretation, since the MTTF becomes too high.

1.2 Objective

The main scope of the master thesis is to develop a method/work process for how to add/how to implement failure modes with corresponding Mean Time to Failure into the Oceaneering Generic Maintenance Concepts.

Oreda Reliability Handbook 5th edition, 2009 will be used as a basis for failure modes and MTTF. A methodology for interpretation the failure into MTTF for preventive maintenance purposes has to be made. This work will include investigation of different possibilities to interpret the data. Subsequently the different suggestions for failure modes in question will be compared with vendor FMECA's and existing intervals for maintenance activities from different Oceaneering databases.

Also a review of the OAI methodology against the PSA regulations RCM methodology shall be included to reveal eventual gaps.

Additionally the thesis will give input to the structure of OAIs software tool, Kamfer 7 to link the failure modes to activities and illustrate the results in the maintenance strategy report or FMECA.

Finally the thesis will give input to how OAI can expand its products to maintenance optimization of based on the future failure mode database.

1.3 Limitations

The Thesis does not go into barriers to a large extent since this subject was covered by a Master`s thesis last year.

Additionally OAIs methodology for Technical Hierarchy and Consequence Classification is mentioned but has not been analysed since a study already has been performed.

Initial age exploration is detected as a deviation between the RCM methodology and NORSOK Z-008 and thus the OAI methodology. The subject is not considered in the thesis.

1.4 Accuracy of Estimates

When calculating the MTTF from the Oreda reliability Handbook several assumptions have been made. All of them will have inaccuracies in them.

The assumption **Failure rate a sum of severities,** list an incipient failure as a fault. This is not correct according to RCM methodology stated in section 2.2.1 but has been made to determine a more correct maintenance interval.

The assumption ***Usage of upper failure rate to determine MTTF*** is a coarse assumption and will in many cases lead to overkill in terms of a low MTTF. This is done due to the face that Oreda data delivers failure rates from equipment with maintenance activities performed on them. The failure rate with no equipment is assumed to me much higher than with run to failure.

Reference data is only based on a three year old failure mode project performed by OAI and Statoil. This is not sufficient as a good reference to the calculations. But with lack of FMECAs from vendors the failure mode project was the best source available.

Calculation examples do not contain calculation per failure object. This is due to the reference data did not contain calculation at that level. The calculation examples main purpose is to show the results of different assumptions on severity and mean or upper value.

2 Short description of Reliability Centred Maintenance

2.1 Definition of RCM

Two typical scenarios are common in a maintenance perspective [1]:

- The plant or installations equipment break down more frequent than expected and thus lead to backlog on preventive Maintenance activities.
- Scheduled inspections only find nothing wrong with the equipment. Thus the equipment has been needlessly dismantled and sometimes faults when put back in operation.

The first example relates to maintenance activities being established as a result of recommendations after breakdowns. The second can relate to following all the vendor recommendations without optimisation.

Time and resources are limited so the main objective of physical asset management is to determine what kind of maintenance activities that needs to be performed and the justification for doing it.

RCM is a structured way to find the needed maintenance activities. Generally speaking it does so by asking the seven questions of the RCM process [2]:

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

The methodology leads to prioritising time and resources to perform maintenance activities on important equipment. As a result the installation will experience better security towards HSE, improved operational performance and reduced down time due to unexpected failures. [3]

2.2 Failure Assessment

2.2.1 Equipment function and performance standard

First the equipment has to be identified and analysed for its performing function. Subsequently the acceptable performance of the function has to be determined.

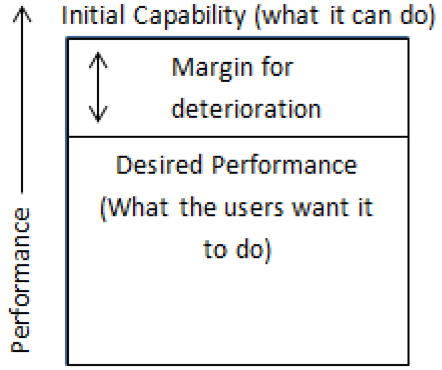


Figure 2.2.1 [4] *– Setting the acceptable performance boundaries*

When defining the boundaries remember:

- Maintenance cannot raise the performance above the initial capacity.
- The desired capacity must be reasonable and take account of the determination experienced in real conditions

The functional failure occurs when the equipment no longer can fulfil the function to the standard wanted by the user.

2.2.2 Failure Patterns

Failure patterns have varied over the year. From Pattern B in pre WW2 era to pattern A post WW2. The last 20 years the equipment has become more complex and has led to the understanding of six failure patterns shown in Figure 2.2.2.

Pattern A is the *bathtub curve* and stands for 4 % of registered failures. It indicates infant mortality in the early stage of the equipment's lifetime. Subsequently comes the useful life phase with probability of failure constant or gradually increasing. Finally the wear out period leads to higher failure rate.

Pattern B is called *wear out* and stands for 2 % of failures. This shows the probability of failure is constant or gradually increasing and end up in the wear out period with a higher failure rate.

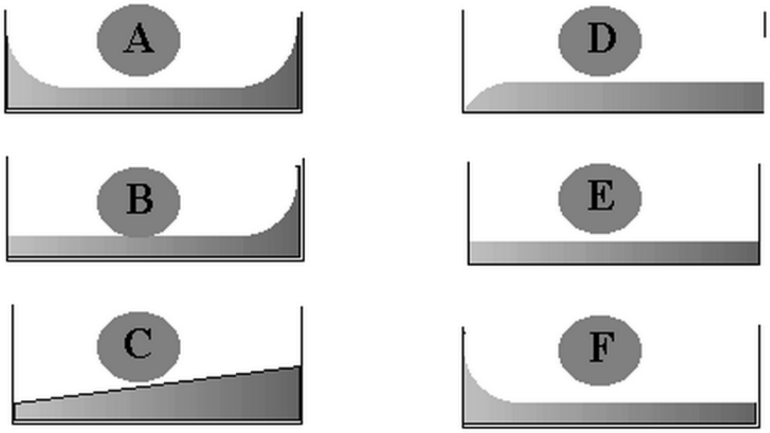


Figure 2.2.3[5] - The six failure patterns

Pattern C is called the *gradually increasing failure pattern* and stands for 5% of failures. This can relate to fatigue or contamination that constantly deteriorate the component and gradually increases the failure rate.

Pattern D is the *Initial break-in period* and related to 7 % of the failures. This can relate to lack of routines of new equipment. For example lack of lubrication, greasing or checks.

Pattern E is the *random failure pattern* with 14% of the failures. This pattern has only a constant probability of failure during its life span.

Pattern F is the *infant mortality pattern* and stands for 68% of the failures. This can both relate to human errors and equipment start up difficulties.

The percentage relates to a study conducted by the civil aircraft industry [6]. Although the percentage does not perfectly represent the offshore industry, it still shows the change of patterns due to more complex equipment and autotomized equipment.

2.2.3 Failure Analysis

The purpose of FMEA is to identify and document potential failure modes with respective causes and mechanisms, and the immediate effect of the failure modes on an item/assembly.

Failure Mode

Is defined as the "manner in which the inability of an item to perform a required function occurs" [7] and can be described as the observed reason why an item is not doing its required function.

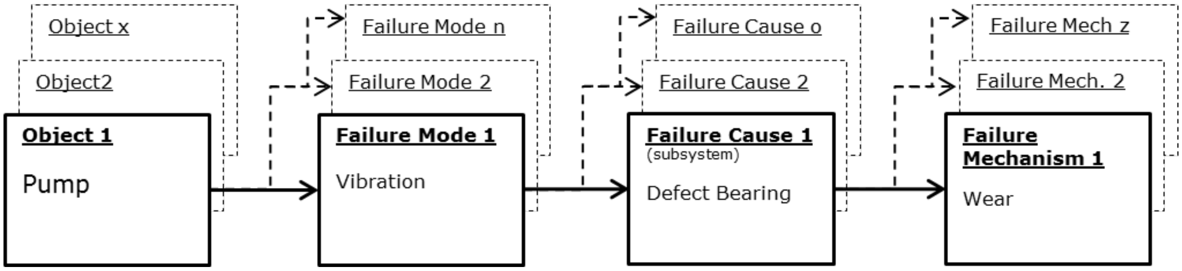


Figure 2.2.2[8] - Relation between Failure Mode, Failure Cause and Failure Mechanism (one-to-many relationship).

Failure Cause

For each failure mode there is one or more failure causes. A failure mode will usually be caused by one or more component failures at a lower level than the item (typically supporting equipment). Thus, a failure cause in this context may be a failure mode of supporting equipment. Due care is required so as not to confuse the Failure Cause terminology used in this thesis with failure (root) cause as it is defined in the ISO 14224 and EN 13306:2010. Root cause analysis is used for design purposes or after failure to reveal the “root cause” of a failure, and is not part of scope for determine maintenance activities.

Failure mechanism

For each failure cause there are one or more failure mechanisms. A failure mechanism is defined as: “*physical, chemical or other processes which may lead or have led to failure*” [9]. Corrosion, fatigue and wear are examples of such processes. It is typically the failure mechanisms that the activities in the Maintenance Strategies are mitigating steps towards, to prevent them from causing a failure.

Effect of failure modes

A failure mode is defines as: *“the manner in which the inability of an item to perform a required function occurs”* [10].

Frequency of Failure

The frequency of each failure mode shall be estimated to be able to assess the risk of each failure mode. For the Generic RCM, this is a quantitative measure, which means the anticipated Mean Time of Failure (MTTF) if no preventive maintenance is carried out to the equipment.

2.3 RCM Decision Logic/Maintenance Types

2.3.1 RCM decision diagram

The Preventive Maintenance Program is developed using a guided logic approach. By evaluating possible failure management policies, it is possible to see the whole maintenance program reflected for a given item. The objective of RCM task selection is to select a failure management policy that avoids or mitigates the consequences of each identified failure mode [11].

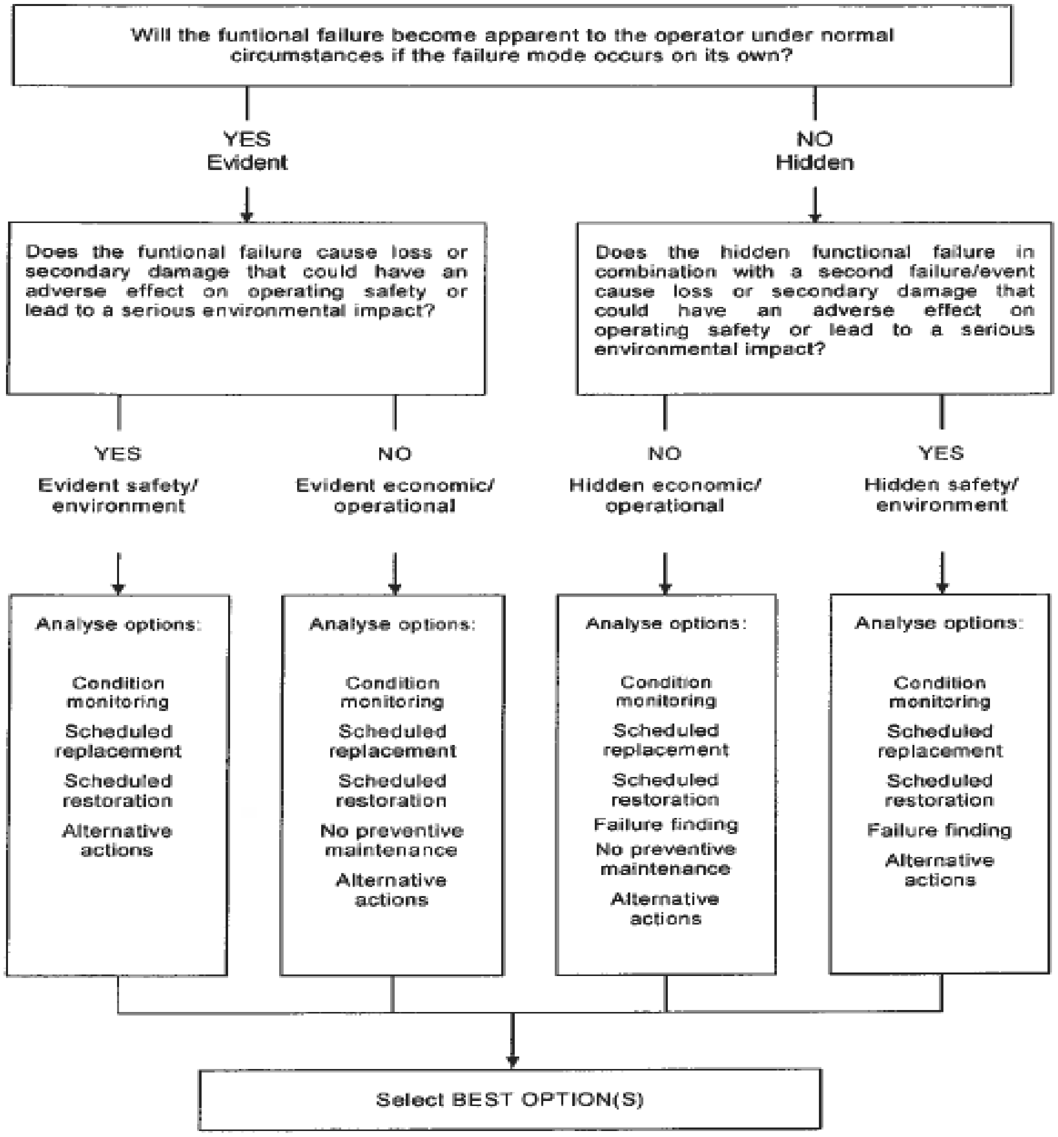


Figure 2.3.1[12] – RCM decision diagram

Input to the RCM task selection process is the information described in 2.2.3 above. Subsequently follows a question-and-answer process in form of RCM decision logic (see Figure 2.3.1) to determine a suitable maintenance activity/task to prevent the failure mechanism to cause a failure.

The detection potential, technology available for failure detection and characteristics of a failure decided in the Decision Tree logic will give guidance to what type of approach is applicable for the maintenance activity/task.

2.3.2 Maintenance types

There are two types of maintenance action (see figure 2.3.1 below):

- Preventive Maintenance, that is undertaken prior to failure to avoid or mitigate consequence of failures.
- Corrective Maintenance, that is undertaken after failure has occurred to restore a function.

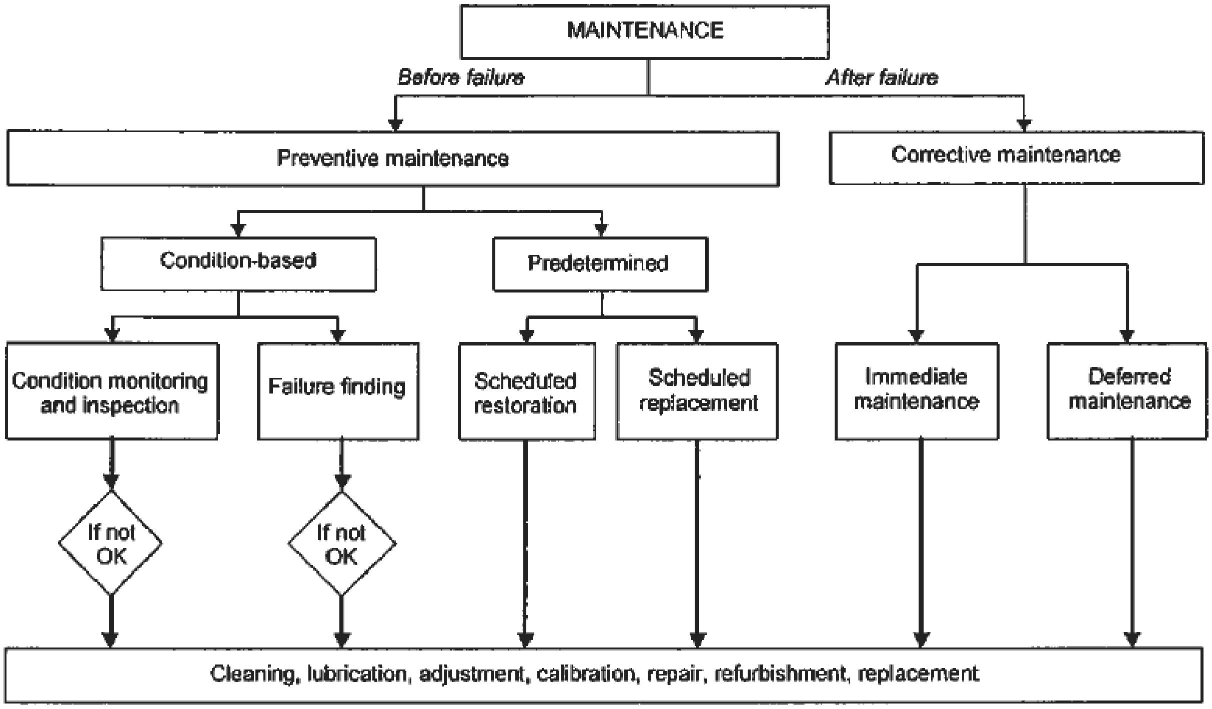


Figure 2.3.2[13] – Types of maintenance

There are two approaches to preventive maintenance defined as[14]:

- Predetermined Maintenance; carried out in accordance with established intervals of calendar time or running hours, but without previous condition investigation.
    - Typical Predetermined Maintenance activities/tasks are Scheduled Restoration or Scheduled Overhaul.
- Condition Based Maintenance; which include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions.
    - Typical Condition Based Maintenance Activities/Tasks are Condition Monitoring, Inspection, Function Test and Failure Finding.
    - The Ensuing Maintenance Activities/Tasks are the actions undertaken due to findings or alarms triggered by Condition Based maintenance Activities/Tasks. This is valuable information for the planning of a PM Program, as the Ensuing Activities/Tasks gives indication regarding expected need for Resources, Workload and Operational Spares and when to expect the Ensuing Activities/Tasks to occur.

In addition, any Failure Mode that is identified to have no effect if it occurs will have an Operator Random Observation/Run Till Failure Approach. This approach will not be part of any schedule preventive maintenance. However, it is assumed that as long as there are personnel present on an installation, any failures should be detected by the Operator in the area, and any ensuing/corrective actions will be handled according to corporate policies.

3 Description of Regulations & Standards

3.1 Background

The Petroleum industry in Norwegian sector is governed by legally binding laws/regulations and norms. Regulations like the Activity regulation have to be met. The activity regulation again refers to the norms for a guideline in how to meet the regulations. This chapter will point out the regulations and standards the thesis will build on as shown in Figure 3.1.1.

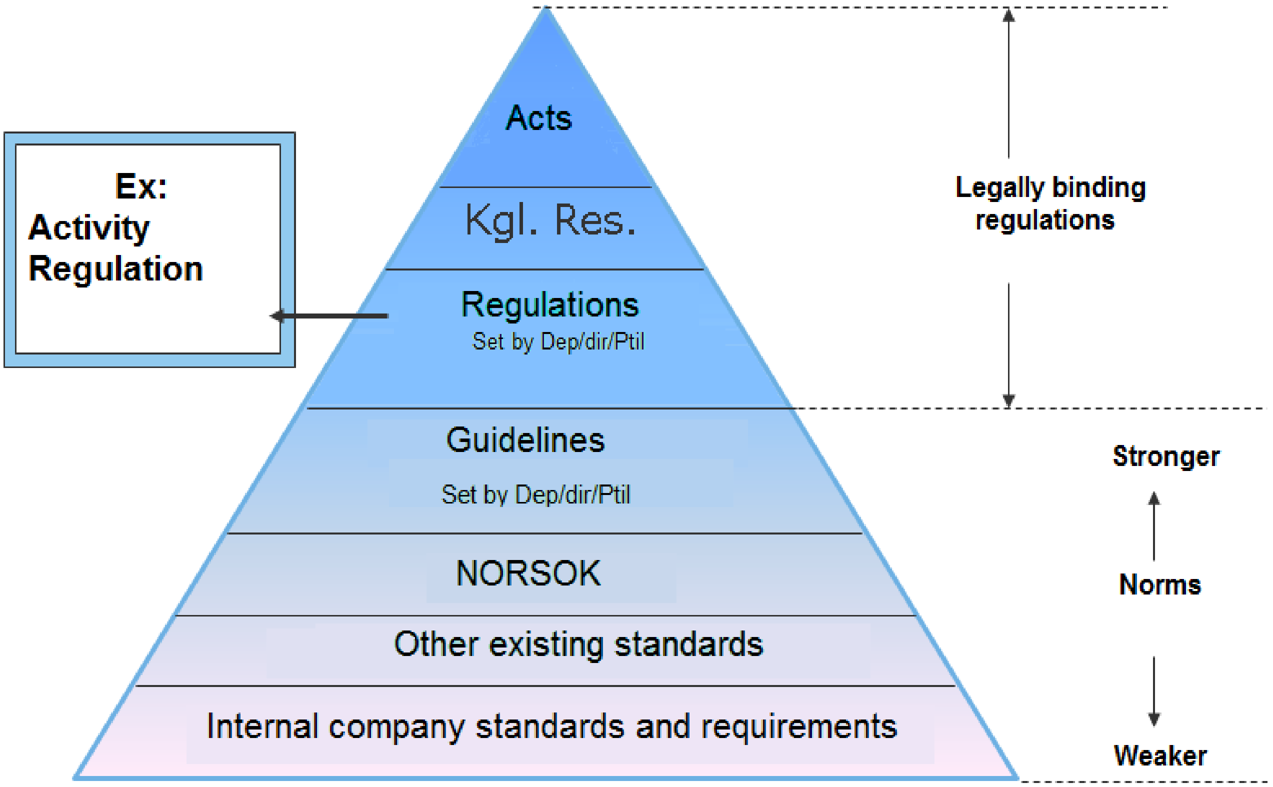


Figure 3.1.1[15] *- Hierarchy of governing laws and regulations*

What's special about the Norwegian system is that the flexibility the PSA gives the companies. For example: Activity Regulations §45 Maintenance;" *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."* The regulation only dictates the functionality of the PSA goal. How the company achieves the PSA goal is up to the company to decide. But NORSOK Z-008 can be used as a guideline to achieve compliance.

3.2 Governing Regulations & Guidelines

3.2.1 Activity Regulation

This regulation deals how to perform petroleum activities with focus on HSE, surveys, operations, maintenance etc. Following is the sections from the activity regulation that build the basis for this thesis[16]:

§45 Maintenance: *"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."*

Guideline: *Maintenance means the combination of all technical, administrative and management measures during the life cycle of a unit intended to keep it in, or restore it to, a state in which it can perform its intended functions, cf. definition 2.1 (with associated terminology) in the NS-EN 13306 standard.*

Maintenance includes activities such as monitoring, inspection, testing and repair, and keeping things tidy.

Functions also mean safety functions, cf. Section 2 of the Facilities Regulations. For these functions, the requirement relating to maintenance entails that performance shall be ensured at all times, cf. Section 8 of the Facilities Regulations.

Facilities or parts of facilities also mean temporary equipment.

All phases also mean periods in which the facility or parts of the facility are temporarily or permanently shut down.

§46 Classification: *"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 probability 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"

Guideline: *"To fulfil the classification requirement, the* NORSOK Z-008 *standard should be used in the area of health, working environment and safety.*

Fault mode, failure cause and failure mechanism as mentioned in the second subsection, are defined in the NS-EN 13306 standard."

§47 Maintenance Programme: "*Fault modes that constitute a health, safety or environment risk, cf. Section 44, shall be systematically prevented through a maintenance programme.*

This programme shall include activities for monitoring performance and technical condition, which ensure identification and correction of fault modes that are under development or have occurred.

The programme shall also contain activities for monitoring and control of failure mechanisms that can lead to such fault mode"

Guideline: *"The maintenance programme can consist of sub-programmes for inspection, testing, preventive maintenance, etc., cf. Section 45.*

The requirement relating to prevention as mentioned in the first subsection entails also that the programmes shall be available at start-up, cf. Section 20, second subsection, litera b. When preparing the maintenance programme as mentioned in the first subsection, the NS-EN ISO 20815:2008 standard, Appendix I and the CEI/IEC 60300-3-11 standard can be used in the area of health, working environment and safety."

§48 Planning and prioritisation: *"An overall plan shall be prepared for conducting the maintenance programme and corrective maintenance activities, cf. Section 12 of the Management Regulations.*

Criteria shall be available for setting priorities with associated deadlines for carrying out the individual maintenance activities. The criteria shall consider the classification as mentioned in Section 46."

Guideline: *"In order to fulfill the requirement relating to time limits as mentioned in the second subsection, the time limits should be calculated from the time when a fault mode is identified as having occurred or is under development."*

§49 Maintenance effectiveness: “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.”

3.2.2 Management Regulation

§12 Planning: *“The responsible party shall plan the enterprise's activities in accordance with the stipulated objectives, strategies and requirements so that the plans give due consideration to health, safety and the environment.*

The resources necessary to carry out the planned activities shall be made available to project and operational organisations.”[17]

Guideline: *“The plans as mentioned in the first subsection can be plans where health, safety and environment are integral parts, or plans for own health, safety and environment activities. Examples of plans where health, safety and environment are an integrated part include plans for maintenance or operations.*

The resources mentioned in the second subsection, can include infrastructure, personnel and information.”

3.3 NORSOK Standard

Since OAI follow NORSOK methodology, NORSOK Z-008 will for the fundament for this thesis.

The NORSOK Standards are developed by the Norwegian petroleum industry to reduce cost in the development and operation phase of installations on Norwegian shelf. Additionally standard serves as a reference to the authority regulations

The NORSOK standard are administrated and published by Standard Norway with the support of The Norwegian Oil Industry Association (OLF), The Federation of Norwegian Industry, Norwegian Ship owners Association and The Petroleum Safety Authority Norway (PSA) [18].

NORSOK Z-008 is made to give requirements and guidelines for establishment of technical hierarchy, consequence classification and spare part evaluation. Additionally it gives guidelines on how to use the consequence classification in the maintenance management as well as establishment and update of the PM program based on risk analysis.

3.3.1 Maintenance Management Loop

The main objective of NORSOK Z-008 is to give input to how to achieve and maintain the maintenance management loop as shown in Figure 3.3.1. The top four blocks deals activity regulation §45, §46, §47 and §48 in how to prepare a PM-program and execute the maintenance. While the bottom three deals with activity regulation §49 in how to enhance the effectiveness.

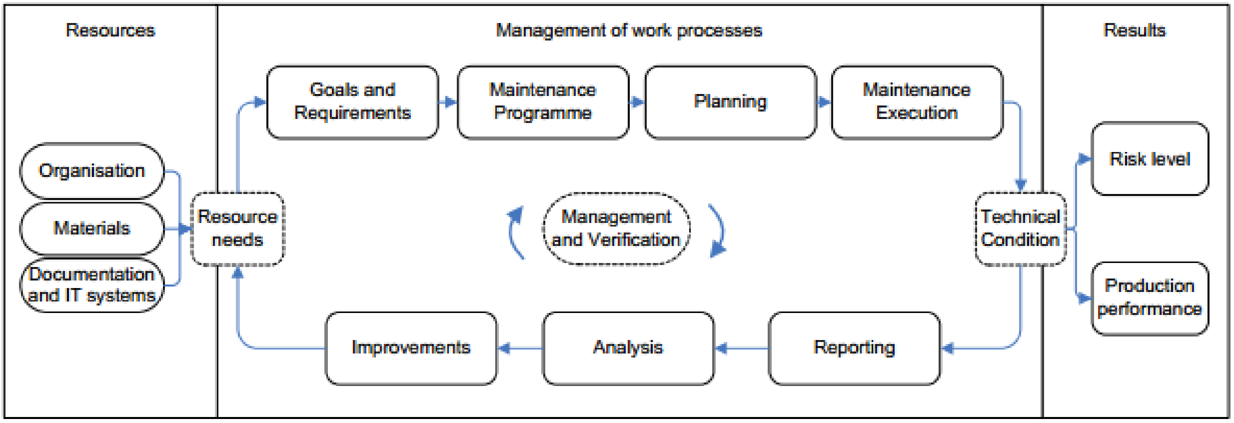


Figure 3.3.1[19] - Maintenance Management Loop

Most companies manage the top four blocks of the maintenance management loop but fail on the bottom three. In other words, they manage to decide what kind of maintenance philosophy to apply to their installation (condition monitoring on high critical equipment, Preventive maintenance on medium and corrective on low critical), make a maintenance strategy (which maintenance activities to perform and when to do it), schedule the work orders in a CMMS system and execute the maintenance.

Where many fail is to improve the maintenance management system. Maintenance reports do not cover proposals for improvement in terms of failure modes, maintenance activity adjustment and resource (work load and material) needs. With no input improving the maintenance system is difficult [20].

3.3.2 Establishment of a New Plant

New installations entering Norwegian waters are required to have an operational PM-program. This is to have control over all equipment in terms of where it is located, what function it does, consequence of failure, if it is a barrier and what kind of maintenance to perform on it. The classical way to establishing the PM-program is the RCM process. But NORSOK encourage using Generic Maintenance concepts in combination with the RCM methodology to better capture the company knowledge of maintenance tasks and make it standardized.

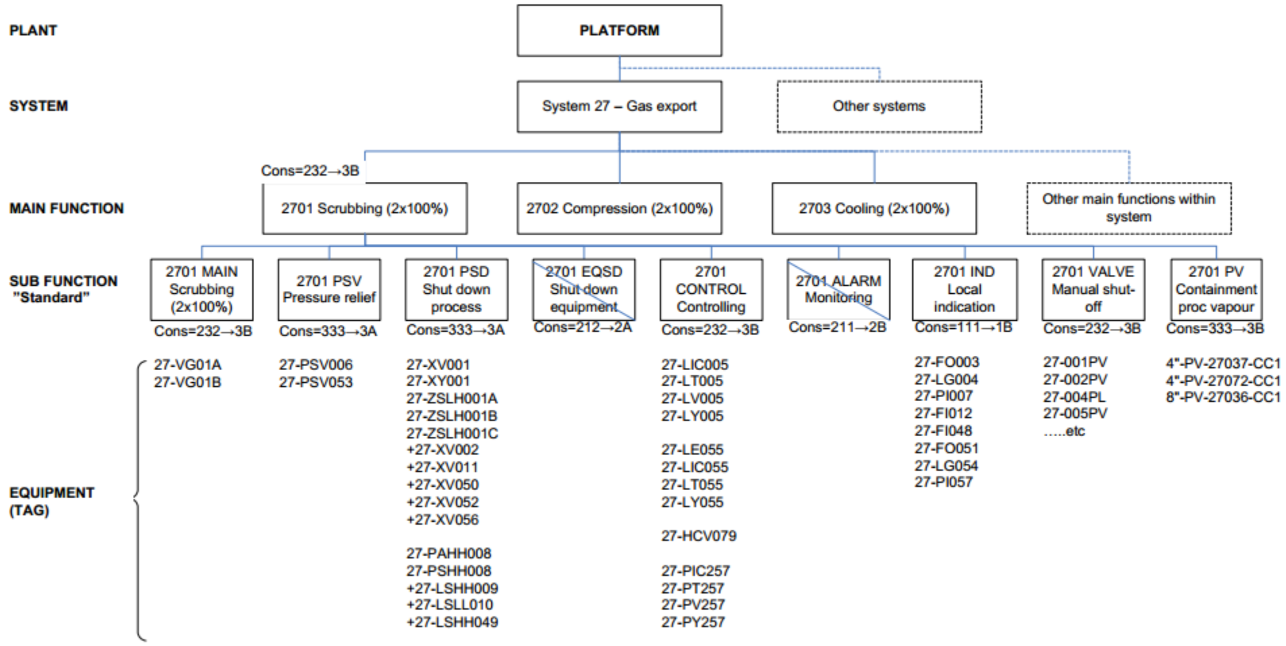
The main building blocks of the maintenance system are Technical hierarchy, consequence classification and generic maintenance concepts

Technical hierarchy - A function based technical structure of an installation that shows how equipment in a function relates to each other. See appendix A for workflow and examples.

The purpose of the technical hierarchy is[21]:

- *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*

Consequence Classification - A classification starts with dividing the installations systems by the function it performs (see appendix B.1 for example). Subsequently this function is classified with the consequence of failure in regard to HSE, production and cost with three grades, high, medium and low and assessed for the functions redundancy (See appendix B.3 for example). The classification is performed based on a consequence criteria matrix where the limit or accept criteria for each consequence grade is determined. Only the main function if evaluated and subsystems inherit a consequence according to the inherit rules (See appendix B.2 for example). Finally tags are linked to correct function and inherit its consequence and redundancy.



Explanation: Cons = Consequence. Figures: 3=High, 2=Medium, 1=Low HSE, Production and Cost respectively. Last result is a combination of the highest Consequence and Redundancy degree (A – No spare, B – One spare, C – Two or more spares) in operational phase.

Figure 3.3.2[22] - Functional hierarchy, example with standard sub function and classification

The consequence classification together with other key information and parameters gives input to the following activities and processes[23]:

- *selection of equipment where detailed RCM/RBI/FMECA analysis is recommended (screening process);*
- *establish PM programme;*
- *preparation and optimisation of GMCs;*
- *design evaluations;*
- *prioritisation of work orders;*
- *spare part evaluations.*

Maintenance Strategy (generic maintenance concept, Performance standards for barriers) - A Generic Maintenance Concept (GMC) is the companies best practice maintenance for an equipment group with same failure modes and operating conditions. The goal for the GMC is to ensure that requirements for HSE, production, cost and other requirements are met and documented in RCM/FMECA analysis. (See Appendix C for GMC example)

The result of a consistent GMC leads to [24]:

- *establish a company`s minimum requirements to maintenance,*
- *reduce the effort in establishing the maintenance programme as similar equipment/technologies are preanalyzed,*
- *ensure uniform and consistent maintenance activities,*
- *facilitate analysis of equipment groups,*
- *provide proper documentation of selected maintenance strategies,*
- *ensure experience transfer between plants with similar technology and operation.*

The workflow of establishment of a new PM-program

1- The equipment is grouped and classified by making the technical hierarchy and consequence classification.

2- Identify the barriers and the performance standards for testing them according to OLF-070 or IEC 61508. These test intervals are scheduled in the PM-program.

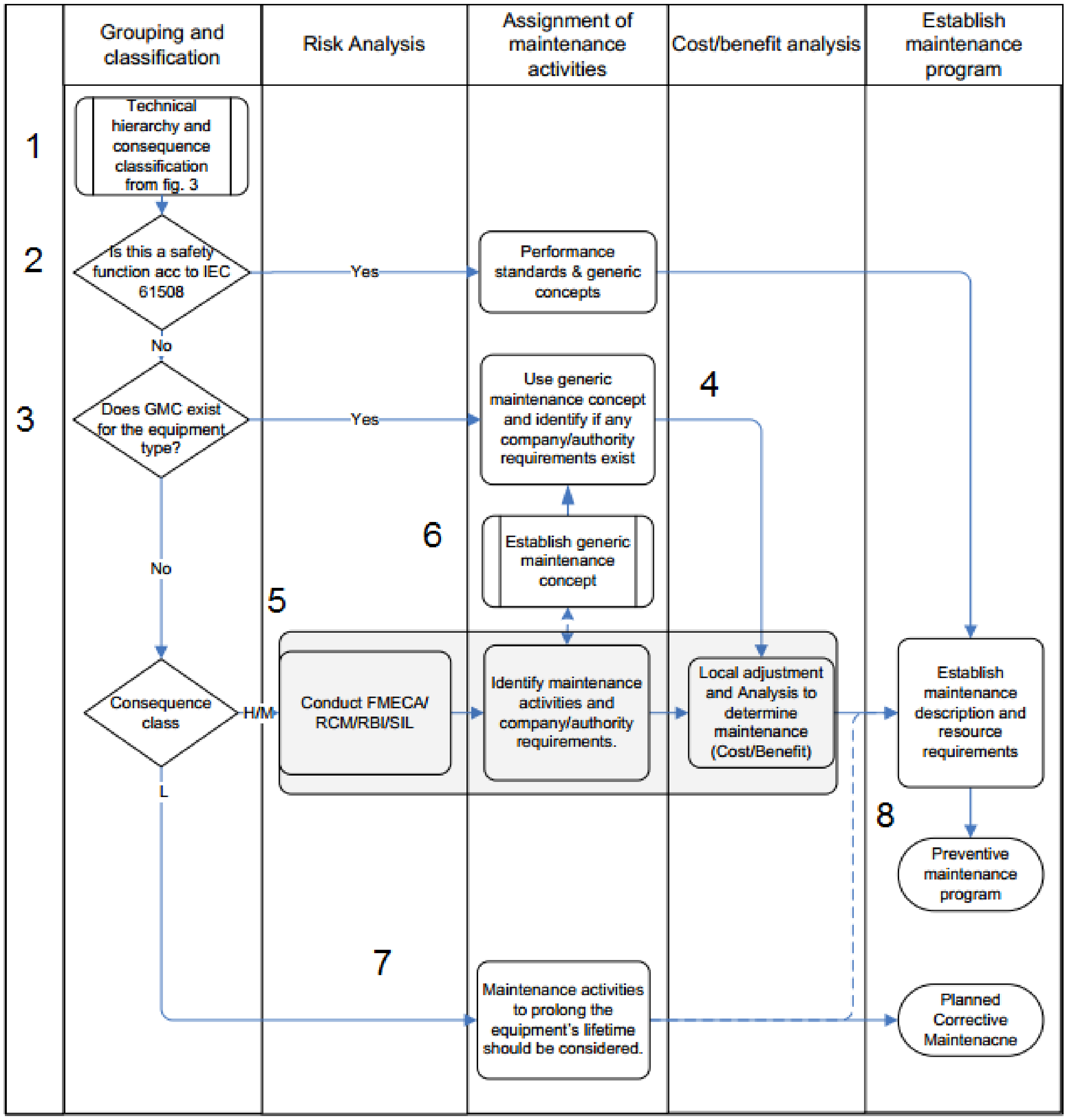


Figure 3.3.3 [25] – Establishment of PM-program for a new installation

3- Determine if a GMC exist for the equipment, if yes update with eventual authority or company requirements.

4- Adjust the GMC to the local conditions on the plant in terms of the production value for the specific case versus and repair capacity to handle the most common failure modes.

5- If no GMC exist a thorough study must be performed for medium and high consequence equipment. NORSOK recommends that a RCM/RBI/SIL analysis should be carried about according to IEC-60300-3-11 and DNV EP-G101. Identification of failure modes and MTTF should primary be based on operational experience of the actual equipment but generic failure data for similar equipment can be used as an alternative.

Intervals are primarily based on engineering judgment and a cost-benefit assessment including:

- 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- Define a maintenance concept from the data gathered in the RCM/RBI/SIL analysis.

7- Low consequence equipment is primarily set to run to failure. If detecting cost-benefit reasons to perform maintenance low consequence equipment can be included in the PM-program.

8- Finally the maintenance program is packed. The maintenance plans and tasks are packed based on production/operation plans, turnaround activities and recourse requirements.

3.3.4 Reporting, Analysis and Improvements

The historical failure rate data used when establishing the new PM-program may be lower or higher than the actual failure rates on the specific installation. To optimize the PM-program, corrective and preventive maintenance activities must be reported according to Table 2.3.1.

Corrective Maintenance	Preventive Maintenance
Failure mode Failure cause Failure mechanisms Equipment down time Spare parts used Man hours for activity Start and finish time to repair	Condition of equipment before PM work Man hours for activity Spare parts used Start and finish time

Table 3.3.1[26] *- Reporting of maintenance data*

With historical data the effectiveness of the maintenance can be evaluated up against the Key performance indicators. According to the minimum of KPIs should be [27]:

- *failure fraction from functional testing of safety critical equipment;*
- *PM man-hours;*
- *corrective maintenance man-hours;*
- *backlog PM, total number of hours;*
- *backlog PM, number of hours HSE critical;*
- *backlog corrective maintenance, total number of hours;*
- *backlog corrective maintenance, number of hours HSE critical.*

Some of the reports will need a further analysis to find the root-cause of the failure to prevent reoccurrence.

The triggers are[28]:

- *HSE related equipment failure,*
- *unacceptable production losses,*
- *cost of single failure events in terms of downtime, repair cost or spare cost,*
- *number of repeated failures over a given time period for key components,*
- *hidden failures (exceeding requirements) detected during test,*
- *technical condition assessments.*

Implementation of actions may lead to update of maintenance program, operational routines, training etc.

3.3.4 Updating the PM-program

A PM-program is a living system and need updates to provide a correct and effective maintenance to the installations equipment.

AN update is needed when[29]:

- *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 historical failure rate data used when establishing the new PM-program may be lower or higher than the actual failure rates on the specific installation. To optimize the PM-program, corrective and preventive maintenance activities must be reported according to Table 2.1.1.

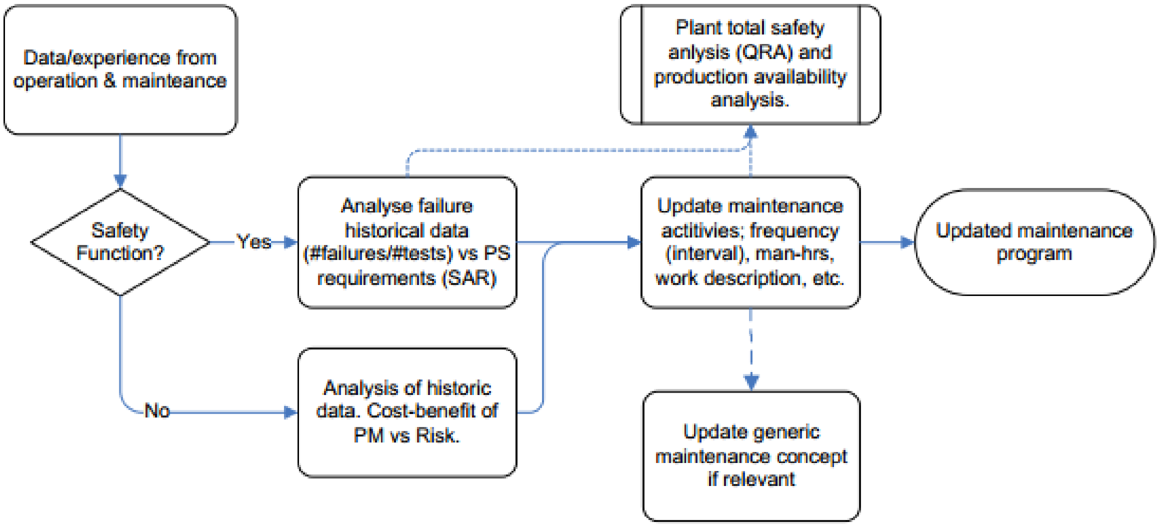


Figure 3.3.2[30] *– Progress for updating maintenance program*

The result will be a failure database for the specific installation which will provide the documentation needed to update the maintenance intervals both for safety critical elements and general equipment as shown in Figure 3.3.2.

3.4 Additional activities based on IEC 60300-3-11

The RCM process defined in IEC 60300-3-11 is shown in Figure 3.4.1 bellow. Several steps in the RCM process are redundant compared to what already has been performed according to NORSOK Z-008, shown in Figure 3.3.2. Additional activities are marked bold.

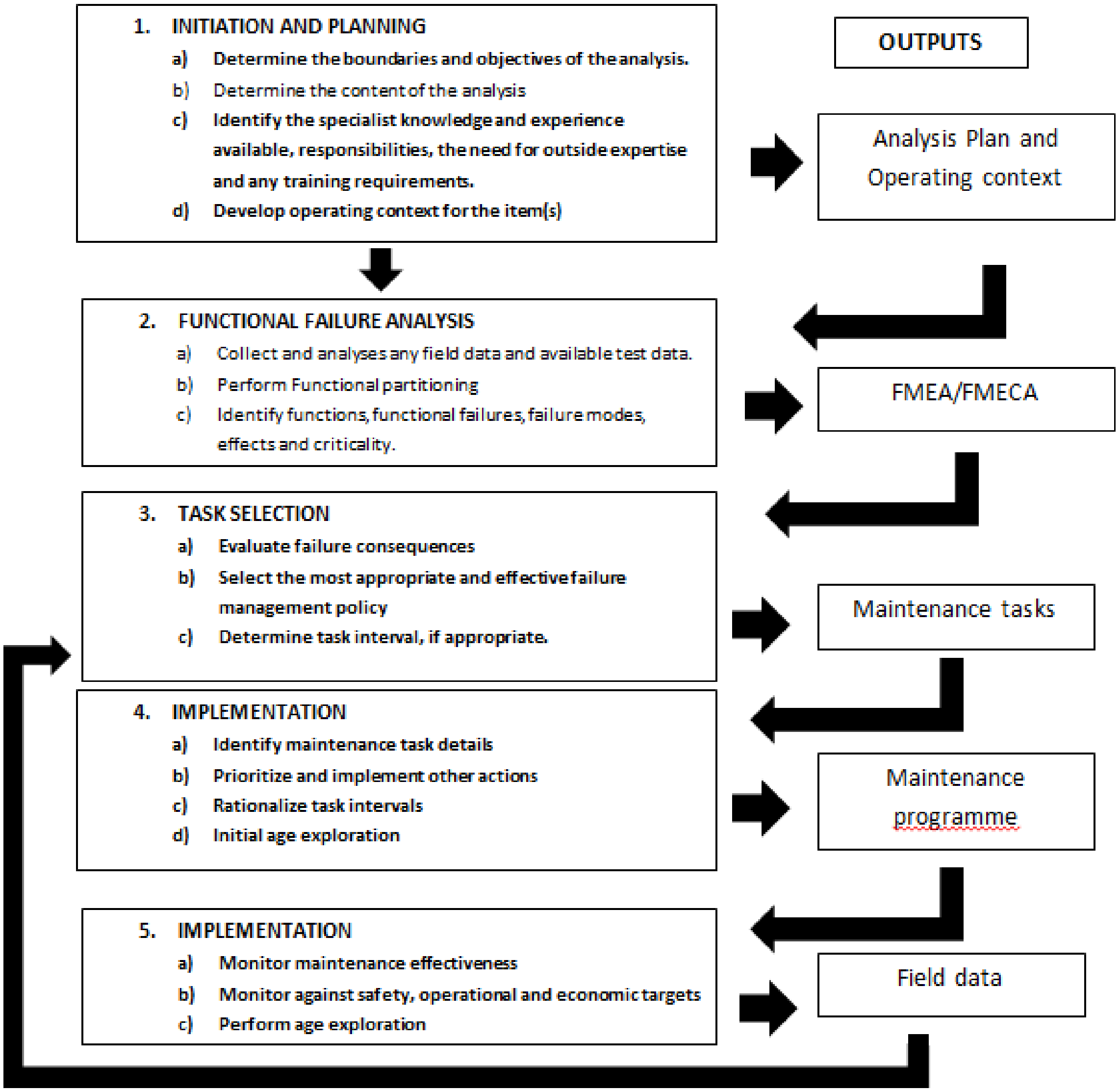


Figure 3.4.1[31] *– Overview of the RCM process*

1 Initiation and planning

a) The boundaries and objectives of the analysis are already covered by establishment of technical hierarchy, consequence classification, and barrier assessment (Step 1, 2 and 3 in Figure 3.3.2). Equipment types not a barrier with a consequence of medium or high without a maintenance concept shall be analysed in a FMECA/RCM.

b) **The content must be decided. For maintenance purposes a failure analysis must be performed to identify the possible failure modes on the equipment type.**

c) **Has not already been covered. Specialist knowledge, outside expertise and responsibilities must be decided.**

d) The operating context should describe how the equipment is operated and give information on desired system operationally. Step 1 in Figure 3.3.2 covers for the most pare the information needed as the consequence classification informs what kind if function the equipment performs and the redundancy grade.
Additional information to determine:

- **environmental conditions (climate) that lead to additional failure modes**
- **inactive equipment must be identified**

2 Functional failure analyses

a, b and c) Failure modes are not covered by Z-008 and has to be performed by a FMECA according to IEC 60300-3-11.

3 Task selection

a) Failure consequences are for the most part already covered by the consequence assessment (Step 1 Figure 3.3.2).

B and c) Countermeasures with intervals against the failure mechanisms need to be determined in GMC workshops according to step 6 in Figure 3.3.2.

4 Implementation

a, b and c) Identefying maintenance details, prioritizing and rationalisation of maintenance intervals are covered in z-008 by stem 4 and 8 shown in figure 3.3.2.

d) Initial age exploration is not covered.

5 Implementation

A and b) Monitoring of maintenance effectiveness and safety, operational and economic targets are covered by z-008 mentioned in section 3.3.3 and 3.3.4 above.

e) Subsequent age exploration is not covered.

3.5 Conclusion

NORSOK Z-008 covers almost all aspects to be in compliance with the PSA demand in terms of the PM-program. The additional information needed deals with failure assessment and is covered by IEC-60300-3-11 and described in Chapter 2.

Failure data play a key role in all phases of the maintenance management. At early stage the maintenance activities are set to prevent or delay a failure mechanism to occur and the maintenance interval is set based on the failure modes MTTF.

In later phases failure data is used to maintenance optimization based on actual failure modes occurring on the installation in relations to both preventive and corrective maintenance activities.

Learning from failure is the key of improving the performance of a maintenance system or organization. Thus, identification of failure modes and using the experienced failure data will lead to good maintenance control and less fire fighting with unexpected corrective maintenance, production loss and danger to HSE.

4 Description of Oceaneering Asset Integrity

4.1 Introduction

Oceaneering Asset Integrity became a new part of Oceaneering after AGR Field Operations was bought in December 2011.

The main focus areas of OAI are inspection (both planning and performing) and maintenance management.

The maintenance management delivers for the most part two services; A project to deliver parts to a PM-program or a service agreement to update and maintain an existing PM-program.

The main modules OIA deliver for a PM-program is:

- Technical hierarchy
- Barrier identification and assessment with performance standards
- Ex, containment identification.
- Consequence classification
- Spare Part Evaluation
- Establishment of Generic Maintenance Concepts
- Packing of PM-program

As mentioned in Chapter 1, OAI use its self-developed *KAMFER* 7 tool for storing, processing and deliver data.

KAMFER 7 consist of three main modules; Technical hierarchy, Consequence Analysis and Maintenance Concept which are under development to include all the functionality for delivering RCM according to PSA regulations.

OAI has also an online portal under development which is linked to KAMFER 7. This view has the same three modules as KAMFER 7. This leads to good illustration of the asset from a customs point of view and can also be used for links to P&ids and other documentation. Additionally the portal can be used by the customers to give feedback on its content directly into KAMFER 7. Thus removing need for point of contact, accumulation of mails and provide records of decisions made and work process.

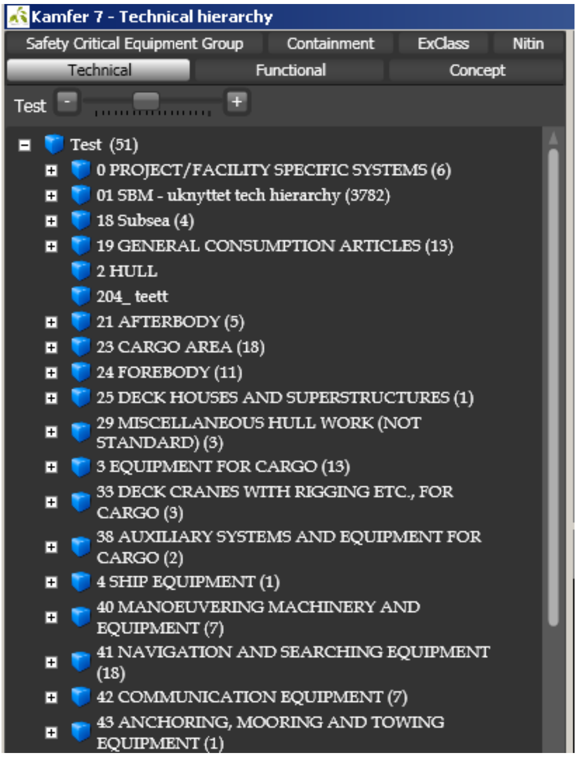
4.2 Technical Hierarchy Module

The Technical Hierarchy Module is a tool for establishing a hierarchical register of all equipment/tags/items in an installation. It is also possible to register all relevant technical data/information for each equipment/tags/items, such as Maker, Ex-class, P&ID etc. as additional attributes.

The methodology for making the technical hierarchy are based on to NORSOK Z-008 with an additional feature; the possibility for numerous custom hierarchies.

The Custom hierarchy application is a useful tool to register attributes to a tag/equipment in a structured manner such as:

- Performance Standards/Barrier tag identification
- Equipment Types and Sub-Equipment Types
- Location (predefined areas on the installation)
- Ex-Class
- Responsible Discipline/Department (useful for packing of PM Program, as some Equipment Strategies can be the responsibility of more than one Discipline/Department)
- Maker/Vendor of equipment
- DNV Class Survey Codes

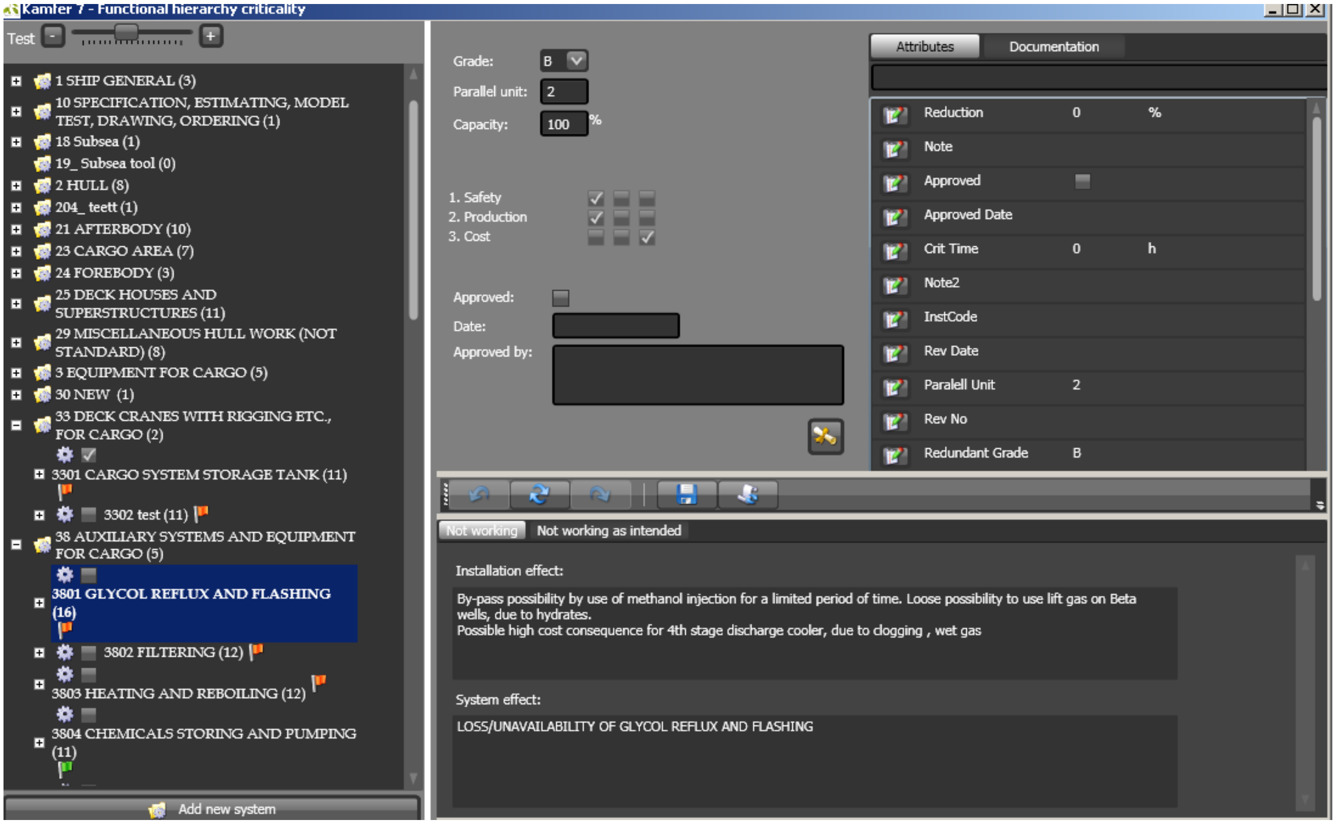


Test (51)
- 0 PROJECT/FACILITY SPECIFIC SYSTEMS (6)
- 01 SBM - uknyttet tech hierarchy (3782)
- 18 Subsea (4)
- 19 GENERAL CONSUMPTION ARTICLES (13)
- 2 HULL
- 204_ teett
- 21 AFTERBODY (5)
- 23 CARGO AREA (18)
- 24 FOREBODY (11)
- 25 DECK HOUSES AND SUPERSTRUCTURES (1)
- 29 MISCELLANEOUS HULL WORK (NOT STANDARD) (3)
- 3 EQUIPMENT FOR CARGO (13)
- 33 DECK CRANES WITH RIGGING ETC., FOR CARGO (3)
- 38 AUXILIARY SYSTEMS AND EQUIPMENT FOR CARGO (2)
- 4 SHIP EQUIPMENT (1)
- 40 MANOEUVERING MACHINERY AND EQUIPMENT (7)
- 41 NAVIGATION AND SEARCHING EQUIPMENT (18)
- 42 COMMUNICATION EQUIPMENT (7)
- 43 ANCHORING, MOORING AND TOWING EQUIPMENT (1)

Figure 4.2.1[32] *- Technical Hierarchy Module*

4.3 Consequence Analysis Module

The Consequence Analysis Module, shown in figure 4.2.2 bellow, is a tool for performing equipment classification in a systematic way according to the NORSOK Z-008 Standard methodology in close cooperation with experienced customer personnel. All functions identified for an installation is structured in a Functional Hierarchy, where system and installation effect (consequence) of a functional failure, redundancy within a function, drawing reference and so on are among data that can be registered and processed in this module.



Grade: B

Parallel unit: 2

Capacity: 100 %

1. Safety ☑ ☐ ☐
2. Production ☑ ☐ ☐
3. Cost ☐ ☐ ☑

Approved: ☐

Date:

Approved by:

Reduction	0	%
Note		
Approved	☐	
Approved Date		
Crit Time	0	h
Note2		
InstCode		
Rev Date		
Paralell Unit	2	
Rev No		
Redundant Grade	B	

Installation effect:

By-pass possibility by use of methanol injection for a limited period of time. Loose possibility to use lift gas on Beta wells, due to hydrates.
Possible high cost consequence for 4th stage discharge cooler, due to clogging , wet gas

System effect:

LOSS/UNAVAILABILITY OF GLYCOL REFLUX AND FLASHING

Figure 4.3.1[33] *– Kamfer 7 Functional hierarchy and consequence view*

After the consequence analysis tags are linked to its belonging sub function according to Figure 3.3.2. Thus receiving a consequence of failure based on high, medium and low for HSE, production and cost (Other).

4.4 Generic Maintenance Concepts Module

4.4.1 Data base history

The development of the OAIs Maintenance Concepts started in the late 80s as a manning analysis for an offshore installation. The goal was to identify the man hours and discipline categories required for maintenance.

In order to give good estimates for the man hours required, it was necessary to identify maintenance activities that were to be done on the installation. Regulatory requirements and criticality of equipment was part of the analyses to identify what activities were required to do as a minimum.

These analyses led to identification of strategies for the various equipment types, compiled on maintenance concepts, where, in a generic way, equal equipment working under equal conditions should be maintained equally.

The RCM methodology was introduced for this work, and the NORSOK Z-008 Standard was established in a parallel process.

In the early 90s the maintenance concepts were continuously improved during a series of workshops with experienced offshore personnel from different offshore production installations. The knowledge they usually carried with them in their "little black book" was now systematically registered and documented for each equipment type as best practice/strategies, i.e. maintenance concepts.

In mid 90s the first version of the Kamfer software was developed to be able to register maintenance activities and man hours in a systematic manner.

Kamfer has since gone through several versions and projects. An extensive database of activities and strategies are built up but the link to the failure modes the corresponding failure mechanisms has been lost. Kamfer 7s GMC module is set to restore that link.

The Maintenance Concepts Module in Kamfer 7 consists of sub-modules which include:

- Failure mode assessment
- Activity selection and work load assessment
- Maintenance Concept creator (Pre-determined, Condition Based and Corrective Activities may be included in scope)

4.2.1 Failure assessment

Input to the RCM task selection process shall be the Failure Modes received from the FMEA module that will be discussed in chapter 7.

The frequency of each failure mode shall be estimated to be able to assess the risk of each failure mode and shall be based on one or more of the following sources:

- Maker/vendor failure data for the component (if available)
- available databases for failure data (OREDA, PDS etc.)
- historical failure data for the equipment (if available)
- expert judgment from available experience and knowledge to the equipment class.

With the failure modes identified follows a question-and-answer process in form of Decision Tree logic to determine a suitable maintenance activity/task to prevent the failure mechanism to cause a failure.

The detection potential, technology available for failure detection and characteristics of a failure decided in the Decision Tree logic will give guidance to what type of approach is applicable for the maintenance activity.

The starting point in the Decision Tree Logic (see Figure 4.4.1) is to specify the Local Effect of any Failure Mode, based on the Local Effect Comments in the FMEA.

The detection method determines how and by which means the failure is detected by operator or maintainer, and is decided by determine if:

- failure is Hidden or Evident
- failure development is detectable
- degradation is evident for the operator
- any state-of-the-art condition assessment is available and cost effective

The failure characteristic is decided by determine whether:

- Hidden failure can be verified by test/inspection
- Failure rate is increasing with age
- Failure resistance can be restored by rework
- Failure is predictable as a function of calendar/operating time

The output of the decisions in the Decision Tree logic will then determine the Maintenance Method/type approach:

- Preventive
    - Pre-determined
    - Condition based

Random Observation/Planned Corrective – Corrective

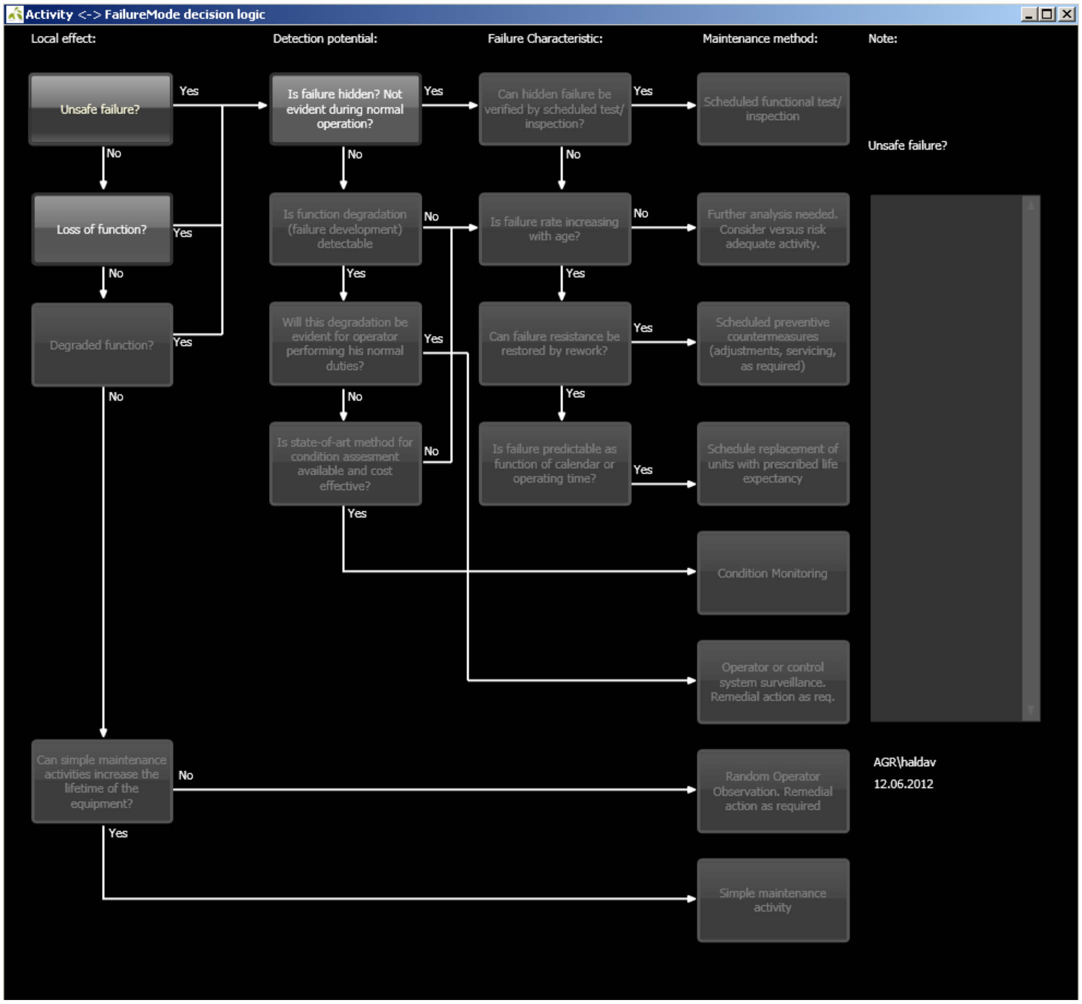


Figure 4.4.1[34] – Decision Tree Logic in Kamfer 7

Activity Class defines the Maintenance Method for each Activity/Task in the OAI Maintenance Concepts, and is the next step from the Decision Tree Logic. As illustrated in Figure 2.3.2 – Types of maintenance tasks, the Activity Class defines whether the Activity/Task is Preventive or Corrective, and whether the Activity/Task is a Predetermined or Condition Based approach.

Preventive Maintenance Activity Classes are defined in Kamfer 7 as:

P - Predetermined

- Typically scheduled replacement or overhaul without previous condition investigation

T - Condition Continuous Monitoring

- Typically instruments online measuring of vibration, self-diagnostics/test etc

I - Condition Periodic Monitoring

- Typically operator/maintainer doing periodic inspection, vibration check etc.

E - Event Based (Predetermined or Condition Based)

- Typical Activity/Task that must be triggered at a change of operational state, prior to/after use of equipment etc. Can be of Predetermined or Condition Based approach.

B - Condition Based Ensuing Activity/Task

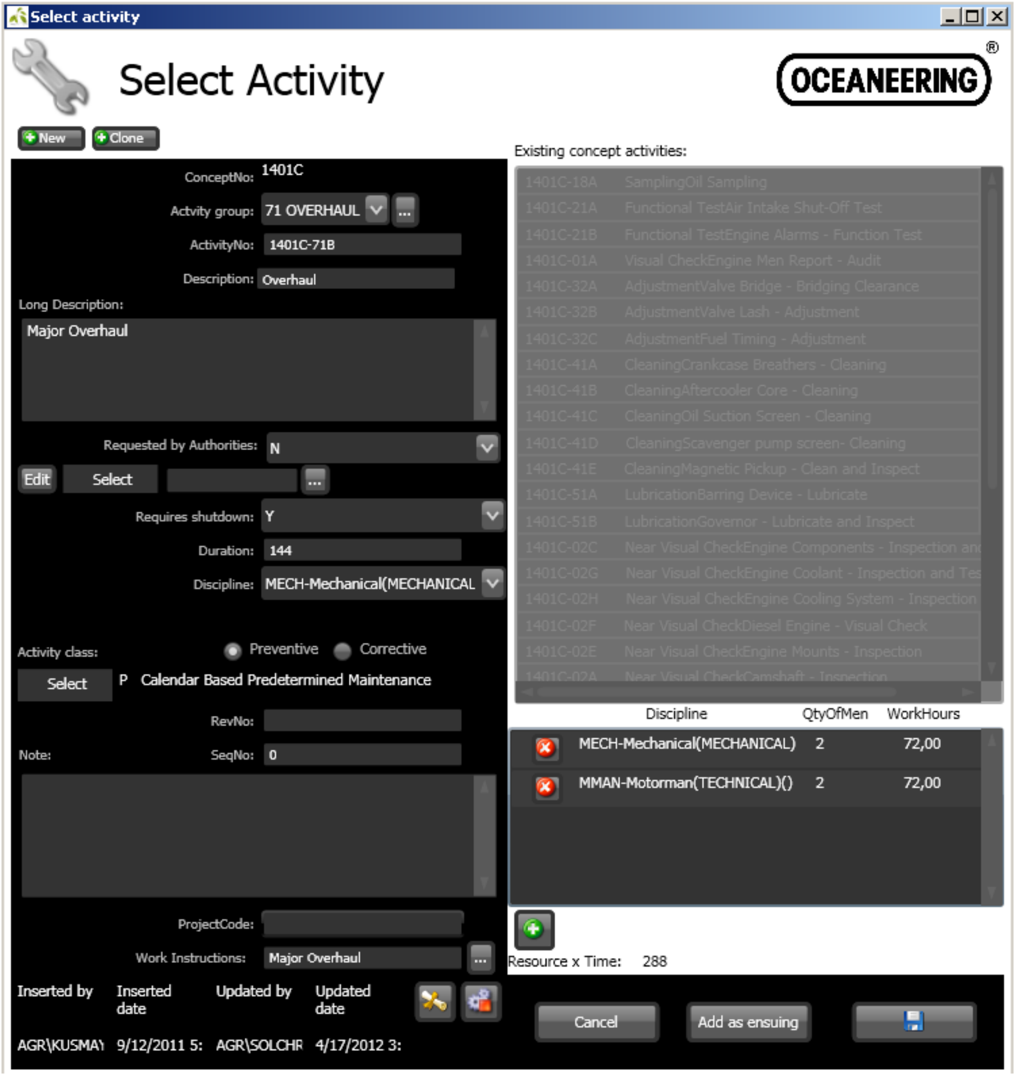
- Activity/Task triggered by an alarm/condition found from Continuous or Periodic Condition Based test/inspection.

C - Planned Corrective Activity/Task

- Activities/Tasks identified needed to be undertaken when Planned Corrective approach is decided for an equipment.

4.4.2 Activity selection and workload assessment

After identifying what kind of maintenance method is needed the maintenance activity is decided in the activity selection window. Several different activities types is stored on the database and the customer can chose the strategy (condition monitoring or preventive maintenance) they want or establish a new activity to mitigate the failure mechanism.



ConceptNo: 1401C
Actvity group: 71 OVERHAUL
ActivityNo: 1401C-71B
Description: Overhaul
Long Description: Major Overhaul
Requested by Authorities: N
Requires shutdown: Y
Duration: 144
Discipline: MECH-Mechanical(MECHANICAL
Activity class: ● Preventive ○ Corrective
P Calendar Based Predetermined Maintenance
RevNo:
Note:
SeqNo: 0
ProjectCode:
Work Instructions: Major Overhaul

Inserted by	Inserted date	Updated by	Updated date
AGR\KUSMA\	9/12/2011 5:	AGR\SOLCHR	4/17/2012 3:

Existing concept activities:

1401C-18A	SamplingOil Sampling
1401C-21A	Functional TestAir Intake Shut-Off Test
1401C-21B	Functional TestEngine Alarms - Function Test
1401C-01A	Visual CheckEngine Men Report - Audit
1401C-32A	AdjustmentValve Bridge - Bridging Clearance
1401C-32B	AdjustmentValve Lash - Adjustment
1401C-32C	AdjustmentFuel Timing - Adjustment
1401C-41A	CleaningCrankcase Breathers - Cleaning
1401C-41B	CleaningAftercooler Core - Cleaning
1401C-41C	CleaningOil Suction Screen - Cleaning
1401C-41D	CleaningScavenger pump screen- Cleaning
1401C-41E	CleaningMagnetic Pickup - Clean and Inspect
1401C-51A	LubricationBarring Device - Lubricate
1401C-51B	LubricationGovernor - Lubricate and Inspect
1401C-02C	Near Visual CheckEngine Components - Inspection an
1401C-02G	Near Visual CheckEngine Coolant - Inspection and Te
1401C-02H	Near Visual CheckEngine Cooling System - Inspection
1401C-02F	Near Visual CheckDiesel Engine - Visual Check
1401C-02E	Near Visual CheckEngine Mounts - Inspection
1401C-02A	Near Visual CheckCamshaft - Inspection

Discipline	QtyOfMen	WorkHours
MECH-Mechanical(MECHANICAL)	2	72,00
MMAN-Motorman(TECHNICAL)()	2	72,00

Resource x Time: 288

Figure 4.4.2[35] - Activity selection and workload assessment

Each activity is assessed for the need of shut down, regulatory demands (if yes, link to the requirement), duration of the activity, responsible discipline, activity class, a long text for explanation of the activity to the maintenance concept and a detailed work instruction to be implemented in the PM-program. Additionally the workload is assessed by identifying the discipline needed, quantity of men per discipline and duration each discipline participates.

4.4.3 Maintenance concept view

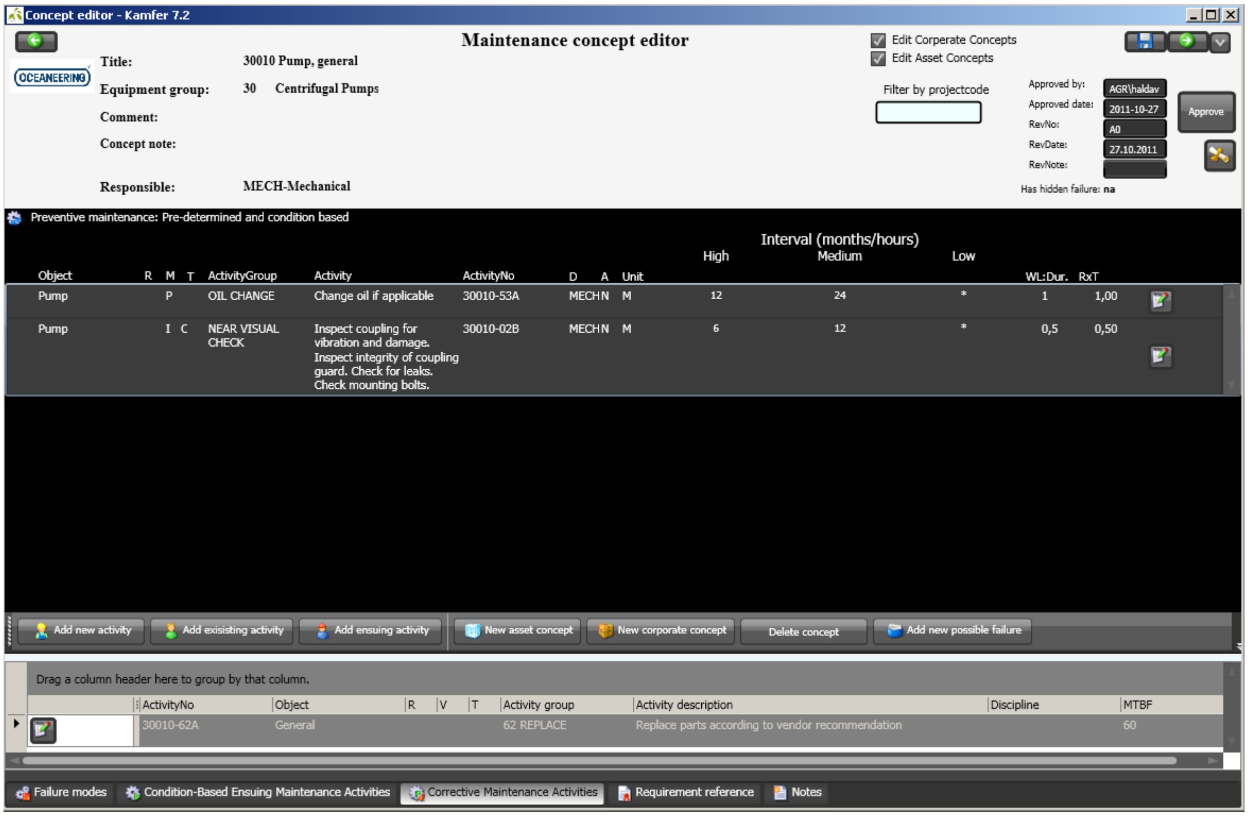
Finally chosen activities are given an interval in and included in the Generic Maintenance concept.

Intervals in the OAI Maintenance Concepts are implicit a risk based approach according to the following Rule of Thumb for setting intervals for Preventive Maintenance Activities from Failure Modes :

Failure Consequence Max	Interval from Failure Frequency
High	Lowest Frequency in range of Failure divided by 3
Medium	Lowest Frequency in range of Failure divided by 2
Low	Planned Corrective (P.C.)

Table 4.4.2[20] - Risk based interval selection

The intervals of the activities can be differentiated on of the Consequence, Redundancy (The example in Figure 4.4.3 only differentiates between consequence high, medium and low.), and also the effect of the failure modes (failure consequence).



Maintenance concept editor

☑ Edit Corperate Concepts
☑ Edit Asset Concepts

Filter by projectcode

Title: 30010 Pump, general
Equipment group: 30 Centrifugal Pumps
Comment:
Concept note:
Responsible: MECH-Mechanical

Approved by: AGR\haldav
Approved date: 2011-10-27
RevNo: A0
RevDate: 27.10.2011
RevNote:
Has hidden failure: na

Preventive maintenance: Pre-determined and condition based

										Interval (months/hours)				
										High	Medium	Low		
Object	R	M	T	ActivityGroup	Activity	ActivityNo	D	A	Unit				WL:Dur.	RxT
Pump		P		OIL CHANGE	Change oil if applicable	30010-53A	MECH	N	M	12	24	*	1	1,00
Pump		I	C	NEAR VISUAL CHECK	Inspect coupling for vibration and damage. Inspect integrity of coupling guard. Check for leaks. Check mounting bolts.	30010-02B	MECH	N	M	6	12	*	0,5	0,50

ActivityNo	Object	R	V	T	Activity group	Activity description	Discipline	MTBF
30010-62A	General				62 REPLACE	Replace parts according to vendor recommendation		60

Figure 4.4.3[36] – Maintenance Concept view

4.5 PM-Program

4.5.1 General packing procedures

The PM-Program is packed to keep down time at a minimum. This is done by differentiation between activities which need for shut down and activities which can be performed under operation in addition to controlling the workload/duration.

The complexity on the packing depends on the customers CMMS system. The packing can range from scheduling activities per tag independently to packing multiple equipment units of belonging functions or areas together, which creates work orders on activities with the same interval.

4.5.2 Prioritizing of preventive work orders

Recommended priority of Preventive Maintenance Program is based on based on Risk, with failure consequence from the consequence assessment and MTTF from the failure mode assessment.

Probability	MTTF	Priority of Preventive Activity		
Very High	0-1 Years	High (to redesign)	High	Medium
High	1-2 Years	High	High	Medium
Moderate	2-5 Years	High	Medium	Low
Low	5-10 Years	High	Medium	Low
Very Low	10-20 Years	Medium	Low	Low
Unlikely	>20 Years	Medium	Low	Low
Failure Consequence		C-High	C-Medium	C-Low

Table 4.5.1[37] – Prioritizing of preventive work orders

4.5.3 Prioritizing of corrective work orders

Recommended Priority of Corrective Work Orders based on Consequence only, as the failure has already occurred, i.e. probability of failure is 100%:

		Redundancy		
		A	B	C
Barrier Tag		High-High (1)	High-High (1)	High-High (1)
Consequence Max of Classification	C-High	High (2)	Medium (3)	Medium (3)
	C-Medium	Medium (3)	Low (4)	Low (4)
	C-Low	Low (4)	Low (5)	Low (5)

Table 4.5.2[38] *– Prioritizing of corrective work orders*

4.6 Conclusion

Oceaneering Asset Integrity in in compliance with the PSA regulation and RCM methodology for the top four phases in the maintenance management loop except for failure modes as a basis for the maintenance activities.

Additionally OAI do not deliver any services for maintenance optimisation other than reducing maintenance activities based on equipment consequence. Which means low and medium equipment can be deleted from the PM-program to only perform maintenance on High consequence equipment and barriers.

However optimization of maintenance intervals and resource needs is not covered.

5 OREDA

5.1 Introduction of OREDA

Reliability of equipment is a decisive factor for HSE and continuous production of offshore installations. Norwegian and foreign oil companies cooperated with SINTEF Technology and Society, Dept. of Safety and Reliability, DNV and other consultants for the collection of maintenance, reliability and safety data on offshore installations. [39]

OREDA (Offshore Reliability Data) Project was initiated by the Norwegian Petroleum Directorate (now Petroleum Safety Authority, PSA) in 1981[39]. The purpose of the project was to survey the reliability of equipment under operational conditions.

Since 1983 OREDA has been run by a group of oil companies. One member and one deputy member from each participating company form the steering comity. The steering comity elects one chairman and a project manager from its members.

At the moment OREDA has established an extensive database with reliability and maintenance data for offshore equipment from different geographic areas, installations, equipment types and operational conditions. The database contains of the moment data from 265 installations and 16 000 equipment with 38 000 failure and 68 000 maintenance records [39] .

The data is collected, retrieved and analysed by the developed OREDA software and stored in the OREDA database.

Several oil and gas companies have contributed to the database. Presently the participants are BP Exploration Operating Company Ltd, ConocoPhillips Skandinavia AS, ENI S.p.S Exploration & Production Division, ExxonMobil Production Company, Gassco, GdF SUEZ E&P Norge AS, Pertobas S.A, Shell Global Solutions UK, TOTAL S.A and Statoil ASA[39].

Steve Burchell from BP has been the chairman of the OREDAs steering comity since February 1st 2010.

5.2 OREDA Reliability Data Handbook

5.2.1 Handbook revisions

The Reliability Data has been published through the OREDA Reliability Data Handbook in five editions (1984, -92, -97, -02, -09), and are sold in over 50 countries worldwide.

As shown in Table 5.2, the OREDA-09 Handbook covers a range of equipment types collected from data collection phase IV to VII in the period 1993-2003.

System	Equipment class	Data from 2002 edition included in 2009 edition		New data in 2009 edition	Total 2009 edition
		Phase IV	Phase V	Phases VI+VII	
		No. of units	No. of units	No. of units	No. of units
1 Machinery	1.1 Compressors	75	56		131
	1.2 Gas Turbines	56	32		88
	1.3 Pumps		160	52	212
	1.4 Comb. Engines		75	23	98
	1.5 Turbo expanders		8	2	10
2 Electric Equipment	2.1 El. Generators		26	6	32
	2.2 El. Motors		128	15	143
3 Mechanical Equipment	3.1 Heat exchangers		17	4	21
	3.2 Vessels	148	50		198
	3.3 Heaters & boilers	11	1		12
4 Other Topside Equipment	4.1 F&G Detectors		779	139	918
	4.2 Process sensors		69		69
	4.3 Contr. Logic Units			10	10
	4.4-4.5 Valves		331	576	907
Sum Topside		**290**	**1732**	**827**	**2849**

Table 5.2.1 [40] - Equipment population in the 2009 OREDA Topside Handbook

OREDA 2009 is issued in two volumes; Volume 1 covers topside equipment while volume 2 covers subsea equipment. As the OIA's Generic Maintenance Concepts covers mainly topside equipment, only Volume 1 of the OREDA Handbook 2009 is considered in this paper.

5.2.2 Equipment boundaries

Each equipment class has surrounding equipment which performs a function for or together with the equipment class in question. Equipment typically part of the equipment unit and equipment essential for the function of the equipment class is placed within the equipment boundary.

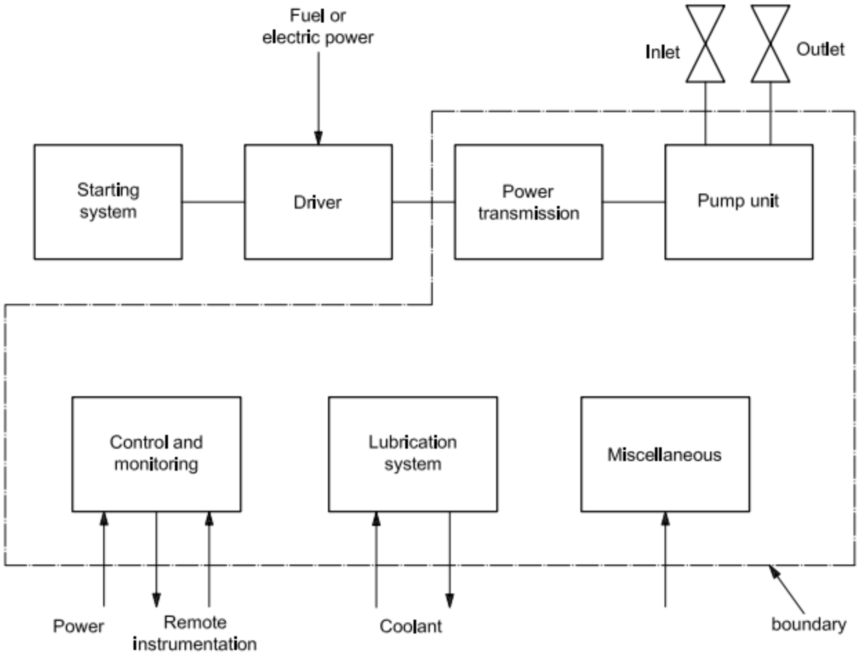


Figure 5.2.1[41] – Boundary definition for pumps

Special considerations:

- Connected units (electric motor on a pump) is considered as an independent equipment unit and not included with the pump. Failures in the connection between the different units (coupling between the motor and pump) are included to the driven unit as long as the fault do not specifically relate to the driving unit outside the boundary.
- Where the driven and the driving unit share a common system (cooling) the common systems failure modes is places under the driven unit.
- Failure recordings for instrumentation is only included if the instrumentation is locally mounted or is performing a control/monitoring function.

5.2.3 Reliability data tables

There are three different information tables belonging to each equipment group. The reliability data shown in Table 5.2 give the failure mode information with belonging failure rate. The Maintenance item versus failure mode shown in table 5.2.3 show which items the failure modes occur on. Finally table5.2.4 shows which failure mechanisms that causes the failure modes.

All estimates are based on the assumption that the equipment is in its useful life phase. This means the bottom of the bath tub shape for failure rates, where the rate is close to constant [42].

Reliability data table:

<table>
<tr><td colspan="2">**Taxonomy no**
1.3.1</td><td colspan="10">**Item**
Machinery
Pumps
Centrifugal</td></tr>
<tr><td rowspan="2">**Population**
156</td><td rowspan="2">**Installations**
19</td><td colspan="6">**Aggregated time in service (10^6 $hours$)**</td><td colspan="4" rowspan="2">**No of demands**
5018</td></tr>
<tr><td colspan="3">**Calendar time ***
3.2412</td><td colspan="3">**Operational time †**
2.1290</td></tr>
<tr><td colspan="2" rowspan="2">**Failure mode**</td><td rowspan="2">**No of failures**</td><td colspan="5">**Failure rates per 10^6**</td><td colspan="2">**Active rep. hours**</td><td colspan="2">**Man hours**</td></tr>
<tr><td>**Lower**</td><td>**Mean**</td><td>**Upper**</td><td>**SD**</td><td>η/τ</td><td>**Mean**</td><td>**Max**</td><td>**Mean**</td><td>**Max**</td></tr>
<tr><td colspan="2">**Critical**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">External leakage- Process Medium</td><td>47*
47†</td><td>-
-</td><td>4.93
8.89</td><td>26.48
48.13</td><td>17.09
22.36</td><td>14.05
22.08</td><td>25</td><td>96</td><td>28</td><td>96</td></tr>
<tr><td colspan="2">**Degraded**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">External leakage- Process Medium</td><td>9*
9†</td><td>0.02
0.08</td><td>2.35
3.79</td><td>7.84
11.71</td><td>2.87
4.13</td><td>2.78
4.23</td><td>9.9</td><td>33</td><td>25</td><td>99</td></tr>
<tr><td colspan="2">**Incipient**</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">External leakage- Process Medium</td><td>**22***
22†</td><td>-
0.03</td><td>3.63
6.68</td><td>17.31
24.73</td><td>7.11
9.13</td><td>6.79
10.33</td><td>10</td><td>44</td><td>23</td><td>206</td></tr>
<tr><td colspan="12">Comments</td></tr>
</table>

Table 5.2.2[43] - Format of Reliability data tables in the OREDA-09 Handbook

The example in Table 5.2.2 show one failure mode for a general centrifugal pump with failure rates for both operational and calendar time per severity class. Since the repair hours and man-hour is not a part of this thesis that information will not be included in the later reliability tables.

Explanation of data entries[47]:

Taxonomy No: The Numerical identification number for the equipment units.

Population: How many units of one equipment type in service during the data gathering.

Installations: Number of installations participated in the data gathering of the equipment group.

Calendar time: The time equipment has performed its function during the data gathering. The calendar time is given with a high accuracy.

Operational time: The time a unit has been under surveillance during data gathering.The operational time is less accurate and is in many cases based in estimates by the data collector.

Severity Class Types:

From ISO 14224, the Failure severities are defined as:

Critical Failure: *"failure of an equipment unit that causes an immediate cessation of the ability to perform a required function. NOTE, Includes failures requiring immediate action towards cessation of performing the function, even though actual operation can continue for a short period of time. A critical failure results in an unscheduled repair."*[44]

Degraded Failure: *"failure that does not cease the fundamental function(s), but compromises one or several functions. NOTE, The failure can be gradual, partial or both. The function can be compromised by any combination of reduced, increased or erratic outputs. An immediate repair can normally be delayed but, in time, such failures can develop into a critical failure if corrective actions are not taken."* [44]

Incipient Failure: *"imperfection in the state or condition of an item so that a degraded or critical failure might (or might not) eventually be the expected result if corrective actions are not taken."* [45]

Failure Impact is defined as: “*impact of a failure on equipment’s function(s) or on the plant. NOTE, on the equipment level, failure impact can be classified in three classes (critical, degraded, incipient).”*[46]

However, as OIA are using the OREDA failure data for establishing Generic Maintenance Concepts, a Critical Failure in the OREDA Handbook is not necessarily a severe failure with regards to HSE, Production or Cost in itself. The failure impact in combination with the consequence from the Function Hierarchy Consequence Assessment as described in chapter 4.3 will determine if a failure is a severe failure in accordance to the requirement in the Activity Regulation §46. The Local Effect, Unsafe failure, in Kamfer 7 will always be a severe failure regardless of the consequence of the equipment, e.g. Earth Fault on a motor that is assessed to be Low Consequence in the Consequence Assessment.

Unknown: Failure severity was not or could not be determined.

Failure rates:

All entries refer to 10^6 *hours and calendar time.*

Failure rate (λ) = $\frac{Failures\ (n)}{Time}$

Mean Time to Failure (MTTF) = $\frac{1}{\lambda}$

Mean: The mean failure rate obtained by the OREDA estimator based on the installation participating in the data gathering

Lower/Upper: An interval covering 90% variation between the various samples

SD: The standard deviation determining the variation between multiple samples.

η/τ: The total amount of failures divided the total time in service assuming homogenous sample.

Maintenance versus failure mode:

To perform a FMEA/FMECA there is need for information about which maintenance items the failure modes occur to.

	AIR	BRD	ELP	ELU	XXX	Sum
Casing	-	0.45	1.05	0.15	XXX	5
Piping	-	-	3.38	3.38	xxx	15
Instrument, flow	4.35	-	0.15	-	xxx	4
Seals	-	0.15	6.68	13.66	xxx	50
Valves	-	-	1.05	0.15	xxx	2
xxx	xxx	xxx	xxx	xxx	xxx	24
Total	4.35	0.6	12.31	17.34	xxx	100

Table 5.2.3[48] - Maintenance item versus Failure mode

Each Maintenance item-Failure mode combination shows the items relative contribution to the total failure rate in percentage. Additionally the sum column show how much each specific maintenance item contributes in percentage to the total failure rates.

Failure mechanism versus failure mode:

A maintenance activity is set to prevent or delay a failure mechanism to occur/develop.

	AIR	BRD	ELP	ELU	XXX	Sum
Blockage/plugged	-	0.45	1.05	0.15	XXX	5
Mechanical failure-general	-	-	3.38	3.38	xxx	15
Instrument failure-general	4.35	-	0.15	-	xxx	4
Corrosion	-	0.15	6.68	13.66	xxx	50
Erosion	-	-	1.05	0.15	xxx	2
xxx	xxx	xxx	xxx	xxx	xxx	24
Total	4.35	0.6	12.31	17.34	xxx	100

Table 5.2.4[49] *– Failure mechanism versus failure mode*

Each failure mechanism-Failure mode combination shows the failure mechanisms relative contribution to the total failure rate in percentage. Additionally the sum column show how much each specific failure mechanism contributes in percentage to the total failure rates.

5.3 Conclusion

The OREDA data is primary a reliability data base to be used in availability analysis to provide a basis for engineering, fabrication and operation.

However in an initial phase of a maintenance system historic data may be lacking and OREDA provide the best available data source to determine failure modes with MTTF.

6 Reference data

6.1 Statoil/OAI Failure Mode Project

The Statoil/OAI failure mode project was performed in late 2008 to early 2009.

The participants were experienced personnel from Statoil and OAI (AGR) and all maintenance concepts in the OAI database were evaluated for Failure modes, cause and mechanism. Additionally local effect, hidden failure and preventive maintenance tasks were evaluated.

OREDA data was used in the early phase were the MTTF was calculated from critical severity and mean failure rate. But eventually the participant used experience to determine the MTTF since the OREDA calculations deviated from the expected values [20].

The MTTF they used were [50]:

- 0-1 Years
- 1-2 Years
- 2-5 Years
- 5-10 Years
- 10-20 Years
- >20 Years

7 Analysis and Discussion

7.1 FMEA module

The Generic Maintenance Strategies lack the FMEA part for documentation of the different maintenance activities. The FMEA module is connected in the Generic Maintenance Module and will be available in GMC workshops and GMC reports.

The following fields shall be implemented in the Failure Mode or FMEA module based in input from IEC-60300-3-11 and ISO 14224:

Prevented by Activity Number(s): This will display the preventive activities/strategies identified as countermeasures for the respective Failure Mode.

Object: Will display the specific object/item influenced by the respective failure mode. Examples, impeller of pump, gasket, bearing etc.

Failure Mode: This needs to be a drop-down box of Failure Modes (See table D.1)based on ISO 14224 with a few modifications by OAI.

This box will display a list of identified Failure Modes for the equipment covered by the GMC.

Failure mode note: This field will be for a description or comments/notes for each respective Failure Mode.

Fail cause: Display the Failure Cause of each respective Failure Mode.

This is a text field where the Failure Cause shall be typed in as "free-text". However, Table D.1 shows examples of failure causes and should be used for consistency.

Fail Mechanism: Display the Failure Mechanism of each respective Failure Cause.

This should be a drop-down box with Failure Mechanisms taken from ISO 14224 (see table D.2).

Fail Mechanism Note: Display additional comments/notes for each respective Failure Mechanism.

Frequency OAI (quantitative MTTF): Display the expected MTTF for each respective Failure Mode based on expert's experiences and analysis.

This Frequency shall be the anticipated Mean Time to Failure if no preventive maintenance is carried out to the equipment.

This quantitative MTTF should be grouped into six levels, to better represent each Clients grading of probability of failure. The recommended six levels of MTTF in the OAI Maintenance Concepts Database for the quantitative MTTF are:

Probability	MTTF
Very High	0-1 Years
High	1-2 Years
Moderate	2-5 Years
Low	5-10 Years
Very Low	10-20 Years
Unlikely	>20 Years

Table7.1.1 [51] *-Recommended OAI frequency*

The Frequency OAI values in the OAI Maintenance Concepts shall be based on the best practice from FMEA/RCM analysis and input from experienced personnel through workshops from a number of installations.

However, for each new Client/Installation, the Frequency Analysis value shall be verified/updated in workshops based on the Client personnel's experiences, FMEA input if any, and the Clients historical failure data if any. This is to establish Client personnel ownership to the analysis, traceability for each Item/Tag to the analysis, and update of Clients database to include new/improved design.

Analysis Ref: Displays reference to the workshop/analysis where each Failure Mode and respective Frequency OAI value is verified/updated.

This field is empty in the OAI Maintenance Concept Database, except for any detailed FMEA/RCM performed by OAI. This field shall be filled with reference to the workshops where a Failure Mode or Frequency AGR field is verified/updated, to establish Client personnel ownership to the analysis, traceability for each Item/Tag to the analysis.

Local Effect: Displays the consequence of each respective Failure Mode on the equipment in the Concept, and is defined in the Decision Tree logic (Figure 4.4.1).

Local Effect is divided into 3 types of consequences in Kamfer 7 as Unsafe Failure, Loss of Function and Loss of Barrier.

Local effect comment: Displays detailed description of consequence for each respective Local Effect and must include a concise description of the effect(s) of the failure mode to explain/justify the “Local Effect”

Hidden: Displays whether the respective Failure Mode (function) is defined as hidden or not, and is defined in the Decision Tree, displayed as Yes or No.

Frequency standard (qualitative MTTF): Displays the expected MTTF for each respective Failure Mode based on failure data standards such as OREDA and PDS Data Handbook. The Frequency standard qualitative data field gives traceability to recognized failure data sources and gives guidance to MTTF value in the Frequency OAI field.

Project Code: This field is used to activate/deactivate each respective failure mode where relevant.

Deactivating Failure Modes may be relevant if the Object for the failure Mode is not applicable for the client, or if Failure Mode is found not to be applicable through analysis for the project.

7.2 Calculation of OREDA Data

7.2.1 Assumptions

Constant failure rate: OREDA base the failure modes on random failure rate pattern since the input come from the equipment's useful life phase.

Failure rate a sum of severities: OREDA classify the failure modes based on severity; Critical, degraded, incipient and unknown.

The failure mode severity Unknown is not taken into account because of its uncertainty and the fact that it is not used to a great extent.

In my experience from reading other consultants FMECAs with MTTF based on OREDA, only the critical severity is taken into consideration. This may be the case since that methodology would be correct for a reliability analysis where the downtime is essential.

Take the oil filter on a car as an example: How often do you experience mechanical problems on your engine as a result of bad oil quality? Almost never. Why? Because the filter and subsequently the oil is changed at regular intervals at incipient or degraded state. But the small amount of registered critical failures does not mean the filter/oil should not be changed or set to an interval for change based on MTTF from Critical failure mode only.

The assumption is based on that the failure mechanism in many cases grows from low severity to critical severity and therefor the failure rate should include the input from all phases. Additionally it is assumed that the amount of failures, n, is recorded for the equipment type at the same period of time. So the total failures n_{total} will be $n_I + n_D + n_C$. Of course it can be argued that a failure is when the equipment does not deliver its intended function as described in section 2.2.1. I can agree that the incipient failure (which I interpret as the last stage in the margin of deterioration) cannot be called a failure. But since you want to detect the failure before the failure is experienced and thus have time to plan a condition based corrective work order, I choose to take the incipient failure mode into consideration.

Usage of upper failure rate to determine MTTF: To determine the optimal interval from maintenance activities the failure rate without maintenance should be determined. The data gathered in OREDA represent failures happened with maintenance and has a mean, lower and upper value of the failure rate to account for the uncertainty of the failure rate.

The assumption defines lower as the best in the class, mean as the average and upper as the worst in the class. Additionally the assumption is made that upper will be similar to no maintenance performed.

This is a coarse assumption and may be overkill. Nonetheless it is better to calculate with a lower MTTF in the initial PM-program and optimize with maintenance data from operation to uphold the safety.

However, if the standard deviation is great (above 20) the mean values can be used. This is due to the great sensitivity in the upper value experience from abnormal reporting.

Obtaining MTTF in years: The failure rate is given in Calendar and Operational time. Calendar time is used since it is stated it the most accurate in the OREDA Handbook. The failure rate in OREDA is based on failure per 10^6 hours.

The assumption states that the maximum amount of hours (24hours*365days) possible in a calendar year should be used to change the MTTF from hours to years.

7.2.2 Methodology

Selecting Failure modes

Based on Activity regulation §46, only severe failures need to be taken into consideration. This means that failure modes (if any) with no critical severity should not be taken into consideration. Thus the performer shall start with a critical severity and then look for degraded and incipient severity

Formulas

The formula for determine Mean Time to Failure is: MTTF = $\frac{1}{\lambda}$

The total failure rate is determined by: λ = $\frac{n_I+n_D+n_C}{Time\ (10^6)}$

n_I – Number of Incipient failures
n_D – Number of Degraded failures
n_C – Number of Critical failures

Calculating failure rate from hours to years: λ = $\frac{n_{total}}{10^6 hours * \frac{1\ year}{8760\ hours}}$

To determine the severity of the failure rate three additional columns should be included in the FMEA sheet when using failure data from OREDA. These columns will show the percentage of each severity representing in the failure rate. This is done to more easily determine is the failure mode is hidden and subsequently determine the maintenance type to prevent the failure mechanism. For example a failure rate with 100% critical failure can have a replacement at certain intervals or function test, while failure modes with growing detectable failure mechanisms (20% Critical, 40% degraded, 40% incipient) can have condition monitoring or routine check with subsequent maintenance activities.

This is calculated by dividing each severity failures with the total failures: $\%_{\text{Critical}} = \frac{n_C}{n_{total}}$

Determining the maintenance item (object)

A Failure mode has several maintenance items contributing to the failure rate. To focus the maintenance activities to the right maintenance items the failure modes versus maintenance item (shown in table 5.2.3) must be consulted. Items representing a different equipment type and thus a different Generic Maintenance Concept shall not be included. As shown in table 5.2.3 is the failure mode versus failure item of a centrifugal pump. Two maintenance item sticks out; valve and instrument flow. These will be represented in their own GMC to not create several redundant failure modes with different failure rates.

Additionally only the maintenance items contributing most to a failure mode should be considered. This is done to focus the analysis where it is most valuable. I use ELU (external leakage utility) as an example. Piping and seals has a relative contribution of 17.04 out of 17.34, thus 98,2% for the failure rate. Thus the 0,08% contribution from the casing is not relevant enough to take into consideration.

To find the maintenance items failure rate the percentage they contribute with must be calculated and the multiplied with the total failure rate

$\%\text{Seal}=\frac{13.66}{17,34}=0,79$ $\lambda_{\text{seal}} = \lambda_{\text{total}} * 0.79$

Determining the failure mechanism

To determine the failure mechanism, the Failure mode versus Failure mechanism (shown in table 5.2.4) must be consulted. Finding the right failure mechanism for each item is based on engineering judgment and can be difficult without practical knowledge. As a starting point the table show which failure mechanisms contributes most. The most evident failure mechanism should be used in the drop-down box, subsequently the failure mechanism note field can be used to explain other contributing factors.

7.2.3 Calculation Examples of different methods

Manual Valve, general (OREDA Taxonomy no 4.4):

External Leakage-Process Medium (ELP), Critical Failure mode and mean failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{0,36}{\frac{10^6}{8760}}\right)}=317\text{ Years}$$

External Leakage-Process Medium (ELP), sum of severities and mean failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{0,36+1,57+0,42}{\frac{10^6}{8760}}\right)}=48\text{ Years}$$

External Leakage-Process Medium (ELP), sum of severities and upper failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{1,88+6,39+2,07}{\frac{10^6}{8760}}\right)}=11\text{ Years}$$

Pump, centrifugal (high standard deviation) (OREDA Taxonomy no 1.3.1)

External leakage utility medium (ELU), Critical Failure mode and mean failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{5,35}{\frac{10^6}{8760}}\right)}=21\text{ Years}$$

External leakage utility medium (ELU), sum of severities and mean failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{5,35+22,45+4,25}{\frac{10^6}{8760}}\right)}=3,6\text{ Years}$$

External leakage utility medium (ELU), sum of severities and upper failure rate

$$\text{MTTF}=\frac{1}{\left(\frac{14,77+103,84+17,92}{\frac{10^6}{8760}}\right)}=0,8\text{ Years}$$

Electric motor, general (Only critical severity recorded) (OREDA Taxonomy no 2.2):

Overheating (OHE), Critical Failure mode and mean failure rate

MTTF=$\frac{1}{\frac{(\frac{0,75}{10^6})}{8760}}$=152 Years

Overheating (OHE), sum of severities and mean failure rate

MTTF=$\frac{1}{\frac{(\frac{0,75}{10^6})}{8760}}$=152 Years

Overheating (OHE), sum of severities and upper failure rate

MTTF=$\frac{1}{\frac{(\frac{2,61}{10^6})}{8760}}$=44 Years

Compressor Reciprocating (No incipient severity) (OREDA Taxonomy no 1.1.2):

Fail to stop on demand (STP), Critical Failure mode and mean failure rate

MTTF=$\frac{1}{\frac{(\frac{4,52}{10^6})}{8760}}$=25 Years

Fail to stop on demand (STP), sum of severities and mean failure rate

MTTF=$\frac{1}{\frac{(\frac{4,52+2,83}{10^6})}{8760}}$=15,5 Years

Fail to stop on demand (STP), sum of severities and upper failure rate

MTTF=$\frac{1}{\frac{(\frac{19,93+7,47}{10^6})}{8760}}$=4,2 Years

7.2.4 Comparing Calculations with reference data

Equipment	Failure modes	Critical Failure mode and mean failure rate (MTTF Years)	Sum of severities and mean failure rate (MTTF Years)	Sum of severities and upper failure rate (MTTF Years)	Reference (MTTF Years)
Manual Valve, general	External Leakage-Process Medium (ELP),	317	48	11	2-5
Pump, centrifugal	External leakage utility medium (ELU),	21	3,6	0,8	5-10
Electric motor, general	Overheating (OHE)	152	152	44	10-20
Compressor Reciprocating	Fail to stop on demand (STP),	25	15	4,2	5-10

Table 7.2.1 – Calculations versus reference data

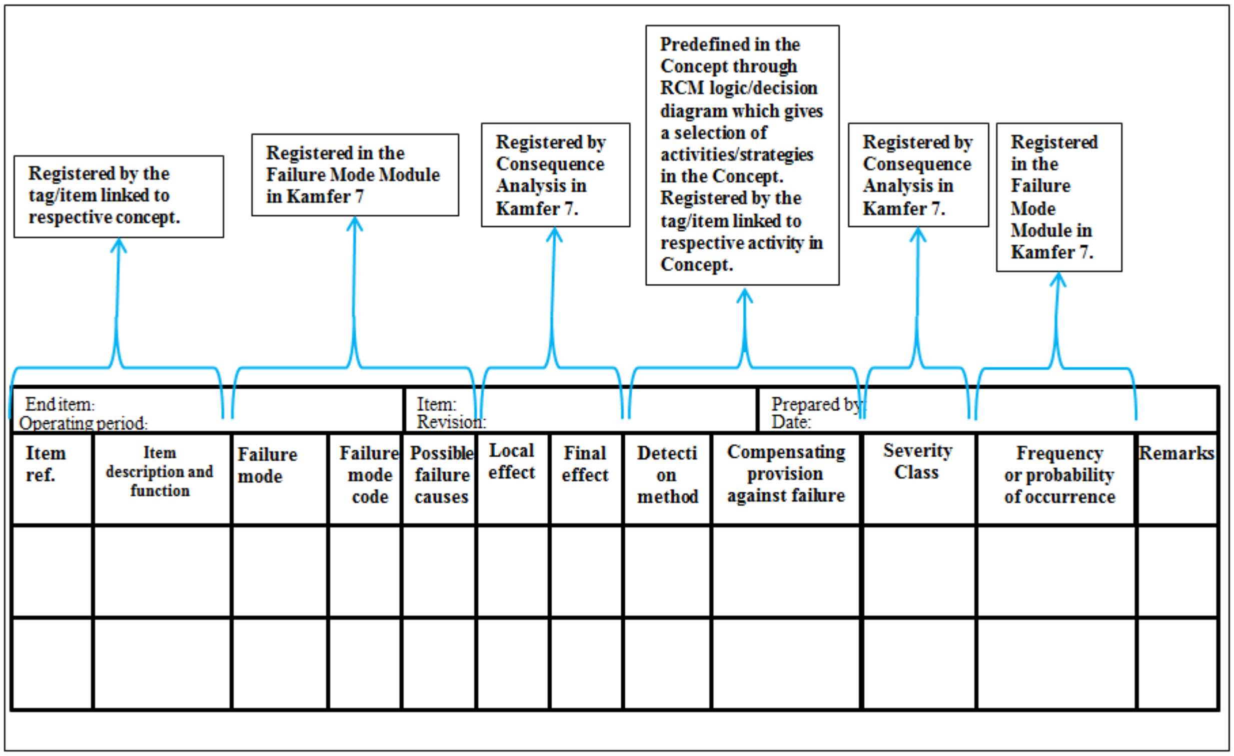
7.2.5 Conclusion

The input from OREDA varies but the four examples cover the different scenarios detected when performing calculations. Based on the examples a combination of mean and upper values be based on the standard deviation should be used to calculate the MTTF. However under in all circumstances the sum of all severities gives a better result that only using critical severity.

The reference data is limited due to the reluctance of vendors to give FMEAs of their equipment.

7.3 Achieving RCM compliance

With the failure mode module OAI can perform FMEAs on installation equipment. An example is shown in table 7.3.1 where an FMEA worksheet from IEC 60812 is used as a basis.



End item: Operating period:					Item: Revision:				Prepared by: Date:			
Item ref.	Item description and function	Failure mode	Failure mode code	Possible failure causes	Local effect	Final effect	Detection method	Compensating provision against failure	Severity Class	Frequency or probability of occurrence	Remarks	

Figure 7.3.1[52] *- Example of the format of an FMEA Worksheet*

Item identification and function is performed by linking a tag to a sub function and a Generic Maintenance Concept.

Failure Modes, causes, mechanisms and MTTF is covered by the Failure Mode Module. A tag is given these failure modes when linked to the GMC containing the failure modes.

Local and final effect is covered by the Consequence Classification and assigned the tag when linked to a sub function. However, if the failure mode is an unsafe failure the local effect will be taken from the failure mode module. (Example earth fault in an electric motor)

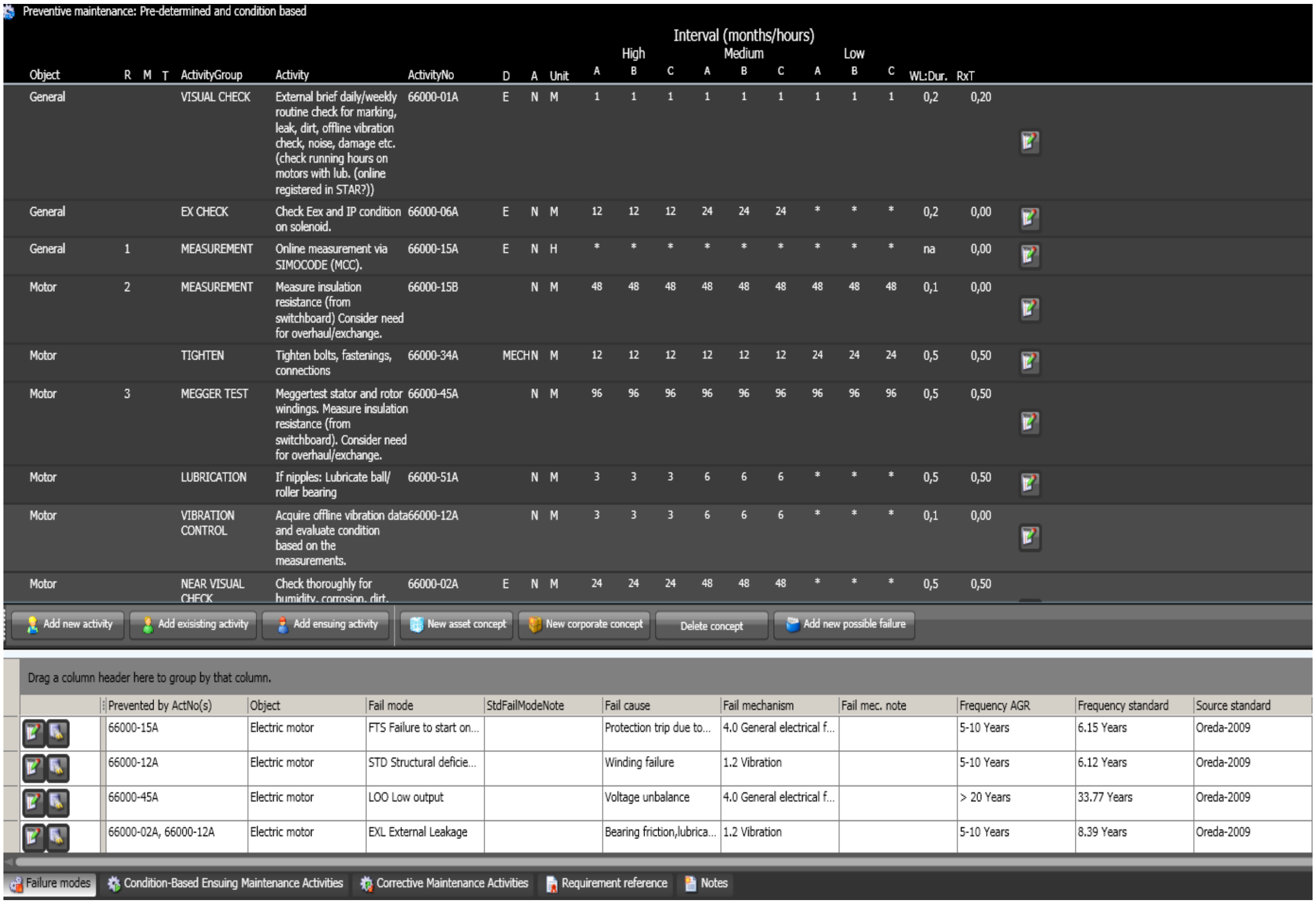
Detection method and compensating provision against failure is determined in the Decision Tree Logic and subsequently by the maintenance activities in the GMC.

Severity Class is determined in the Consequence classification and assigned; high, medium or low.

8 Results

A work process for how to add failure modes to the OIA Generic Maintenance Concepts has been established. The Failure Mode Module has been developed with functionality to be aligned with this new work process and is implemented into Kamfer 7. Failure Modes from OREDA-2009 based on input and assumptions made in Chapter 7 has in turn been implemented in the Generic Maintenance Concepts by use of the newly developed Failure Mode Module. It is now possible to document the process of identifying failure modes and establishment of maintenance concepts with the improvements implemented in Kamfer 7. Any client can document the decisions and analysis that led to the chosen maintenance strategy for each equipment, and show traceability all the way from identification of failure modes to the CMMS and Work Order History.

In addition, any clients historical data can be used at a later stage to optimize the maintenance program as described in chapter 7.4.



										Interval (months/hours)										
										High			Medium			Low				
Object	R	M	T	ActivityGroup	Activity	ActivityNo	D	A	Unit	A	B	C	A	B	C	A	B	C	WL:Dur.	RxT
General				VISUAL CHECK	External brief daily/weekly routine check for marking, leak, dirt, offline vibration check, noise, damage etc. (check running hours on motors with lub. (online registered in STAR?))	66000-01A	E	N	M	1	1	1	1	1	1	1	1	1	0,2	0,20
General				EX CHECK	Check Eex and IP condition on solenoid.	66000-06A	E	N	M	12	12	12	24	24	24	*	*	*	0,2	0,00
General	1			MEASUREMENT	Online measurement via SIMOCODE (MCC).	66000-15A	E	N	H	*	*	*	*	*	*	*	*	*	na	0,00
Motor	2			MEASUREMENT	Measure insulation resistance (from switchboard) Consider need for overhaul/exchange.	66000-15B		N	M	48	48	48	48	48	48	48	48	48	0,1	0,00
Motor				TIGHTEN	Tighten bolts, fastenings, connections	66000-34A	MECH	N	M	12	12	12	12	12	12	24	24	24	0,5	0,50
Motor	3			MEGGER TEST	Meggertest stator and rotor windings. Measure insulation resistance (from switchboard). Consider need for overhaul/exchange.	66000-45A		N	M	96	96	96	96	96	96	96	96	96	0,5	0,50
Motor				LUBRICATION	If nipples: Lubricate ball/ roller bearing	66000-51A		N	M	3	3	3	6	6	6	*	*	*	0,5	0,50
Motor				VIBRATION CONTROL	Acquire offline vibration data and evaluate condition based on the measurements.	66000-12A		N	M	3	3	3	6	6	6	*	*	*	0,1	0,00
Motor				NEAR VISUAL CHECK	Check thoroughly for humidity, corrosion, dirt.	66000-02A	E	N	M	24	24	24	48	48	48	*	*	*	0,5	0,50

Prevented by ActNo(s)	Object	Fail mode	StdFailModeNote	Fail cause	Fail mechanism	Fail mec. note	Frequency AGR	Frequency standard	Source standard
66000-15A	Electric motor	FTS Failure to start on...		Protection trip due to...	4.0 General electrical f...		5-10 Years	6.15 Years	Oreda-2009
66000-12A	Electric motor	STD Structural deficie...		Winding failure	1.2 Vibration		5-10 Years	6.12 Years	Oreda-2009
66000-45A	Electric motor	LOO Low output		Voltage unbalance	4.0 General electrical f...		> 20 Years	33.77 Years	Oreda-2009
66000-02A, 66000-12A	Electric motor	EXL External Leakage		Bearing friction,lubrica...	1.2 Vibration		5-10 Years	8.39 Years	Oreda-2009

Figure 8.1[53] - Maintenance concept with Failure mode

9 Recommendations

For further utilization of the failure mode module a FMECA report should the created in Kamfer 7. This will create possibilities to supply a customer with a full FMECA of all equipment in the Kamfer database which can be delivered as an addition to the Generic Maintenance Concept and Consequence Classification reports and may lead to a better understanding of the deliverables.

Additionally the Online Portal should be developed to receive input from maintenance reports. Today the Online Portal has feedback possibilities which the developers can build on. Meanwhile Oceaneering Asset Integrity should develop a methodology for performing optimisation of maintenance intervals and methods. Subsequently an optimization module should be developed in Kamfer 7 to perform the calculations.

The calculations could be based on the formula OREDA use for weighting one data source against another:

$$\lambda_{\text{estimated}} = \frac{\lambda_a^2 + \lambda_b^2 \left(\frac{\lambda_a}{\lambda_b} + \frac{|\lambda_a - \lambda_b|}{SD_b} \right)^2}{\lambda_a + \lambda_b \left(\frac{\lambda_a}{\lambda_b} + \frac{|\lambda_a - \lambda_b|}{SD_b} \right)^2} \qquad \lambda_a = \text{original failure rate},\ \lambda_b = \text{new failure rate}$$

Adding maintenance optimisation to the service portfolio will enable OAI to perform services in all the aspects of the Maintenance Management Loop.

10 References

[1]: Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, page 271

[2]: Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, page 273

[3]: Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, page 288.

[4]: Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, Figure 11.1, page 274

[5]: Picture taken from: http://www.plant-maintenance.com/tzd.shtml, downloaded 14.03.2012

[6]: Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, Figure 11.1, page 278

[7]: European Standard, EN 13306:2010, page 9

[8]: Figure taken from: Jørn Vatn, World Class Maintenance-Maintenance optimization. The figure was by mail so I do not have the figure reference.

[9]: European Standard, EN 13306:2010, page 10

[10]: European Standard, EN 13306:2010, page 9

[11]: International Standard, IEC 60300-3-11:2009, page 13

[12]: International Standard, IEC 60300-3-11:2009, Figure 5

[13]: International Standard, IEC 60300-3-11:2009, Figure 3

[14]: International Standard, IEC 60300-3-11:2009, page 14

[15]: Figure taken from internal document in OAI

[16]: Activity Regulation, Chapter 9 Maintenance, Stipulated by the Petroleum Safety Authority Norway on 29 April 2010

[17]: Management Regulation, §12 Planning, Stipulated by the Petroleum Safety Authority Norway on 29 April 2010

[18]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 4

[19]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Figure 1

[20]: Interview with Jan Cato Vestvik, Department Manager, Maintenance Engineering, Oceaneering Asset Integrity

[21]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 16

[22]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Figure D.3

[23]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 17

[24]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 22

[25]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, figure 3

[26]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, table 2

[27]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 26

[28]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 27

[29]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, page 23

[30]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, figure 4

[31]: International Standard, IEC 60300-3-11:2009, figure 1

[32]: Picture acquired by screenshot of Kamfer 7

[33]: Picture acquired by screenshot of Kamfer 7
[34]: Picture acquired by screenshot of Kamfer 7
[35]: Picture acquired by screenshot of Kamfer 7
[36]: Picture acquired by screenshot of Kamfer 7
[37]: Table taken from OAI PM-program manual
[38]: Table taken from OAI PM-program manual
[39]: http://www.oreda.com/history.htm
[40]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, table 2
[41]: International Standard, ISO 14224, 2 Edition 2006, figure A.6
[42]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, page29
[43]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, table 7
[44]: International Standard, ISO 14224, 2 Edition 2006, page 3
[45]: International Standard, ISO 14224, 2 Edition 2006, page 5
[46]: International Standard, ISO 14224, 2 Edition 2006, page 4
[47]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, page 35-43
[48]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, page 149
[49]: OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009, page 151
[50]: Taken from Statoil/OAI failure mode project access database
[51]: Table created after discussions with Ingvar Ringdal
[52]: International Standard, IEC 60812, 2006, figure A.1
[53]: Picture acquired by screenshot of Kamfer 7
[54]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Annex D.1
[55]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Annex A
[56]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Annex B
[57]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, table C.3
[58]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, table C.2
[59]: STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3, Annex D.4
[60]: International Standard, ISO 14224, 2 Edition 2006, tables B.6-B.12
[61]: Failure Cause table created with input from Kjell Ervik, Retired Maintenance Specialist, OAI.
[62]: International Standard, ISO 14224, 2 Edition 2006, table B.2

Literature

- Dr. Alan Wilson, Asset Maintenance Management- A Guide to developing Strategy & Improving Performance, 1 Edition 2002, page 271-291.
- STANDARD NORGE 2011: NORSOK STANDARD Z-008, Edition 3
- International Standard, ISO 14224, 2 Edition 2006
- International Standard, IEC 60300-3-11, Edition 2 2009
- European Standard, EN 13306:2010
- Jørn Vatn, World Class Maintenance-Maintenance optimization
- OREDA, Offshore Reliability Handbook, Volume 1- Topside Equipment 5th Edition, 2009
- International Standard, IEC 60812, 2006

Appendix A Establishment of Technical hierarchy NORSOK Z-008[53]

The level of detail with regards to tagging is in many ways a deciding factor to ensure that the equipment will receive the adequate maintenance. On the Norwegian Continental Shelf there is an industrial heritage of tagging to a detailed level where even instrumentation and equipment in support of MFs and sub functions are tagged The tagging is to be consistent from drawings, the actual equipment in the installation and the CMMS and is an important part of documenting the equipment through its life cycle.

Figure A.1 illustrates the workflow to establish a technical hierarchy

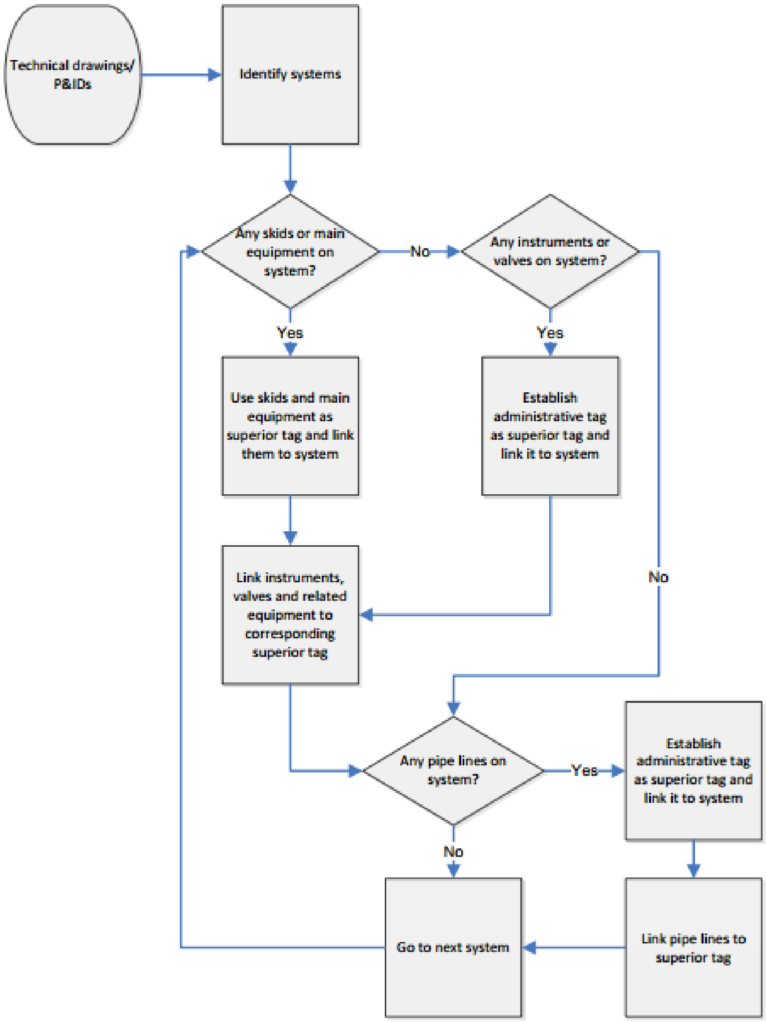


Figure A.1 – Work process technical hierarchy

To establish a technical hierarchy it is necessary with a set of technical drawings, e.g. flow and one-line diagrams, P&IDs etc. and a list of tags and a tool for linking tags to each other.

The top of the technical hierarchy normally starts with the installation code with the system numbers listed in Figure D.2. The usage of system numbers may vary from plant to plant NORSOK Z-DP-002 uses system numbers between 00 and 99. Other standards like SFI [Ship research institute of Norway (Skipsteknisk Forskningsinstitutt)] would have a 3 digit numbers as system numbering, but the principles may be similar.

Technical drawings can be used to identify skids, packages and main equipment that can work as a superior tag for the connected instruments, valves and other kinds of equipment. There can be several levels beneath a level, e.g. a skid that contains 2 pumps with electric motors. The skid will then be the top level, the pumps will be the 2nd level, and the electric motors will be the 3rd level to the corresponding pump. Each level can hold corresponding instruments and valves. See Figure A.2.

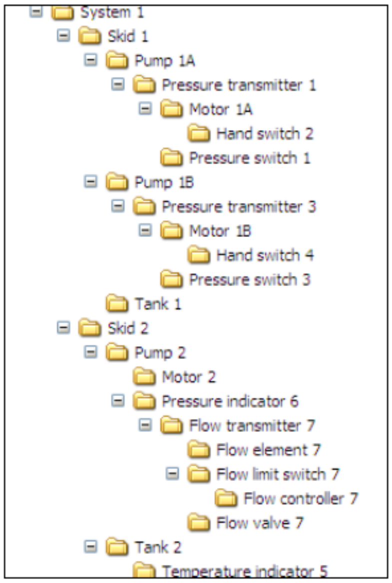


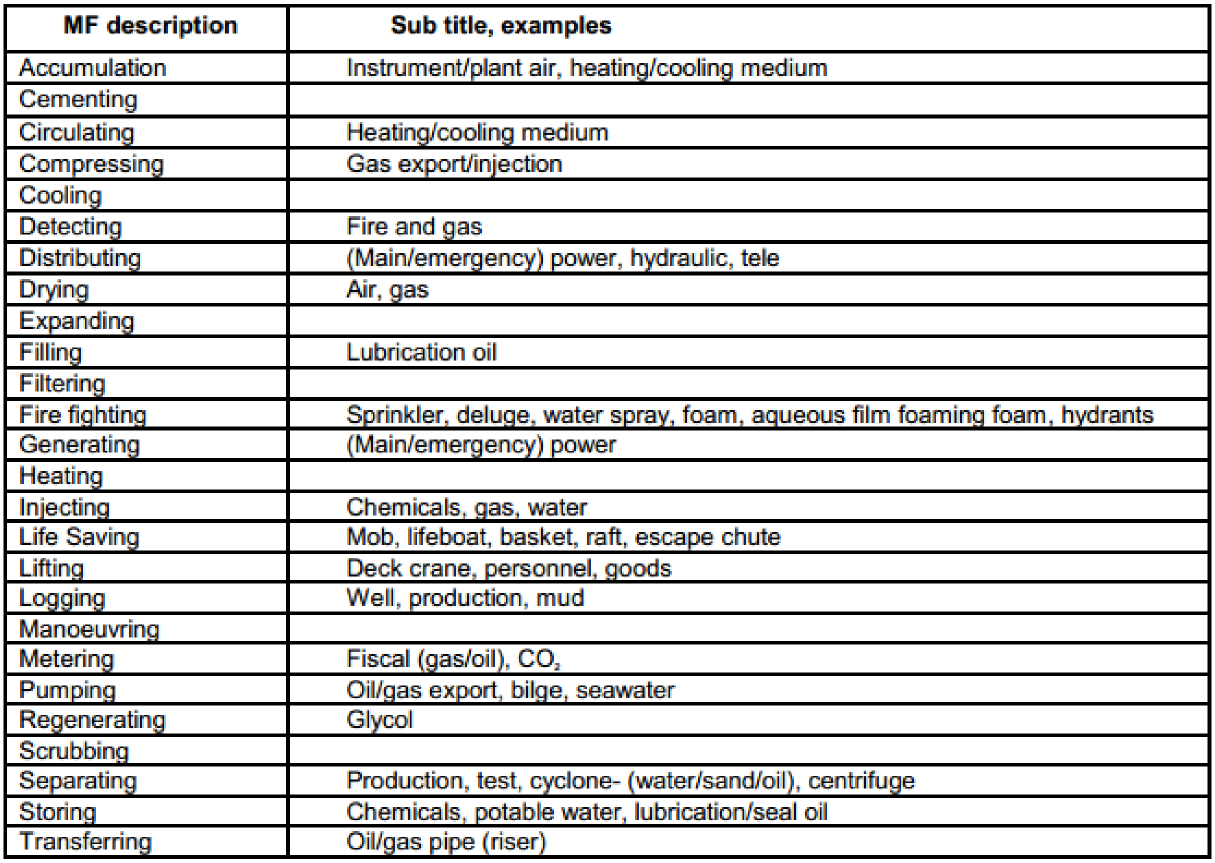
Figure A.2- Technical hierarchy

Start with a system by identifying skids and main equipment. Then link all the skids and main equipment that will be used as a superior tag to the system number in the tree structure. Next step is to identify the instruments, valves and other kinds of equipment on the system and connect them to the corresponding skid or main equipment. If there are no skids or main equipment, but only e.g. instruments or valves, then administrative tags should be established to form the level above. The instruments, valves and other kinds of equipment are then linked to the administrative tags. In instrument loops one of the components can represent the whole loop e.g. a transmitter or valve, while the rest of the loop lie beneath.

Appendix B Consequence classification NORSOK Z-008

B.1 Main function description and boundaries[55]

Descriptions of MFs should aim to describe an active function (i.e. ‟Pumping„ instead of ‟Pump„). Descriptions commonly used for MFs are shown in Table B.1. Normally a further specification is required to describe the MF sufficiently. If relevant, the availability, capacity and performance should be specified.



MF description	Sub title, examples
Accumulation	Instrument/plant air, heating/cooling medium
Cementing	
Circulating	Heating/cooling medium
Compressing	Gas export/injection
Cooling	
Detecting	Fire and gas
Distributing	(Main/emergency) power, hydraulic, tele
Drying	Air, gas
Expanding	
Filling	Lubrication oil
Filtering	
Fire fighting	Sprinkler, deluge, water spray, foam, aqueous film foaming foam, hydrants
Generating	(Main/emergency) power
Heating	
Injecting	Chemicals, gas, water
Life Saving	Mob, lifeboat, basket, raft, escape chute
Lifting	Deck crane, personnel, goods
Logging	Well, production, mud
Manoeuvring	
Metering	Fiscal (gas/oil), CO_2
Pumping	Oil/gas export, bilge, seawater
Regenerating	Glycol
Scrubbing	
Separating	Production, test, cyclone- (water/sand/oil), centrifuge
Storing	Chemicals, potable water, lubrication/seal oil
Transferring	Oil/gas pipe (riser)

Table B.1 – Examples of Main Function descriptions

Examples displaying the MF HF2020 (along with others) with boundaries marked on a flow diagram, and the same MF with boundaries marked on the more detailed P&ID is shown on Figure B.1 and B.2

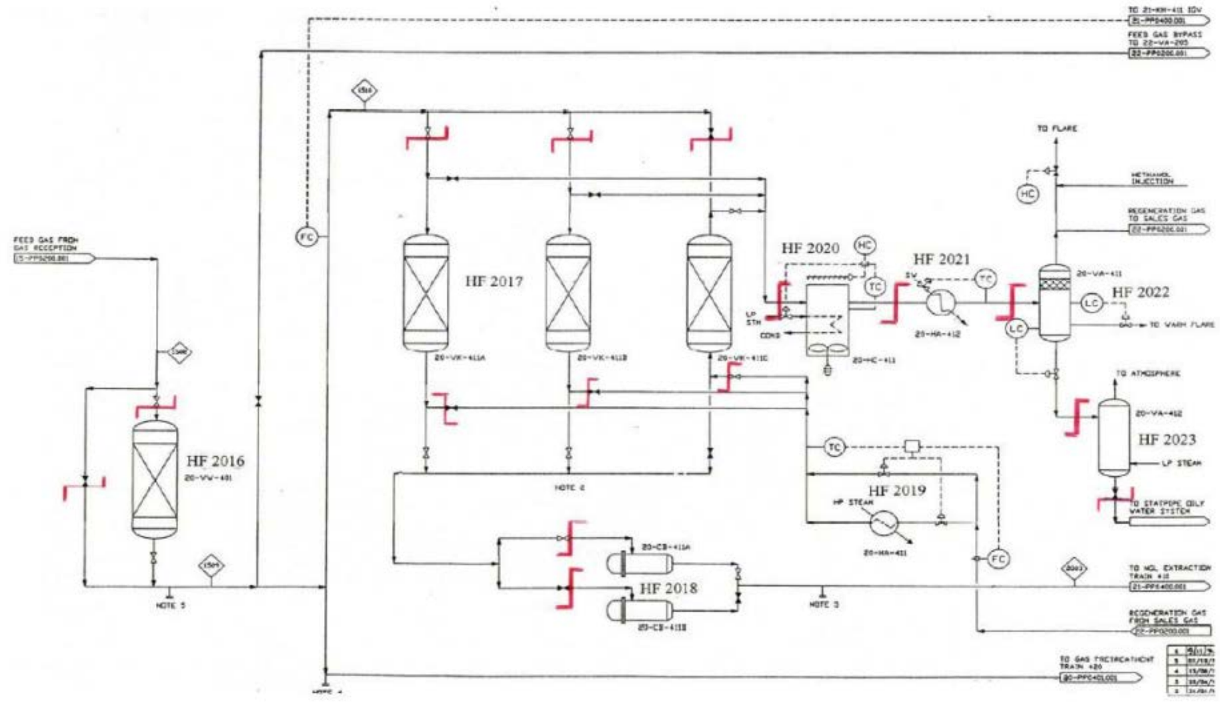


Figure B.1 - – Flow diagram showing borderlines between MFs (HF2017, HF2020)

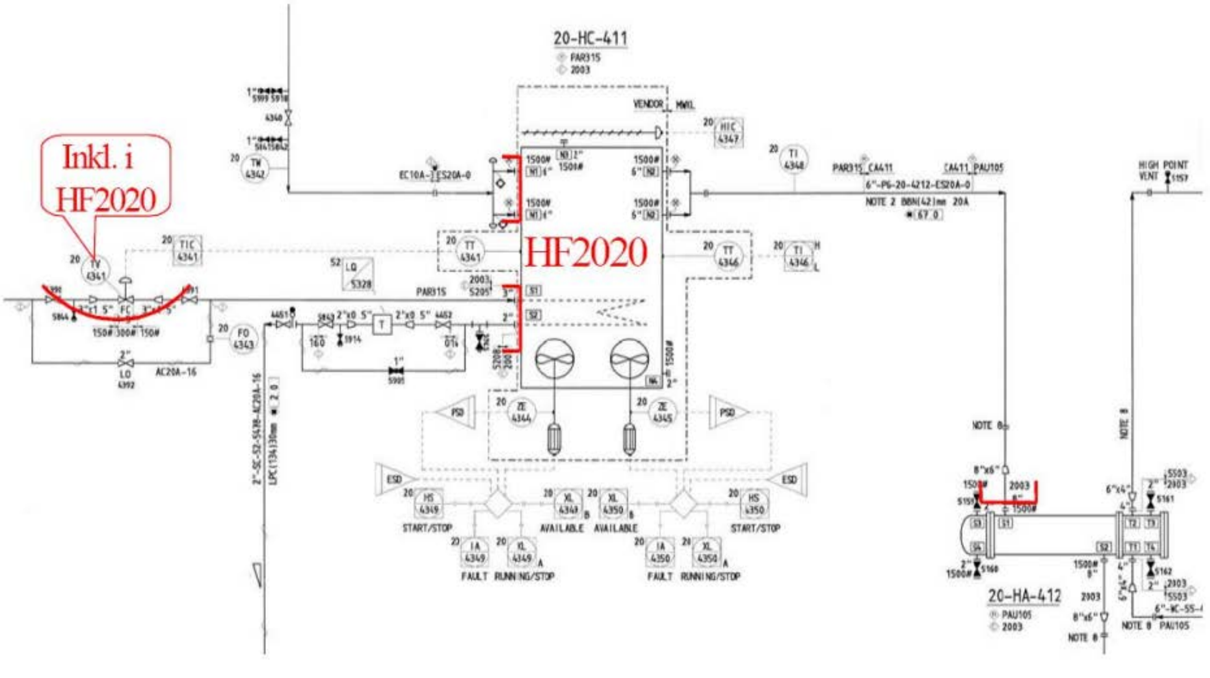


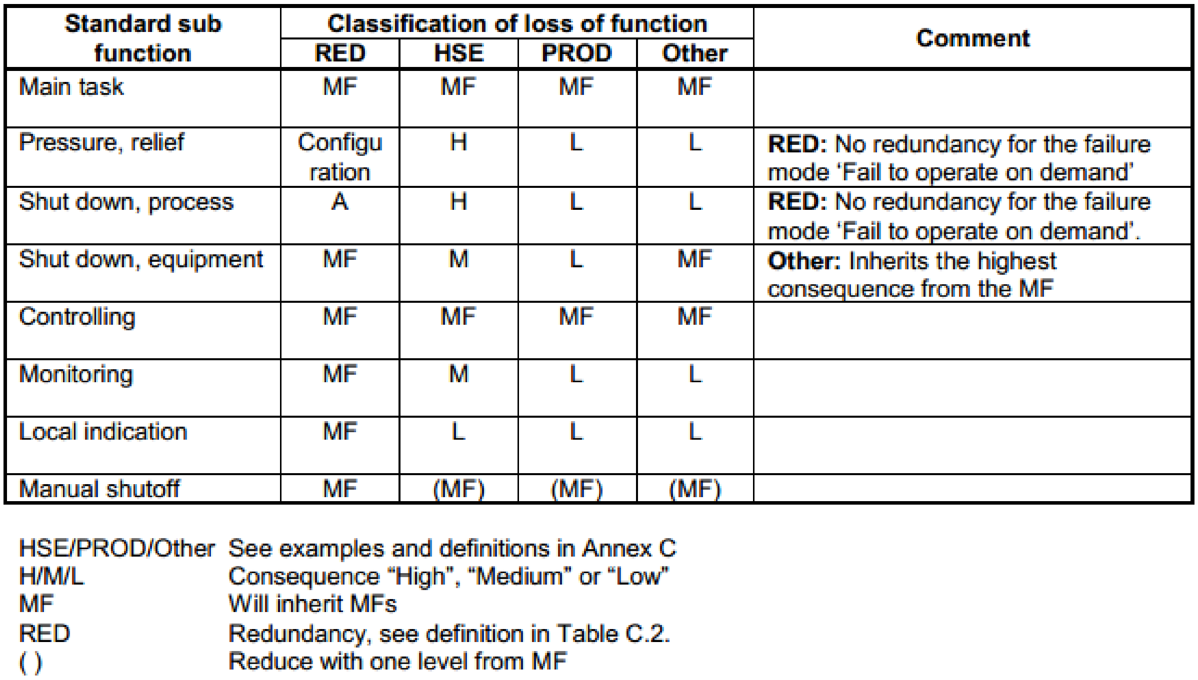
Figure B.2 – P&ID showing borderlines for MF HF2020

B.2 Simplifying consequence assessment of standard sub functions [56]

The consequence assessment of the MF already performed may be used as a basis for establishing the consequence assessment for the standard sub functions. It is recommended that these evaluations are verified by experienced process personnel and adjusted individually, if needed.

An example of guidelines for the standardized sub functions for one project is shown in Table B.1.

NOTE – ‟Other functions„ have to be assessed independently.

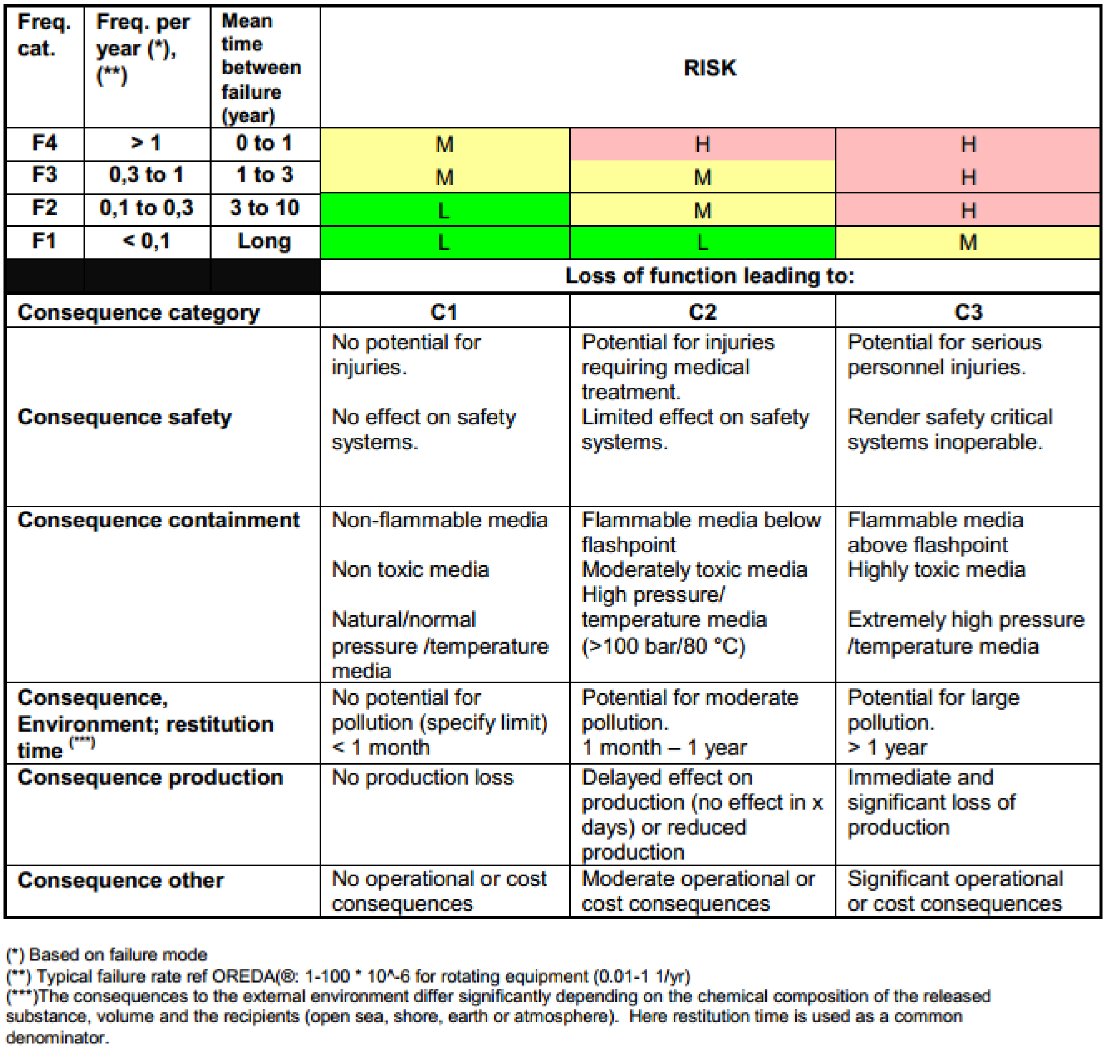


Standard sub function	**Classification of loss of function**				**Comment**
	RED	**HSE**	**PROD**	**Other**	
Main task	MF	MF	MF	MF	
Pressure, relief	Configuration	H	L	L	**RED:** No redundancy for the failure mode ‘Fail to operate on demand’
Shut down, process	A	H	L	L	**RED:** No redundancy for the failure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

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

Table B.2 - Project guideline example of consequence assessment of standardized sub functions, based on the MF consequence assessment

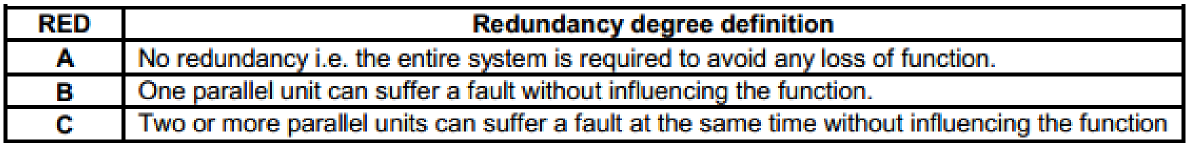
B.3 Risk matrix and redundancy definition



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

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

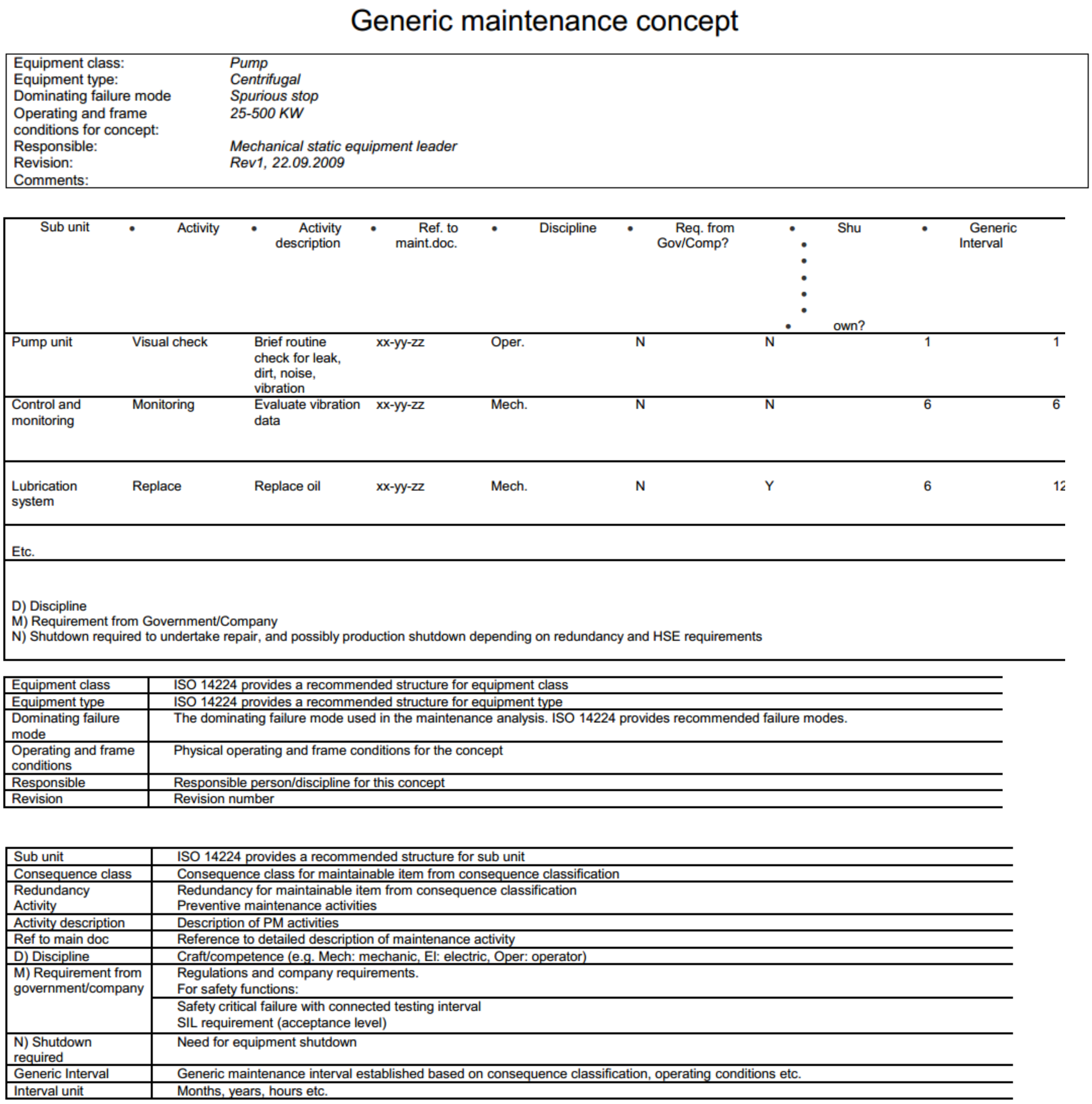
Table B.2 [57] - Example of risk matrix used for consequence classification and for decisions



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

Table B.3 [58] - Example of redundancy definitions

APENDIX C Generic Maintenance Concept (GMC)



Generic maintenance concept

Equipment class:	*Pump*
Equipment type:	*Centrifugal*
Dominating failure mode	*Spurious stop*
Operating and frame conditions for concept:	*25-500 KW*
Responsible:	*Mechanical static equipment leader*
Revision:	*Rev1, 22.09.2009*
Comments:	

Sub unit	Activity	Activity description	Ref. to maint.doc.	Discipline	Req. from Gov/Comp?	Shu own?	Generic Interval	
Pump unit	Visual check	Brief routine check for leak, dirt, noise, vibration	xx-yy-zz	Oper.	N	N	1	1
Control and monitoring	Monitoring	Evaluate vibration data	xx-yy-zz	Mech.	N	N	6	6
Lubrication system	Replace	Replace oil	xx-yy-zz	Mech.	N	Y	6	12
Etc.								

D) Discipline
M) Requirement from Government/Company
N) Shutdown required to undertake repair, and possibly production shutdown depending on redundancy and HSE requirements

Equipment class	ISO 14224 provides a recommended structure for equipment class
Equipment type	ISO 14224 provides a recommended structure for equipment type
Dominating failure mode	The dominating failure mode used in the maintenance analysis. ISO 14224 provides recommended failure modes.
Operating and frame conditions	Physical operating and frame conditions for the concept
Responsible	Responsible person/discipline for this concept
Revision	Revision number

Sub unit	ISO 14224 provides a recommended structure for sub unit
Consequence class	Consequence class for maintainable item from consequence classification
Redundancy	Redundancy for maintainable item from consequence classification
Activity	Preventive maintenance activities
Activity description	Description of PM activities
Ref to main doc	Reference to detailed description of maintenance activity
D) Discipline	Craft/competence (e.g. Mech: mechanic, El: electric, Oper: operator)
M) Requirement from government/company	Regulations and company requirements. For safety functions:
	Safety critical failure with connected testing interval SIL requirement (acceptance level)
N) Shutdown required	Need for equipment shutdown
Generic Interval	Generic maintenance interval established based on consequence classification, operating conditions etc.
Interval unit	Months, years, hours etc.

Figure C.1 [59] – NORSOKZz-008 Example of Generic Maintenance Concept

Appendix D – Failure Mode, Cause and Mechanism tables

D.2 Failure Modes

Failure Mode Code	Failure Mode Description	Examples
AIR	Abnormal instrument reading	False alarm, faulty instrument indication
BRD	Breakdown	Serious damage (seizure, breakage)
DEX	Defect EX barrier	Defect EX barrier
ELP	External leakage - Process medium	Oil, gas, condensate, water
ELU	External leakage - Utility medium	Lubricant, cooling water
ERO	Erratic output	Oscillating, hunting, instability
FCO	Failure to connect	Failure to connect
FDC	Failure to disconnect	Failure to disconnect when demanded
FOF	Faulty output frequency	Wrong/oscilliating frequency
FOV	Faulty output voltage	Wrong/unstable output voltage
FRO	Failure to rotate	Failure to rotate
FTC	Failure to close on demand	Doesn't close on demand
FTF	Failure to function on demand	Doesn't start on demand
FTI	Failure to function as intended	General operation failure
FTL	Failure to lock/unlock	Doesn't lock or unlock when demanded
FTO	Failure to open on demand	Failure to respond on signal/activation. Doesn't open on demand.
FTR	Failure to regulate	Failure to respond on signal/activation.
FTS	Failure to start on demand	Doesn't start on demand
HIO	High output	Overspeed/output above acceptance
IHT	Insufficient heat transfer	Cooling/heating below acceptance
INL	Internal leakage	Leakage internally of process or utility fluids
LBB	Loss of buoyancy	Loss of buoyancy in idle position (Code LOB in ISO14224)
LBP	Low oil supply pressure	Low oil supply pressure
LCP	Leakage in closed position	Leak through valve in closed position
LOA	Load drop	Load drop
LOB	Loss of barrier	One or more barriers against oil/gas escape lost
LOO	Low output	Delivery/output below acceptance. Performance below specifications.
LOP	Loss of performance	Loss of performance

LOR	Loss of redundancy	One or more redundant units not functioning (e.g. main/backup control system, runs on backup server).
MOF	Mooring failure	Mooring failure
NOI	Noise	Abnormal/excessive noise
NON	No immediate effect	No effect on function
NOO	No output	No output
OHE	Overheating	Overheating of machine parts, exhaust, cooling water
OTH	Other	Failure modes not covered in list
PDE	Parameter deviation	Monitored parameter exceeding limits, e.g. high/low alarm
PLU	Plugged / Choked	Partial or full flow restriction due to contamination, objects, wax, etc.
POD	Loss of function on both PODs	Both pods (on BOP) are not functioning as desired
POW	Insufficient power	Lack of or too low power supply
PTF	Power/signal transmission failure	Power/signal transmission failure
SER	Minor in-service problems	Loose items, discoloration, dirt
SET	Failure to set/retreive	Failed set/retreive operations
SHH	Spurious high alarm level	e.g. 60% of Lower Explosion Limit (LEL) on fire/gas detectors
SLL	Spurious low alarm level	e.g. 20% of Lower Explosion Limit (LEL) on fire/gas detectors
SLP	Slippage	Wire slippage
SPO	Spurious operation	Unexpected operation, fails to operate as demanded, (false alarm)
SPS	Spurious stop	Unexpected stop, fails to operate as intended
STD	Structural deficiency	Material damages (cracks, wear, fracture, corrosion, rupture)
STP	Failure to stop on demand	Doesn't stop on demand
UNK	Unknown	Too little information to define a failure mode
UST	Spurious stop	Unexpected shutdown
VIB	Vibration	Abnormal vibration
VLO	Very low output	e.g. reading between 11% Lower Explosion Limit (LEL) to 30% LEL upon gas test

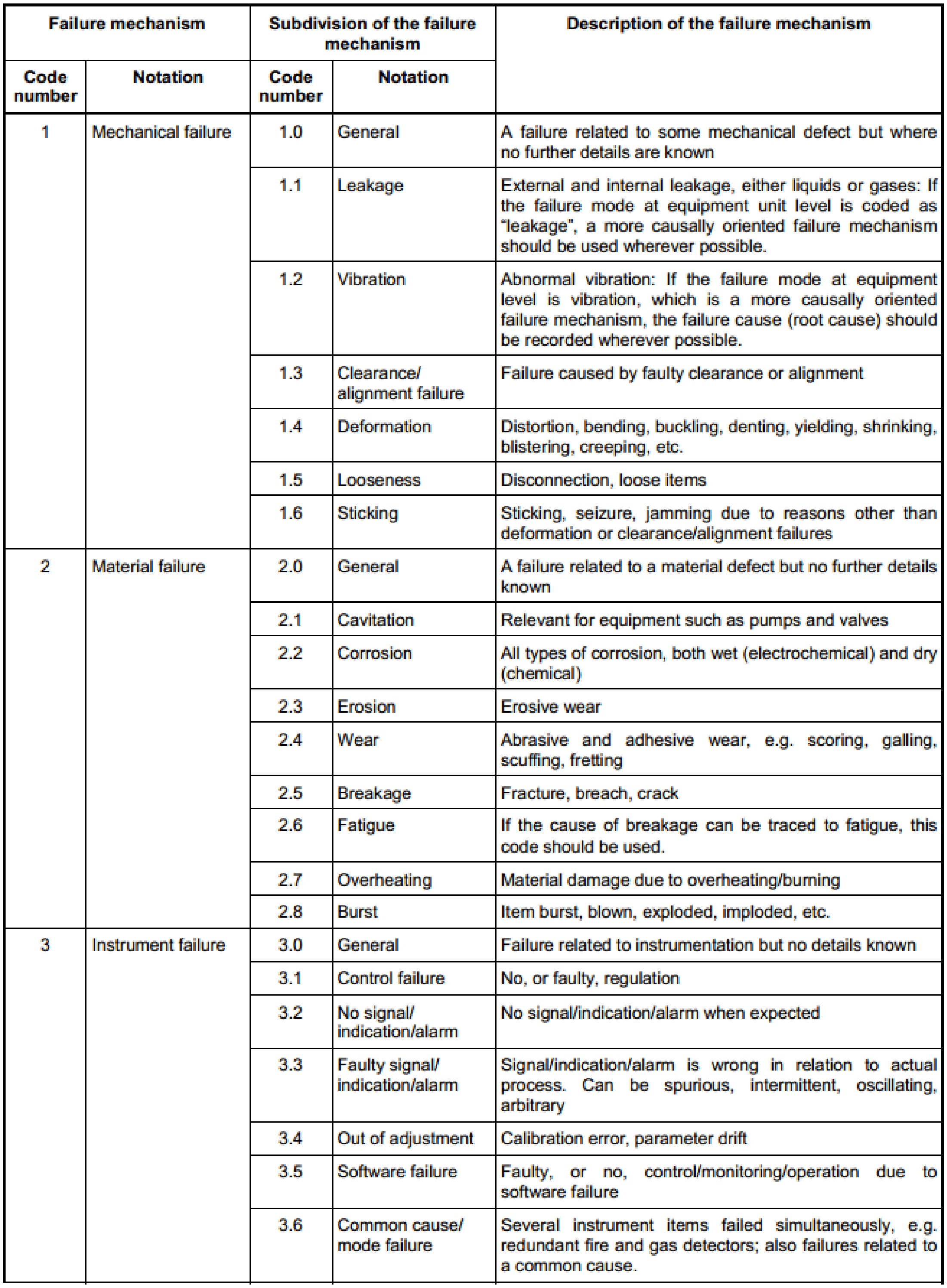
Table D.1 [60] *– Failure Modes*

D.2 Failure Causes

Failure Cause
Mechanical fracture
Axle fracture
Bearing fracture / fault
Mechanical damage / fault
Mechanical breakdown
Rupture / Crack
Loose fasteners / bolts
Defect spring
Defect clutch
Stuck in one position
Internal lekage
Leaking past piston
Faulty sealing/ membrane
Faulty pilot/ control system
Blocked / clogged
Undesired pressure build-up
Cavitation
Scaling
Wire/connection fracture/ fault
Faulty controller (internal)
Short circuit
Faulty component
Faulty circuit board
Erratic calibration
Set-point deviation
Magnetic conditions

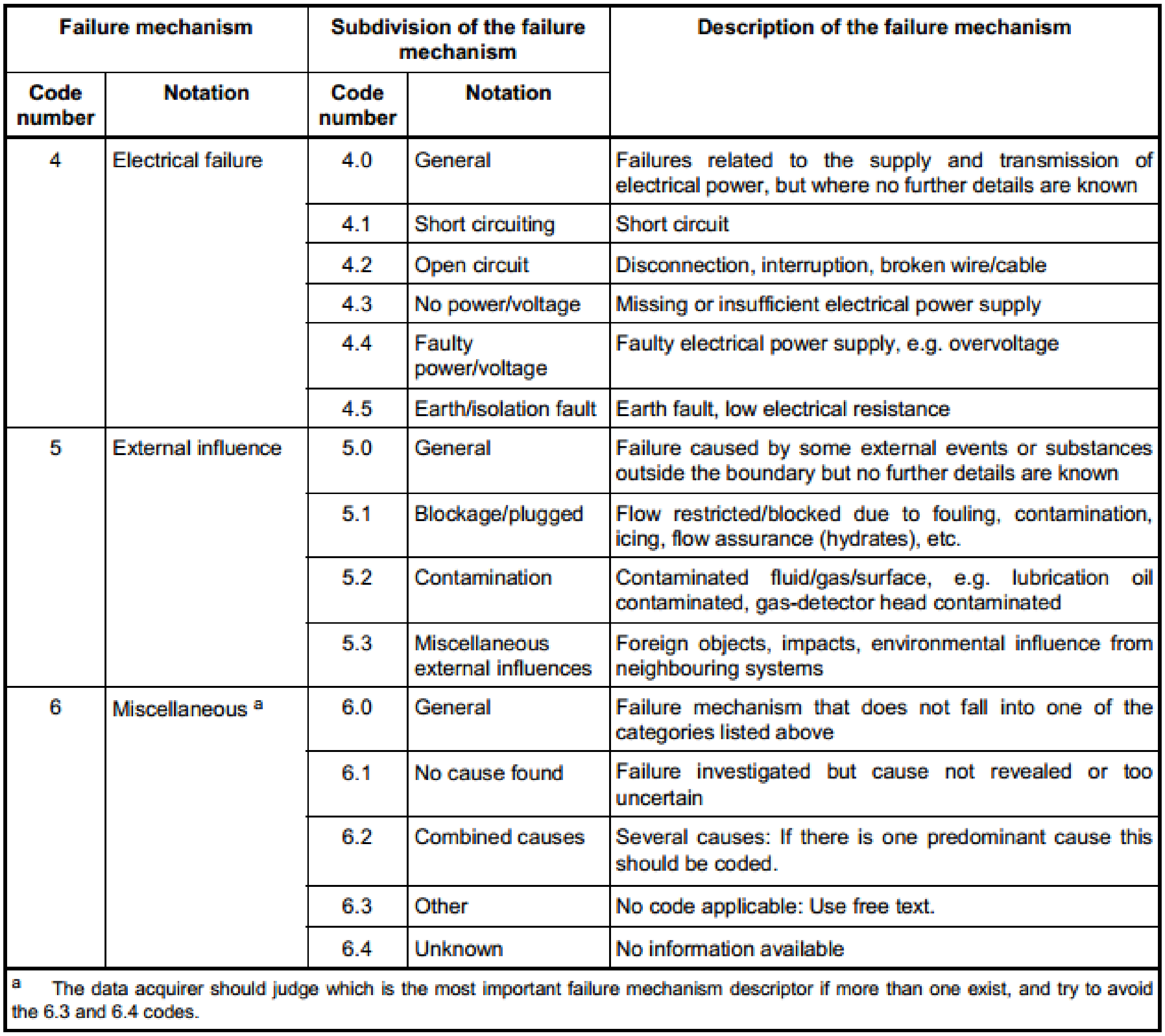
Table D.2 [61] *– Recommended failure causes*

D.3 Failure Mechanisms



Failure mechanism		Subdivision of the failure mechanism		Description of the failure mechanism
Code number	Notation	Code number	Notation	
1	Mechanical failure	1.0	General	A failure related to some mechanical defect but where no further details are known
		1.1	Leakage	External and internal leakage, either liquids or gases: If the failure mode at equipment unit level is coded as "leakage", a more causally oriented failure mechanism should be used wherever possible.
		1.2	Vibration	Abnormal vibration: If the failure mode at equipment level is vibration, which is a more causally oriented failure mechanism, the failure cause (root cause) should be recorded wherever possible.
		1.3	Clearance/ alignment failure	Failure caused by faulty clearance or alignment
		1.4	Deformation	Distortion, bending, buckling, denting, yielding, shrinking, blistering, creeping, etc.
		1.5	Looseness	Disconnection, loose items
		1.6	Sticking	Sticking, seizure, jamming due to reasons other than deformation or clearance/alignment failures
2	Material failure	2.0	General	A failure related to a material defect but no further details known
		2.1	Cavitation	Relevant for equipment such as pumps and valves
		2.2	Corrosion	All types of corrosion, both wet (electrochemical) and dry (chemical)
		2.3	Erosion	Erosive wear
		2.4	Wear	Abrasive and adhesive wear, e.g. scoring, galling, scuffing, fretting
		2.5	Breakage	Fracture, breach, crack
		2.6	Fatigue	If the cause of breakage can be traced to fatigue, this code should be used.
		2.7	Overheating	Material damage due to overheating/burning
		2.8	Burst	Item burst, blown, exploded, imploded, etc.
3	Instrument failure	3.0	General	Failure related to instrumentation but no details known
		3.1	Control failure	No, or faulty, regulation
		3.2	No signal/ indication/alarm	No signal/indication/alarm when expected
		3.3	Faulty signal/ indication/alarm	Signal/indication/alarm is wrong in relation to actual process. Can be spurious, intermittent, oscillating, arbitrary
		3.4	Out of adjustment	Calibration error, parameter drift
		3.5	Software failure	Faulty, or no, control/monitoring/operation due to software failure
		3.6	Common cause/ mode failure	Several instrument items failed simultaneously, e.g. redundant fire and gas detectors; also failures related to a common cause.

Table D.3 [62] *– Failure Mechanisms*



Failure mechanism		Subdivision of the failure mechanism		Description of the failure mechanism
Code number	Notation	Code number	Notation	
4	Electrical failure	4.0	General	Failures related to the supply and transmission of electrical power, but where no further details are known
		4.1	Short circuiting	Short circuit
		4.2	Open circuit	Disconnection, interruption, broken wire/cable
		4.3	No power/voltage	Missing or insufficient electrical power supply
		4.4	Faulty power/voltage	Faulty electrical power supply, e.g. overvoltage
		4.5	Earth/isolation fault	Earth fault, low electrical resistance
5	External influence	5.0	General	Failure caused by some external events or substances outside the boundary but no further details are known
		5.1	Blockage/plugged	Flow restricted/blocked due to fouling, contamination, icing, flow assurance (hydrates), etc.
		5.2	Contamination	Contaminated fluid/gas/surface, e.g. lubrication oil contaminated, gas-detector head contaminated
		5.3	Miscellaneous external influences	Foreign objects, impacts, environmental influence from neighbouring systems
6	Miscellaneous [a]	6.0	General	Failure mechanism that does not fall into one of the categories listed above
		6.1	No cause found	Failure investigated but cause not revealed or too uncertain
		6.2	Combined causes	Several causes: If there is one predominant cause this should be coded.
		6.3	Other	No code applicable: Use free text.
		6.4	Unknown	No information available

[a] The data acquirer should judge which is the most important failure mechanism descriptor if more than one exist, and try to avoid the 6.3 and 6.4 codes.

Table D.3 – (continued)