Title: # Condition Monitoring and Opportunity Maintenance in Offshore Operations	**Delivered:** 11.6.2010 **Availability:** Open
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Abstract:

This master thesis includes a discussion on technical and organisational aspects that should be considered if a shift to an OBM scheme is desired. Organisational aspects include agility and resilience. The technical aspects include Onshore Support Centre (OSC), prepositioning of spares and tools and standard operating procedures.

A Failure Mode Effects and Criticality Analysis (FMECA) have been performed on a simplified oil and gas process line. Based on this FMECA critical equipment was identified and CM methods have been suggested.

With the help of Genetic Algorithms (GA) six different OBM schemes have been proposed. The length of the opportunity was varied in the six different scenarios. The OBM model produced the lowest costs when the opportunity was long. The minimum costs increased as the length of the opportunity decreased.

Lastly areas where OBM may influence the logistics planning have been discussed and ways to mitigate these areas of impact have been suggested. Investment in a fully automated warehouse is one such measure.

Keyword:

Condition Monitoring, Opportunity Based Maintenance

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MASTER THESIS

for

M.Sc. student Jon Inge Kristoffersen

Department of Marine Technology

Spring 2010

Condition Monitoring and Opportunity Based Maintenance in Offshore Operations.

(Tilstandskontroll og opportunity basert vedlikehold for operasjoner offshore.)

Offshore operations are often organised with a division of responsibility between three major entities; drilling and well construction, reservoir and production management, and operations and maintenance. Offshore operations are dependent on a common logistics supply support, and utilisation of Condition Monitoring (CM) for critical equipment together with Opportunity Based Maintenance will enable more efficient utilisation of already limited logistics resources. Within the Center for Integrated Operations in the Petroleum Industry (IOCenter) there is an interest for developing CM methods together with collaborative maintenance and logistics planning schemes to improve the economic and HSE (Health, Safety and Environment) levels associated with offshore operations.

The M.Sc. thesis therefore includes the following tasks:

1. CM information and Opportunity Based Maintenance (OBM):
    a. Discuss technical and organisational aspects that need to be considered before equipment can be a candidate for OBM.
    b. Identify/propose ways to prioritise equipment considered for OBM.
    c. Describe how Genetic Algorithms (GA) can be used for optimal organisation of OBM.
2. CM methods:
    a. Describe functionality and layout of a topside O&G processing plant.
    b. Choose one main equipment or part of a system as a case, and perform a FMECA and RCM to identify critical components that should be considered for Condition Monitoring.
    c. Describe the applicable CM methods for the chosen equipment.
    d. Based on Point 1, propose an OBM scheme for the most critical components for the chosen equipment.

3. OBM and logistics planning:
    a. Describe how logistics planning relates to maintenance of O&G equipment today.
    b. Discuss how OBM will influence logistics and how OBM should be related to logistics planning.

The work should be carried out in close cooperation with MARINTEK and the IO Center program. Contact person at MARINTEK is Torgeir Brurok

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

Three paper copies of the thesis are required. A CD with complete report should also be delivered to the department. One of the paper copies and a CD should be delivered to MARINTEK by the candidate.

Starting date: 18th January 2010

Completion date: 11th June 2010

Handed in:

Trondheim 18th January 2010.

Magnus Rasmussen

Professor

Master Thesis

Condition Monitoring and Opportunity Based Maintenance in Offshore Operations

6/11/2010
NTNU
Jon Inge Kristoffersen

Preface

This report is the accumulated results of the work put into the Master Thesis course TMR 4905 at Norwegian University of Science and Technology (NTNU) in the spring of 2010. Working on this thesis has been challenging as well as rewarding.

People that deserve a thank you for their help, patience and time include Kenneth Juul and Tor – Ole Bang Steinsvik at ABB Oil, Gas and Petrochemicals department for Integrated Operations for information regarding HXAM and DriveMonitor. Research scientist at SINTEF MARINTEK and IO Centre contact Torgeir Brurok for his time and help. My advisor Professor Magnus Rasmussen at NTNU for his time, input and help when it was needed. Professor II Tom Anders Thorstensen at NTNU for his help and assistance with Manifer. Ralph Hansen and Ida Kastrud at TOTAL E&P Norge for their help and input regarding equipment types in analyses performed in this thesis. Lastly I would like to thank my fellow students for their help, patience and taking the time from their own thesis's to listen to some of my ideas.

Trondheim, 11.6.2010

Jon Inge Kristoffersen

Summary

In this M.Sc. thesis organisational and technical aspects related to the implementation of an Opportunity Based Maintenance (OBM) scheme for Oil and Gas facilities have been discussed. Organisational aspects of importance include agility and resilience. Agility can be understood as the ability of organisation to benefit from unexpected events. Resilience can be understood as damage control. Logistics support elements from the space industry can also be beneficial to implement in the logistics support of Oil and Gas facilities. Elements from the space industry include the implementation of Onshore Support Centre (OSC), prepositioning of spares and tools and standard procedures for critical equipment.

A simplified oil and gas production system has been used as a basis for a Failure Mode Effects and Criticality Analysis (FMECA), identifying critical components that should be considered for Condition Monitoring (CM). The results of the FMECA were that centrifugal compressors and shell and tube heat exchangers were ranked as critical equipment. Gate valves were also ranked as critical but have been neglected in the further analysis due to heat exchangers and compressors being more critical.

Several different CM methods have been described, emphasis have been put on detection method, application and words of warning when implementing the method. CM methods relevant to the critical equipment have also been discussed. For compressors the most relevant CM methods includes Vibration monitoring, Power and Load monitoring. In addition to these general methods special software applications are also available through different distributors. For monitoring heat exchangers internal inspection is most commonly used. The inspection interval can be determined by a Risk Based Inspection (RBI) scheme. When an inspection is due Eddy Current Testing (ECT) or gas leak tests can be used to determine diminishing pipe thickness in the tube section of the heat exchanger. HXAM supplied by ABB is also an interesting solution offering real time measurement of the performance of the heat exchangers.

Lastly how logistics planning is related to maintenance of oil and gas facilities today have been discussed. How a shift to OBM will impact the logistics planning have also been discussed. Means that can reduce any negative impact that a shift to OBM may have has also been discussed. One such measure is the investment in a fully automated warehouse. Also lessons that can be learnt from the logistics support in the space industry have been emphasised again.

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1 Introduction

This master thesis is the continuation of work done in the project thesis (Kristoffersen, 2009). The recommended areas for further study in the project thesis will form the basis for this master thesis. This master thesis is written as a part of project 3.2 within the Centre for Integrated Operations in the Petroleum Industry (IOCentre). Project 3.2 deals with condition monitoring of oil and gas facilities. The work has been carried out in cooperation with contact person at MARINTEK Torgeir Brurok.

Offshore operations are split between three major entities: drilling and well construction, reservoir and production management and operations and maintenance. All these entities rely on a common logistical supply support chain. Therefore better utilisation of Condition Monitoring (CM) for critical equipment along with Opportunity Based Maintenance (OBM) will enable a more efficient use of limited logistical recourses. This master thesis will focus on how CM can be used in OBM and logistics planning. For OBM planning and organisation Genetic Algorithms (GA) will be used. In order to identify critical equipment and CM methods a Failure Mode Effects and Criticality Analysis (FMECA) will be performed using the software tool Manifer. Areas where OBM may have an effect or impact will be discussed along with possible measures to reduce any negative impacts OBM may have on the regular operations.

2 CM information and Opportunity Based Maintenance (OBM)

Before equipment can be considered for Opportunity Based Maintenance (OBM) there are several technical and organisational aspects that need to be considered before OBM can successfully be implemented. In this section some of these aspects will be discussed, as well as how equipment can be prioritised in an OBM scheme. Lastly how Genetic Algorithms (GA) can be used to organise OBM will be discussed.

2.1 OBM Considerations

If OBM is to be implemented an organisation needs to be agile and resilient. But what does agile and resilient mean? Different sources have different points of view when it comes to defining agility and resilience when they talk about organisations. For more information about what different sources think agility and resilience mean for them I recommend (Værnes, 2008), in this report different points of view are presented. However no single definition of what agility and resilience is can be found, instead what agility and resilience mean in different contexts is presented. Therefore the definition of agility and resilience presented in (Wahl, Sleire, Brurok, & Asbjørnslett, 2008) will be used instead. In (Wahl, Sleire, Brurok, & Asbjørnslett, 2008) agility is said to be the ability to respond to changing environment and be able to benefit from the change. Resilience is described as the ability of an organisation to respond, monitor and anticipate threats to normal operations. These two organisational aspects are crucial if OBM is to be utilised by the organisation. The organisation needs to be agile enough to be able to utilise an opportunity to its benefit and thus generate added value. In addition to agility the organisation needs to be resilient. Resilience can be understood as the organisations ability to not be crippled when something changes. An unexpected event should not mean that the other activities of the organisation are affected. Resilience can therefore be seen as a form of damage control.

In space operations the culture is focused on maximising the use of scarce resources e.g. logistics availability. While in oil and gas operations the focus is on fixing failures. Should OBM be implemented in oil and gas operations a shift towards the view inhabited by space operations seems necessary. Another lesson that can be learnt from space operation is the development of standard operating procedures for critical equipment.

Another element that will help the organisation when implementing OBM is the establishment of Operations Support Centres (OSC). The objective of the OSC is to manage established plans and handle any plan deviations. In the OSC relevant information is traded across disciplines such as drilling, production management, maintenance and logistics. The goal of the OSC is to support the offshore team in problem solving when deviations occur. For the OSC to function properly it needs to be composed of people from all the relevant disciplines e.g. logistics, maintenance, drilling etc. either by being there in person or through the use of ICT (Information and Communication Technology).

The development of standard operating procedures for critical equipment along with prepositioned spares and general crew training will also help in the implementation of OBM. If storage capacity is limited at the facility or at the supply base then supplier retention can be used to guarantee spare availability. The idea behind supplier retention is that the supplier guarantees access to spares within a defined response time.

On the technical side there are several different aspects that need to be considered before equipment can be a candidate for OBM. One such factor is the availability of spare parts or tools needed to perform whatever maintenance task is considered for execution during an opportunity. If spares and tools are not readily available other maintenance tasks should be considered instead, as it is uncertain how long the opportunity will be and how much time it will take to transport spares and tools to the facility. Should specialists be required to perform maintenance the equipment should not be considered for OBM. This is because opportunities will for the most part occur at random and therefore specialists are not likely readily available at the facility or at a nearby facility either offshore or onshore. If specialists can be located in short time and the maintenance job is minor the specialists can guide offshore personnel from the OSC. Offshore personnel should be able to handle most minor maintenance jobs, it is therefore convenient to only consider minor maintenance jobs when talking about OBM.

Should there be a need for spare parts, tools or people to do maintenance on the equipment and these are not present at the facility then the need for transport arise. The need for transport capacity is a third factor to consider before equipment should be considered a candidate for OBM. Important logistical aspects to consider is the availability of transport capacity and the logistics lead time.

If scaffolding is needed to reach the equipment or the equipment is in hard to reach places other equipment should be considered for short opportunity windows. If the window of opportunity is longer or expected to be longer in duration equipment that requires scaffolding or similar rigging may be a candidate for maintenance.

If a failure is the cause of a maintenance opportunity and an OBM strategy have been implemented there is a risk that a lot of time will be spent on identifying ways to exploit the opportunity, and that the event that triggered the opportunity will be neglected leading to more downtime. To counter this it would be beneficial to divide the maintenance planners into two teams. The first team should work on fixing the failure that triggered the opportunity while the second team works on finding ways to exploit the opportunity. This will ensure that the maintenance planners keep their priorities on both sides and that downtime costs are kept as low as possible.

2.2 Prioritising equipment for OBM

In the aircraft industry components are changed after a set number of running hours. This strategy makes it easy to know when a certain component should be changed next. This replacement strategy also makes it easy to organise and prioritise equipment when it comes to OBM. This is not the case when it comes to equipment used in oil and gas facilities. Therefore there are several challenges when it comes to prioritising equipment considered for OBM.

One of those challenges is that knowing the length of the opportunity is almost impossible. How long the window of opportunity is will also affect what can be maintained during the opportunity. Because of this fact most of the literature dealing with opportunity based maintenance only considers smaller maintenance jobs for opportunity maintenance, while allocating larger overhauls to large maintenance campaigns and annual shutdowns. In theory there is no obstacle in scheduling large maintenance jobs to opportunities, but it practice it may be difficult to do. If the opportunities to do maintenance are short large and time consuming maintenance tasks will most likely be deferred to a later time. If this is repeated enough times the item will eventually fail causing expensive downtime. It is possible to schedule large maintenance jobs to periods in time when it is known that the facility will not be operational such as well intervention and maintenance. During such a period it should also be possible to do maintenance on topside equipment and not only downhole maintenance. Major maintenance jobs on equipment should therefore be given a low priority if it is expected that the window of opportunity is short. Such maintenance jobs and equipment requiring long time for maintenance should be given a high priority if a long window of opportunity is expected.

Equipment located in places that require scaffolding should also not be considered for small windows of opportunity. This is due to the fact that assembling and disassembling the scaffolding is a time consuming task and will eat away the total amount of time available during the opportunity. Time spent on rigging could be spent performing other minor maintenance jobs elsewhere in the facility. Equipment located in places that proves to be hard to reach may be considered for longer opportunities. The same reasoning can be used for prioritising equipment in hard to reach places as it was for minor and major maintenance jobs. That is equipment in hard to reach places is given a low priority if the opportunity is expected to be short and a high priority if the opportunity is expected to be longer.

The failure rate of the equipment will play a role in how often maintenance has to be executed. Therefore it would be prudent to use failure data from OREDA (SINTEF Industrial Management, 2002) if own failure data is unavailable. In some cases the data presented in OREDA may be on the conservative side, therefore some corrections can be made to the failure data. If data from OREDA or own failure data is used the same principle of prioritising equipment applies. Equipment with a high Mean Time to Failure (MTTR) should be given a low priority if expected length of opportunity is short and high priority if opportunity is expected to be long. The Mean Time Between Maintenance (MTBM) and Mean Time Between Failure (MTBF) of different equipment can also be used to prioritise equipment considered for OBM. If records are kept on when the last replacement or maintenance action was completed these records can be used as an indication of when the equipment is likely to fail next. Equipment that has run for a long time will have a shorter Remaining Useful Life (RUL) than equipment that was just installed. Therefore RUL can be used for prioritising equipment for OBM. Equipment that have little RUL left should be considered for maintenance during an opportunity compared to equipment that have a lot of RUL left. Estimating RUL is a large field on its own and has been omitted from this thesis. For more information about how RUL can be estimated I recommend using the internet a lot of information on the field is available there. Figure 1 illustrates three possible RUL predictions for one unit nearing the end of its life.

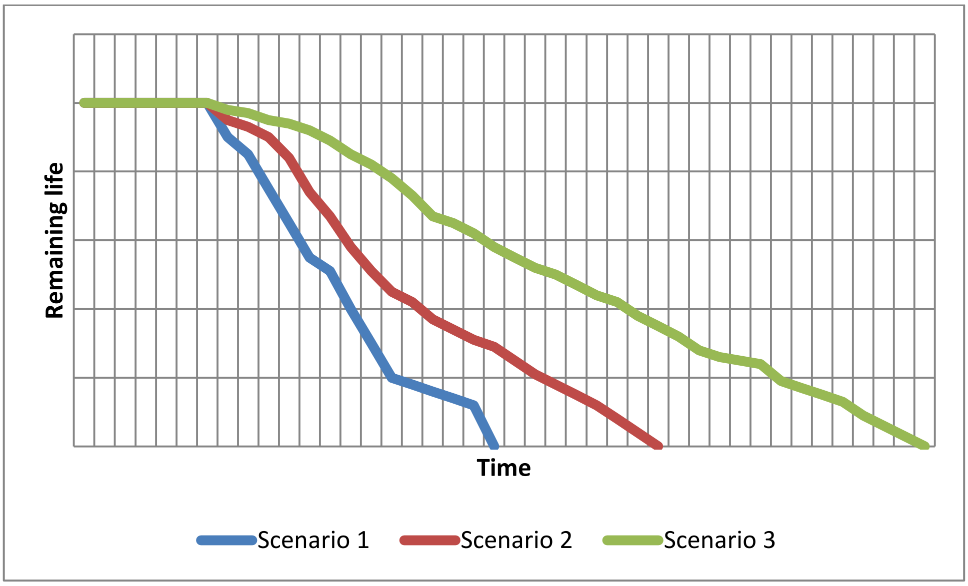


Figure 1 - Example of RUL predictions

From OREDA (SINTEF Industrial Management, 2002) the definitions of different failure modes are obtained. A Critical failure will cause the immediate and complete loss of the systems capability to provide its output. A Degraded failure is not critical, but it prevents the system from provided the specified output. Given enough time a degraded failure may develop into a critical failure. Degraded failures are usually gradual or partial. An Incipient failure is a failure that does not immediately cause loss of system output. If an incipient failure is left unattended it may develop into either a degraded or critical failure. The last failure type defined in OREDA is the Unknown failure. An Unknown failure is a failure where the severity could not be determined or was not recorded. In prioritising equipment for OBM the degraded and incipient failures are the most interesting, since the critical failure triggers a corrective maintenance action. Unknown failures are also not considered because their impact could not be determined. It can be expected that unknown failures if left unattended will develop to one of the other failure modes.

To summarise a flowchart has been developed outlining the aspects needed to be considered before equipment can be considered for OBM as well as prioritising equipment for OBM. The flowchart can be seen in Figure 2. Consider an equipment of type A that is considered for maintenance the next time an opportunity arises. The first thing that should be considered is the RUL of A. If it is expected that A has a long RUL left then it would be better to consider equipment that have a short RUL left e.g. equipment of type B. If A has short RUL then the location of A should be considered. If A is located in a place where no scaffolding or only minor scaffolding is required then the size of the planned maintenance activity will play a role. Minor maintenance jobs that require no or only minor scaffolding are ok to consider for OBM. If the maintenance job is a major overhaul, but limited scaffolding is required then the length of the opportunity will play a role. With a long window of opportunity a major maintenance job can be considered for OBM. A short window of opportunity combined with a major maintenance job and no scaffolding would disqualify the equipment from OBM. If major scaffolding is required for the maintenance job the size of the maintenance job needs to be considered. A minor job will be ok for OBM while a major job will require the length of the opportunity to be considered as well. If the opportunity is expected to be long then the equipment can be a candidate for OBM. A short opportunity will disqualify the equipment from OBM.

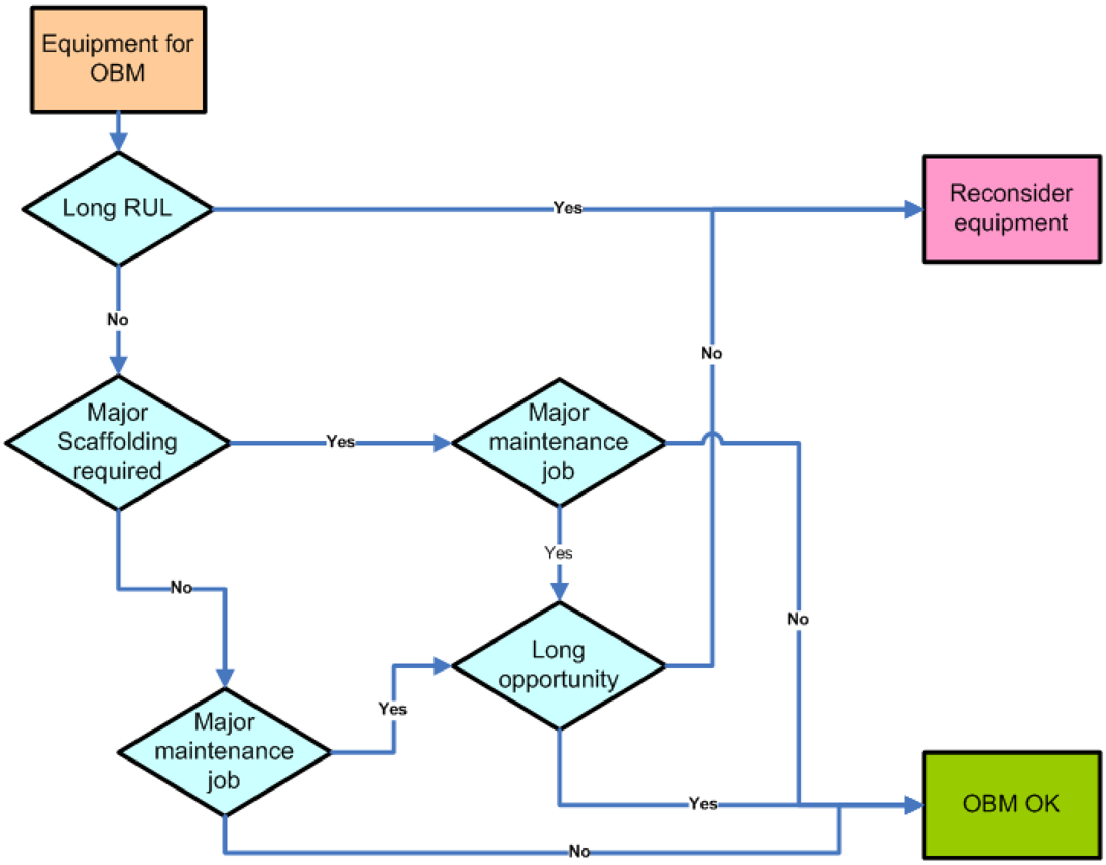


Figure 2 - OBM flowchart

2.3 Organising OBM with GA

In (Saranga, 2004) GA is suggested for OBM planning. In this section ideas presented in this article will be further developed and adapted for oil and gas facilities and equipment. First an introduction to GA will be given. For more detailed information about GA I recommend (Wikipedia, 2010).

GA is a subset of Evolutionary Algorithms, and is a search technique used to find exact or approximate solutions to optimisation problems. In order to arrive at a new solution GA use inheritance, mutation, selection and crossover. All these techniques are inspired by evolutionary biology. The first step in setting up an optimisation problem using GA is to create a first generation consisting of chromosomes. Each chromosome corresponds to a variable in the solution space. The next step is to pass a random selection of the initial population through the fitness function. The fitness function can be seen as the objective function in other optimisation problems. The individuals with the best fitness are selected for reproduction according to the concept of survival of the fittest, to see if a better solution can be obtained. To create new generations GA use three processes:

1) Reproduction, here selected individuals of one generation are randomly selected for mating. The selection is biased towards best fitted, only decided by the fitness function i.e. survival of the fittest.
2) Crossover, here individuals are mated randomly. Not to be confused with reproduction where characteristics are copied. This mating process creates new characteristics in the next generation. Information is exchanged in blocks. See Figure 3.

3) Mutation plays only a secondary role in the process. Using mutation new characteristics can be introduced in the next generation or lost characteristics can be reintroduced. Will avoid being stuck in local optima.

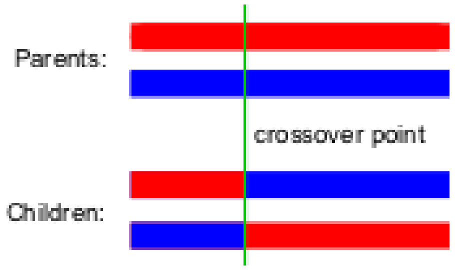


Figure 3 - Crossover

The GA process is illustrated in Figure 4. It starts with a parent generation. This generation is then evaluated against the fitness function, those individuals with the best fitness is selected for breeding. The offspring from the first generation replaces the individuals of the first generation who had the worst fit. Then the second generation is evaluated and the process repeats. The process can be set to end after a set number of generations, when the algorithm does not produce offspring with a better fit than the parent generation, when budgeted time/money have been reached or by manual inspection. A combination of the above mentioned conditions is also possible.

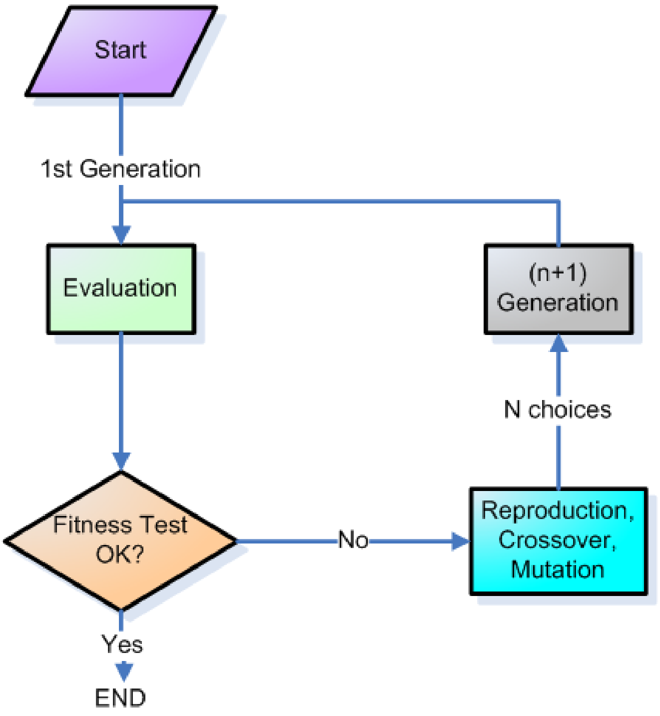


Figure 4 - GA flow

In OBM planning GA can be used to find the optimal organisation. Depending on the chosen fitness function different optimisations can be found. According to (Rasmussen, Driftsteknikk Grunnkurs, 2003) any maintenance strategy must satisfy two basic demands:

- Applicability
- Cost effectiveness

Applicability means that preventive maintenance prevents all failures or reduces the amount of failures. Cost effectiveness relates to the consequences of failures and the costs associated with doing maintenance to prevent failure. Any OBM scheme that is produced by GA simulations should therefore satisfy these two demands. Based on the prioritisation suggested in chapter 2.2 All in all 17 parameters have been identified that will influence the OBM organisation. These parameters can be divided into two different groups. The first group is associated with characteristics of the equipment such as name, failure mode, fault type, criticality of failure, MTTR etc. The second group are the costs related to both the equipment and the equipment characteristics. These costs include costs of logistic, work, downtime, risk, RUL, scaffolding etc. What is included in the costs will be discussed more thoroughly in section 3.4.1.

3 Oil and gas production and CM methods

The flow from the well head may contain crude oil, gas, condensates, water as well as other contaminants. Before the hydrocarbons can be sold they need to be processed. This processing is done by the topside processing equipment. The layout of one such topside processing plant along with a Failure Mode Effect and Criticality Analysis (FMECA) and some simulations using GA will be done in this section.

3.1 System layout

A simplified model of a topside processing plant is shown in Figure 5 in this figure all of the metering equipment and much of the control equipment have been omitted. Some equipment that may be present in other processing facilities has been omitted from this overview. One such example is the hydrocyclone used for water treatment. Differentiating between different types of valves in the process is also something that has not been done to a large degree. In Figure 5 a red line represents gas flow, a yellow line represents two phase flow, the black line is oil flow and the blue line is produced water.

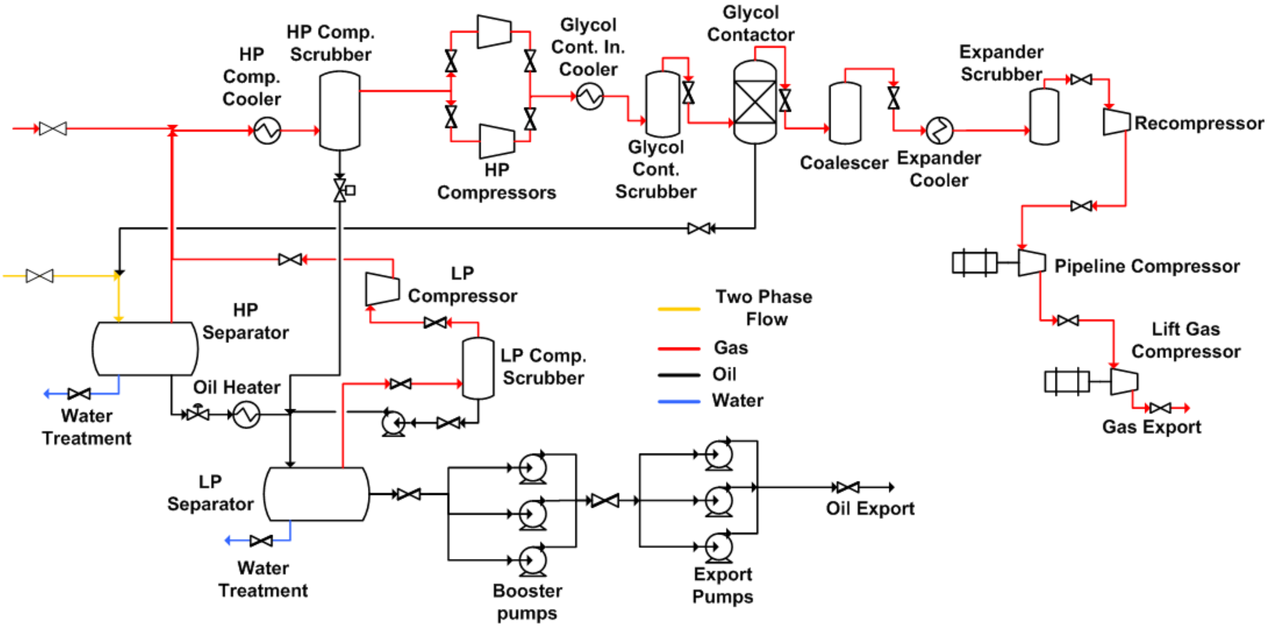


Figure 5 - System layout

The process shown in Figure 5 does not include the water treatment plant. The process only exports oil and gas.

3.1.1 Separators

The purpose of the separator is to split the two phase flow from the well into more desirable parts such as oil, gas and condensates. The production choke reduces the pressure of the flow coming into the separator to about 3 - 5 MPa (Devold, 2009). Pressure is often reduced in several stages to avoid flash vaporisation that may cause instability and safety hazards. Figure 6 show a cross-sectional view of a separator. The retention period is typically 5 minutes. This allows the gas to bubble out, water to sink to the bottom and oil to be extracted in the middle. At the inlet the separator has a slug catcher used to catch large gas bubbles or liquid plugs. The slug catcher should not make the flow through the separator laminar, as some turbulence is desired to speed up the separation of gas. At the end of the separator there is a level barrier to keep water and oil from mixing. Vortex breakers are installed at the outlets to prevent disturbances in the liquid. The vortex breaker is basically a flange trap that prevents vortices from dragging oil into the water outlet and vice versa. A demister is installed before the gas outlet to ensure that liquid droplets are not tapped off at the gas outlet. First stage separators or high pressure separators can depending on the water cut in the incoming flow reduce the water content downstream of the separator to about 5 %.

The second stage separator or low pressure separator operates around a pressure of about 1 MPa, and is similar in design to the first stage separator. The second stage separator may also be connected to low pressure manifolds. In Figure 5 an oil heater is located between the first and second separator. Heating the flow from the first stage separator will help in extracting water from the flow if the water cut is high and the temperature is low. The oil heater is typically a shell and tube heat exchanger where the oil passes through the tubes and the heating medium is in the shell. Heat exchangers and heat exchanger types will be discussed later.

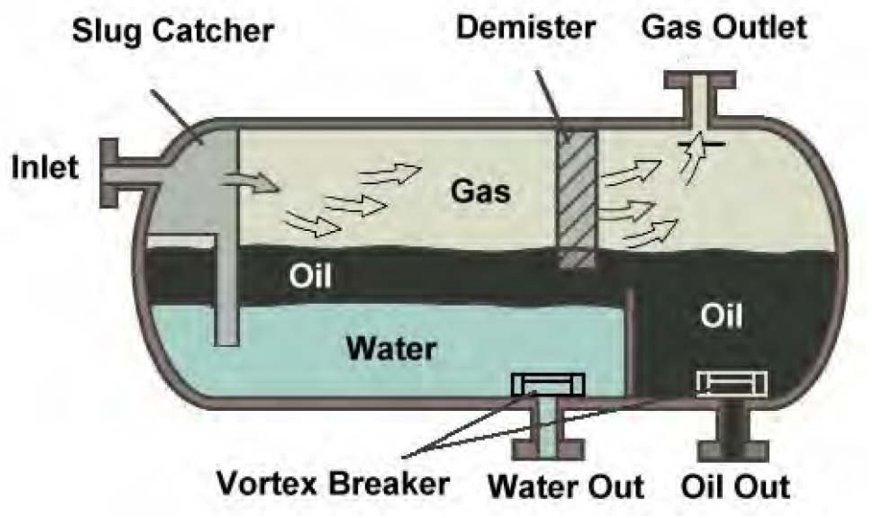


Figure 6 – Separator (Devold, 2009)

3.1.2 Coalescer

A coalescer is used to remove the final remains of water/liquid in the oil and gas. The colaescer uses internal electrodes to create an electric field that breaks the surface bonds between the oil/gas and the water/liquid in the oil water emulsion. With a coalescer the water/liquid content can be brought down to below 0.1% according to (Devold, 2009). The grid layout and field intensity of the coalescer varies depending on the manufacturer and oil types.

3.1.3 Heat exchangers

In order for the compressors to operate as efficiently as possible the temperature should be as low as possible. Lowering the temperature of the gas is done using heat exchangers. In heat exchangers a hot and a cold medium passes each other separated by plates. There are two types of heat exchangers that are most commonly used in the oil and gas industry. These are the shell and tube heat exchangers and the plate heat exchangers. Plate exchangers consist of several plates where the gas and cooling medium pass between alternating plates in opposing directions. A principal view is given in Figure 7. In a shell and tube exchanger the gas passes through tubes and the cooling medium is contained by the outer shell. The cooling medium is commonly water with chemical additives that inhibits corrosion. Figure 8 shows an example of a shell and tube heat exchanger.

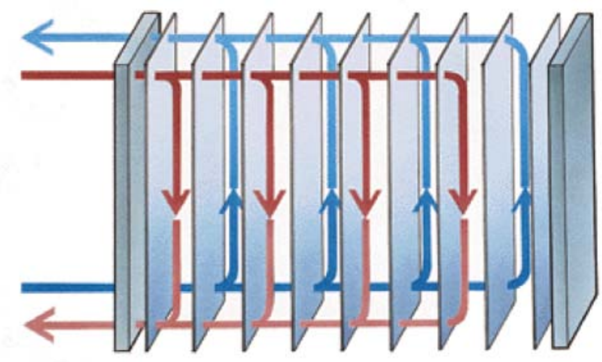


Figure 7 - Plate heat exchanger (Devold, 2009)

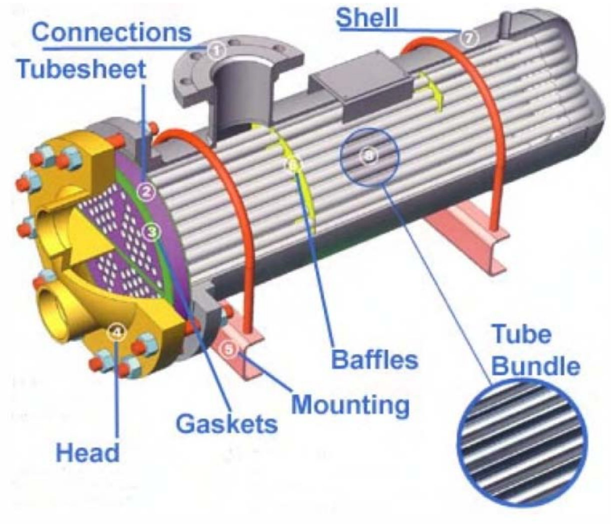


Figure 8 - Shell and tube heat exchanger (Devold, 2009)

3.1.4 Scrubbers

Should droplets of oil or other liquids enter the compressor the fast rotating blades will be damaged by erosion. To prevent this gas is passed through a scrubber that removes the droplets. Many different designs are available but the most common type uses Triethylene Glycol (TEG). A principal drawing of a TEG scrubber is shown in Figure 9. The gas enters the scrubber at the bottom and passes through several layers of glycol before exiting at the top. The detail in Figure 9 shows the gas trap that forces the gas to bubble through each level of the scrubber. Glycol is pumped from the holding tank and into the top of the scrubber. As the glycol overflows the gas trap it spills down to the next level absorbing liquid from the gas in the process. Rich glycol is then recycled in the reboiler.

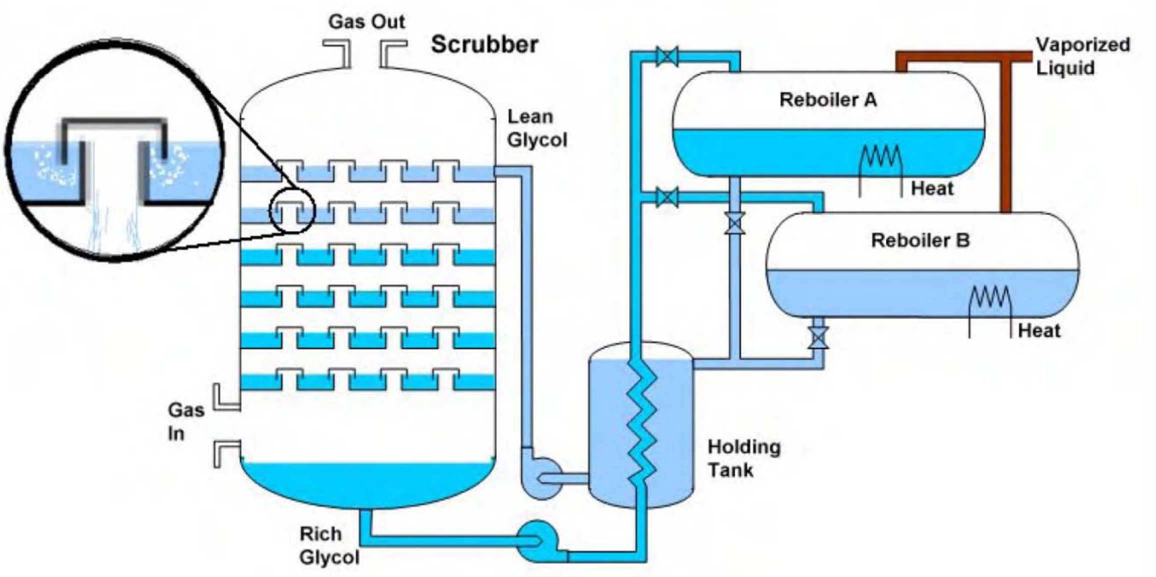


Figure 9 - TEG scrubber (Devold, 2009)

3.1.5 Compressors

In an oil and gas facility compressors are used for compressing gas. Depending on the usage different types of compressors can be used. For high pressure gas injection and where a low capacity is needed reciprocating compressors is mostly used. For gathering of natural gas screw compressors are mostly used. Axial compressors are used for air compression and LNG (Liquefied Natural Gas) cooling. On large installations centrifugal compressors with between three and ten radial wheels are used according to (Devold, 2009).

On an oil and gas facility one compressor type and size will not be capable of covering the full pressure range effectively. Pressures required on oil and gas facilities will range from atmospheric pressure to 20 MPa and higher. Therefore compression is divided into several stages to improve maintainability as well as availability.

3.1.6 Valves and other control equipment

In order to avoid undesired events and production shutdowns valves and other control equipment is used to monitor and control the flow of hydrocarbons through the facility. Valves are used to restrict or stop the flow of hydrocarbons from one part of the facility to another. Different measuring equipment is located throughout the plant to monitor temperature, pressure, vibrations and flow. These attributes when monitored and presented to operators will help in decision making and alert operators if deviations from normal operation is detected.

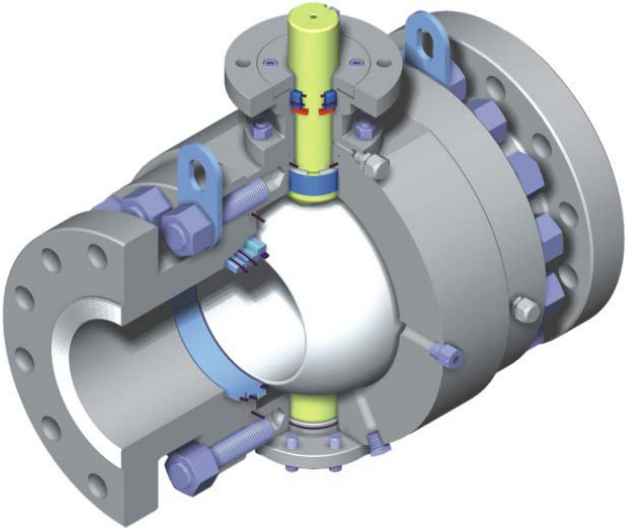


Figure 10 - Ball valve

Devices that are installed on oil and gas facilities need to be protected from becoming ignition sources if a hydrocarbon leak should occur. Devices are classified accordingly to what kind of protection it has from becoming an ignition source e.g. Ex.p. if the device is safe by pressurisation. Also all the different areas of the facility are mapped into different zones depending on the explosion hazard. The zone ranking ranges from zone 0 to zone 2 and safe area. Zone 0 is defined as an area where hydrocarbons will be present such as inside pipes and vessels. Zone 1 is an area where there is a high risk of hydrocarbons being present. While zone 2 is an area where there is a low risk of hydrocarbons being present. The safe zone is typically the living quarters where hydrocarbons are not present.

3.2 FMECA

The Failure Mode Effects and Criticality Analysis (FMECA) is a systematic approach used to analyse systems, how they fail and the consequences these failures will have on the system on a component level. The first step of any risk analysis technique is describing the system that is going to be analysed. The following six steps summarises the general approach in performing a FMECA:

1) Describe components
2) Describe possible failures and failure modes
3) Describe failure effects of each failure mode
4) Ranking failure effects in terms of frequency, severity and specifying reliability data.
5) Specifying methods for detection.
6) Describe how unwanted effects can be reduced and eliminated

The FMECA is a part of the Reliability Centred Maintenance (RCM) concept. The RCM concept is a method used for establishing cost effective maintenance plans. The RCM concept can be deployed in any phase of the life cycle of a system or facility. In the design phase RCM analysis will for example help in removing design alternatives that require a lot of preventive maintenance. In the operational phase a RCM analysis can be used to review the maintenance plans that already in place. The RCM process is illustrated in Figure 11. As Figure 11 illustrates there are a lot of different inputs and outputs form the different phases. The end result from the process is maintenance packages consisting of jobs grouped in a cost effective manner.

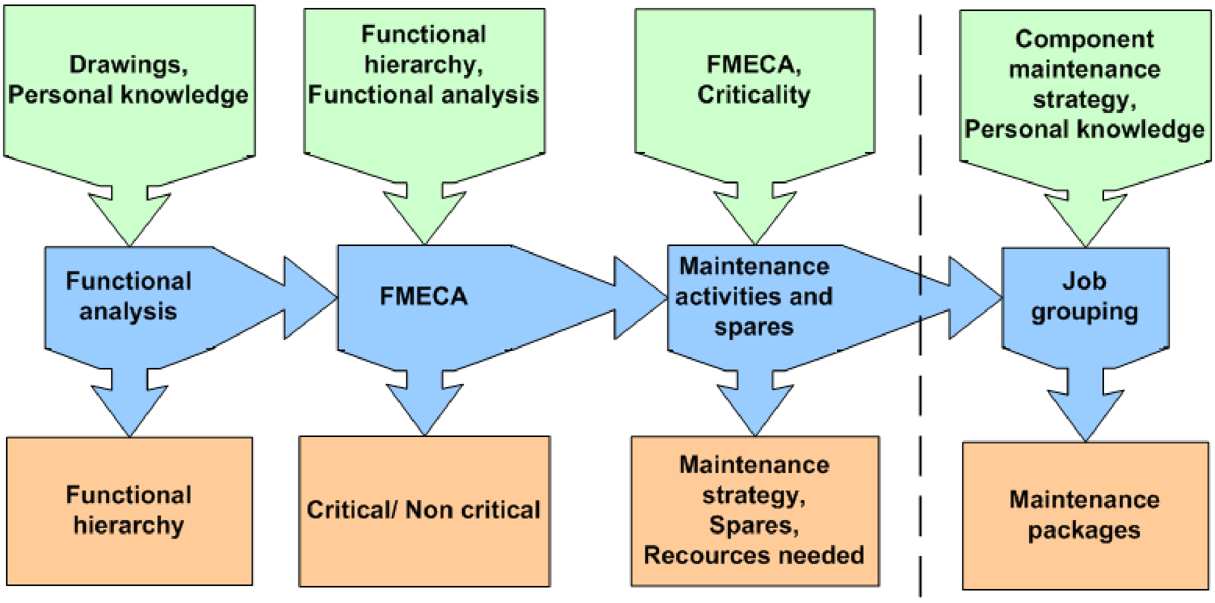


Figure 11 - RCM process

3.2.1 Functional hierarchy

When describing the components it is useful to create a functional hierarchy to get a better idea of what function a component serves and how it interacts with its environment as well as what might happen should the component fail. The functional hierarchy is a logical representation of the system as a whole where equipment is tied to a specific function. It clearly shows what functions that are dependent on certain equipment. A failure in any component may in turn result in reduced performance of the associated function or in a worst case scenario total loss of the function. A functional hierarchy for the oil and gas production system shown in Figure 5 has been developed and can be seen in Figure 12. In Figure 12 the main function can be seen in green, while 1st stage sub functions are in blue and 2nd stage sub functions are in yellow. The associated equipment is shown in pink.

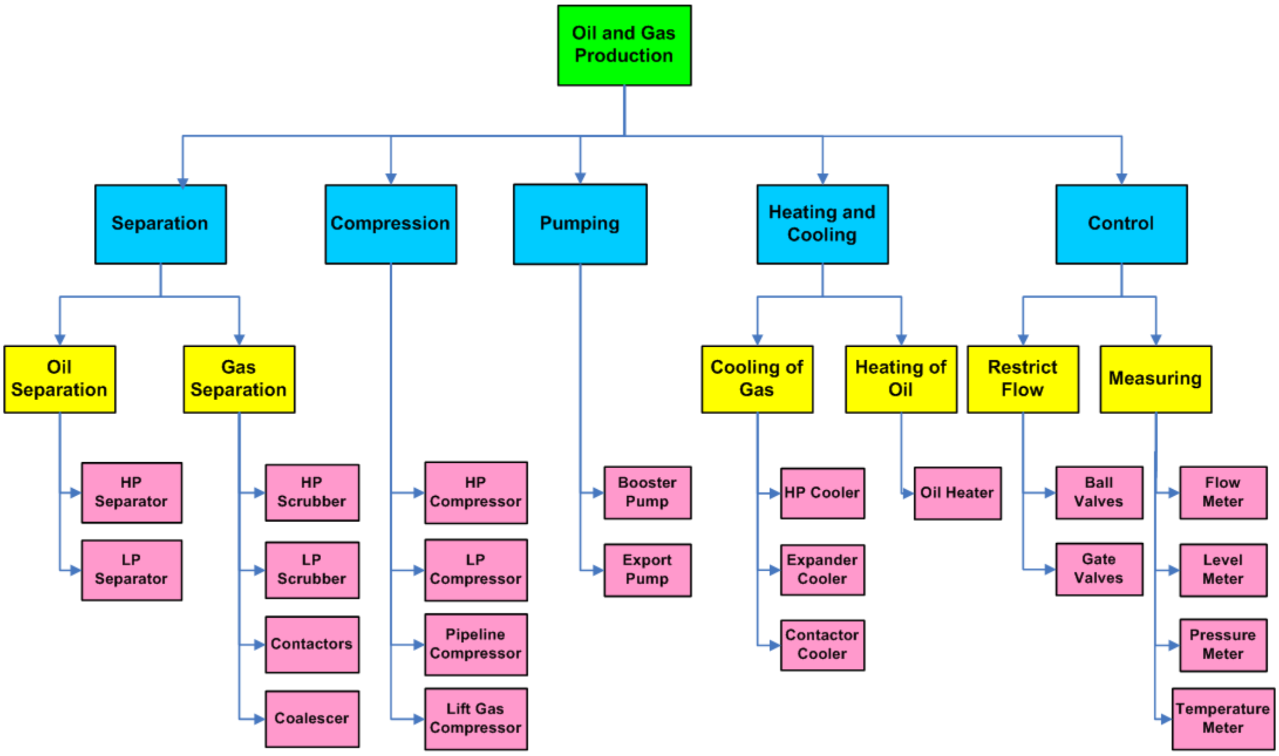


Figure 12 - Functional hierarchy

Once the functional hierarchy had been established the hierarchy needed to be transferred to the software application Manifer where the FMECA will be performed.

3.2.2 Definitions

To rank the effects of the different failure modes in a systematic manner a risk matrix is needed. The risk matrix used in this thesis is presented in Table 1. The risk matrix is based on a set of definitions shown in Table 3 for the different areas of interest. The scale used here ranges from an insignificant failure (0) to a catastrophic failure (5). Usually a limit of what is acceptable is chosen e.g. 4. This would indicate that any failure mode that leads to a consequence ranked 4 or above is unacceptable. For some applications failures ranked as 3 or medium criticality can also be ranked as unacceptable.

Table 1: Risk matrix

	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2
Probable	4	4	3	2
Occasional	4	3	3	1
Remote	3	3	2	1
Very unlikely	3	2	1	0

In order to precede a definition of the frequency term is needed. In (Kristiansen, 2004) the frequency is defined in a "once per X years" manner while the OREDA handbook (SINTEF Industrial Management, 2002) uses a failure rate given in "failures per 10^6 running hours". In this thesis a modification of the two will be used. However the definition can be chosen arbitrarily as long as it is maintained throughout the analysis. The definitions of frequency classes can be seen in Table 2.

Table 2: Frequency classes

	Failure rate grouping	In “x per year” equivalent
Frequent	100 -	0.87 or more faults pr year
Probable	50 – 100	0.44 – 0.87 faults per year
Occasional	20 – 50	0.17 – 0.44 faults per year
Remote	10 – 20	0.08 – 0.17 faults per year
Very unlikely	0 – 10	0 – 0.08 faults per year

The consequences of a failure will be judged against three classes. These categories have been chosen are assumed to be the most important for an oil and gas facility. The definitions might seem strict but it is assumed that the facility I question is operated in the North Sea where the public tolerance for safety and environmental mishaps is low, so it seems like a fair definition. The consequences with respect to production have been given that division because downtime and production loss is so expensive. Table 3 shows the definitions of consequence classes used in this thesis.

Table 3: Consequence classes

Consequence	Safety	Environment	Costs/Production
Catastrophic	Death of personnel	Large spill > 100m3	Complete shutdown
Critical	Severe personnel injury	Medium spill <100 m3	Risk of down time, reduced production
Major	Personnel injury	Small spill <10 m3	No downtime, reduced production
Minor	No injury	No spill	No downtime, no reduction in capacity

3.2.3 Failure rates and types

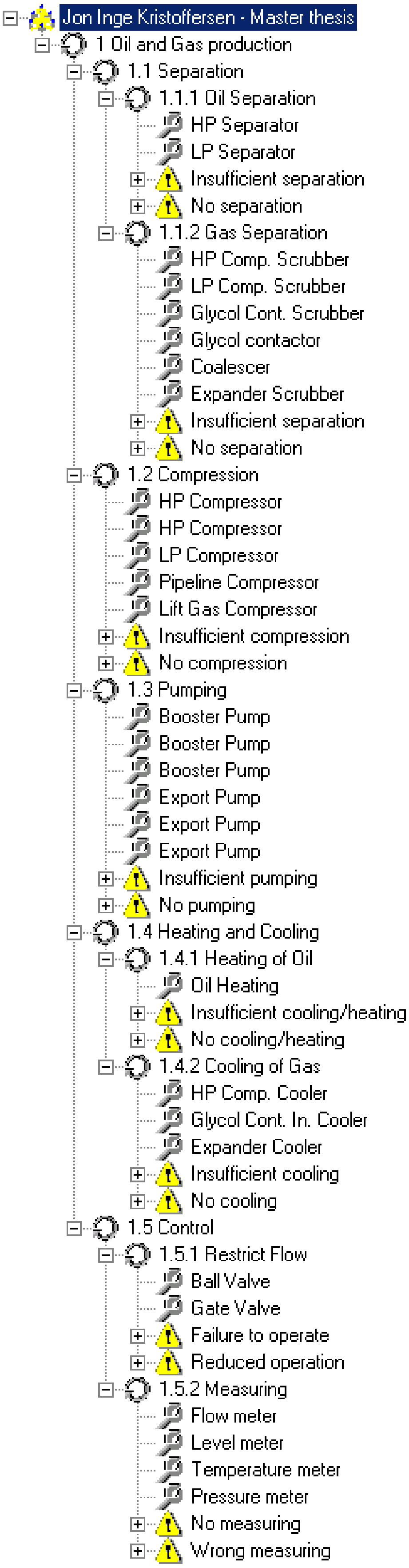
All failure data has been taken from the OREDA handbook, (SINTEF Industrial Management, 2002). Other elements that have been taken from OREDA include the system boundaries and failure modes. Only the most common failure modes have been used, and failure modes from all the different criticality categories have been included. Where three or more failure modes are common a subjective choice has been made on which failure mode to include in the analysis. Since OREDA have three failure rates listed the mean value has been used in this thesis, both calendar time and operational time is listed in OREDA and only the operational time has been used here. Several different equipment types are listed in the OREDA handbook in this thesis only failure data from centrifugal compressors have been used. Failure data from both plate and shell and tube heat exchangers have been included. Only the general failure data for separators, scrubbers, contactors and coalescers have been used since the capacity of these equipment types are not known. General fault data for different sensor types have also been used. In total four different sensor types have been included. Both ball and gate valves have been included in the analysis. The failure database can be found in Appendix 1: Failure database. When it comes to relating failure mode to maintainable items e.g. actuating device for valves and failure mechanisms e.g. wear the most common type listed for that failure mode is used.

3.2.4 Results and comments

As stated earlier the FMECA has been performed using the software application Manifer. Figure 13 show how the functional hierarchy was implemented into Manifer. In Figure 13 the first stage sub function is numbered with two numbers e.g. 1.1 Separation, while second stage sub functions are numbered with three numbers e.g. 1.1.2 Gas Separation. Functional errors can be seen as yellow triangles. On the level below functional errors equipment is tied to different failure modes. It should be noted that failure modes taken from the Degraded and Incipient failure modes in OREDA have been assigned to the insufficient failure mode while Critical failure modes from OREDA have been assigned to the total loss failure mode. The failure modes used in the analysis are shown in Table 4.

Table 4: Failure modes

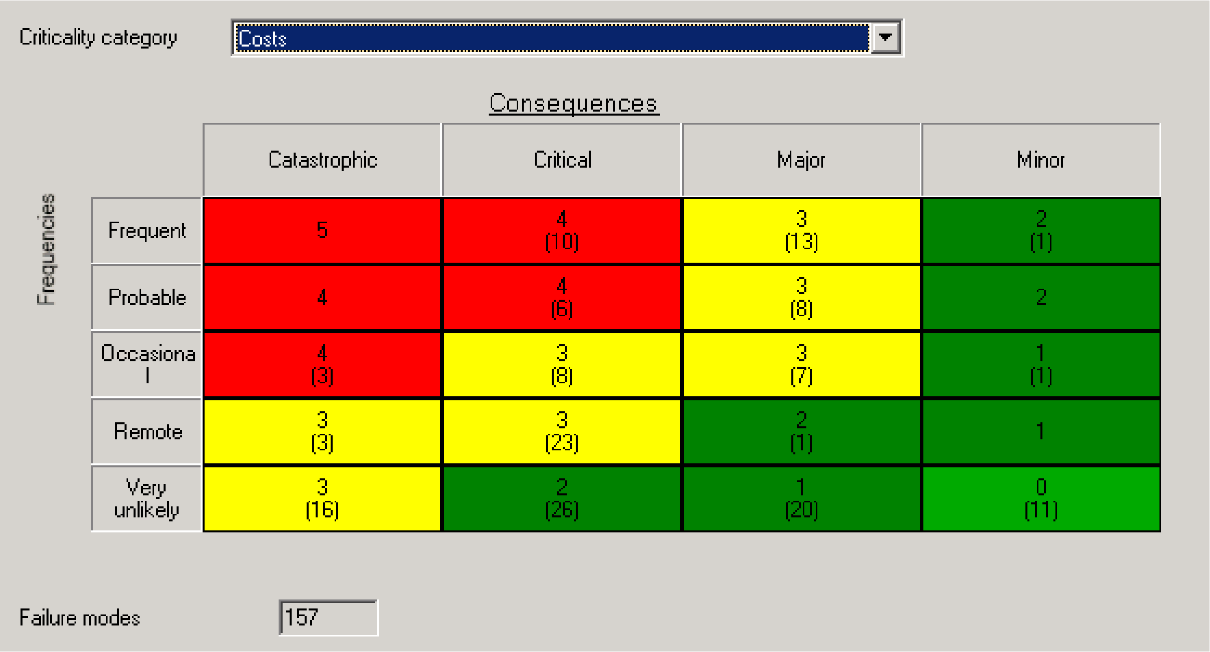
Code	Name
AR	Abnormal instrument reading
DO	Delayed operation
ELP	External leakage - Process
ELU	External leakage - Utility
EO	Erratic output
FCD	Fail to close on demand
FD	Fail to function on demand
FOD	Fail to open on demand
FS	Fail to start on demand
IL	Internal leakage
IP	Minor in-service problem
LCP	Leakage in closed position
LO	Low output
O	Other
PC	Plugged/Chocked
PD	Parameter deviation
SD	Structural deficiency
SS	Spurious stop
V	Vibration



- Jon Inge Kristoffersen - Master thesis
  - 1 Oil and Gas production
    - 1.1 Separation
      - 1.1.1 Oil Separation
        - HP Separator
        - LP Separator
        - Insufficient separation
        - No separation
      - 1.1.2 Gas Separation
        - HP Comp. Scrubber
        - LP Comp. Scrubber
        - Glycol Cont. Scrubber
        - Glycol contactor
        - Coalescer
        - Expander Scrubber
        - Insufficient separation
        - No separation
    - 1.2 Compression
      - HP Compressor
      - HP Compressor
      - LP Compressor
      - Pipeline Compressor
      - Lift Gas Compressor
      - Insufficient compression
      - No compression
    - 1.3 Pumping
      - Booster Pump
      - Booster Pump
      - Booster Pump
      - Export Pump
      - Export Pump
      - Export Pump
      - Insufficient pumping
      - No pumping
    - 1.4 Heating and Cooling
      - 1.4.1 Heating of Oil
        - Oil Heating
        - Insufficient cooling/heating
        - No cooling/heating
      - 1.4.2 Cooling of Gas
        - HP Comp. Cooler
        - Glycol Cont. In. Cooler
        - Expander Cooler
        - Insufficient cooling
        - No cooling
    - 1.5 Control
      - 1.5.1 Restrict Flow
        - Ball Valve
        - Gate Valve
        - Failure to operate
        - Reduced operation
      - 1.5.2 Measuring
        - Flow meter
        - Level meter
        - Temperature meter
        - Pressure meter
        - No measuring
        - Wrong measuring

Figure 13 - Functional hierarchy from Manifer

In Figure 14, Figure 15 and Figure 16the total number of registered failure modes for the whole process shown in Figure 5 is summarised. If an acceptance level of 4 is chosen then the risk matrices show that for all criticality categories there are failure modes that have been ranked as unacceptable. To prevent these failure modes form happening or mitigating the consequences of these failure modes happening further investigation is needed. The risk matrices for all sub functions are presented with all criticality categories included can be found in Appendix 3: Risk matrices for sub – functions. Due to some difficulties with Manifer, it was impossible to export the full analysis to Excel, only a smaller version of the FMECA report was exported to .pdf format. The .pdf – version contains most of the information, but alas some of the information has been left out. The complete .pdf – version of the FMECA report can be found in Appendix 2: FMECA Report.



Criticality category: Costs

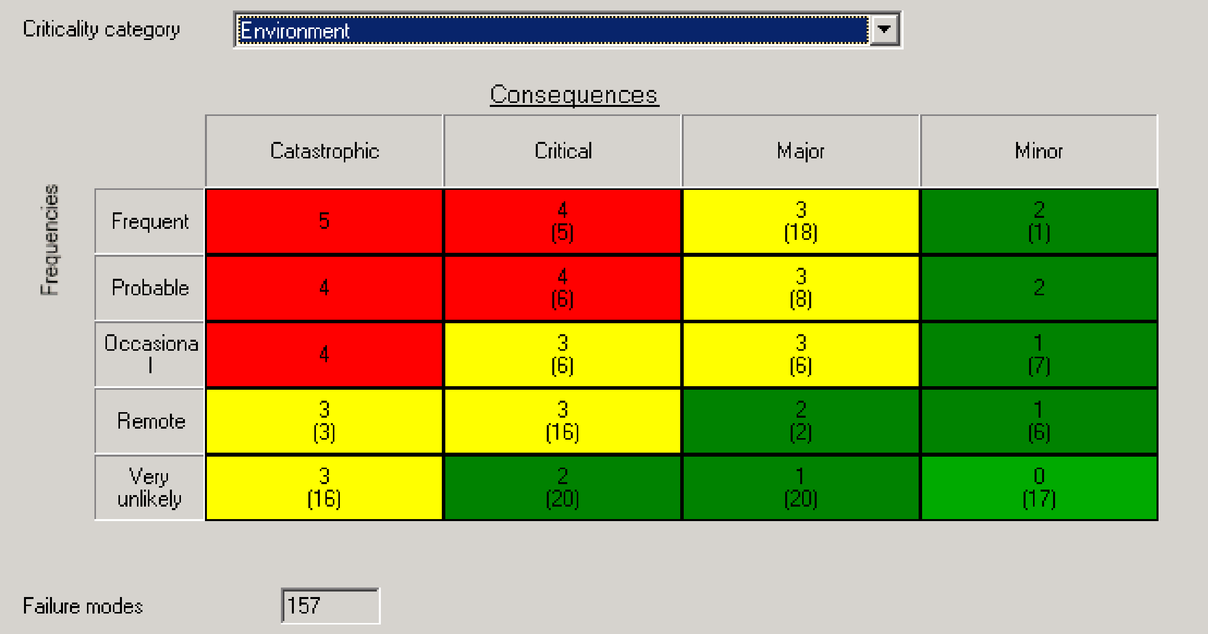
Consequences

Frequencies

	Catastrophic	Critical	Major	Minor
Frequent	5	4 (10)	3 (13)	2 (1)
Probable	4	4 (6)	3 (8)	2
Occasional	4 (3)	3 (8)	3 (7)	1 (1)
Remote	3 (3)	3 (23)	2 (1)	1
Very unlikely	3 (16)	2 (26)	1 (20)	0 (11)

Failure modes: 157

Figure 14 - Risk matrix: Costs



Criticality category: Environment

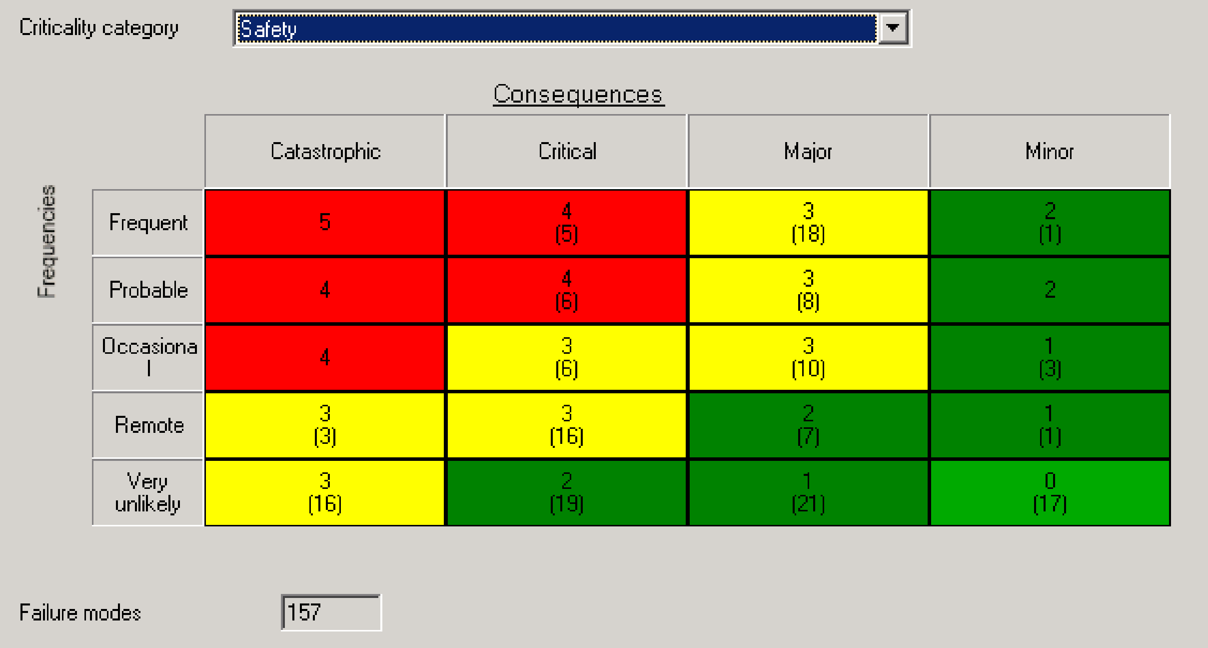
Consequences

Frequencies

	Catastrophic	Critical	Major	Minor
Frequent	5	4 (5)	3 (18)	2 (1)
Probable	4	4 (6)	3 (8)	2
Occasional	4	3 (6)	3 (6)	1 (7)
Remote	3 (3)	3 (16)	2 (2)	1 (6)
Very unlikely	3 (16)	2 (20)	1 (20)	0 (17)

Failure modes: 157

Figure 15 - Risk matrix: Environment



Criticality category: Safety

Consequences

Frequencies

	Catastrophic	Critical	Major	Minor
Frequent	5	4 (5)	3 (18)	2 (1)
Probable	4	4 (6)	3 (8)	2
Occasional	4	3 (6)	3 (10)	1 (3)
Remote	3 (3)	3 (16)	2 (7)	1 (1)
Very unlikely	3 (16)	2 (19)	1 (21)	0 (17)

Failure modes: 157

Figure 16 - Risk matrix: Safety

Form Appendix 3: Risk matrices for sub – functions the most critical components can be found to be the compressor with 35 failures ranked as unacceptable and the heat exchangers with a total of 3 failure modes ranked as unacceptable. Valves also had failures ranked as unacceptable but due to time constraints and engineering judgement valves have been omitted from further investigation in this thesis.

In order to reduce the chance of a failure occurring CM can be applied to the equipment that has been defined as critical. If any of the failures that represent a medium risk are found to be unacceptable the ALARP (As Low As Reasonably Practicable) principle can be applied to these to reduce the risk. The idea behind the ALARP principle is to obtain a balance between risk reducing measures and the costs of implementing them. The ALARP principle is illustrated in Figure 17. The black circles in Figure 17 represent identified risks. Risks located in the red region are only tolerable in extraordinary cases, but normally risk reducing measures are implemented to reduce the risk level to tolerable. In the orange region risk reducing measures are only implemented if the benefit of implementing the measure is larger than the costs associated with implementing the measure. The orange region is also called the ALARP region illustrating that it is in this region that risk reducing measures are implemented if it is practicable. In the green region risk reducing measures are generally not implemented unless the benefit of implementing the risk reducing measure greatly overshadows the costs of implementing the measure.

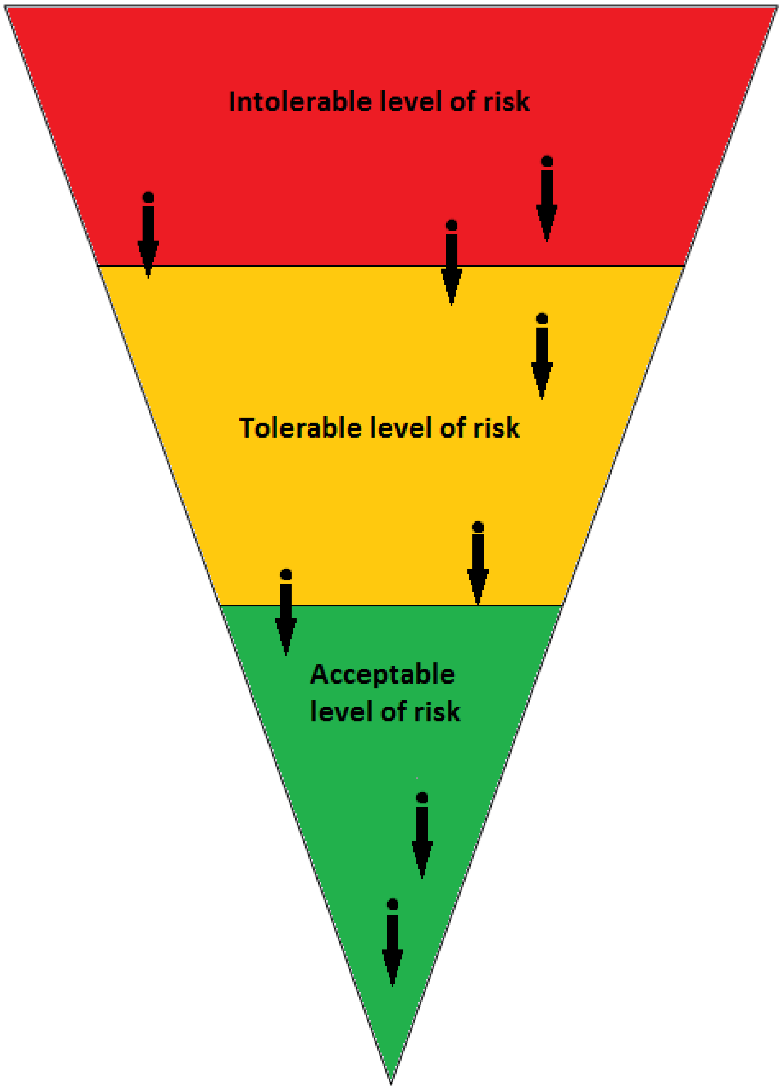


Figure 17 - ALARP principle

When it comes to CM the challenge is to find the right monitoring method to apply from the wide spectrum of methods available. In section 3.3 different CM methods will be described.

3.3 CM methods

In (Hunt, 2006) 15 different methods for Condition Monitoring (CM) are presented. All the different CM methods are presented in a similar manner with emphasis put on the purpose, measurements taken, applicability, what kind of sensors and instrumentation used and words of warning regarding each method. In addition to the CM methods presented in (Hunt, 2006) Electromagnetic Testing, Magnetic Particle Inspection and Visual Inspection from (DNV, 2007) will also be included. The complete list of CM methods included in this thesis therefore encompasses:

- Acoustic emissions and Ultrasonics
- Colour
- Corrosion
- Environment
- Electromagnetic testing
- Level, Leakage & Flow
- Load
- Magnetic Particle Inspection
- Noise
- Oil analysis
- Position
- Power
- Smell and Taste
- Temperature
- Thermography
- Vibration
- Visual Inspection
- Wear and debris analysis

In this thesis environment monitoring has been omitted, due to most of it being covered in several of the other CM methods. In the following sections a brief summary of each of the CM methods will be given. Not all of the CM methods presented in the book may be appropriate for oil and gas facilities.

3.3.1 Acoustic emissions and Ultrasonics monitoring

The purpose of acoustic emissions and ultrasonic is to detect changes in a machines condition using high frequencies. The frequencies typically range from 25 kHz up to 1 MHz. These frequencies are not detectable by the human ear which can hear up to about 20 kHz (Wikipedia, 2008). Since the human ear comes up short in detecting these frequencies a piezoelectric transducer is usually used. Since all machines produce some acoustic emissions it is the type of signal produced that is of interest. A deteriorating machine condition can typically be associated with an increase in the continuous signal level. Friction, impacts and cavitations will also change the acoustic emissions levels. In (DNV, 2007) several sub types of ultrasonic imaging is presented. The different sub groups are based on separate methods for generating and collecting the ultrasonic signals and as a consequence the different methods have different applicability and different depths of penetration.

For analysing the signals different methods can be used. But trending is very common for many different CM methods. The simplest method of trending is to plot the logarithmic acoustic level and look for a change.

Acoustic emissions can be applied to most equipment that gives of sound either by rotating or changing flow through the equipment.

Special attention should be paid to make sure that frequency range of the sensors is matched with the required performance of the component. Also transducers should be placed in the region where the signal strength is the highest. Sensors that detect peak values should be oriented into the best direction to make sure that the instantaneous value of bursts can be recorded.

3.3.2 Colour monitoring

Colour monitoring is a form of visual inspection where the change of colour in the component surface or liquid will indicate a developing fault. The change in colour may be caused by either internal or external effects. Internal effects that may change the surface colour include temperature and variations in loading or vibrations. External effects that may alter the surface colour include temperature, corrosion, leakage and physical damage.

The hue of a colour can be measured in two different ways. The first way is to detect the presence of red, blue and green in the colour. This is related to the sensitivity of the human eye. The second option is spectral content in which the individual frequencies in the visual spectrum are recorded. In addition a specific colour sample needs to be defined in terms of saturation and intensity. Saturation means the vividness of the colour. Terms like “bold” and “insipid” can be used to describe saturation. Intensity can be understood as brightness with “white” and “black” as the two extremes of the intensity scale.

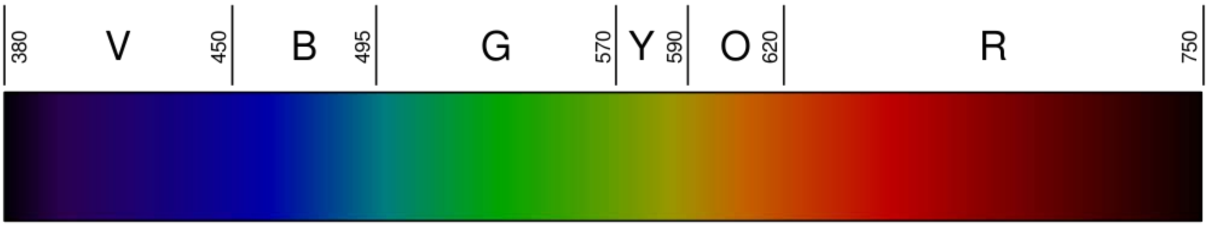


Figure 18 - Visual spectrum in nm

If absolute values of the two features are used slight changes in the colour may go unnoticed as atmospheric conditions affect the results. Therefore trending is by far a much better option.

Colour monitoring can be used to detect oil degradation due to overheating. System overheat may also be detected using colour. Industries that may use colour as a CM method includes any industry that works with oils, all industries where internal temperatures may affect surface temperatures and industries where gas is involved.

The basic equipment used for collecting data include colorimeter, spectrophotometer and gloss meter.

If colour monitoring is to be used care should be taken to ensure that the light conditions are the same every time measurements are taken. Artificial light sources are better than daylight. Atmospheric changes may cause the spectre to change, humidity may introduce new spectres and particles may filter certain frequencies.

3.3.3 Corrosion monitoring

Corrosion is material degradation caused by the environment through chemical, electrochemical or biological actions or reactions. Corrosion monitoring is used to detect the early stages of surface degradation caused by faults in the system or failure of protective mechanisms.

The techniques employed to detect corrosion are numerous. Every detection method has its own strengths and weaknesses. Most of the analyses based on corrosion measurements are based on an estimated corrosion rate e.g. 5 micron per year.

Faults that can be detected using corrosion monitoring include leakage, failing barriers and protective coatings.

Figure 19 - Corrosion monitor by (Roxar)

Corrosion monitoring is employed in numerous industries spanning from oil and gas production, transportation and process industry. Corrosion monitoring is applied to two major areas of the industry today, namely pipes and vessels and reinforced concrete.

The most common sensors used in corrosion monitoring today is the corrosion coupon and probe. The corrosion coupon and probe is designed to be sensitive to what is causing the corrosion and provide a sample of the real situation.

When choosing a corrosion monitoring technique care should be taken to ensure that the technique is capable of detecting the corrosion and what surface is suffering from the corrosion. A matching of corrosion type and corrosion measurement technique is necessary. Another thing to be aware of is that corrosion is a slow process. Data collection and analysis may take a long time.

3.3.4 Electromagnetic testing

Electromagnetic testing uses electromagnetic induction to detect flaws in conductive materials. The most common type of electromagnetic testing is Eddy Current Testing (ECT). Conventional ECT has limited penetration depth and is therefore only suited to test for cracks in surfaces. However more advanced ECT methods have been developed and are capable of deeper penetration (DNV, 2007). Among the more advanced ECT methods Pulsed Eddy Current Testing and Saturated Low Frequency Eddy Current (SLOFEC) are interesting.

Pulsed ECT can be used to detect corrosion and erosion over large areas. It does not detect smaller pits and the test results may be influenced by the presence of large metal masses. Pulsed ECT can be used to detect faults in wall thicknesses up to 100 mm.

Saturated Low Frequency Eddy Current is based on ECT where direct currents are used for magnetisation. SLOFEC is according to (DNV, 2007) capable of penetrating wall thicknesses of about 30 – 35 mm and is therefore best suited for inspecting pipes and corrosion in vessel shells.

3.3.5 Level, leakage & flow monitoring

These three types of monitors are used to determine the condition of a machine or system by analysing the fluid movements and positions. The condition of the system will then be expressed by the levels, leakages and flows in the system. The level gives an indication of the amount of fluid in the system. The leakage indicates at what rate the level declines. Trace gas can also be used in leak testing. The flow indicates the efficiency of movement through the system.

Measurements of level, leakage and flow can be done by a variety of different meters. All the different meter types have their own strengths and weaknesses.

3.3.6 Load monitoring

Load monitoring encompasses the measuring of six different aspects of loads. These six aspects include load, force, pressure, strain, torque and weight. Each aspect can be used to detect a deteriorating condition in a machine or system.

Faults can be detected by measuring one or more of the six aspects. Load can be measured by a load cell. Force can be measured by a strain gauge, which measures the deformation of a structural element. Pressure can either be measured by a pressure gauge or by a Bourdon tube connected to a dial. Strain can be measured by a strain gauge. Torque is measured by a rotational strain gauge or by angular deformation. Weight can be measured by load cells.

The analysis method is very straight forwards: Simply look for unacceptable changes in the parameters when the running conditions are identical.

The faults detectable by this kind of CM depend on the parameters that are being monitored. In many cases the basic sensors used are strain gauges.

When using load monitoring great care should be taken to ensure that the sensors employed can operate in the expected load range of normal operations. A sensor with a too large range would not be able to pick up minor changes, while a sensor with too small range would not tolerate overloading. Strain gauges need to be bonded to the surface with the proper adhesive, otherwise slipping may occur. Load cells need to be aligned in the direction of the expected load.

An industrial example of electrical load monitoring is the DriveMonitor system offered by ABB. DriveMonitor is intended to monitor compressor drives (ABB Oil, Gas and Petrochemicals). The basic functionality of DriveMonitor is to watch the frequency converter of the drive system as well as it collects and analyses selected drive signals. But it can also be configured to monitor other components such as the circuit breaker, transformer and driven machine i.e. the compressor according to (ABB, 2008).

3.3.7 Magnetic Particle Inspection

This form of testing is used for detecting surface and near surface cracks in ferromagnetic materials. This method is one of the most extensively used methods in the industry today. The test is performed by magnetising the component that is to be tested. The magnetisation is achieved by applying a permanent magnet, electromagnet or an electric current. A magnetic field is produced inside the component and the magnetic field is distorted by the presence of flaws in the material. Flaws are detected by applying magnetic particles either in the form of a powder or as a liquid. The magnetic particles accumulate in and around the area of flaws thereby making it visible.

When this kind of testing is applied the orientation of the magnetic field and the imperfection is important. The best result is achieved when the angle between field lines and imperfection is 30° –

90°. Therefore it is best to apply the magnetic field in two directions to ensure that all flaws are detected. Magnetic Particle Inspection (MPI) can only be applied to surface cracks.

3.3.8 Noise & acoustics monitoring

Noise and acoustics monitoring covers the frequency ranges that the human ear can hear typically from 20 Hz to 20 kHz. It is important to include acoustics because the surroundings will have an impact on what is heard.

Faults are detected using a microphone that receives sound pressure waves, a weighting network that gives acceptable emphasis to each frequency and a display showing the noise signature so that a comparison can be made against the signature of a "good" machine.

Figure 20 - Handheld sound meter

Four ways of analysing noise signatures are mentioned. These include sound pressure over time, sound level versus time, sound level versus frequency and noise indices versus speed or time.

This kind of monitoring can be used to detect faults in bearings, gears, pumps, rollers and lack of lubrication. Industries or systems where noise and acoustics monitoring can be used include hydraulically and mechanical systems as well as production industry, rail and marine transport.

When implementing noise and acoustics monitoring it is important that appropriate meters are used. Special attention should be paid to the type of analysis, the time weighting, noise and frequency level, accuracy and output. When using this kind of monitoring the positioning of the meter is of great importance. If a comparative analysis is used the meter needs to be placed in the exact same spot with the same alignment each time and the machine needs to be in the same operating condition.

3.3.9 Oil analysis

Monitoring the condition of a machine or system using the fluids of the system is called oil analysis. It should be noted that it is only chemical analysis of the fluid and not analysing any solids that may be present in the fluid. Analysis of the solids present in the fluid will be covered in wear and debris analysis later. Calling this kind of monitoring for oil analysis may be somewhat misleading as a chemical analysis of any fluid in the system may be performed to give an indication of the systems condition.

Several basic chemical properties that can be measured to give an indication of the condition of a machine or system include temperature, viscosity and density. However the main aspect of oil monitoring is the measurement of the additives. The additives are present in the fluid to nullify errors in the operation. An example is antifoam that reduces the formation of foam generated from either serious machine problems, or sloshing in a production separator. If a fault is developing and the additives do their job the amount of additives present in the fluid should diminish.

A spectrometric chemical analysis of the fluid will give a breakdown of the different elements present in the fluid. When using oil analysis it is of paramount importance that the sample containers are cleaned prior to use. Contaminants entering the sample prior to analysis are also important to avoid.

3.3.10 Position monitoring

This kind of CM is one of the most basic that exists today. It can be performed by asking two simple questions:

1) Is anything out of place?
2) Is anything moving in the wrong direction or at the wrong speed?

Large deviations can be detected by a human operator, but the small gradual changes needs to be detected by sensors. The purpose of position monitoring is the detection of abnormal movements that have happened, is happening or may happen due to a developing fault in a machine or system.

This kind of monitoring can be used by all industries. The measuring of different developing faults is what will differ from one industry to another.

The analysis is typically taken on a trend basis. Where a gradual change form an acceptable position is recorded. In order to use this kind of monitoring it is necessary to define a reference point so a deviation from this point can be detected. The reference point can either be a local point such as its normal position or a global position by using GPS.

There exists a large range of position monitors today all with different accuracies and variety of application.

When choosing position monitoring it is important that the sensors chosen deliver the required accuracy. Since the cost range of different sensors is huge selecting the right sensor for the job is a challenge. The loss of reference point is another issue when using position monitoring. Losing the reference point can be attributed to vibrations.

3.3.11 Power monitoring

This kind of monitoring may also includes performance and efficiency monitoring. Monitoring all three attributes will enable a better view of developing fault in the system. In Power monitoring the input to the machine is monitored while the output is assumed to be constant. In performance monitoring the output of the machine is monitored while the input is assumed to be constant. While in efficiency monitoring both input and output has to be monitored to give usable data, for conventional purposes the same units for input and output would be required but this is not the case. However for some application only one of the three attributes is relevant for detecting faults. An example where only one attribute is relevant for the condition of a machine is a pump that is supplying constant pressure downstream. In this example only the power consumed by the pump motor is relevant as the pump delivers a constant output. Depending on developing faults in the pump the power consumed by the motor will increase.

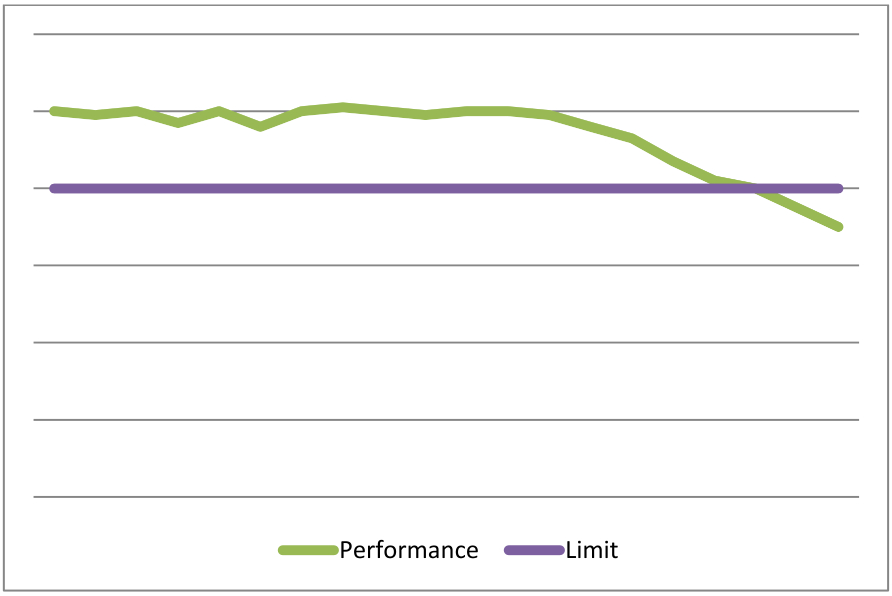


Figure 21 - Example of performance monitoring

As already explained the input and the output do not need to have the same unit for a comparison to be made. All that is required is a set of twin features unique for that system. Such a set of twin features can be electrical power consumed and shaft torque. The analysis then becomes a comparison between acceptable and unacceptable ratios or differences.

When employing power monitoring it is advisable to try and use existing sensors in the system for financial reasons. A decision also has to be made with respect to what is going to be monitored, is both input and output needed or will just one suffice. When using power monitoring it is necessary to also look at the reason behind changes i.e. a rise in oil viscosity will result in an increase in power even if no fault is present.

For monitoring heat exchangers ABB is developing HXAM – G (generic) and HXAM – ST (shell and tube). What HXAM – G and HXAM – ST does is monitor the efficiency of the heat exchanger without regard for the design or structure of the heat exchanger. HXAM is an abbreviation for heat exchanger asset monitors. The system detects gross changes in the heat exchanger efficiency as opposed to small minute changes. The way the system works is by monitoring readable process variables around the heat exchanger, noting trends in these variables can then be used as an indication of declining performance. The system alerts maintenance personnel of changes in the KPI (Key Performance Indicators) associated with fouling indicated by drifting ΔT at reference hot and cold flow, increasing ΔP across the heat exchanger at either hot or cold leg, low flow or low ΔT readings for either leg and significant changes in operating point. HXAM – ST is also capable of detecting process errors indicated by temperature crossover, low shell side flow, low heat transfer, high or low tube velocity and low limiting approach temperature. The required input to both versions of HXAM is temperature of hot and cold flow going into and coming out of the heat exchanger. However for better results more input information can be supplied including mass and volume flow of both hot and cold side, incoming and out going pressure for both sides.

A strength of HXAM is that it requires little configuration. Another element that speaks for HXAM is that it can use existing instrumentation, so there is no need to fit additional sensors. One of the weaknesses of HXAM is that best results are obtained if both the hot and cold side is liquid. This is an area where improvements can be made in the future. Another weakness is that HXAM treats the heat exchanger as a “black box”. The same model is used regardless of the heat exchanger type, mediums etc. HXAM has been tested as a pilot and early results called for improvements to the system. In theory HXAM can be installed today, but the efficiency of the system may be debated. According to ABB they are working on an improved version of HXAM. This improved version is expected to be on the market within two years i.e. 2012.

3.3.12 Smell & taste monitoring

The purpose of this kind of monitoring is the detection of developing faults using the smell surrounding the system or from the smell and taste of the product of the system. This kind of monitoring is mostly used in food and drinks industry or pharmaceutical industry. Therefore it will only be mentioned here for more information I recommend (Hunt, 2006).

3.3.13 Temperature monitoring

In temperature monitoring the temperature surrounding a machine or system is used to determine the condition of the component.

There are two features that are important when it comes to temperature monitoring. These features are the sensor type used in the measuring and the location of the sensor when the temperature was measured. When it comes to sensor type many different sensor types exists, depending on the application either a resistance thermometer or a thermocouple type of sensor may be suitable. Depending on what is being monitored the location of the temperature sensor will be important. A bearing being monitored will benefit from having the temperature sensor as close to the rolling element as possible. The same applies to a liquid, the thermometer needs to be submerged in the liquid to obtain accurate readings. If the overall temperature of a machine says something about the condition of the machine then several surface measurements needs to be taken to obtain the machine condition.

When analysing temperature data trending is usually the most appropriate method. On the other hand if a critical temperature exists for the machine or system then an alarm just below the critical level will be a better option.

Figure 22 - Temperature meter TF202 by ABB

Temperature monitoring is applicable to almost all industries due to the conversion of energy taking place. Energy conversion is in turn likely to lead to a temperature increase.

When choosing temperature monitoring it is important to consider the wide range of sensors available and what is to be measured. When using temperature monitoring it is important to remember that heat can be convected and conducted as well as radiated. Therefore it is important to insulate from regions that is not tested.

3.3.14 Thermography

Thermography or thermal imaging is a condition monitoring technique where the surface temperature of a machine or system is used to determine the internal condition. Thermography can be applied to any system where a developing fault may lead to an increase in heat. Thermography is a CM technique that does not require contact with the machine or system. All that is needed is an infrared camera to take a picture of the component then a comparison with another image of the same component may reveal a developing fault. The comparison can either be done by eye or by computer.

Figure 23 - Handheld IR camera

Thermography is capable of detecting faults in mechanical components, electrical machines, energy systems such as boilers and heat exchangers and electronic systems. This kind of CM can be applied to most industries where this kind of equipment is present.

When choosing thermography as a CM method it is important to specify the requirements that the user needs fulfilled by the infrared camera. Special attention should be put on resolution, temperature range, weight, battery life, data storage and transmission and if the camera should be used inside or outside. When using an infrared camera it is important to remember that the optics are vulnerable.

3.3.15 Vibration monitoring

In vibration monitoring the running vibrations of a machine or system is measured in order to determine if a fault is developing. Vibration monitoring is one of the largest fields of CM, covering a wide range of techniques ranging form out of balance sensors to multi frequency measurements.

Vibration monitoring can be applied to any rotating or reciprocating machine as these generate vibrations when they are running normally. Because of this any change or growth in these natural vibrations will indicate that everything is not as it should be.

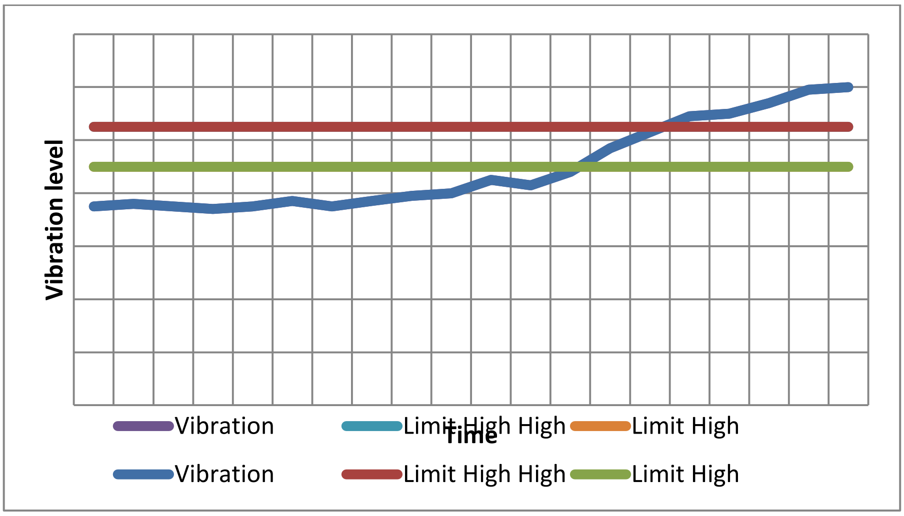


Figure 24 - Example of vibration monitoring

Figure 24 shows an illustration of a possible vibration monitoring scheme with high and high – high limits. The idea is that when operators get the high alarm an inspection is scheduled to determine if the machine needs to be shutdown to fix the problem or not. When the high – high alarm is received then the machine needs to be shutdown to do maintenance to avoid severe machine damage. The shutdown can be done automatically by the control system with an alarm that needs to be acknowledged by the operator.

Any industry that works with rotating machinery can benefit from vibration monitoring. There is also a wide range of sensors available depending on the sensor type and size.

It is important to be aware of that vibrations may be transferred through solids and that measurements are taken at the component of interest. When considering vibration monitoring it is important to consider the complexity of the system. The more complex the system is the harder it will be to decide on what to monitor.

3.3.16 Visual Inspection

In Visual Inspection (VI) a borescope is used to detect developing failures. VI is as the name implies a method where faults are detected by looking at the sample. The borescope can either be flexible or rigid. Figure 25 show a flexible borescope. Rigid borescopes are limited by the need for a straight line between the observer and the object to be observed. Flexible borescopes are used when there is no straight line between the observer and the area to be inspected. Both types of borescopes can be configured to suit the needs whatever they may be. Options for consideration include the size of the probe and the length of the probe. A choice between video or fibre scope can also be made when it comes to flexible borescopes.

Figure 25 - Example of flexible borescope

3.3.17 Wear debris analysis

This kind of CM analyses the solids present in fluids in order to determine the condition of the machine or system. A number of features are analysed to determine the origin of the solids.

This kind of analysis can be applied to any oil lubricated system, including hydraulic systems. This kind of monitoring can detect faults in rubbing surfaces e.g. bearings, gears, etc., wear of reciprocating machines and others. Wear debris analysis can be applied by all industries using oil for lubrication.

The analysis of the debris is usually conducted in an offsite laboratory, but instruments for analysing the samples closer to the system is being developed.

When selecting this kind of monitoring technique it is important to note that not all analysers are appropriate for all systems. Some analysers only detect ferrous metals while others detect all metallic particles. Another thing to remember is that the oil can only contain particles from where the oil has been. When using wear debris analysis great care should be taken to make sure that the equipment used in collecting the samples is cleaner than the requirements of the normal system. This will ensure that no foreign contaminants spoil the sample.

In Table 5 a summary of the CM methods presented above is given.

Table 5: CM methods summary

Method	Method used in fault detection	Measurements	Applicability	Warnings
Acoustic emissions and Ultrasonics	Acoustic emissions from macihne	Acoustic emission level	Most equipment that emits sound	Frequency ranges, sensor alignment

Colour	Visual inspection	Hue, spectral, saturation and intensity	Any industry using oil	Light conditions, environmental conditions
Corrosion	Corrosion coupon	Corrosion rate	Most industries	Technique capable of detecting corrosion type
Electromagnetic Testing	Electromagnetic field	Visual and display readouts	Most industries, vessels and pipes.	Surface thickness
Level, Leakage & Flow	Unacceptable changes in parameters	Level, leakage and flow	Any industry working with vessels	Sensor selection
Load	Unacceptable changes in parameters	Six aspects of load	Most industries	Sensor selection
Magnetic Particle Inspection	Electromagnetic field in combination with magnetic particles	Visual look for gatherings of particles	Surfaces of vessles and pipes	Wall thickness
Noise	Microphones	Sounds emitted from machines	Hydraulic and mechanical systems	Microphone position, Microphone selection
Oil analysis	Chemical analysis of fluid sample	Chemical properties, ammount of addatives	Any industry working with oils	Clean sampling equipment
Position	Comparrison of normal position/speed and actual position/speed	Position, Vibration	Most industries	Sensor accuracy, reference point
Power	Input, output and efficiency of machine	Consumption and production of machine	Most industries where sensors are already fitted	Use existing sensors, what to monitor, reasons for changes
Smell and Taste	Smell and taste of products and surrondings	Smell and taste	Food, drinks and pharmaceutical	Results affected by environment
Temperature	Temperature	Temperature	Most industries	Sensor selection
Thermography	Surface temperature using IR camera	Surface temperature	Most industries	Specifications of camera
Vibration	Increasing vibrations	Vibrations	Any industry working with rotating machinery	Complex systems, where to measure
Visual Inspection	Visual	Look for flaws in development	Vessles such as heat exchangers	Configuration of borescope

3.3.18 Applicable CM methods

From section 3.2.4 and Appendix 2: FMECA Report it can be seen that heat exchangers and compressors are equipment of a critical nature. Implementing CM for these equipment types will provide early warnings for developing failures and hopefully prevent failure and downtime for the system. From Table 5 CM methods that are best suited for monitoring heat exchangers and compressors can be chosen. It should be noted that Table 5 only presents the general type of monitoring method and that many different commercial solutions within one method may exist. Finding the best solution may be challenging and time consuming, therefore only a recommendation for where to look further will be given here.

For monitoring compressors the obvious choice is Vibration monitoring presented in 3.3.15, but both Power monitoring and Load monitoring presented in 3.3.11 and 3.3.6 respectively are also possibilities. Finding industrial solutions that corresponds to these monitoring techniques should not be a problem as all three methods are used today. Some industrial solutions include ABB's DriveMonitor and GE's System 1 software for CM. System 1 can be configured to monitor most assets and extension packages exists to specialise the software to suit special needs (GE). System 1 was not covered in the previous sections because it is a CM software package and may therefore be compromised of several of the different methods presented earlier depending on how the system has been configured.

When it comes to CM methods applicable to heat exchangers the list of possibilities diminishes. What is done today is internal visual inspection. This method however has the huge disadvantage of requiring major dismantling of the heat exchanger, meaning that the whole system needs to be shutdown and cleaned before the inspection can be done. The inspection interval can depend on local rules and regulations as well as the company rules of the operator. In some cases the inspection interval can be decided by a Risk Based Inspection (RBI). RBI is a decision making technique for inspections based on risk. Both the consequence of failure and the probability of failure are included (DNV, 2009). The RBI delivers the following to the inspection program:

- What to inspect
- When to inspect
- Where to inspect
- How to inspect
- What to report

The result of the RBI is an inspection plan. The period between inspections will also be defined. For static equipment the inspection interval may return as one inspection every 5 or 10 years as an example. When an internal inspection is due and the heat exchanger has been dismantled either leak gas testing or ECT can be used to detect developing cracks and leaks in the tubes.

However inspection of the internals of the heat exchanger requires the whole system to be shutdown, this is only something that is desired to do as rarely as possible due to the costs. Therefore a monitoring technique where the heat exchanger does not need to be shutdown would be preferable. HXAM is one such solution, although still in development and pilot testing HXAM seems to be a good alternative in addition or as a replacement for RBI. A prerequisite for implementing HXAM is that sensors are already fitted to the heat exchanger and that the information received from these sensors is reliable. In new facilities fitting the required sensors and implementing HXAM should not be a problem.

3.4 OBM simulations using GA

In this section some simulations using GA will be run to try and find an optimal organisation of equipment for OBM. All simulations will be done in Excel with the aid of an upgraded version of the Excel Solver developed by Frontline Systems called Premium Solver. The model can be used as a decision support tool when considering equipment for OBM, given certain inputs from the user. The model requires the user to specify the expected length of an opportunity, probability for logistics delay and length of the delay, need for scaffolding, and the equipment that is to be considered.

3.4.1 Costs included in the model

In this optimisation problem the objective is to organise equipment into an OBM scheme that has the lowest total cost. The following cost functions where used:

- Logistics delay costs (CLD)
    - Costs of extra trip with spares, tools and people. Also includes probability for delay and increased costs if there is a delay.
- Work costs (CW)
    - Costs related to the work associated with changing the component including wages and administration etc.
- Downtime costs (CDT)
    - Costs associated with having to shutdown the facility
- Risk costs (CR)
    - Costs associated with keeping a unit nearing the end of it's life in operation
- RUL costs (CRUL)
    - Costs associated with changing the unit before its useful life has been exhausted.
- Spares and tools (CST)
    - Costs of spare parts and specialised tools that may be required.
- Miscellaneous costs (CMI)
    - Miscellaneous costs include different smaller costs not included in the other costs categories.
- Scaffolding (CS)
    - Costs associated with renting scaffolding and putting up scaffolding if required.

These costs where combined to give the total unity cost for each item.

$$Unit\ Cost = \sum_{i} CLD_i + CW_i + CDT_i + CR_i + CRUL_i + CST_i + \ CMI_i + CS_i \tag*{1}$$

The logistics delay cost was modelled using an if – sentence. If logistics delay is not expected the costs of logistics is set to 20 000 NOK. If logistics delay is expected the costs of the logistics costs becomes the product of the length of the delay multiplied by a flat rate of 15 000 NOK. The length of the delay is user defined.

The work costs were based on the MTTR for each unit and multiplied by an hourly rate set to 2 000 NOK. The MTTR has been taken from OREDA, mean value has been used.

Downtime costs was modelled as 100 000 NOK per hour and multiplied by the length of the opportunity. The length of the opportunity is specified by the user.

The risk cost was modelled based on the failure category from OREDA and a flat rate of 2 000 NOK for all units. If the unity is not included in the OBM scheme then the flat rate is increased to 2 250 NOK. This is expected to reflect the increased risk of failure when postponing maintenance on an item. The Critical failure category was given a rating of 3, the Degraded failure category was given a rating of 2 while the Incipient failure category was given a rating of 1. The Unknown failure category was excluded. The criticality rating was then used as a power for the flat rate. This organising means that a degraded failure carries more costs and higher risks than an incipient failure.

The RUL costs were modelled using the investment cost of the unity multiplied by the remaining useful life and then divided by the mean time between failures (MTBF) for that unit. This representation means that the RUL cost for each unity will be unique and depend on whether the unit in question is unique to this system e.g. compressor, separator etc. or more common and off the shelf e.g. sensors. The cost of RUL can be seen in equation 2. In equation 2 λ is the failure rate.

$$CRUL = I * \frac{RUL}{MTBF} = I * \frac{RUL}{\frac{1}{\lambda}} \qquad 2$$

The investment costs assumed in this thesis can be seen in Table 6. The investment costs are assumed based on engineering judgement as well as how customised the unit is e.g. a compressor will be more tailor made to this installation than a temperature sensor will be.

Table 6: Investment costs

Investments	
Equipment	**Cost**
Coalescer	kr 5 000 000
Compressor	kr 9 000 000
Contactor	kr 8 000 000
Heat Exchanger	kr 10 000 000
Pump	kr 900 000
Scrubber	kr 3 000 000
Sensors	kr 500 000
Separator	kr 10 000 000
Valves	kr 750 000

The costs related to spares and tools were assumed to depend on the repair time. The higher the repair time the higher the costs. It is assumed that the longer it takes to repair a certain failure the higher the probability that special tools or spares will be needed. The cost is quantified by a flat rate of 10 000 NOK plus a time rate of 5 000 NOK/hours multiplied by the MTTR.

The miscellaneous costs were set to 1 500 000 NOK for both doing maintenance at the current opportunity and postponing the maintenance work. It is believed that this is sufficient to cover anything that may have been forgotten.

If the unit under consideration is located in a place that is hard to reach or dismantling is needed then there may be a need for scaffolding. The need for scaffolding was determined based on the failure mode, the fault type and engineering judgment. The amount depends on user input of yes or no. If the unit requires scaffolding then costs will be higher than if scaffolding is not required. The costs of scaffolding at opportunity basis was set to 750 000 NOK if scaffolding is required and 100 000 NOK if scaffolding is not required. If maintaining the unit is postponed the costs of scaffolding was set to 600 000 NOK if required and 75 000 NOK if scaffolding is not required. The differences in costs are believed to cover the sudden need for scaffolding at opportunity basis and that there is room for more planning later.

To be able to run any simulations it was necessary to define some objectives and constraints. The objective has already been discussed. The initial constraint used in this problem was that the time of the selected maintenance jobs could not exceed the length of the opportunity. The decision to include a unit was set to be binary. If the decision variable returned as zero the unity would not be included and if it returned as one it would be included.

3.4.2 Developing the model

The model is set up in such a manner that the costs of doing maintenance on opportunity basis will occur now and the costs of delaying the maintenance action will occur some time in the future. To be able to compare a cost that occurs now with a cost that may occur in the future it is necessary to use present values. The equation used in calculating the present value can be seen in equation 3

$$P = F * (1 + p')^{-n} \qquad 3$$

In equation 3 the P is the present value today, while the F is the amount that occurs some time in the future. The p' is the interest rate corrected for inflation and the n is the time until the cost occurs in years. The interest rate will change over time depending on several factors. One of these factors is the Consumer price index (CPI). Norges Bank publishes both the key policy rate and the CPI the predictions of both can be seen in Figure 26 and Figure 27 respectively. As these figures show the CPI is expected to be stable at around 2.5 % while the interest rate is more unpredictable. In the simulations the interest rate was set to 4.7% and the inflation rate was set to 2.5%. These numbers where kept the same in all of the simulations. The time until the cost F will incur was set to 1.5 years. This time horizon seems reasonable since no unit in this case have a RUL that is longer than 3 000 hours. It can therefore safely be assumed that all of the units will have failed 1.5 years from now if no maintenance is carried out.

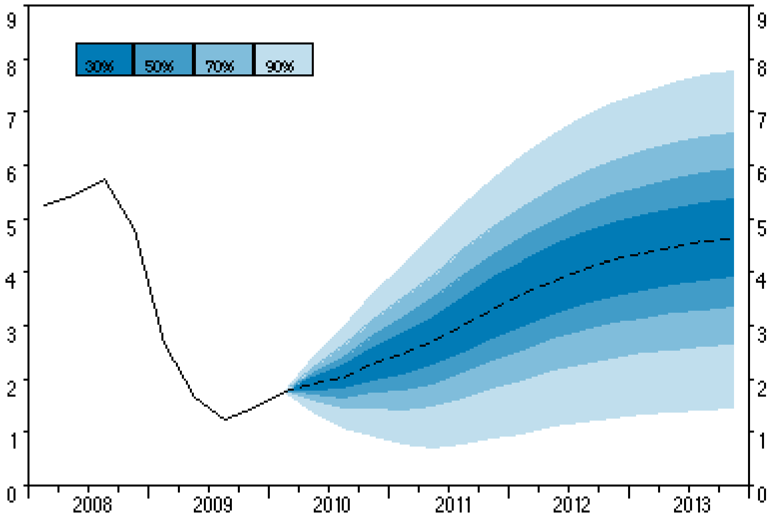


Figure 26 – Key policy rate development and prediction by Norges Bank (Norges Bank)

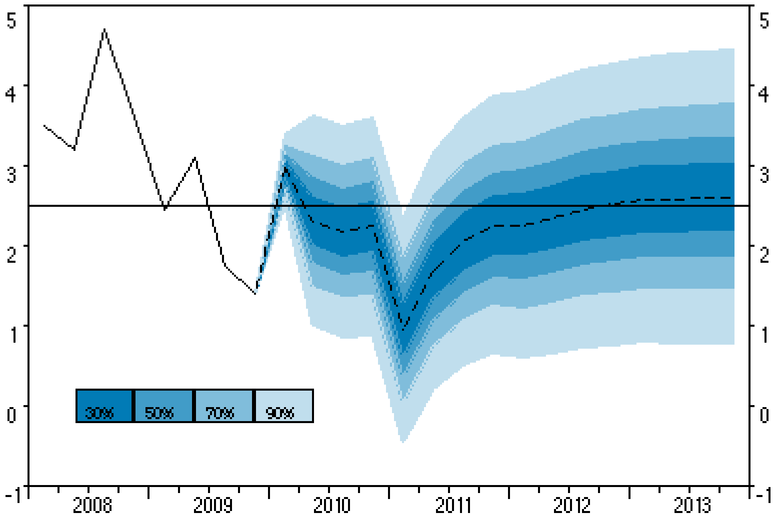


Figure 27 - CPI development and prediction by Norges Bank (Norges Bank)

The objective function that the GA should try and minimise was expressed as the costs of doing maintenance later subtracted with the units chosen for OBM subtracted by the cost for maintaining these units later. This ensures that all elements are only counted once. A mathematical expression of the objective function can be found in equation 4.

$$Z = \sum Total\ Costs_{later} - \sum_{i} Costs_{now\_i} - Costs_{later\_i} \qquad 4$$

The expected length of the opportunity can be specified by the user along with the length of the logistics delay. The time available to do maintenance was set to be the length of the opportunity subtracted by the logistics delay if a delay in the logistics chain has occurred. It is believed that this represents a more realistic view of the world than just having the whole opportunity available to do maintenance. When a delay in the logistics chain has occurred it is unlikely that the crew offshore will be able to do any maintenance work aside for minor preparations, therefore the opportunity window is reduced depending on the length of the delay. Both the length of the opportunity, length of delay and whether there will be a delay or not are all parameters that are subject to user input. A screenshot of the entire OBM model can be found in Appendix 5: OBM model.

3.4.3 Results and comments

Several issues were discovered during the development of the model. The issues have been mended as they have been discovered.

When the model had been developed to a satisfactory level some simulations where run. In this section only the minimum costs will be presented. Several scenarios of interest have been identified. One scenario should have a long opportunity (+100 hours), the second scenario should have a medium length opportunity (50 – 100 hours) and in the final scenario should have a short opportunity (< 50 hours). All scenarios where run with and without logistics delay obtaining six different scenarios in total. After each run the model is reset to not doing maintenance on opportunity basis.

Table 7: Summary of scenarios

Scenario	Length of opportunity	Length of delay	Delay included
1	120	15	yes
2	120	15	no
3	75	15	yes
4	75	15	no
5	40	15	yes
6	40	15	no

Three runs will be run for each scenario. This is done to check the results after the GA have been applied. This is important because of the random selection process applied by the GA. The random selection means that in theory different results can be obtained each time. Running three simulations is a simple check to see if the results come up the same. Ideally several runs should be made, but do to time constraints I have decided to limit myself to three runs to check the solutions. To make the results easier to read the cells containing the decision variables have been given unique names making it easier to separate them form one another. The relationship between the cell naming and the actual equipment can be interpreted as follows:

- The capital letters gives the name and type of the equipment i.e. HEST means Heat Exchanger Shell and Tube.
- The “D” or “I” after the name indicates if the failure type is either “Degraded” or “Incipient”
- The number at the end is used to separate different failure modes.

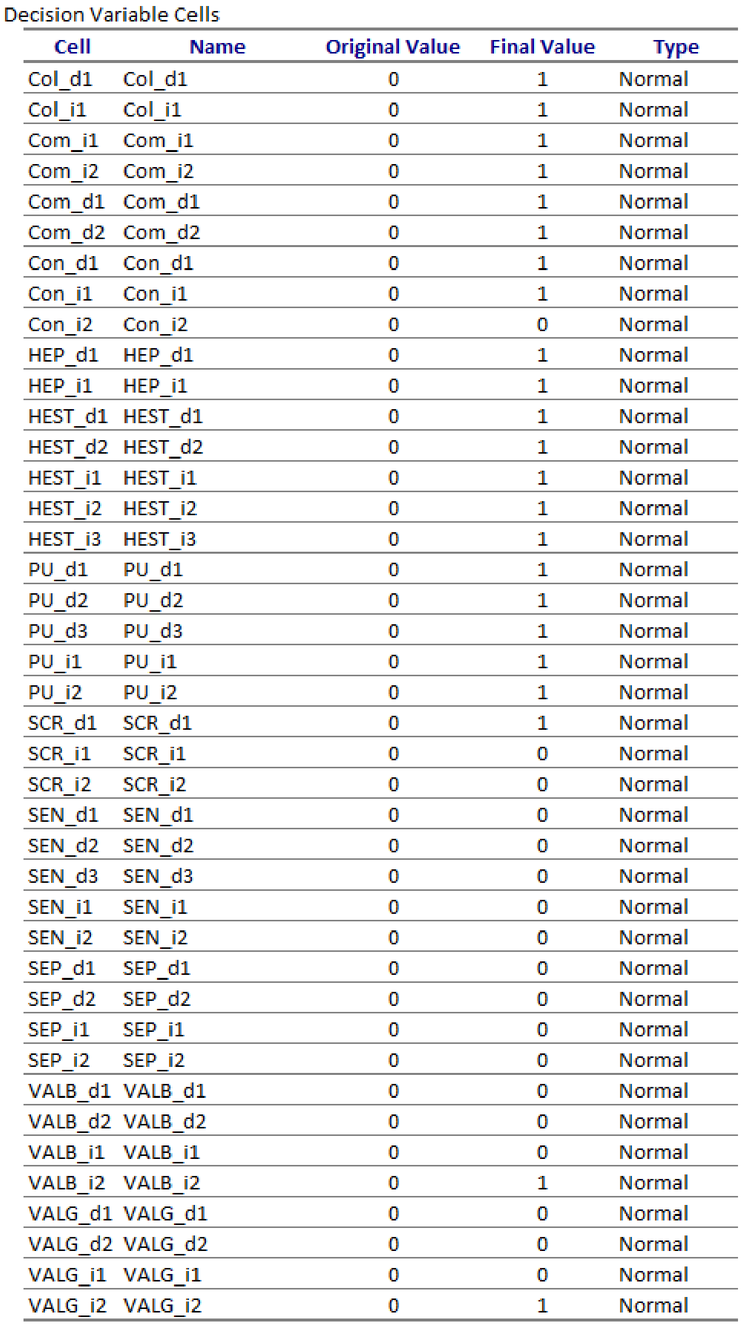
The relationship can be seen in Table 8.

Table 8: Relationship between equipment name, failure mode, type and cell name

Name	Failure Mode	Failure Type	Cell Name
Coalescer	Parameter deviation	Degraded	COL_D1
Coalescer	Minor in-service problem	Incipient	COL_I1
Compressor	External Leakage - Utility	Degraded	COM_D1
Compressor	Low Output	Degraded	COM_D2
Compressor	Abnormal instrument reading	Incipient	COM_I2
Compressor	Internal Leakage	Incipient	COM_I1
Contactor	External Leakage - Process	Degraded	CON_I1
Contactor	External Leakage - Process	Incipient	CON_I1
Contactor	Abnormal instrument reading	Incipient	CON_I2
Heat Exchanger Plate	Internal leakage	Degraded	HEP_D1
Heat Exchanger Plate	Abnormal instrument reading	Incipient	HEP_I1
Heat Exchanger Shell and tube	External Leakage - Utility	Degraded	HEST_D1
Heat Exchanger Shell and tube	Parameter deviation	Degraded	HEST_D2
Heat Exchanger Shell and tube	Abnormal instrument reading	Incipient	HEST_I1
Heat Exchanger Shell and tube	External Leakage - Process	Incipient	HEST_I2
Heat Exchanger Shell and tube	Minor in-service problem	incipient	HEST_I3
Pump	External Leakage - Utility	Degraded	PU_D1
Pump	Structural deficiency	Degraded	PU_D2
Pump	Vibration	Degraded	PU_D3

Pump	Abnormal instrument reading	Incipient	PU_I1
Pump	Minor in-service problem	Incipient	PU_I2
Scrubber	External Leakage - Process	Degraded	SCR_D1
Scrubber	Abnormal instrument reading	Incipient	SCR_I1
Scrubber	Minor in-service problem	Incipient	SCR_I2
Sensors	Erratic output	Degraded	SEN_D1
Sensors	Minor in-service problem	Incipient	SEN_I1
Sensors	Low output	Degraded	SEN_D2
Sensors	Erratic output	Incipient	SEN_I2
Sensors	Other	Degraded	SEN_I3
Separator	Plugged/Chocked	Degraded	SEP_D1
Separator	Parameter deviation	Degraded	SEP_D2
Separator	Abnormal instrument reading	Incipient	SEP_I1
Separator	Minor in-service problem	Incipient	SEP_I2
Valves Ball	Delayed operation	Degraded	VALB_D1
Valves Ball	External Leakage - Utility	Degraded	VALB_D2
Valves Ball	Abnormal instrument reading	Incipient	VALB_I1
Valves Ball	Minor in-service problem	Incipient	VALB_I2
Valves Gate	Valve leakage in closed position	Degraded	VALG_D1
Valves Gate	Other	Degraded	VALG_D2
Valves Gate	Abnormal instrument reading	Incipient	VALG_I1
Valves Gate	External Leakage - Utility	Incipient	VALG_I2

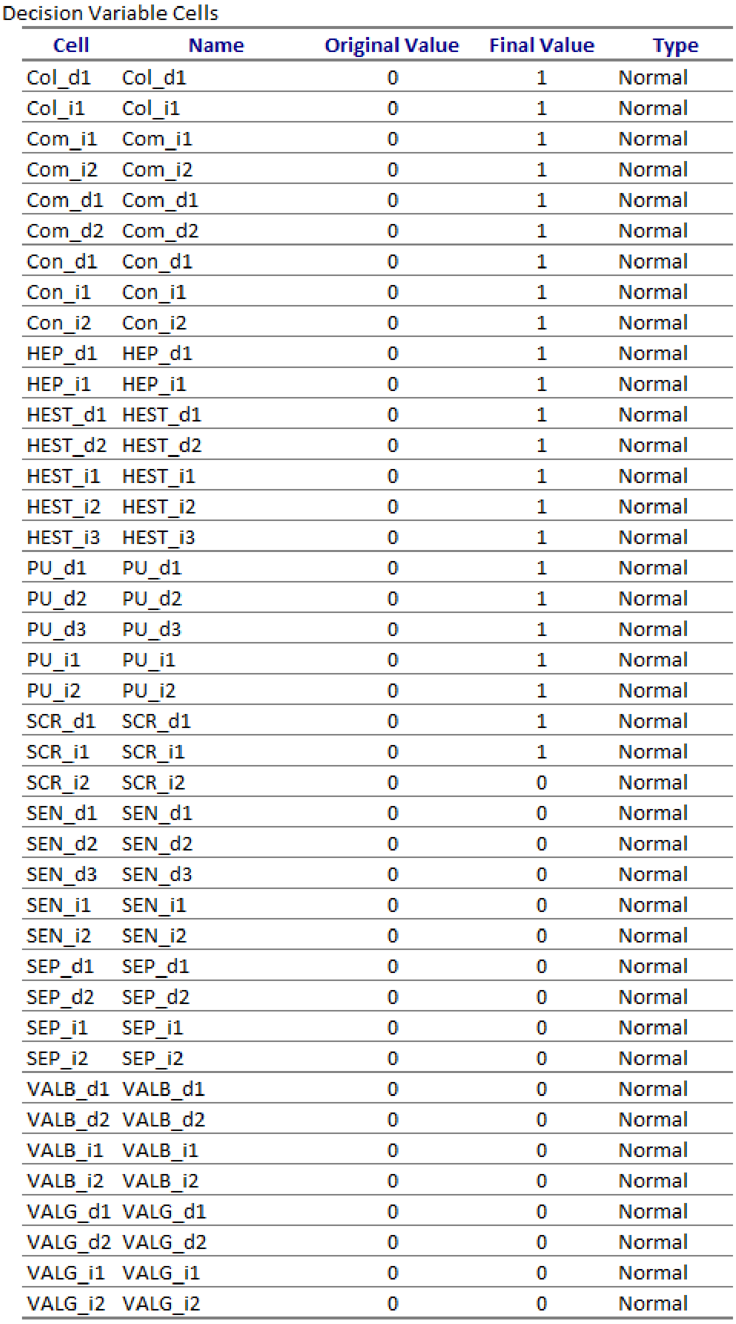
The first scenario was with a long opportunity i.e. more than 100 hours. The length of the opportunity was set to 120 hours in this case. This scenario was run without delay in the logistics chain. The length of the logistics delay was set to 15 hours. The simulation was set to run for 15 minutes. After three runs of the simulation the lowest cost for scenario 1 was 10 272 062 NOK. This result was obtained in two of the three runs indicating that this is the optimum. Interestingly the equipment selected in the two runs that obtained the minimum cost where different. But both runs selected 23 units. The total time used in scenario 1 was 119.9 hours of the 120 hours available. The results from the two runs that produced the minimum cost can be seen in Figure 28 and Figure 29. In Figure 28 and Figure 29 a one in the final value column indicates that this unit is included in the OBM scheme.



Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	1	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	1	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	0	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	1	Normal
PU_d2	PU_d2	0	1	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	1	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	1	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	1	Normal

Figure 28 - Units included in scenario 1 run 2

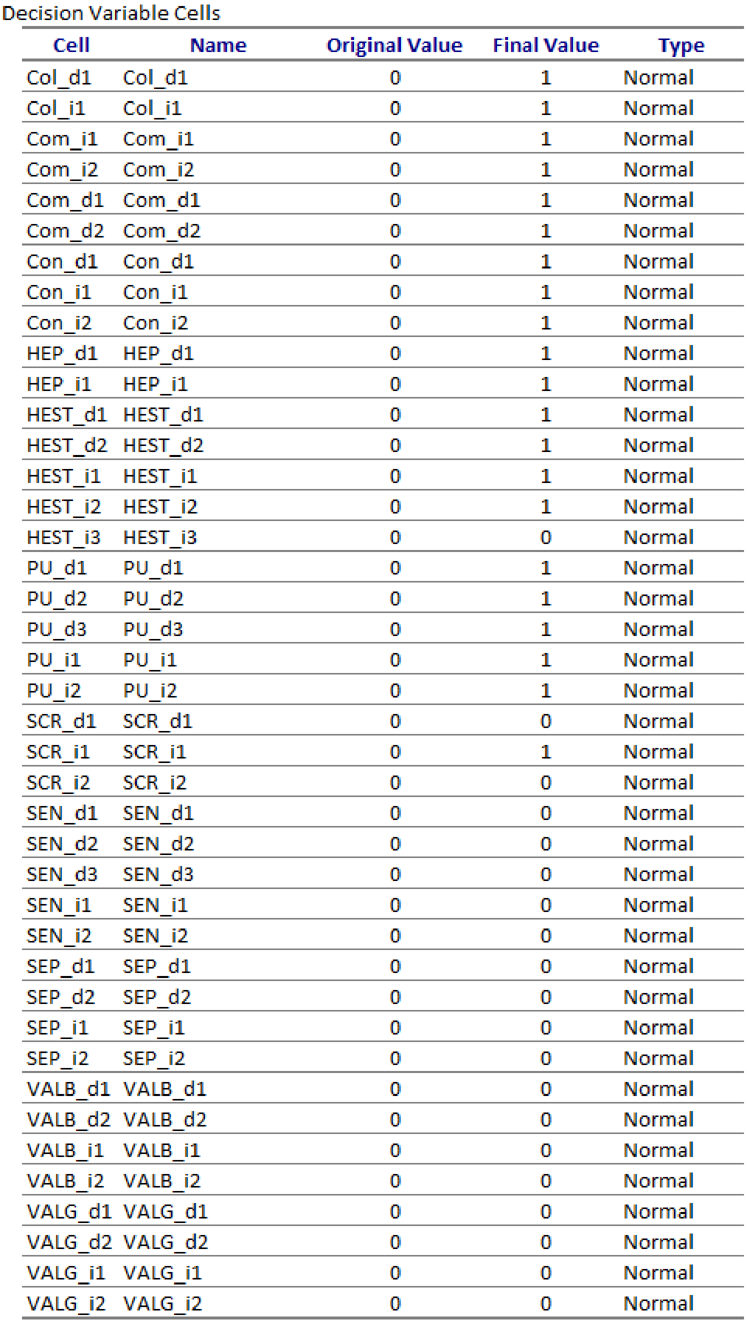


Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	1	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	1	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	1	Normal
PU_d2	PU_d2	0	1	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	1	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 29 - Units included in scenario 1 run 3

The second scenario was set up with a delay in the logistics chain and the same length in opportunity. In this scenario the time available to do maintenance was reduced from 120 hours to 105 hours i.e. the logistics delay was 15 hours. After three runs the minimum cost obtained from scenario 2 was 71 474 244 NOK. In this scenario the model included 21 units in the OBM scheme. This result was obtained in two of the three simulation runs. The units included were the same in both cases. In scenario two the time used was 104.9 hours. The units included in this case can be seen in Figure 30.

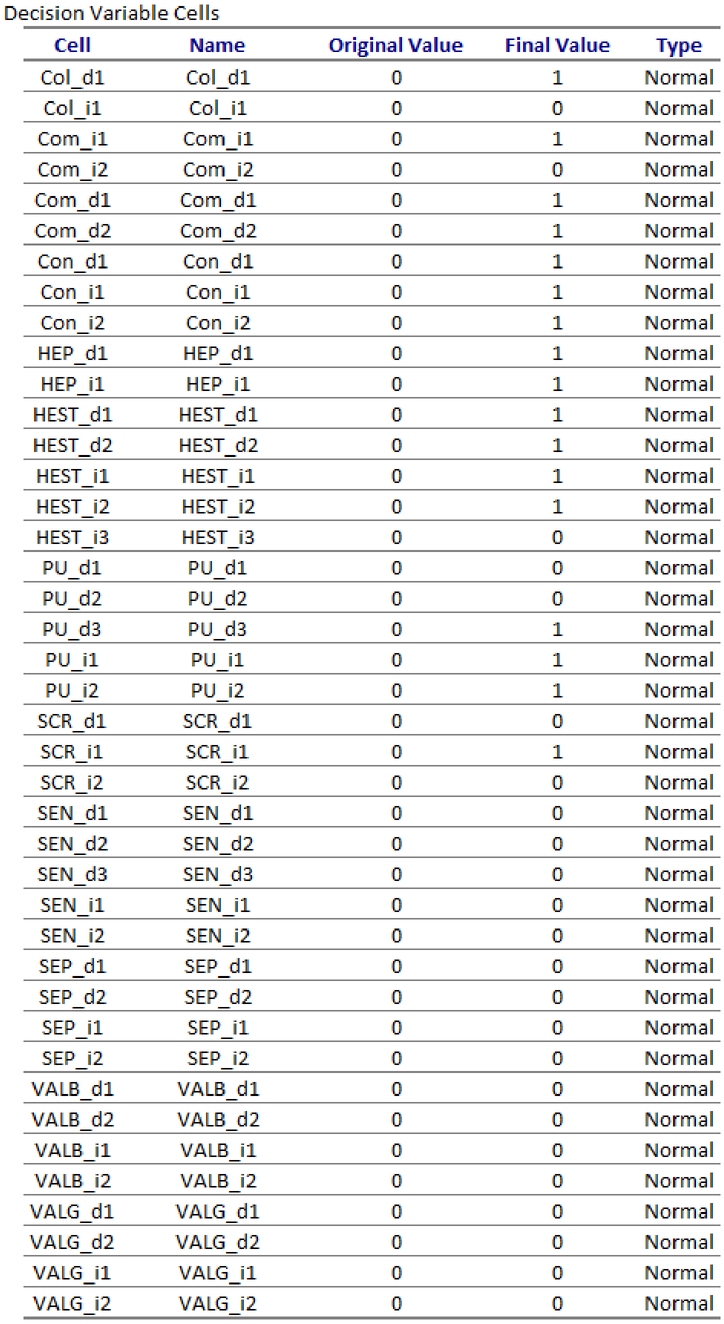


Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	1	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	1	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	1	Normal
PU_d2	PU_d2	0	1	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 30 - Units included in scenario 2

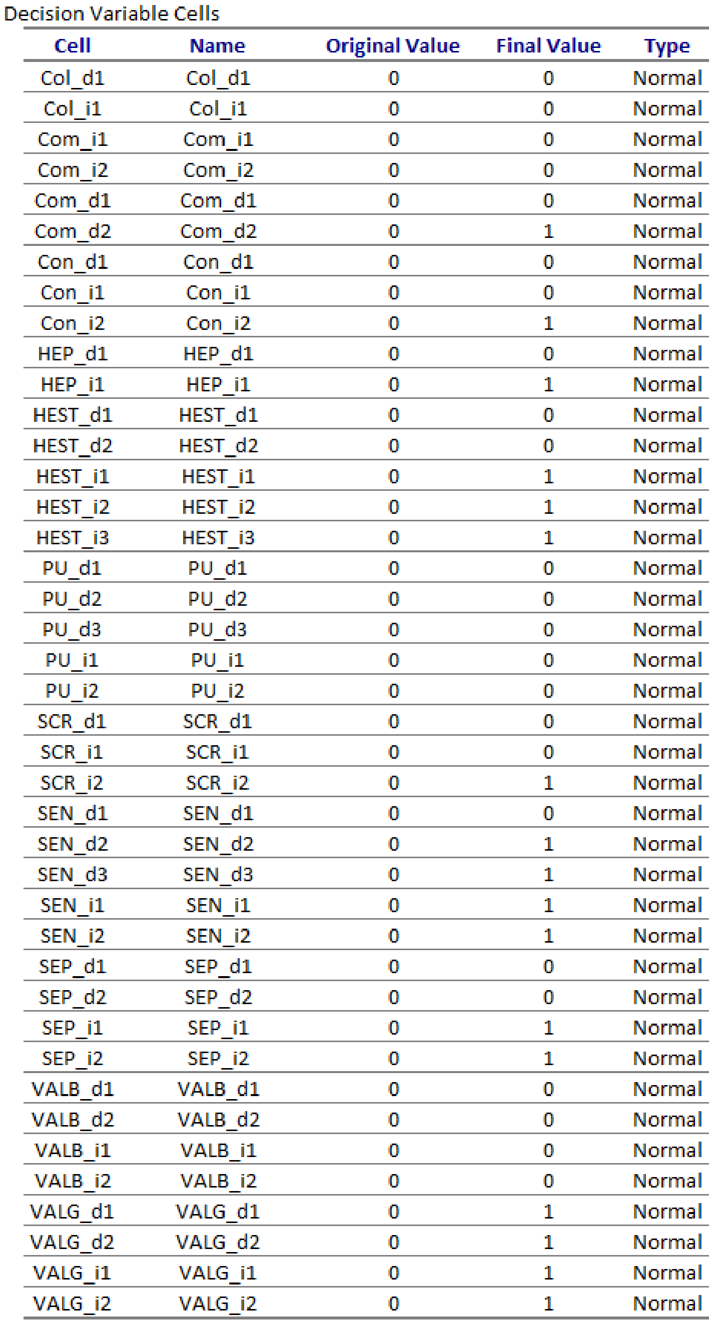
In scenario three the length of the opportunity was set to 75 hours. In scenario three the simulations were run without logistics delay. So time available for maintenance was 75 hours. After three runs the lowest costs were obtained in two simulation runs and was 180 785 167 NOK. This result was obtained using different selection in both scenarios but the number of units included in both cases was 17. The different selections can be seen in Figure 31 and Figure 32. The time used in this scenario was 75 hours.



Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 31 - Units included in scenario 3 run 1

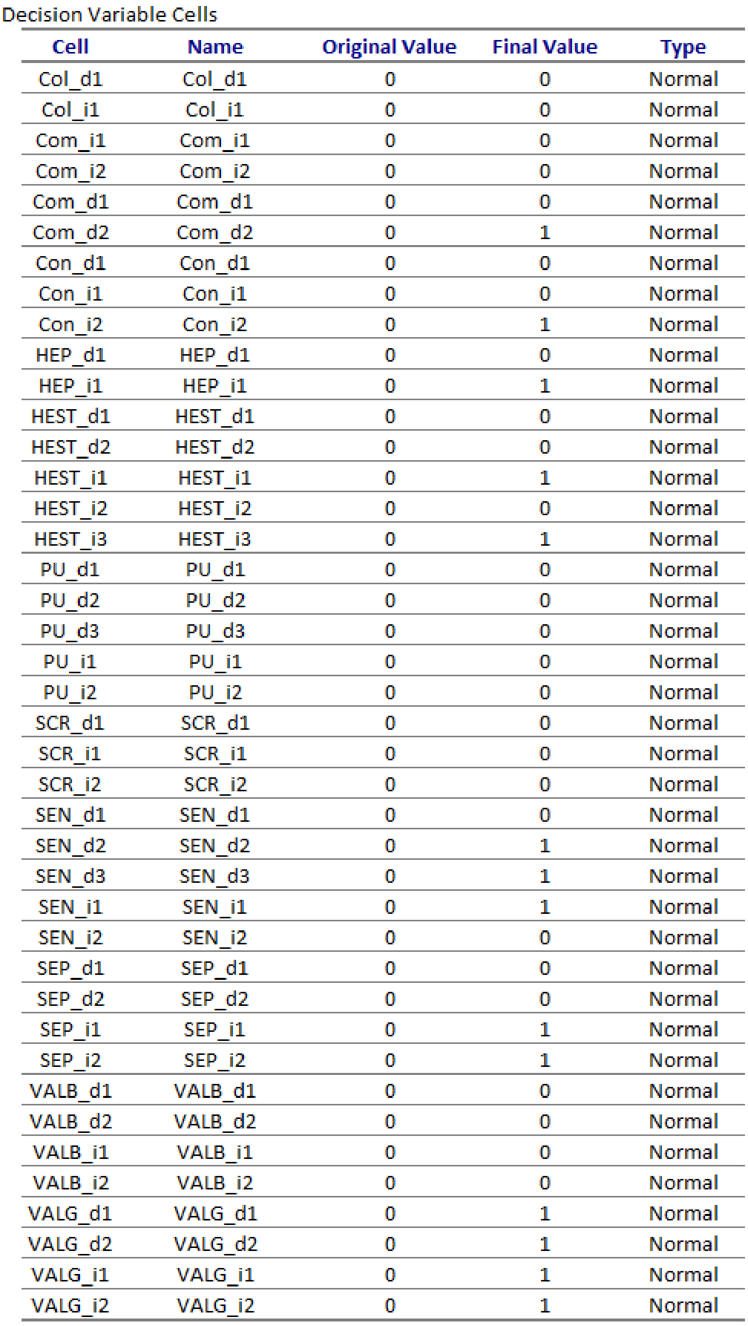


Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	0	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	0	Normal
HEST_d2	HEST_d2	0	0	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	1	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	1	Normal
SEN_i1	SEN_i1	0	1	Normal
SEN_i2	SEN_i2	0	1	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	1	Normal
SEP_i2	SEP_i2	0	1	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	1	Normal
VALG_d2	VALG_d2	0	1	Normal
VALG_i1	VALG_i1	0	1	Normal
VALG_i2	VALG_i2	0	1	Normal

Figure 32 - Units included in scenario 3 run 3

The fourth scenario was run with the same length of the opportunity as in scenario three, but in this case the logistics delay came into play, reducing the length of the opportunity to 60 hours. After three runs the lowest cost that was obtained was 254 351 906 NOK. In this simulation 14 units was included in total and the time used in this case was 58.1 hours. Figure 33 shows the units included in scenario 4.

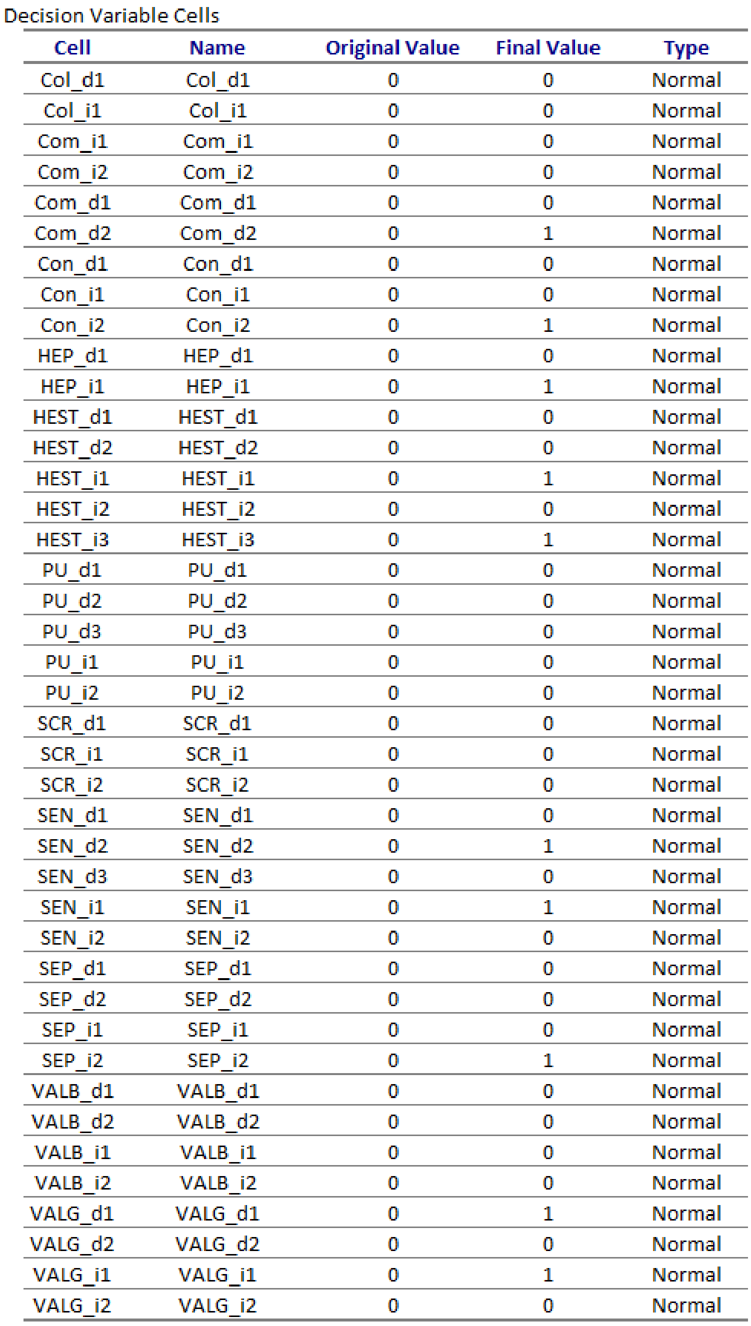


Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	0	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	0	Normal
HEST_d2	HEST_d2	0	0	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	1	Normal
SEN_i1	SEN_i1	0	1	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	1	Normal
SEP_i2	SEP_i2	0	1	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	1	Normal
VALG_d2	VALG_d2	0	1	Normal
VALG_i1	VALG_i1	0	1	Normal
VALG_i2	VALG_i2	0	1	Normal

Figure 33 - Units included in scenario 4

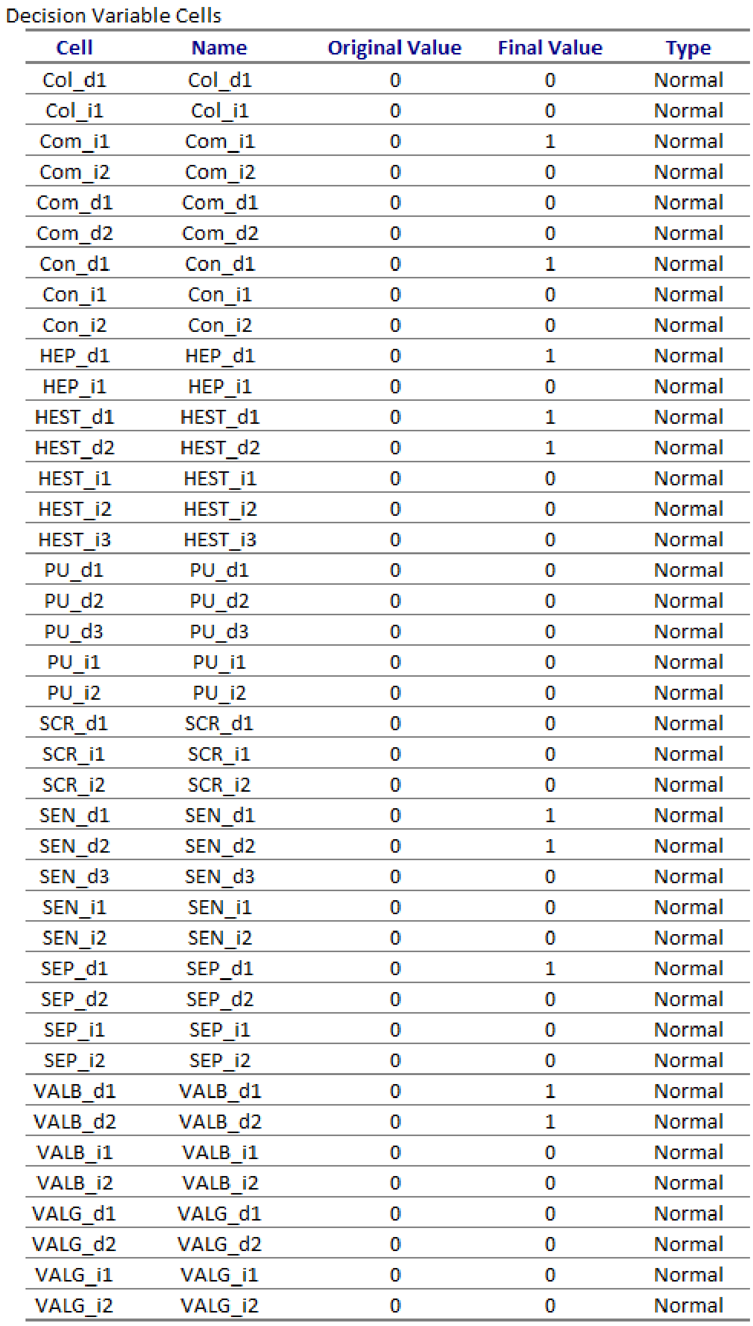
In the fifth scenario the length of the opportunity was set to 40 hours without logistics delay. After three simulation runs the lowest cost obtained in two of the simulation runs was 271 909 927 NOK. The two runs that produced the minimum cost selected different units but both produced the same minimum cost. The selection can be seen in Figure 34 and Figure 35. The time spent on maintenance in this scenario was 39.5 hours.



Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	0	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	0	Normal
HEST_d2	HEST_d2	0	0	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	1	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	1	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	1	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	1	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 34 - Units included in scenario 5 run 2

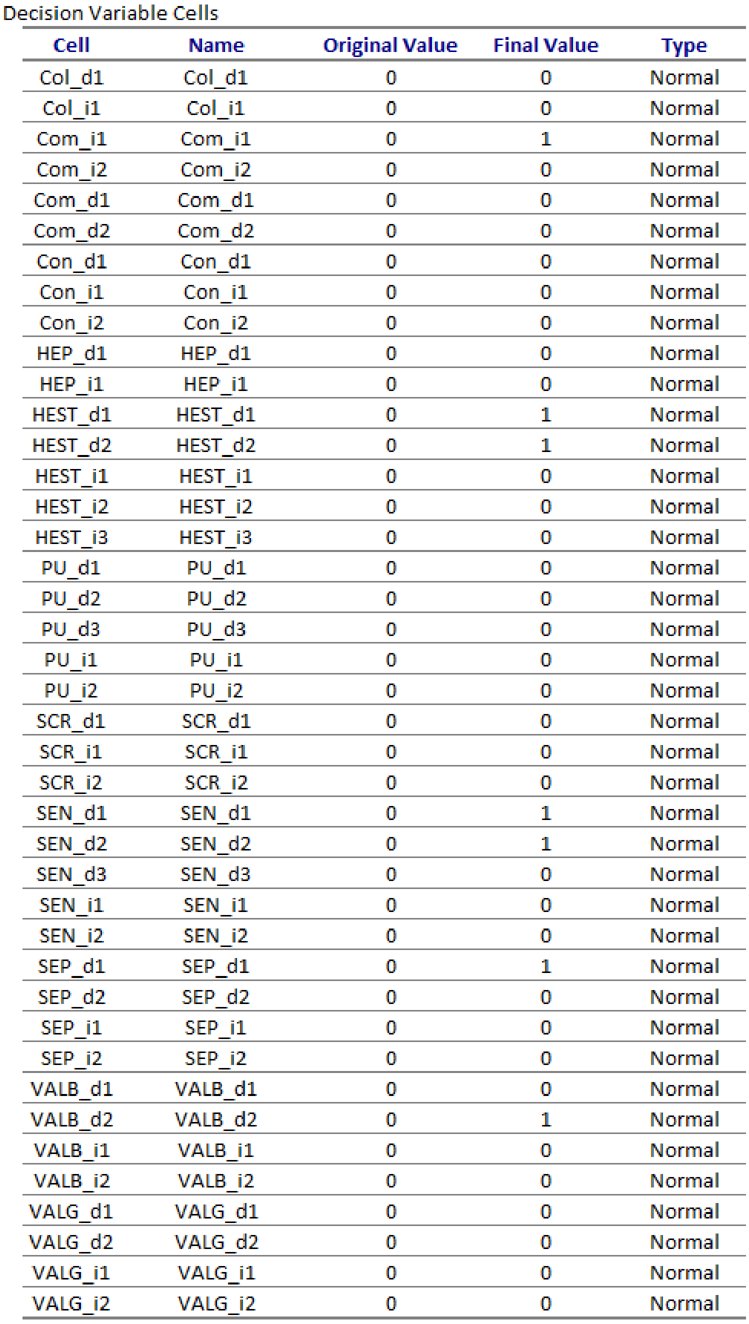


Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	0	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	0	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	0	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	0	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	1	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	1	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	1	Normal
VALB_d2	VALB_d2	0	1	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 35 - Units included in scenario 5 run 3

In the sixth scenario the length of the opportunity was the same as in scenario 5 i.e. 40 hours. However, in this scenario the logistics delay was included and thus the time available to do maintenance was reduced to 25 hours. The minimum cost in this scenario was 333 048 877 NOK. This simulation run selected 7units for OBM. The time used in this case was 24.9 hours. In this case the minimum cost was obtained by selecting the same unity in the two of the three simulation runs. Selected units for this scenario can be seen in Figure 36.



Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	0	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	0	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	0	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	0	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	1	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	1	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	1	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Figure 36 - Units selected in scenario 6

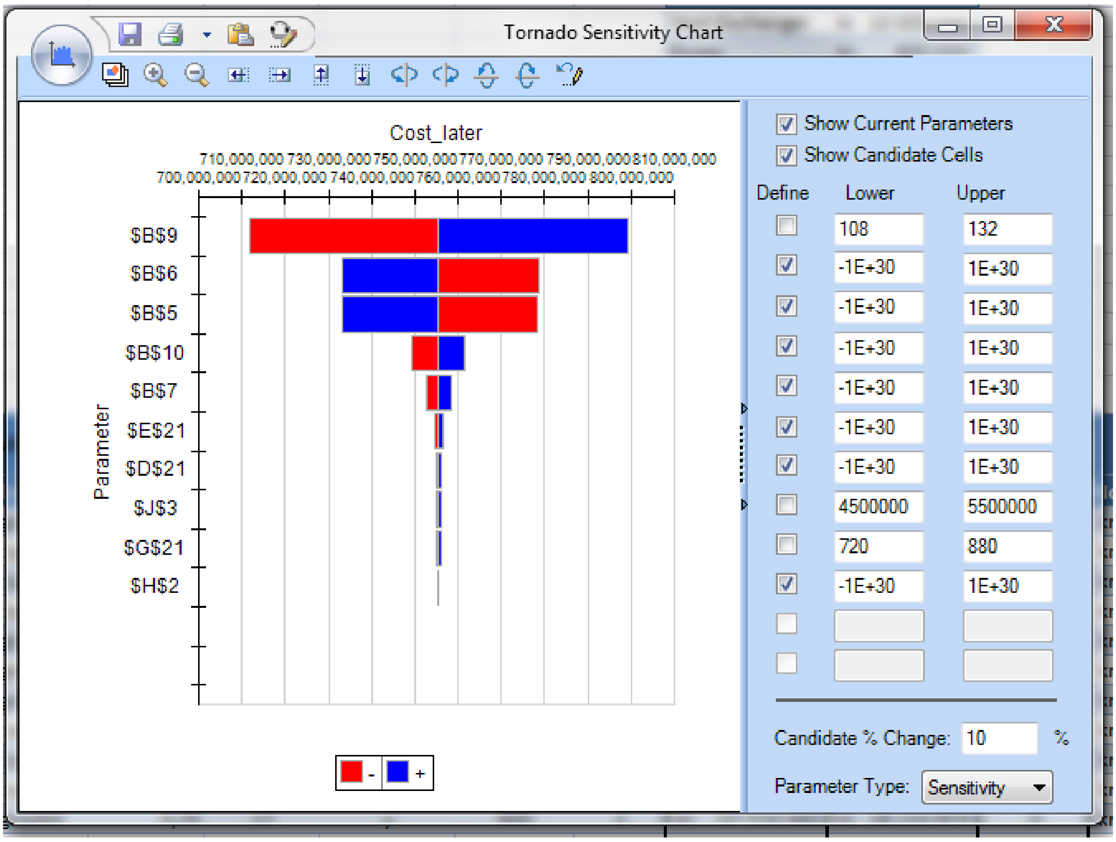
After all the simulations had been run a table was compiled summarising the results obtained. The results can be seen in Table 9.

Table 9: OBM result summary

Scenario	Minimum cost	Units included	Time available [hours]	Time used [hours]
1	kr 10 272 062	23	120	119,9
2	kr 71 474 244	21	105	104,9
3	kr 180 785 167	17	75	75
4	kr 254 351 906	14	60	58,1
5	kr 271 909 927	10	40	39,5
6	kr 333 048 877	7	25	24,9

As Table 9 shows the costs of doing maintenance on opportunity basis increases as the length of the opportunity decreases, the number of units included also decreases with the decreasing length of the opportunity.

The corrected interest rate and the time horizon will both have an impact on the present values used in these simulations. In order to determine how big this impact will be a sensitivity analysis was performed. During this analysis the inflation was kept constant at 2.5 %. By comparing the sums of postponing maintenance and doing maintenance at opportunity basis it was determined that an interest rate of approximately 25 % would be interesting to investigate further. With an interest rate at 25 % the total costs of doing maintenance on opportunity basis were higher than the costs of doing maintenance later. A new simulation was run with the interest rate at 25 %. This simulation was run with the same inputs as scenario number one. This scenario was run for 5 minutes to get a quick result. It should be noted that an interest rate of 25 % is much higher than the interest rate predictions published by Norges Bank (Figure 26). The result from this simulation was that the total cost of OBM became – 78 541 140 NOK. This result was not unexpected as the goal of the model is to minimise the costs associated with OBM. When the costs of postponing the maintenance work to a later date are lower than those of doing maintenance now and the way that the objective function have been defined a negative result is not out of the question. This selection included 23 units and spent 119.9 of the 120 hours available. To get a result comparable to the results obtained earlier an additional constraint was added. This constraint stated that the objective function had to be larger or equal to zero. During this simulation the time horizon was kept the same at 1.5 years from now. As already discussed in section 3.4.2 the time horizon and its impact will not be investigated further. With the new constraint the simulation minimum cost was 148 772 NOK this selection included 21 units and spent 119.8 of the 120 hours available. In Figure 37 a screenshot of a parameter analysis of the total costs later can be seen. The figure show how big an impact the value of different cells has on the final results. In Figure 37 cell B9 is the length of the opportunity, B6 is the interest rate and B5 is the time horizon. Figure 38 show the same analysis but this time for total costs now. In this figure H3 is the criticality rating and B9 is the length of the opportunity. A red column in Figure 37 and Figure 38 indicates a negative impact on the final value of the cell and a blue column indicates a positive impact.



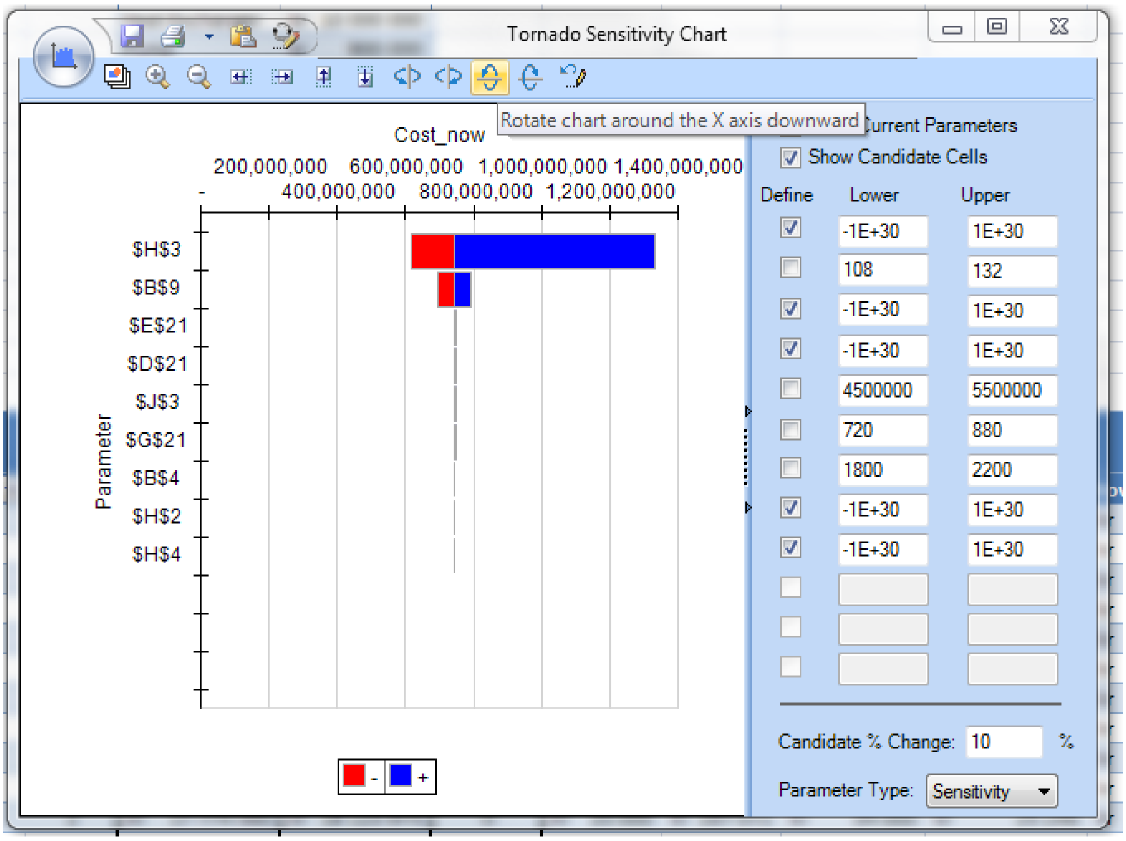
☑ Show Current Parameters
☑ Show Candidate Cells

Define	Lower	Upper
☐	108	132
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☐	4500000	5500000
☐	720	880
☑	-1E+30	1E+30
☐		
☐		

Candidate % Change: 10 %

Parameter Type: Sensitivity

Figure 37 - Screenshot from parameter analysis of total costs later



urrent Parameters
☑ Show Candidate Cells

Define	Lower	Upper
☑	-1E+30	1E+30
☐	108	132
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☐	4500000	5500000
☐	720	880
☐	1800	2200
☑	-1E+30	1E+30
☑	-1E+30	1E+30
☐		
☐		
☐		

Candidate % Change: 10 %

Parameter Type: Sensitivity

Figure 38 - Screenshot from parameter analysis of total costs now

One last simulation was run with a more realistic interest rate of 8 %. After one simulation that ran for 5 minutes the minimum cost was 13 973 002 NOK. This selection included 22 units and used 118.1 of the 120 hours available.

From Figure 37 it can be seen that the interest rate (B6) is one of the parameters that has the potential to greatly influence the results in both a positive and a negative direction. The time horizon (B5) also has the potential to influence the result but as already discussed this effect can be neglected. As shown above the interest rate needs to be at an unrealistic level (approximately 25%) before any real impact will materialise.

4 OBM and logistics planning

Planning of the logistical needs of any facility or technical system should ideally start in the concept development phase. It is important to consider logistical aspects in all phases of the life cycle of any system. A supportability analysis can in this respect be very useful. The supportability analysis is the foundation on which logistical requirements are founded (Blanchard, 1998). The supportability analysis will influence the shape of plans later in the design process.

In the operational phase ongoing improvements to support plans and capabilities made or assumed in earlier life cycle phases are made. The changes are implemented through reporting of operational and maintenance data. This data is first collected before it is analysed. The results are used to improve the supportability analysis from an earlier life cycle phase. The updated supportability analysis is in turn used in the procurement process for additional spares. Major problem areas are also noted and recommendations for corrective actions or improvements are initiated where possible. This iterative process is illustrated in Figure 39.

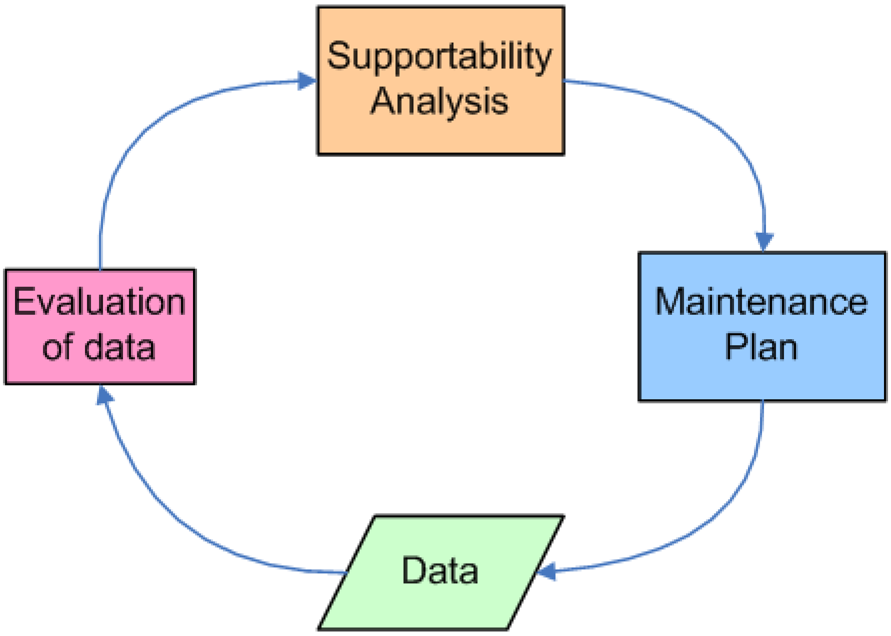


Figure 39 - SA cycle

The maintenance planners have demands for spares, tools and people that need to be satisfied by the logistics planners. In order to meet these demands the logistics planners require input from the maintenance department. The input could include priority of certain spares or tools as well as the size and weight of what is to be shipped to the facility.

4.1 Logistics planning and maintenance today

Most offshore operations today are divided into three different areas of responsibility:

1) Drilling and well construction
2) Reservoir and production management
3) Operations and maintenance

These three entities relays on a common logistic supply support. When it comes to maintenance it is common to use an overcapacity strategy (Brurok & Sleire, Opportunity Based Maintenance in offshore operations, 2009). The overcapacity strategy is designed in such a manner that the total scheduled activity never exceeds a limit of the total available capacity at any time e.g. 70%. This ensures that unforeseen events such as sudden failures can be handled by the remaining capacity e.g. 30%. However even with this overcapacity strategy some jobs are still postponed to the next period. A job can be postponed due to failures requiring immediate attention or delayed logistics support vessels due to weather conditions. In the end jobs from earlier planning periods accumulate. It should also be noted that a job cannot be scheduled until it has been technically planned meaning instructions, safe job analysis, required skills, tools, materials etc. needs to be defined before the job can be scheduled.

If maintenance tasks are grouped together costs can be shared. Examples of cost that can be shared includes logistical support cost related to tools and transportation of personnel and spares both offshore and possibly to the supply base as well, down time costs, costs associated to administration, coordination and planning as well as completion and documentation. When organising maintenance tasks into maintenance packages it is beneficial to organise groups that require similar resources such as tools, competencies, transportation, personnel etc. In addition it is important to look at what systems that are interconnected. If one system is shutdown for maintenance then it is a good idea to identify other equipment that can be maintained at the same time without requiring further maintenance shutdowns. The condition of the equipment is also important when organising maintenance packages. When is it sensible to do maintenance? Is it possible to continue and risk a shutdown due to failure or should an opportunity be exploited since the maintenance shutdown is planned anyway. Other aspects to consider are the maintainability and access. If major components must be dismantled to do maintenance it is wise to inspect and possibly maintain other components at the same location. Doing so will reduce the need for major dismantling later. This will help in avoiding long shutdowns later.

The nine basic elements of logistics support can be seen in Figure 40**.** Each of these nine elements needs to be considered in some way when maintenance and logistics plans are made. What each element in Figure 40 contains will be described in the following section.

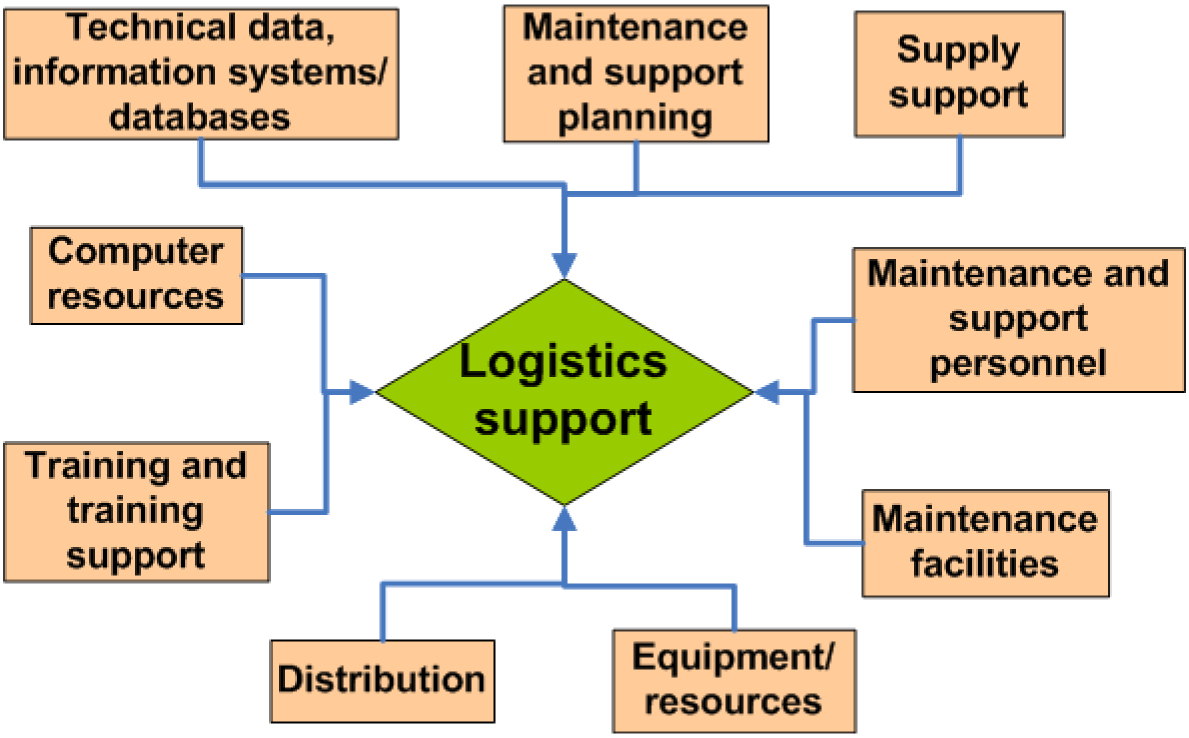


Figure 40 - Elements in logistics support

Technical data, information systems/databases is a necessary element in logistics support because this is where information regarding procedures dealing with system installation, check out and calibration and instructions regarding operations, maintenance, overhauls etc. are stored. Access to this information through out the life cycle is important. The maintenance and support planning entity contains all planning and analysis relevant for the establishment of requirements for the system through all life cycle phases. Supply support includes all spares for repairable equipment and repair parts for non – repairable equipment, consumables such as lubrication etc and special supplies to maintaining the primary mission related equipment. Supply support also includes procurement activities and documentation related to material acquisition, handling, recycling and disposal. Maintenance and support personnel category includes personnel needed for performing maintenance and support elements related to the systems primary mission. But other elements are also included such as test equipment. This category includes personnel on all levels. Maintenance facilities include facilities related to the support of scheduled and unscheduled maintenance activities. Maintenance activities at all levels need to be considered. Facilities that need to be considered include physical plant, housing, workshops and calibration laboratories. The equipment/resources category includes all tools, CM equipment, test and calibration equipment and equipment for handling all scheduled and unscheduled maintenance activities for the system in question. Equipment requirements for all levels of maintenance must be addressed. The distribution category encompasses all materials, special provisions, equipment, containers etc. needed to support the packing, handling, storing and transport of mission related elements such as personnel, spares, test equipment etc. In short the distribution category covers the transport requirements for supporting the system in performing its mission. In the training and training support category personnel, equipment, facilities, documentation and associated resources needed for training operational and maintenance personnel is located. This category contains resources for both initial and replenishment training. Equipment such as simulators, mock ups etc. used in both informal day to day training as well as more formal training can be developed when required. The last category of basic logistics support elements is computer resources. This category includes computers, software, interfaces and networks necessary to assist in scheduled and unscheduled maintenance activities. Software for CM, diagnostic tapes, etc. can also be included in this category.

Today supply chain management is the technical term most used when it comes to logistics planning. Supply chain management involves managing a network of businesses involved in providing a product or service package as required by the end customer. Supply chain management spans all areas from point of origin to point of consumption i.e. the supply chain (Wikipedia, 2010). Supply chain management must address problem areas such as the configuration of the distribution network, the distribution strategy, information flow, managing inventory, cash flow and trade – offs in logistics activities. Of particular importance for the interaction between maintenance and logistics planning today is the distribution network configuration, information flow and inventory management. The configuration of the distribution network is important because it defines the number, location and network mission of different suppliers, production facilities, warehouses etc. In other words the configuration of the distribution network defines how many, where and what. Information flow is important because sharing of information regarding demand signals, forecasts, inventory levels etc. will enable better collaboration between different actors along the supply chain. A challenge is to decide who and how much information different actors in the supply chain should be privy to. Having an overview of the inventory through inventory management will help in managing the supply chain through improved information regarding the quantity and location of inventory such as spares and tools. Inventory management could also be extended to include where in a repair cycle repairable items are. All these factors are important when planning logistics activities. Depending on the demand from the maintenance planners different modes of transport between suppliers, warehouses, base and offshore needs to be considered to minimise the logistics costs as well as the maintenance downtime.

Trade – Offs in logistics activities may be needed and finding an optimal solution can be challenging. Close coordination of all elements involved is required to obtain the lowest total logistics cost. An example from road transport illustrates this point. The rates for full truck loads are more economical on a cost pr. load basis compared to less than full loads. But transporting only full trucks may increase the costs associated with keeping inventory and warehousing thus full load transport may not be the option that delivers the lowest total logistics cost. As the hypothetical example illustrates the whole supply chain needs to be considered when making decisions affecting the whole supply chain. The same point applies to transportation to and from offshore facilities.

In order to deal with deviations in the supply chain supply chain event management can be used. Supply chain event management considers all possible events and factors that can disrupt the supply chain. Different scenarios are created and solutions can be found.

Vulnerability assessment is another method of identifying and mitigating unwanted events that may influence the supply chain. The vulnerability assessment differs from risk analysis in that the focus is different. While risk analysis focuses on human, environmental and property impacts of an accident, Vulnerability analysis is focused on the system mission and the survivability of the system (Asbjørnslett, 2009).

4.2 OBM influence on logistics planning

A transition to a maintenance philosophy where OBM is predominant is challenging because opportunities occur at a short time horizon and therefore the organisation needs to utilise short term maintenance planning which in itself is challenging. However there are several benefits of implementing OBM as a part of the organisations maintenance plan. One of the largest contributors to operational expenditures is lost production. Implementing OBM will therefore be beneficial as little or no extra production is lost, aside form what already has been lost in the event that triggered the opportunity. OBM will also keep logistical support costs at a minimum as OBM efficiently utilises the same resources. If the goal is to reduce down time costs and increase availability, while keeping HSE (Health, Safety and Environment) levels, system reliability and functionality at the required level then OBM is the answer.

The oil and gas industry today only uses OBM to a limited extent (Brurok & Sleire, Opportunity Based Maintenance in offshore operations, 2009). The reason for this is that the cost of lost production greatly overshadows the benefit of exploiting an opportunity. This reason is a cultural issue where fixing a fault is valued higher than exploiting opportunities triggered by mishaps and plan deviations. The lack of the total picture also restricts the ability to see the benefits from utilising opportunities.

If a maintenance strategy based on OBM is implemented there will be an impact on the logistics planning. Areas such as availability of spares, tools, personnel and procedures etc. can be impacted if an OBM strategy is implemented. To reduce the probability of logistical delay due to these factors the establishment of standard procedures and increased levels of training for offshore personnel can be beneficial. This will help in making the planning period ahead of maintenance jobs shorter as well as to a large degree eliminate the need for specialised personnel. Should specialised personnel still be required it may be enough to have the specialist at the OSC and not offshore. The specialist will then guide the offshore crew in the maintenance work. Communication between the OSC and offshore is done using ICT. To ensure that spares and tools are available when they are needed an increased use of pre – positioned spares and tools can be used either offshore or at the supply base. If space is limited offshore or at base supplier retention guaranteeing that tools and spares will be available in a short time can be used as an alternative. Predefined procedures will to a large degree eliminate the need for planning and performing analyses such as safe job analysis before a job can scheduled. Having procedures in place that clearly defines what is to be done along with what is required to get the job in place will also make the job of the logistics planners easier as well as giving them more time to plan and procure the necessary services.

As discussed in section 4.1 maintenance planning influences some areas related to supply chain management. In an OBM scheme it is beneficial to put even more emphasis on these areas. How the distribution network is configured will play a larger role when it comes to OBM. The distances between suppliers, warehouses, supply bases and offshore consumers are even more important if an OBM scheme is implemented. This is because opportunities for maintenance will occur on a short time horizon and as such transporting spares, tools and people between suppliers and supply base becomes a time sensitive matter. The flow of information between the offshore production and maintenance department and the onshore OSC is important. This is the channel that communicates information regarding need for tools and spares that needs to be ordered from warehouses or suppliers. Inventory management is also important in an OBM based maintenance strategy. Having spares and tools readily available in the warehouse inventory means that purchasing of new stock does not need to be done during the time sensitive opportunity.

Organising maintenance tasks into maintenance packages is expected to contribute to better utilisation of opportunities. To effectively pick necessary spares and tools required in any given maintenance package a fully automated warehouse with radio – frequency identification (RFID) tags, identifying single pieces of equipment or an equipment category, can be used. Most RFID tags today contain two parts the first part is an integrated circuit where information is processed and stored and radio signals are modulated and demodulated. The second part is an antenna used for receiving and transmitting the signal (Wikipedia, 2010). Using RFID will help in improving the efficiency of inventory tracking and management. The idea is that an order for a maintenance package is sent to the warehouse management software. Once the order is received the automated system reads the identification tags required to build the package and then starts to pick necessary equipment and tools from the warehouse. The layout of the warehouse will depend on the supplier of the automated warehouse. But in general the warehouse will consist of metal racks with narrow aisles between them and rails running down the centre of the aisles. Along the rail a pole can travel up and down the aisle. Once the pole is in the right position a carriage travels up or down the pole to the location of the desired payload. A tool for grabbing the payload extends and either picks up the payload or delivers a new payload to the stock. The stock level for tools and spares is reported once the equipment is picked up and a warning if stock is low is sent to the purchasing department.

Some of the benefits of implementing an automated warehouse are that inventory control will improve. It will become easier to keep accurate records of available inventory. The labour productivity will improve while strain on the workers will decrease as the automated systems will take care of all the heavy lifting. Excessive handling of equipment will be reduced along with damage to tools and spares as well as misplacing tools and spares. An automated warehouse will also increase the productive capacity of existing space since the automated systems do not require the same amount of space to move around on as humans do. With an automated warehouse it is also possible to include more shelves in the height thus increasing floor space utilisation. The automated system will also contribute to lowering the response time as no one has to walk around looking for equipment in the warehouse as well as the capability to quickly move equipment from the warehouse to a packing station.

Factors speaking against an automated warehouse include the high investment costs along with a very long payback period. Having implemented an automated system to a warehouse makes the warehouse difficult and expensive to move, remove and modify. An automated warehouse will contain mechanical and software components of a high complexity and therefore problem solving and debugging is likely to require mechanics and electricians to fix. Also if a major part of the system fails the entire system will likely need to be shutdown due to the high degree of integration and lack of backup systems.

However the benefits of implementing an automated warehouse seem to outweigh the drawbacks and limitations, but a cost – benefit analysis may be required in order to verify this.

With reference to Figure 40 the following categories will be influenced by adopting an OBM strategy:

- Maintenance and support planning

- Maintenance and support personnel
- Supply support
- Facilities
- Test equipment

The planning of maintenance and support activities and required resources will in an OBM strategy be focused on maximising short windows of time. This is due to opportunities on a general basis occurring on a short time horizon. Limited time for executing maintenance activities will mean that the support plans needs to be agile enough to handle sudden demands for capacity while still being though enough to withstand sudden changes this is also true for the organisation as discussed in section OBM Considerations2.1. Maintenance and support personnel will be influenced in a similar manner as the planning activities. An OBM strategy will in general be dominated with long periods of low demand and short bursts where the demand is high. Savings can potentially be made by having a smaller permanent staff and hire subcontractors when the demand exceeds what the permanent staff can handle (Rasmussen, Operation Technology; Maintenance, 2002).

The supply support category will be influenced by the sudden raises in demands during opportunities before stabilising to a lower level during normal operations. This may lead to higher storage and warehouse costs during sustained normal operations. An alternative could be extended use of supplier retention as described earlier to reduce some of the storing and warehousing costs.

In an OBM strategy the facilities need to be designed so that the through put is high and the service time is as short as possible while still fulfilling requirements to HSE and the quality of work. High through put and short service time is essential as opportunities to do maintenance are short and the total downtime of the system as a whole should be kept at a minimum.

It is important that the location of tools and equipment for CM, testing and calibration is kept within reach. This will ensure a more efficient utilisation of opportunities for either maintenance or inspections and help in keeping the total downtime of the system as low as possible.

5 Conclusions

This master thesis covers the areas of offshore operations dealing with condition monitoring and opportunity based maintenance. How OBM can and may effect the organisation and what is required of an organisation that wishes to start utilising OBM have been discussed. Organisational factors that needs to be considered or in place before OBM can be implemented includes: resilience, agility, standard operating procedures, OSC and prepositioning of spares at supply base or through supplier retention. Technical aspects that need to be considered before OBM is implemented includes spare parts, need for scaffolding, RUL of unit in question etc. The technical aspects have been implemented into a flowchart (Figure 2). The OBM flowchart can also be used as a general guide when it comes to prioritising equipment for OBM.

A FMECA has been performed on a simplified process line for oil and gas. The purpose of the FMECA is to identify critical equipment that should be considered for CM. The critical equipment in this case included heat exchangers of shell and tube type and compressors of the centrifugal type. Valves also had the potential to be selected for CM but were neglected due to time constraints as well as heat exchangers and compressors had more failures ranked as critical.

Based on the equipment found to be most critical in the FMECA general CM methods have been described with emphasis on detection method, data collected, application and elements that should be considered when implementing this kind of CM. Specific CM methods that can be used to monitor the failures found to be most critical in the FMECA have also been discussed. Some industrial solutions and CM software packages have also been discussed where appropriate. For compressors Vibration, power and load monitoring are possibilities. For heat exchangers HXAM or a similar real time performance monitoring scheme is the only option that does not require major dismantling.

Based on the OBM scheme some optimisations have been run using GA. In total six scenarios were run. The length of the opportunity was varied between short and long. Two scenarios were run with the same opportunity. One of the scenarios had a delay in the logistics chain meaning that the time available to do maintenance was decreased. To ensure that the results obtained were the minimum cost three simulations were run for each scenario. This is due to the random selection process employed by the GA. Three simulation runs have been judged sufficient to indicate the minimum costs obtained are in fact the minimum costs. The minimum costs were lowest when the length of the opportunity was long, with decreasing length of opportunity the costs increased. This has to do with the defined objective function. A short opportunity means that most maintenance tasks have to be postponed to a later date. A simple sensitivity analysis determined that the interest rate and thus the corrected interest rate would have an impact if the interest rate became 25 % or larger. Minor changes in the interest rate will not have a significant impact on the results.

How logistics planning can be related to maintenance of Oil and Gas facilities have been discussed along with how OBM will impact logistics planning. Some measures that can help in mitigating the impact of shifting to an OBM strategy have also been discussed. Some measures that can be implemented to reduce the impact of OBM include fully automated warehouse with RFID tags identifying spares and tools. Another element that is expected to help mitigate a shift to OBM is the implementations of the support strategy used in space operations with the implementation of OSC and prepositioning of spares and tools.

6 Future work

During the spring of 2010 a new OREDA handbook was published. The updated data in this edition could potentially alter the information in the failure database along with the results of the FMECA and the OBM organisation. It would be preferable to check the data used in this thesis against the data in the new edition of the OREDA. Updates and changes should be made were necessary and the FMECA and OBM organisation should be performed again if changes have been made.

The OBM model could be developed further and made more advanced with implementing failure distributions for the failure modes. This could give better and more realistic results.

In this thesis most cost figures have been assumed based on engineering judgment. Some of these assumptions may very well be off the mark. Time and effort should be put into confirming the assumed figures used in this thesis. I have talked with some of my fellow students who needed relevant cost figures and they have told me that such figures are hard to come by. Therefore it may be difficult to get confirmation on the numbers used in this thesis.

Only detailed CM methods from ABB have been used in this thesis, this is because I know people working with this on a daily basis in ABB. Other providers of CM equipment and methods have not been contacted for detailed information. Given more time this should be done. In this thesis only some information available from company websites has been used. Interesting suppliers of CM equipment includes GE, Siemens, SKF, ValveWatch etc. Company web pages are included below:

- www.ge.com
- www.siemens.com
- www.skf.com
- www.valvewatch.com/

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Appendix

Appendix 1: Failure database

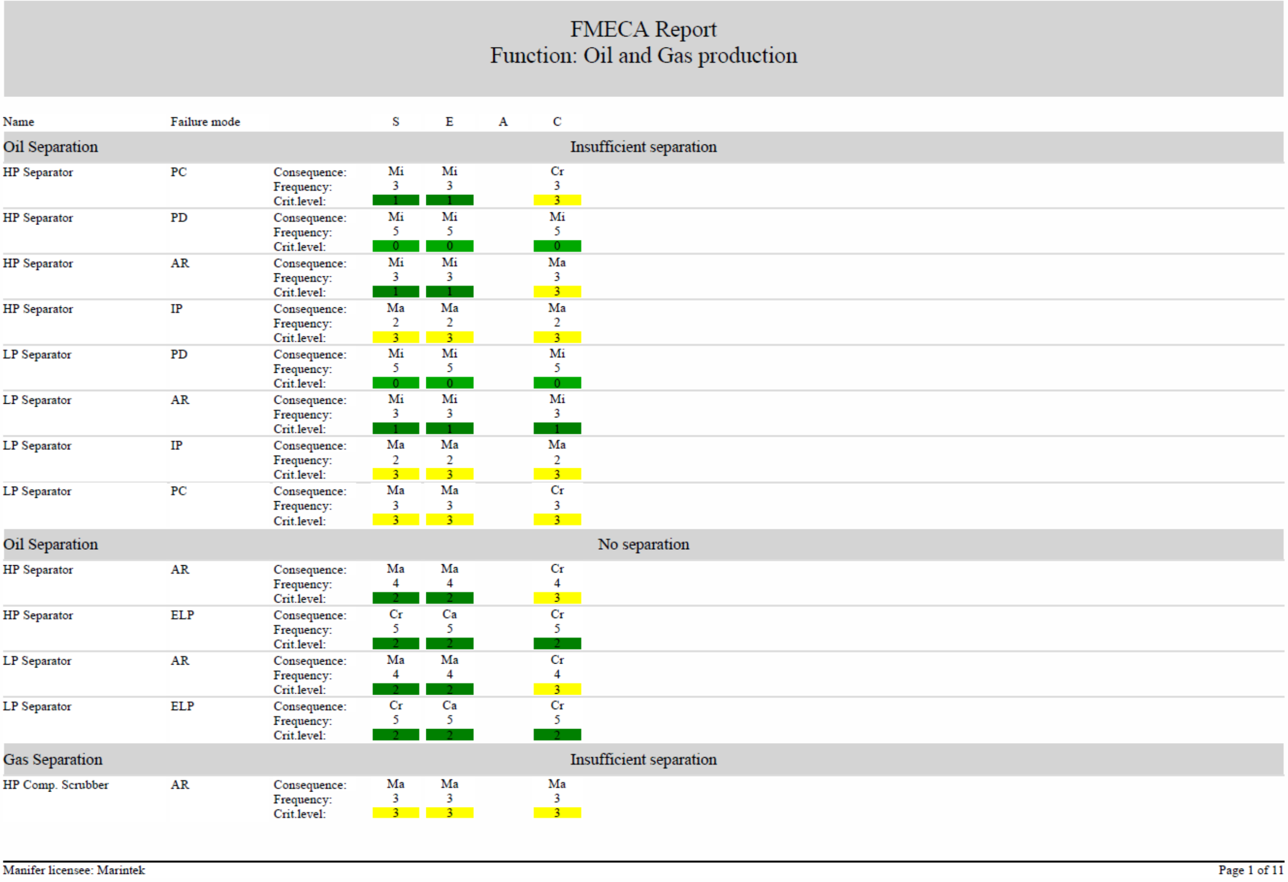
Item	Type/Use	Failure mode	Failure rate [per 10^6 h]	MDT [manhours]	Comment	Source
Coalescer						
	General	Abnormal instrument reading	14,25	6,3	Critical	3.2.1
		Parameter deviation	20,63	92,3	Critical	3.2.1
		Parameter deviation	53,34	48,4	Degraded	3.2.1
		Minor in-service problem	84,28	12,7	Incipient	3.2.1
Compressor						
	Centrifugal	Fail to start on demand	41,89	44	Critical	1.1.1
		Spurious stop	44,02	47,4	Critical	1.1.1
		External Leakage - Utility	48,64	24,1	Degraded	1.1.1
		Low Output	10,75	14,1	Degraded	1.1.1
		Abnormal instrument reading	143,25	7,8	Incipient	1.1.1
		Internal Leakage	476,62	3	Incipient	1.1.1
Contactor						
	General	Abnormal instrument reading	40,39	31,2	Critical	3.2.2
		Structural deficiency	36,15	19,5	Critical	3.2.2
		External Leakage - Process	18,47	5,7	Degraded	3.2.2
		External Leakage - Process	40,70	13,7	Incipient	3.2.2
		Abnormal instrument reading	106,37	5,9	Incipient	3.2.2

Heat Exchanger						
	Plate	External Leakage - Process	10,65	30,7	Critical	3.1.3
		Internal leakage	4,26	17	Degraded	3.1.3
		Abnormal instrument reading	8,74	3,5	Incipient	3.1.3
	Shell and Tube	Structural deficiency	6,17	81,2	Critical	3.1.5
		External Leakage - Utility	4,41	3,3	Degraded	3.1.5
		Parameter deviation	2,88	12	Degraded	3.1.5
		Abnormal instrument reading	22,99	5,8	Incipient	3.1.5
		External Leakage - Process	8,19	2,4	Incipient	3.1.5
		Minor in-service problem	17,31	18,1	incipient	3.1.5
Pump						
	Centrifugal	Spurious stop	22,56	45	Critical	1.3.1
		External Leakage - Process	7,04	42	Critical	1.3.1
		Low output	4,62	45,3	Critical	1.3.1
		External Leakage - Utility	57,14	36,3	Degraded	1.3.1
		Structural deficiency	5,75	33,9	Degraded	1.3.1
		Vibration	8,58	78,1	Degraded	1.3.1
		Abnormal instrument reading	274,18	8,1	Incipient	1.3.1
		Minor in-service problem	391,65	10,4	Incipient	1.3.1
Scrubber						

	General	Structural deficiency	5,18	19	Critical	3.2.7
		External Leakage - Process	8,88	7,5	Degraded	3.2.7
		Abnormal instrument reading	52,12	11,1	Incipient	3.2.7
		Minor in-service problem	12,50	14,5	Incipient	3.2.7
Sensors						
	Flow	Fail to function on demand	3,59	9	Critical	4.2.1
		Erratic output	2,04	4	Degraded	4.2.1
		Minor in-service problem	4,56	3,6	Incipient	4.2.1
	Level	Spurious operation	1,55	9	Critical	4.2.2
		Low output	2,43	5,3	Degraded	4.2.2
		Erratic output	3,67	7	Incipient	4.2.2
	Pressure	Other	5,55	5,3	Degraded	4.2.3
	Temperature	Fail to function on demand	3,10	4,3	Critical	4.2.4
		Spurious operation	3,10	2,7	Critical	4.2.4
Separator						
	General	Abnormal instrument reading	14,03	6,9	Critical	3.2.8
		External Leakage - Process	9,55	6,1	Critical	3.2.8
		Plugged/Chocked	29,68	4,3	Degraded	3.2.8
		Parameter deviation	8,92	6,3	Degraded	3.2.8
		Abnormal instrument reading	23,71	6,8	Incipient	3.2.8
		Minor in-service problem	49,42	8	Incipient	3.2.8

Valves						
	Ball	Fail to close on demand	5,85	9,9	Critical	4.3.1
		Fail to open on demand	3,46	9,9	Critical	4.3.1
		Delayed operation	2,13	10,9	Degraded	4.3.1
		External Leakage - Utility	2,94	14,7	Degraded	4.3.1
		Abnormal instrument reading	4,91	10,1	Incipient	4.3.1
		Minor in-service problem	5,57	3,6	Incipient	4.3.1
	Gate	Fail to close on demand	9,62	9,7	Critical	4.3.5
		Fail to open on demand	66,05	12	Critical	4.3.5
		Valve leakage in closed position	2,84	9,4	Degraded	4.3.5
		Other	4,55	5,4	Degraded	4.3.5
		Abnormal instrument reading	262,36	3,4	Incipient	4.3.5
		External Leakage - Utility	19,29	2,6	Incipient	4.3.5

Appendix 2: FMECA Report



FMECA Report
Function: Oil and Gas production

Name	Failure mode		S	E	A	C	
Oil Separation							Insufficient separation
HP Separator	PC	Consequence:	Mi	Mi		Cr	
		Frequency:	3	3		3	
		Crit.level:	1	1		3	
HP Separator	PD	Consequence:	Mi	Mi		Mi	
		Frequency:	5	5		5	
		Crit.level:	0	0		0	
HP Separator	AR	Consequence:	Mi	Mi		Ma	
		Frequency:	3	3		3	
		Crit.level:	1	1		3	
HP Separator	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	2	2		2	
		Crit.level:	3	3		3	
LP Separator	PD	Consequence:	Mi	Mi		Mi	
		Frequency:	5	5		5	
		Crit.level:	0	0		0	
LP Separator	AR	Consequence:	Mi	Mi		Mi	
		Frequency:	3	3		3	
		Crit.level:	1	1		1	
LP Separator	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	2	2		2	
		Crit.level:	3	3		3	
LP Separator	PC	Consequence:	Ma	Ma		Cr	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	
Oil Separation							No separation
HP Separator	AR	Consequence:	Ma	Ma		Cr	
		Frequency:	4	4		4	
		Crit.level:	2	2		3	
HP Separator	ELP	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
LP Separator	AR	Consequence:	Ma	Ma		Cr	
		Frequency:	4	4		4	
		Crit.level:	2	2		3	
LP Separator	ELP	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
Gas Separation							Insufficient separation
HP Comp. Scrubber	AR	Consequence:	Ma	Ma		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	

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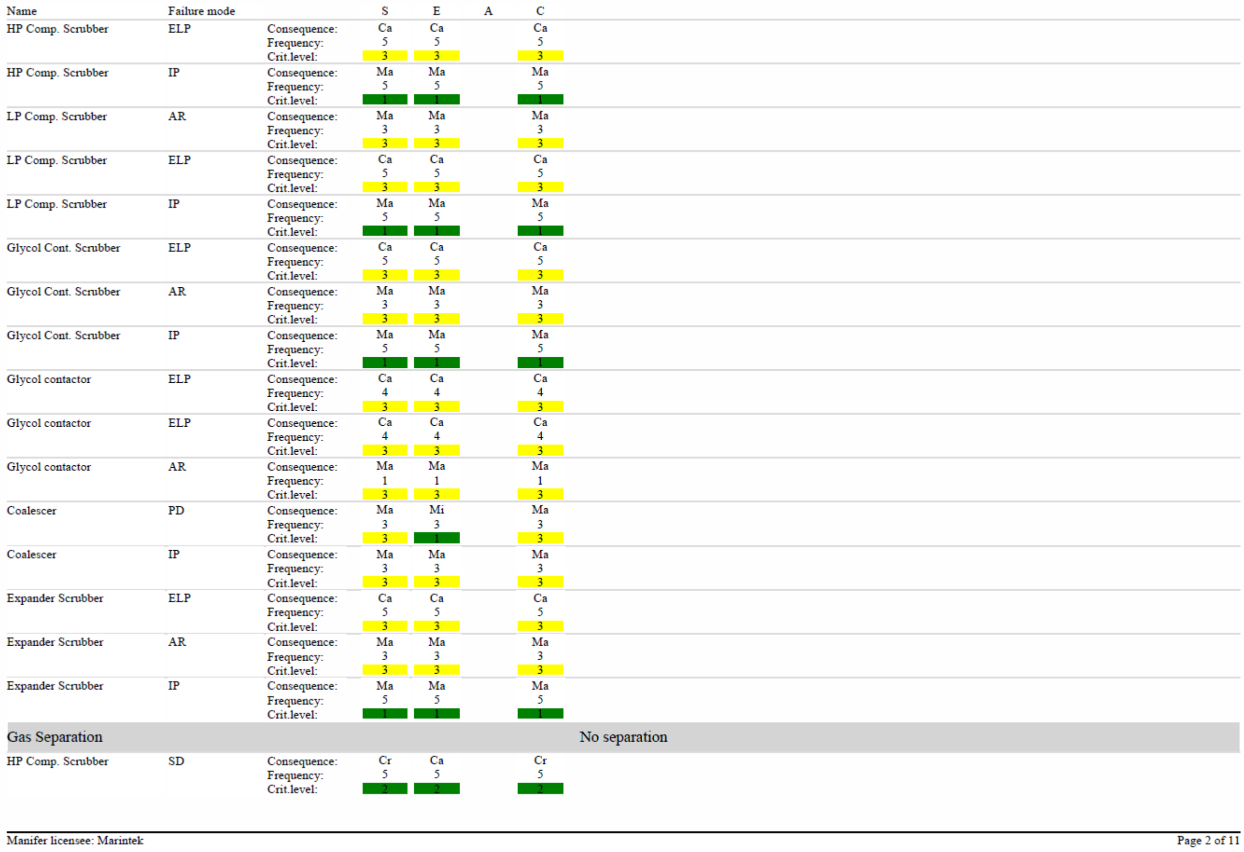

Name	Failure mode		S	E	A	C	
HP Comp. Scrubber	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
HP Comp. Scrubber	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
LP Comp. Scrubber	AR	Consequence:	Ma	Ma		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	
LP Comp. Scrubber	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
LP Comp. Scrubber	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Glycol Cont. Scrubber	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Glycol Cont. Scrubber	AR	Consequence:	Ma	Ma		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	
Glycol Cont. Scrubber	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Glycol contactor	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	4	4		4	
		Crit.level:	3	3		3	
Glycol contactor	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	4	4		4	
		Crit.level:	3	3		3	
Glycol contactor	AR	Consequence:	Ma	Ma		Ma	
		Frequency:	1	1		1	
		Crit.level:	3	3		3	
Coalescer	PD	Consequence:	Ma	Mi		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	1		3	
Coalescer	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	
Expander Scrubber	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Expander Scrubber	AR	Consequence:	Ma	Ma		Ma	
		Frequency:	3	3		3	
		Crit.level:	3	3		3	
Expander Scrubber	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Gas Separation							No separation
HP Comp. Scrubber	SD	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	

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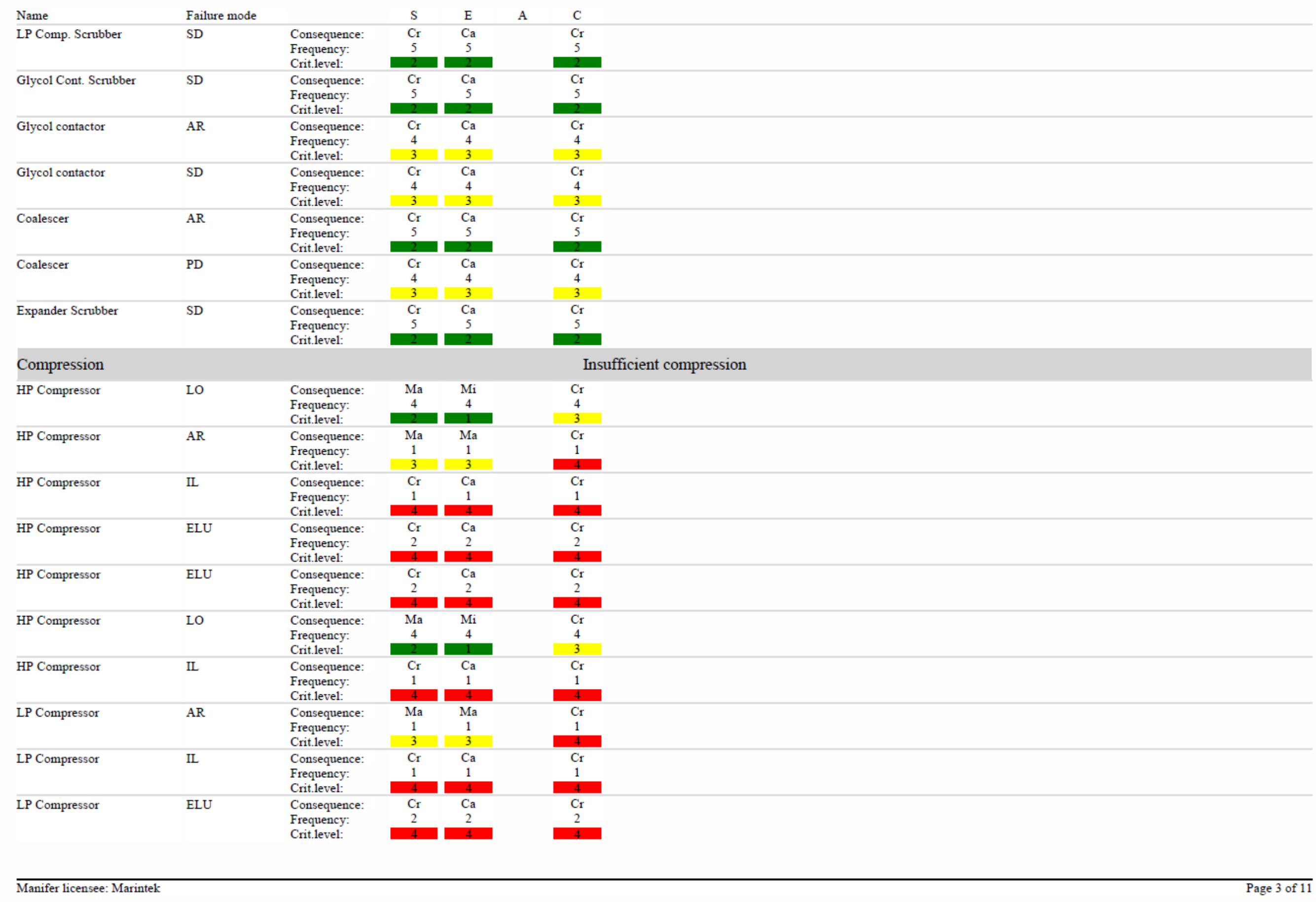

Name	Failure mode		S	E	A	C
LP Comp. Scrubber	SD	Consequence:	Cr	Ca		Cr
		Frequency:	5	5		5
		Crit.level:	2	2		2
Glycol Cont. Scrubber	SD	Consequence:	Cr	Ca		Cr
		Frequency:	5	5		5
		Crit.level:	2	2		2
Glycol contactor	AR	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Glycol contactor	SD	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Coalescer	AR	Consequence:	Cr	Ca		Cr
		Frequency:	5	5		5
		Crit.level:	2	2		2
Coalescer	PD	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Expander Scrubber	SD	Consequence:	Cr	Ca		Cr
		Frequency:	5	5		5
		Crit.level:	2	2		2
Compression						Insufficient compression
HP Compressor	LO	Consequence:	Ma	Mi		Cr
		Frequency:	4	4		4
		Crit.level:	2	1		3
HP Compressor	AR	Consequence:	Ma	Ma		Cr
		Frequency:	1	1		1
		Crit.level:	3	3		4
HP Compressor	IL	Consequence:	Cr	Ca		Cr
		Frequency:	1	1		1
		Crit.level:	4	4		4
HP Compressor	ELU	Consequence:	Cr	Ca		Cr
		Frequency:	2	2		2
		Crit.level:	4	4		4
HP Compressor	ELU	Consequence:	Cr	Ca		Cr
		Frequency:	2	2		2
		Crit.level:	4	4		4
HP Compressor	LO	Consequence:	Ma	Mi		Cr
		Frequency:	4	4		4
		Crit.level:	2	1		3
HP Compressor	IL	Consequence:	Cr	Ca		Cr
		Frequency:	1	1		1
		Crit.level:	4	4		4
LP Compressor	AR	Consequence:	Ma	Ma		Cr
		Frequency:	1	1		1
		Crit.level:	3	3		4
LP Compressor	IL	Consequence:	Cr	Ca		Cr
		Frequency:	1	1		1
		Crit.level:	4	4		4
LP Compressor	ELU	Consequence:	Cr	Ca		Cr
		Frequency:	2	2		2
		Crit.level:	4	4		4

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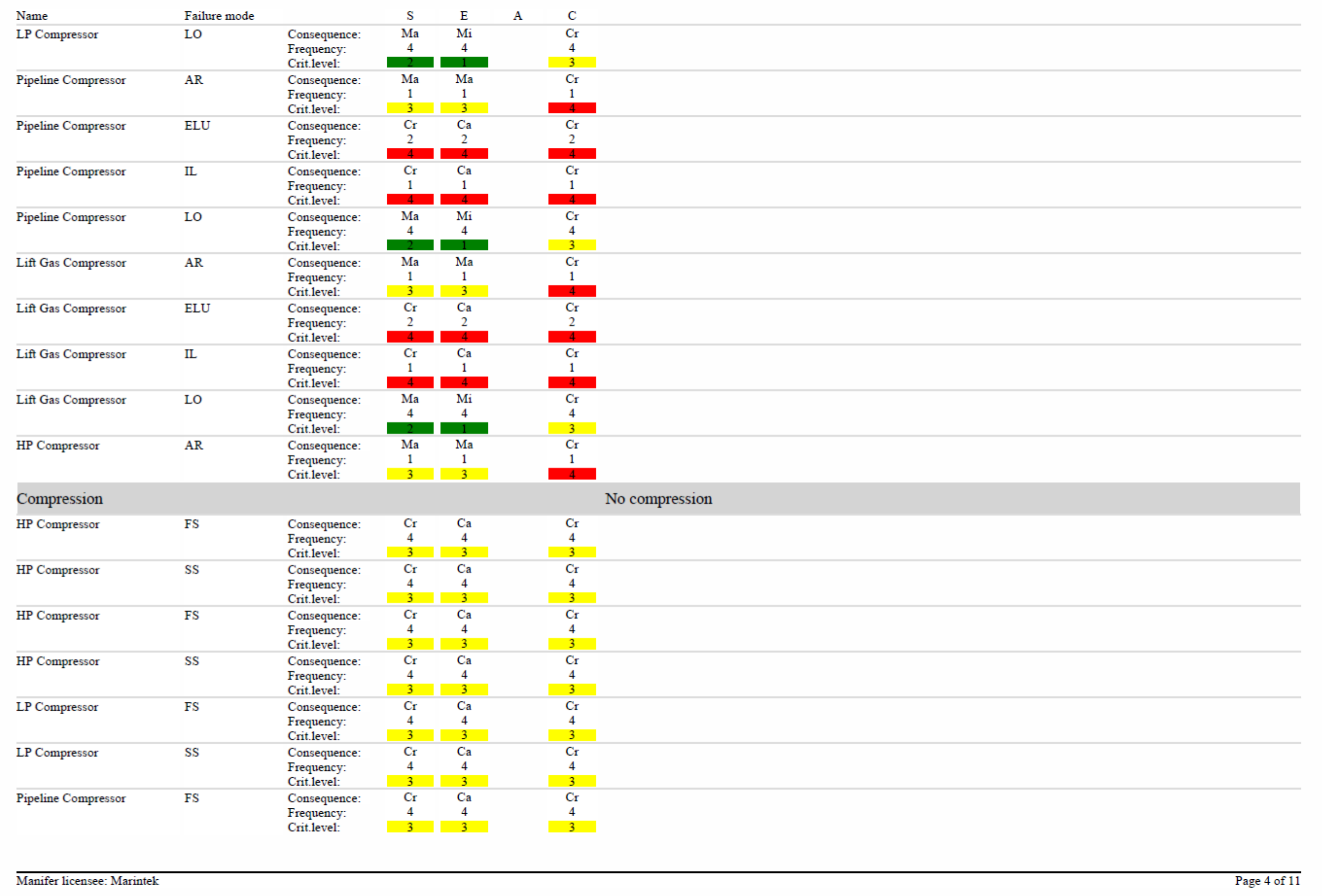

Name	Failure mode		S	E	A	C
LP Compressor	LO	Consequence:	Ma	Mi		Cr
		Frequency:	4	4		4
		Crit.level:	2	1		3
Pipeline Compressor	AR	Consequence:	Ma	Ma		Cr
		Frequency:	1	1		1
		Crit.level:	3	3		4
Pipeline Compressor	ELU	Consequence:	Cr	Ca		Cr
		Frequency:	2	2		2
		Crit.level:	4	4		4
Pipeline Compressor	IL	Consequence:	Cr	Ca		Cr
		Frequency:	1	1		1
		Crit.level:	4	4		4
Pipeline Compressor	LO	Consequence:	Ma	Mi		Cr
		Frequency:	4	4		4
		Crit.level:	2	1		3
Lift Gas Compressor	AR	Consequence:	Ma	Ma		Cr
		Frequency:	1	1		1
		Crit.level:	3	3		4
Lift Gas Compressor	ELU	Consequence:	Cr	Ca		Cr
		Frequency:	2	2		2
		Crit.level:	4	4		4
Lift Gas Compressor	IL	Consequence:	Cr	Ca		Cr
		Frequency:	1	1		1
		Crit.level:	4	4		4
Lift Gas Compressor	LO	Consequence:	Ma	Mi		Cr
		Frequency:	4	4		4
		Crit.level:	2	1		3
HP Compressor	AR	Consequence:	Ma	Ma		Cr
		Frequency:	1	1		1
		Crit.level:	3	3		4
Compression						No compression
HP Compressor	FS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
HP Compressor	SS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
HP Compressor	FS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
HP Compressor	SS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
LP Compressor	FS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
LP Compressor	SS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Pipeline Compressor	FS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3

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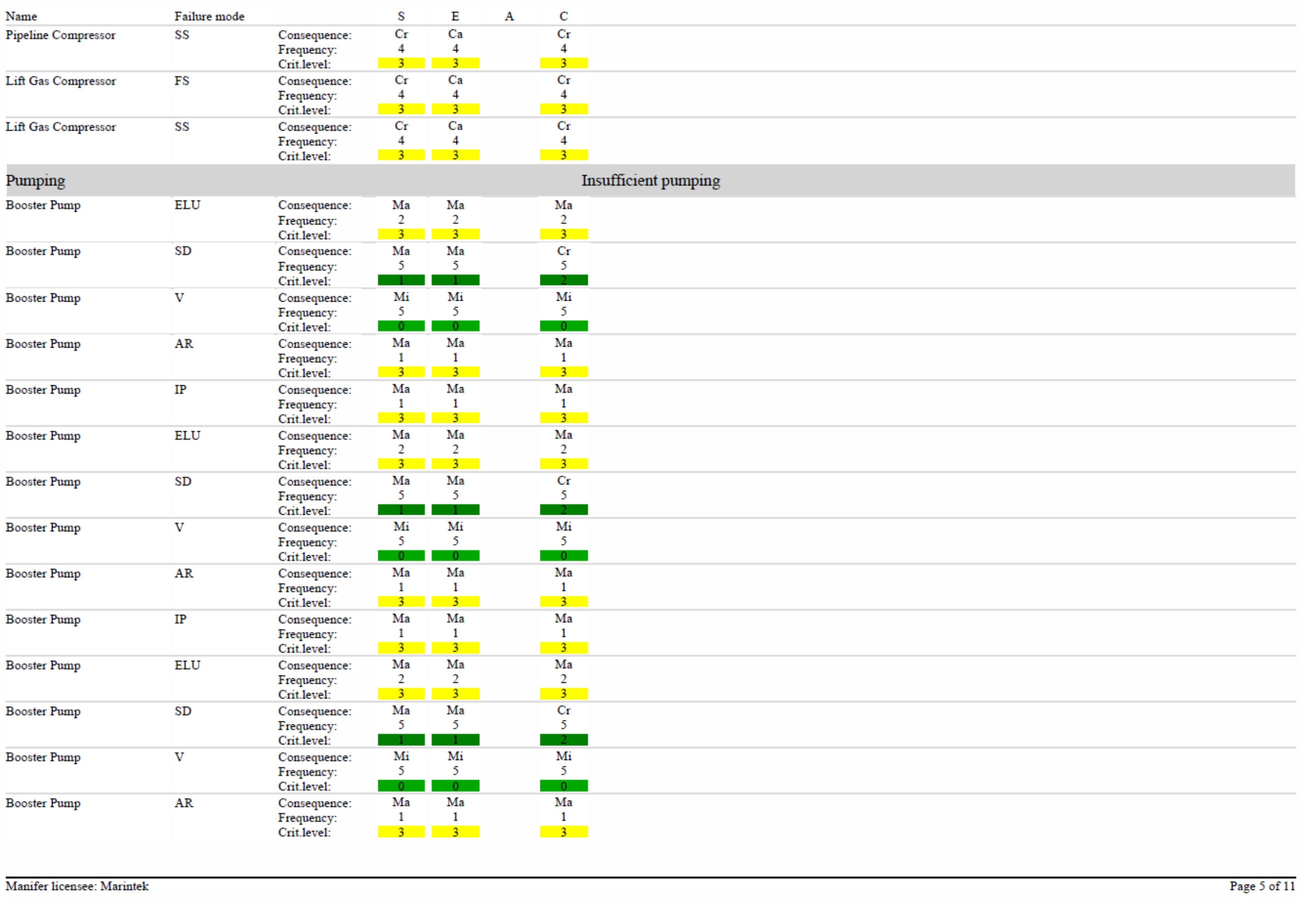

Name	Failure mode		S	E	A	C
Pipeline Compressor	SS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Lift Gas Compressor	FS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Lift Gas Compressor	SS	Consequence:	Cr	Ca		Cr
		Frequency:	4	4		4
		Crit.level:	3	3		3
Pumping						Insufficient pumping
Booster Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Booster Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Booster Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Booster Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Booster Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Booster Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Booster Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Booster Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Booster Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Booster Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Booster Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Booster Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Booster Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Booster Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3

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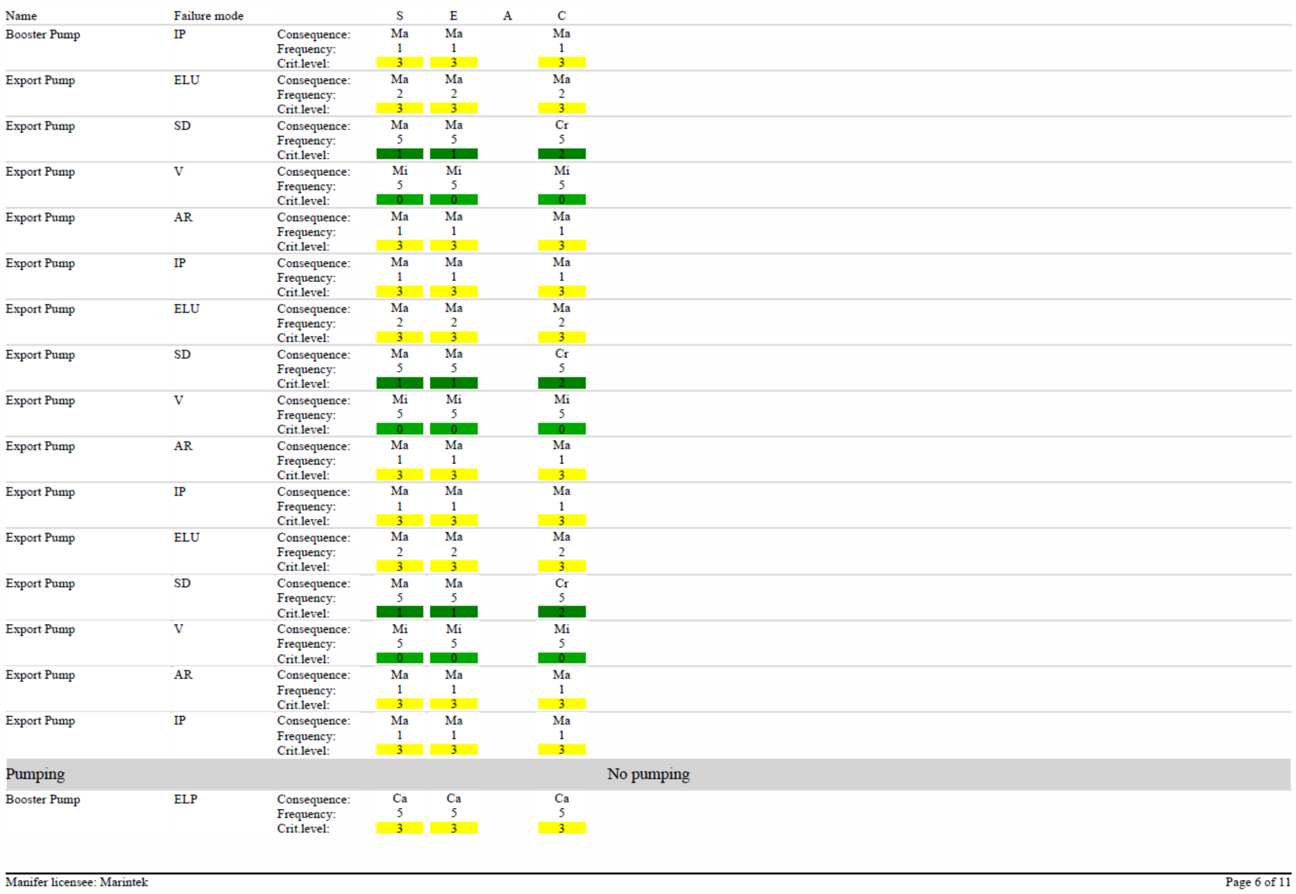

Name	Failure mode		S	E	A	C
Booster Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Export Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Export Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Export Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Export Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Export Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Export Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	ELU	Consequence:	Ma	Ma		Ma
		Frequency:	2	2		2
		Crit.level:	3	3		3
Export Pump	SD	Consequence:	Ma	Ma		Cr
		Frequency:	5	5		5
		Crit.level:	1	1		2
Export Pump	V	Consequence:	Mi	Mi		Mi
		Frequency:	5	5		5
		Crit.level:	0	0		0
Export Pump	AR	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Export Pump	IP	Consequence:	Ma	Ma		Ma
		Frequency:	1	1		1
		Crit.level:	3	3		3
Pumping						No pumping
Booster Pump	ELP	Consequence:	Ca	Ca		Ca
		Frequency:	5	5		5
		Crit.level:	3	3		3

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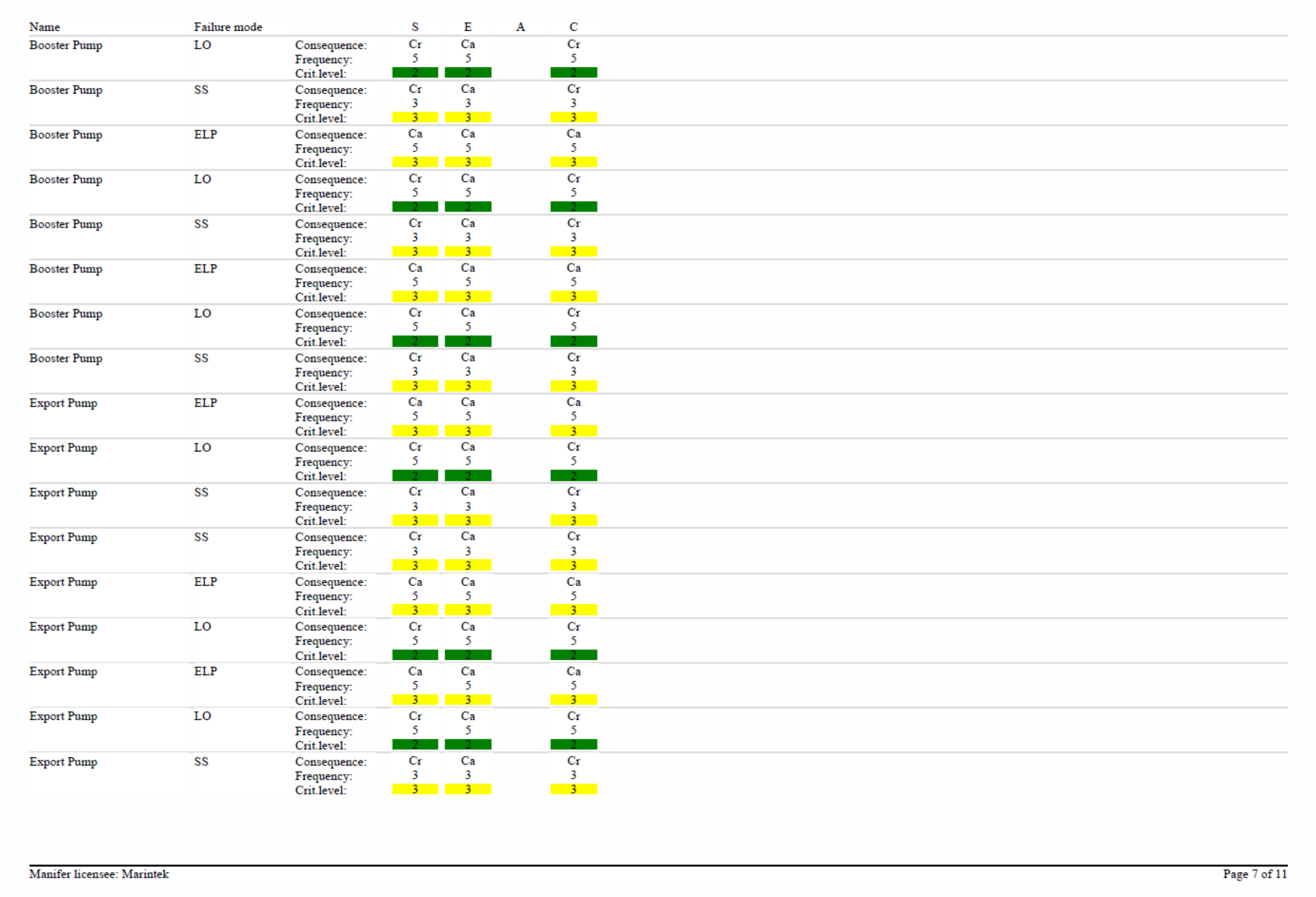

Name	Failure mode		S	E	A	C
Booster Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Booster Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3
Booster Pump	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Booster Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Booster Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3
Booster Pump	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Booster Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Booster Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3
Export Pump	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Export Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Export Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3
Export Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3
Export Pump	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Export Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Export Pump	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Export Pump	LO	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Export Pump	SS	Consequence: Frequency: Crit.level:	Cr 3 3	Ca 3 3		Cr 3 3

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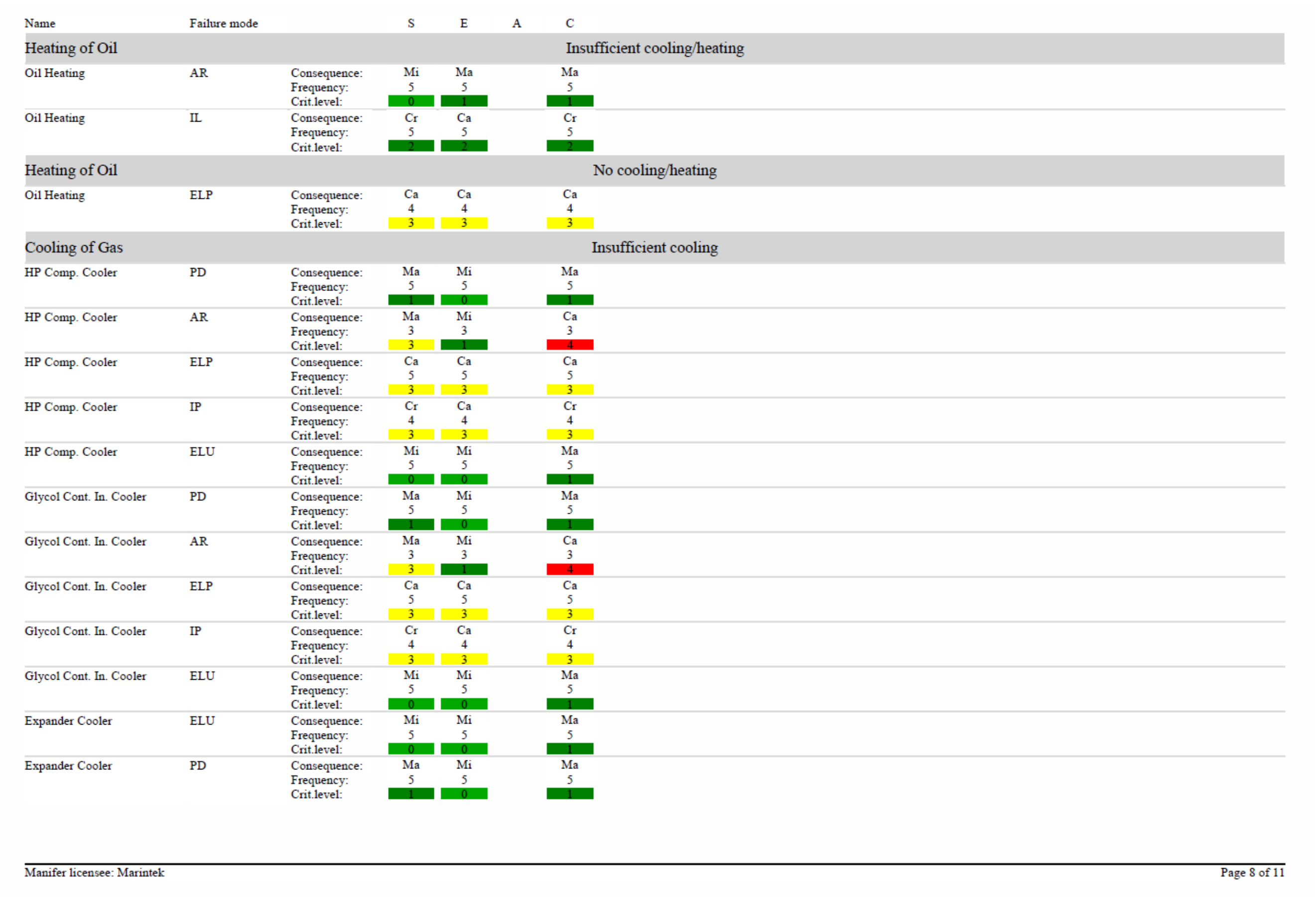

Name	Failure mode		S	E	A	C
Heating of Oil						Insufficient cooling/heating
Oil Heating	AR	Consequence: Frequency: Crit.level:	Mi 5 0	Ma 5 1		Ma 5 1
Oil Heating	IL	Consequence: Frequency: Crit.level:	Cr 5 2	Ca 5 2		Cr 5 2
Heating of Oil						No cooling/heating
Oil Heating	ELP	Consequence: Frequency: Crit.level:	Ca 4 3	Ca 4 3		Ca 4 3
Cooling of Gas						Insufficient cooling
HP Comp. Cooler	PD	Consequence: Frequency: Crit.level:	Ma 5 1	Mi 5 0		Ma 5 1
HP Comp. Cooler	AR	Consequence: Frequency: Crit.level:	Ma 3 3	Mi 3 1		Ca 3 4
HP Comp. Cooler	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
HP Comp. Cooler	IP	Consequence: Frequency: Crit.level:	Cr 4 3	Ca 4 3		Cr 4 3
HP Comp. Cooler	ELU	Consequence: Frequency: Crit.level:	Mi 5 0	Mi 5 0		Ma 5 1
Glycol Cont. In. Cooler	PD	Consequence: Frequency: Crit.level:	Ma 5 1	Mi 5 0		Ma 5 1
Glycol Cont. In. Cooler	AR	Consequence: Frequency: Crit.level:	Ma 3 3	Mi 3 1		Ca 3 4
Glycol Cont. In. Cooler	ELP	Consequence: Frequency: Crit.level:	Ca 5 3	Ca 5 3		Ca 5 3
Glycol Cont. In. Cooler	IP	Consequence: Frequency: Crit.level:	Cr 4 3	Ca 4 3		Cr 4 3
Glycol Cont. In. Cooler	ELU	Consequence: Frequency: Crit.level:	Mi 5 0	Mi 5 0		Ma 5 1
Expander Cooler	ELU	Consequence: Frequency: Crit.level:	Mi 5 0	Mi 5 0		Ma 5 1
Expander Cooler	PD	Consequence: Frequency: Crit.level:	Ma 5 1	Mi 5 0		Ma 5 1

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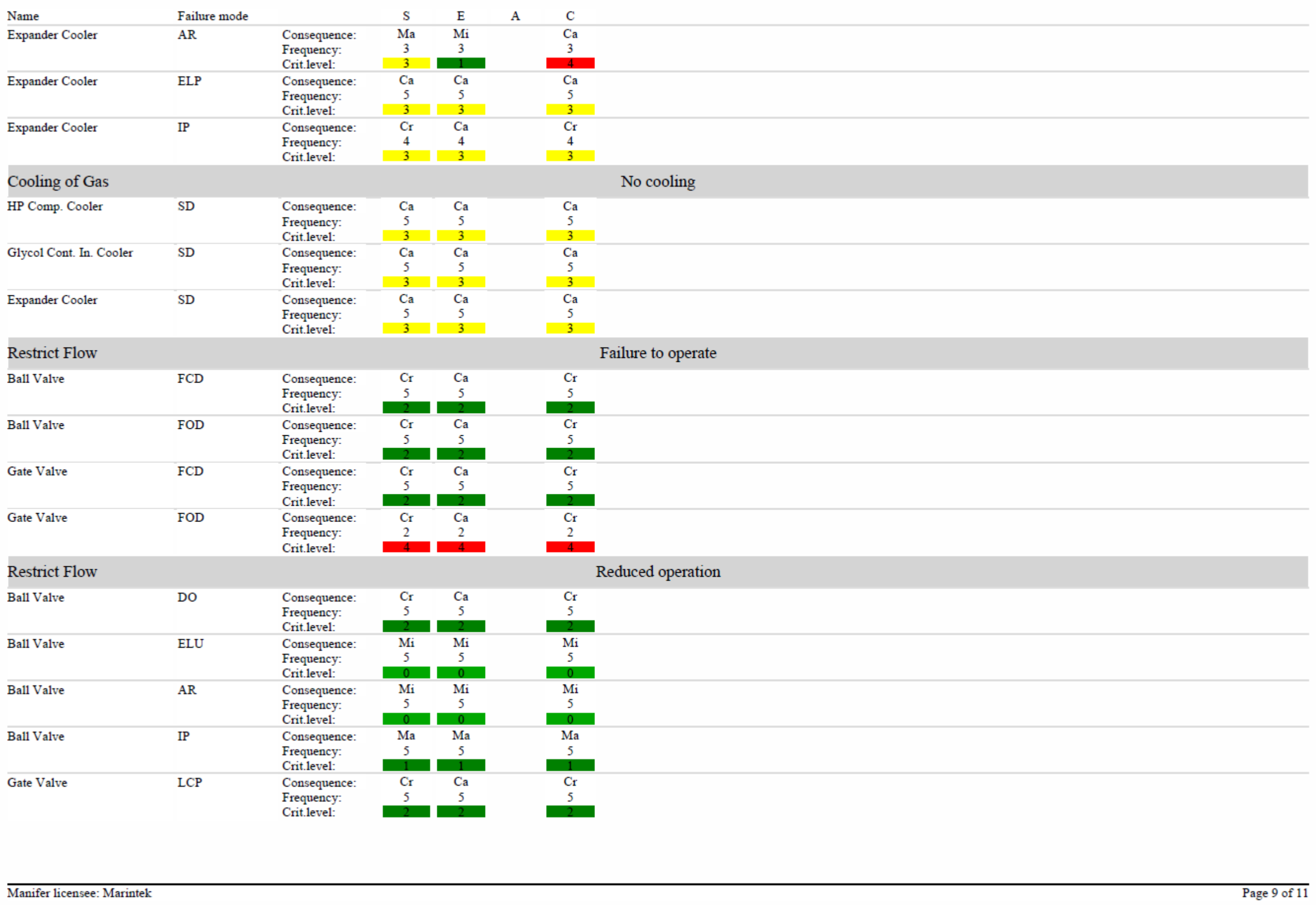

Name	Failure mode		S	E	A	C	
Expander Cooler	AR	Consequence:	Ma	Mi		Ca	
		Frequency:	3	3		3	
		Crit.level:	3	1		4	
Expander Cooler	ELP	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Expander Cooler	IP	Consequence:	Cr	Ca		Cr	
		Frequency:	4	4		4	
		Crit.level:	3	3		3	
Cooling of Gas							No cooling
HP Comp. Cooler	SD	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Glycol Cont. In. Cooler	SD	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Expander Cooler	SD	Consequence:	Ca	Ca		Ca	
		Frequency:	5	5		5	
		Crit.level:	3	3		3	
Restrict Flow							Failure to operate
Ball Valve	FCD	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
Ball Valve	FOD	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
Gate Valve	FCD	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
Gate Valve	FOD	Consequence:	Cr	Ca		Cr	
		Frequency:	2	2		2	
		Crit.level:	4	4		4	
Restrict Flow							Reduced operation
Ball Valve	DO	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	
Ball Valve	ELU	Consequence:	Mi	Mi		Mi	
		Frequency:	5	5		5	
		Crit.level:	0	0		0	
Ball Valve	AR	Consequence:	Mi	Mi		Mi	
		Frequency:	5	5		5	
		Crit.level:	0	0		0	
Ball Valve	IP	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Gate Valve	LCP	Consequence:	Cr	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	2	2		2	

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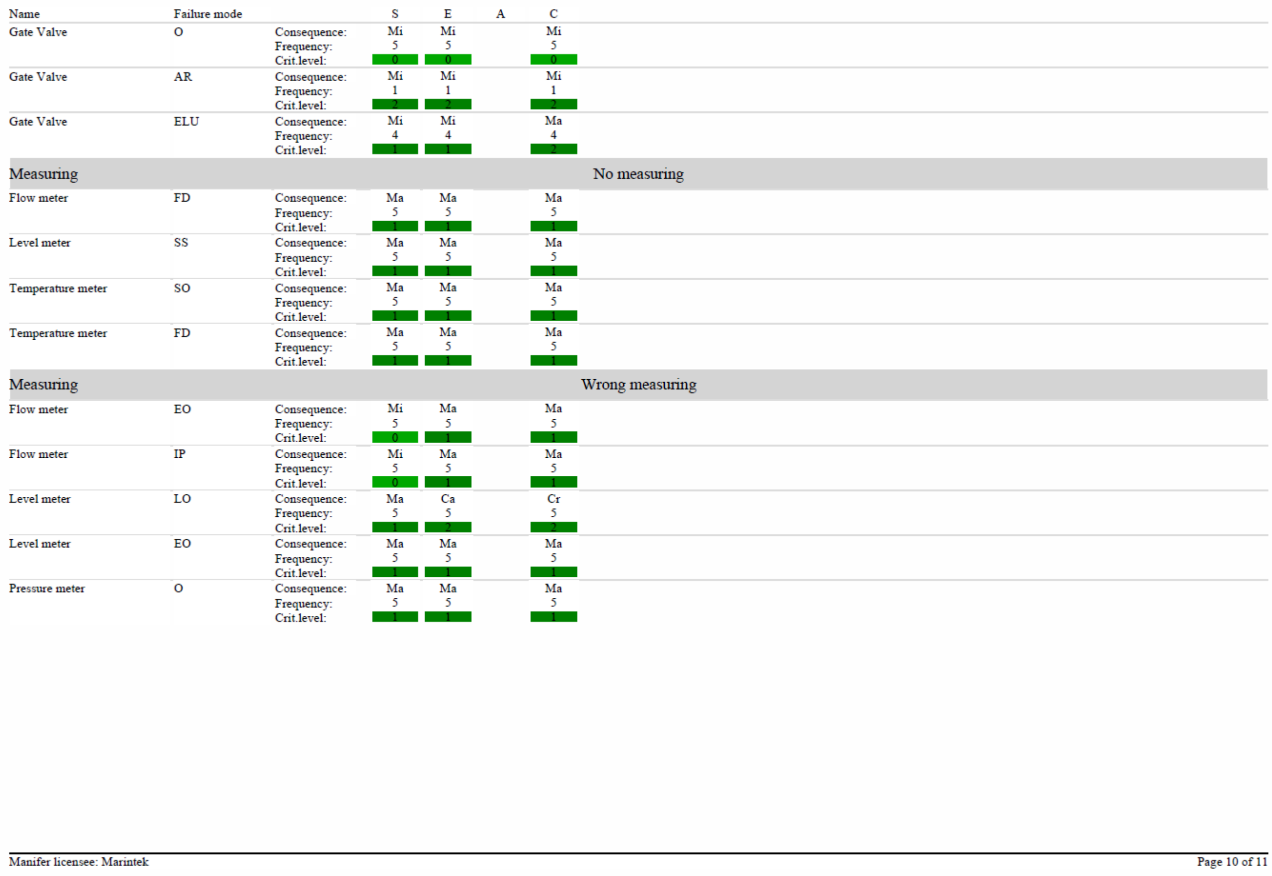

Name	Failure mode		S	E	A	C	
Gate Valve	O	Consequence:	Mi	Mi		Mi	
		Frequency:	5	5		5	
		Crit.level:	0	0		0	
Gate Valve	AR	Consequence:	Mi	Mi		Mi	
		Frequency:	1	1		1	
		Crit.level:	2	2		2	
Gate Valve	ELU	Consequence:	Mi	Mi		Ma	
		Frequency:	4	4		4	
		Crit.level:	1	1		2	
Measuring							No measuring
Flow meter	FD	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Level meter	SS	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Temperature meter	SO	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Temperature meter	FD	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Measuring							Wrong measuring
Flow meter	EO	Consequence:	Mi	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	0	1		1	
Flow meter	IP	Consequence:	Mi	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	0	1		1	
Level meter	LO	Consequence:	Ma	Ca		Cr	
		Frequency:	5	5		5	
		Crit.level:	1	2		2	
Level meter	EO	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	
Pressure meter	O	Consequence:	Ma	Ma		Ma	
		Frequency:	5	5		5	
		Crit.level:	1	1		1	

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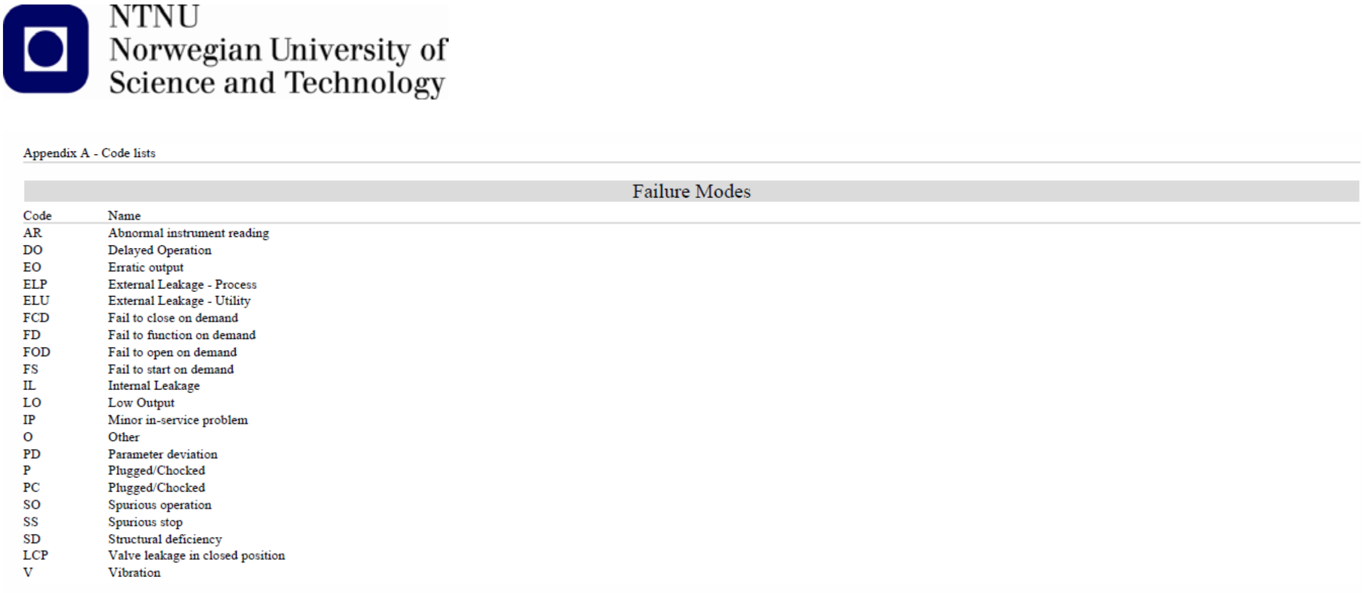

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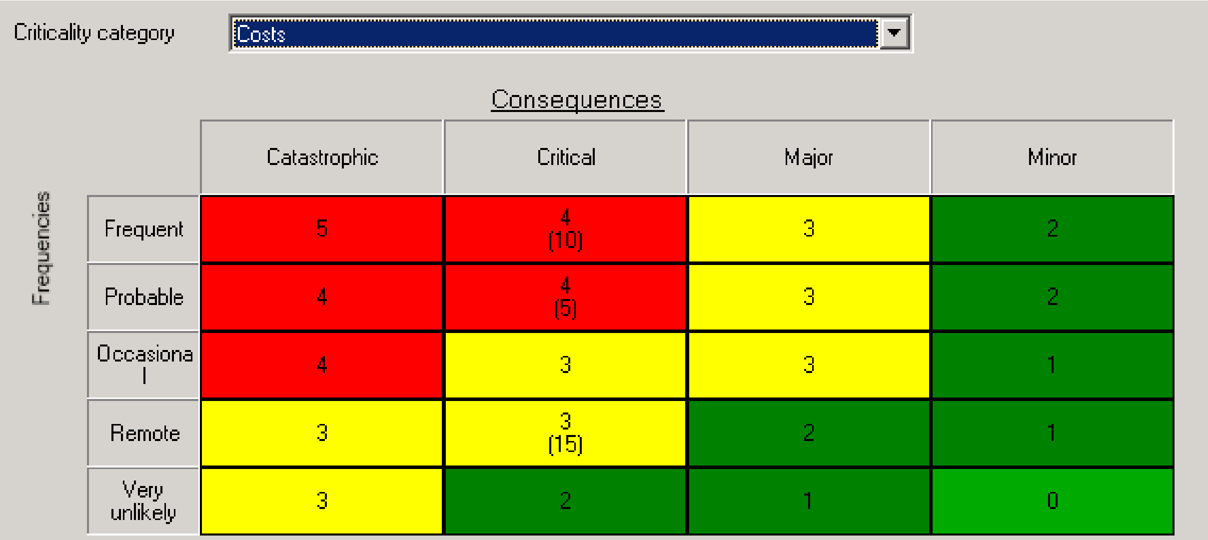
Appendix A - Code lists

Failure Modes

Code	Name
AR	Abnormal instrument reading
DO	Delayed Operation
EO	Erratic output
ELP	External Leakage - Process
ELU	External Leakage - Utility
FCD	Fail to close on demand
FD	Fail to function on demand
FOD	Fail to open on demand
FS	Fail to start on demand
IL	Internal Leakage
LO	Low Output
IP	Minor in-service problem
O	Other
PD	Parameter deviation
P	Plugged/Chocked
PC	Plugged/Chocked
SO	Spurious operation
SS	Spurious stop
SD	Structural deficiency
LCP	Valve leakage in closed position
V	Vibration

Appendix 3: Risk matrices for sub – functions

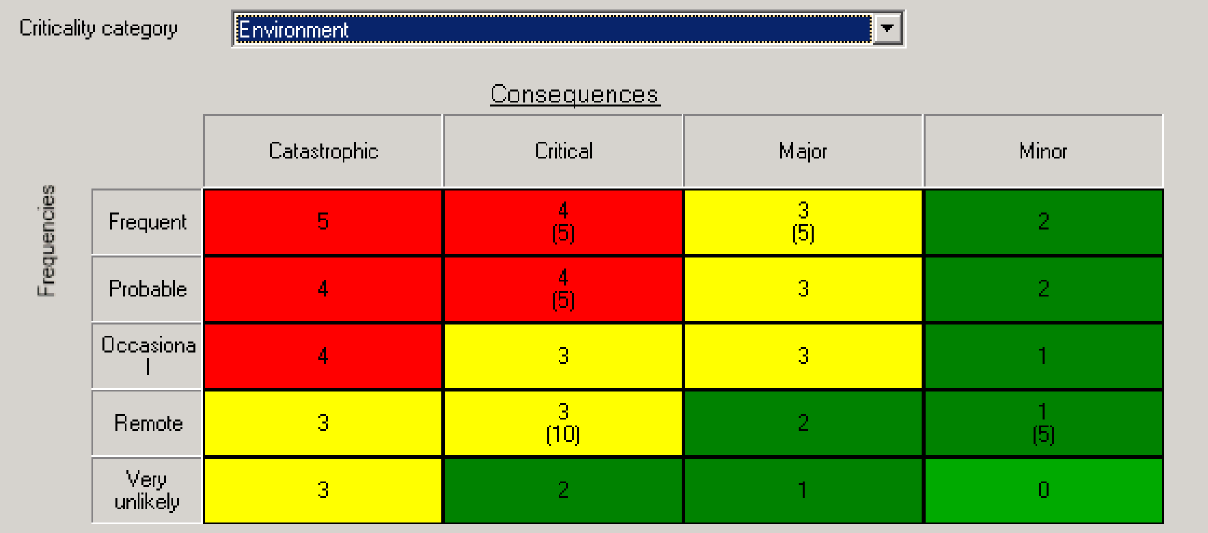
Risk matrices: Compression



Criticality category: Costs

Consequences

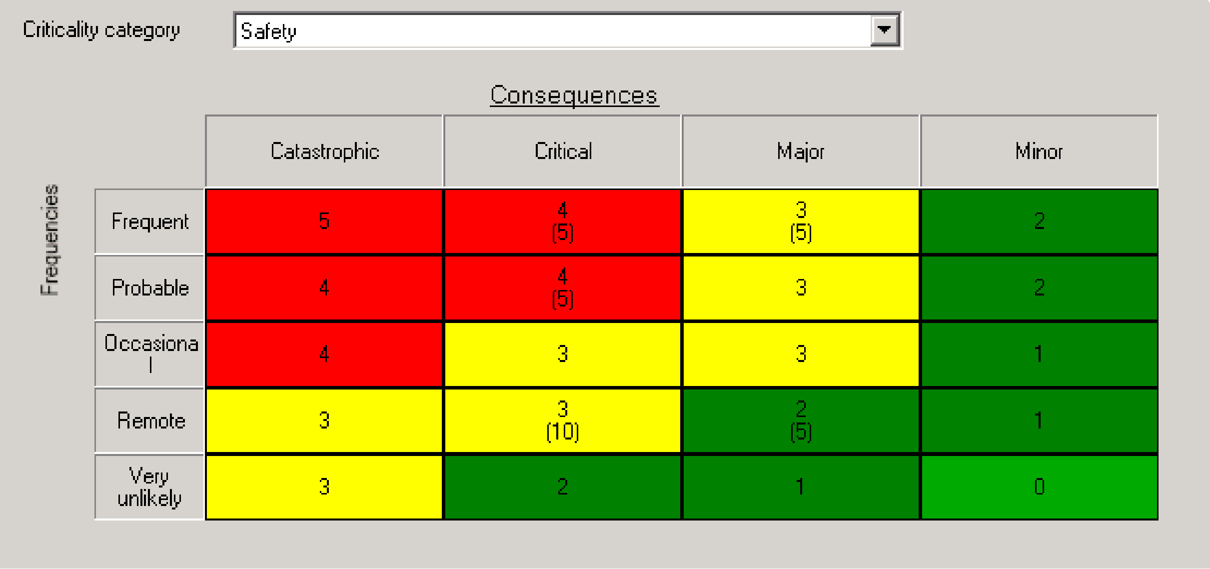
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4 (10)	3	2
Probable	4	4 (5)	3	2
Occasional	4	3	3	1
Remote	3	3 (15)	2	1
Very unlikely	3	2	1	0



Criticality category: Environment

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4 (5)	3 (5)	2
Probable	4	4 (5)	3	2
Occasional	4	3	3	1
Remote	3	3 (10)	2	1 (5)
Very unlikely	3	2	1	0

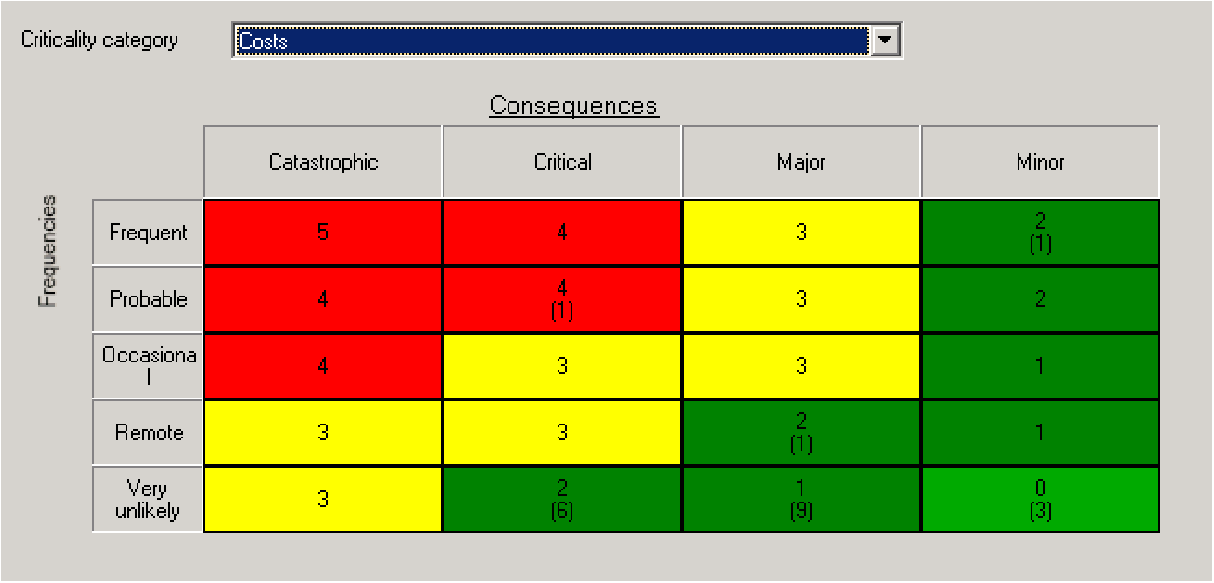


Criticality category: Safety

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4 (5)	3 (5)	2
Probable	4	4 (5)	3	2
Occasional	4	3	3	1
Remote	3	3 (10)	2 (5)	1
Very unlikely	3	2	1	0

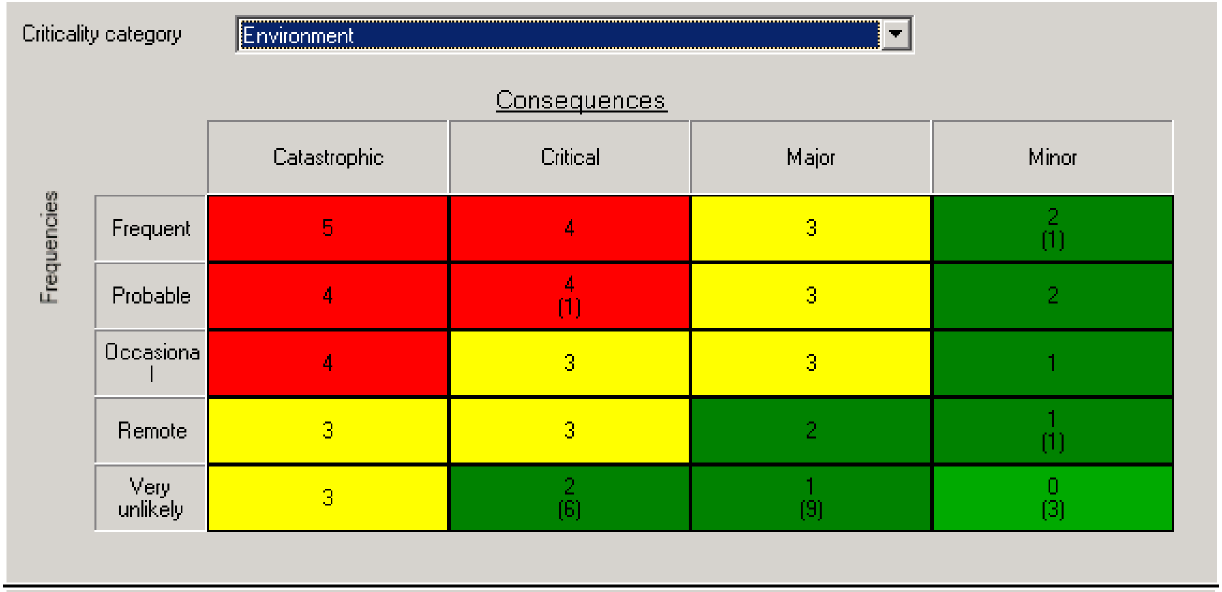
Risk matrices: Control



Criticality category: Costs

Consequences

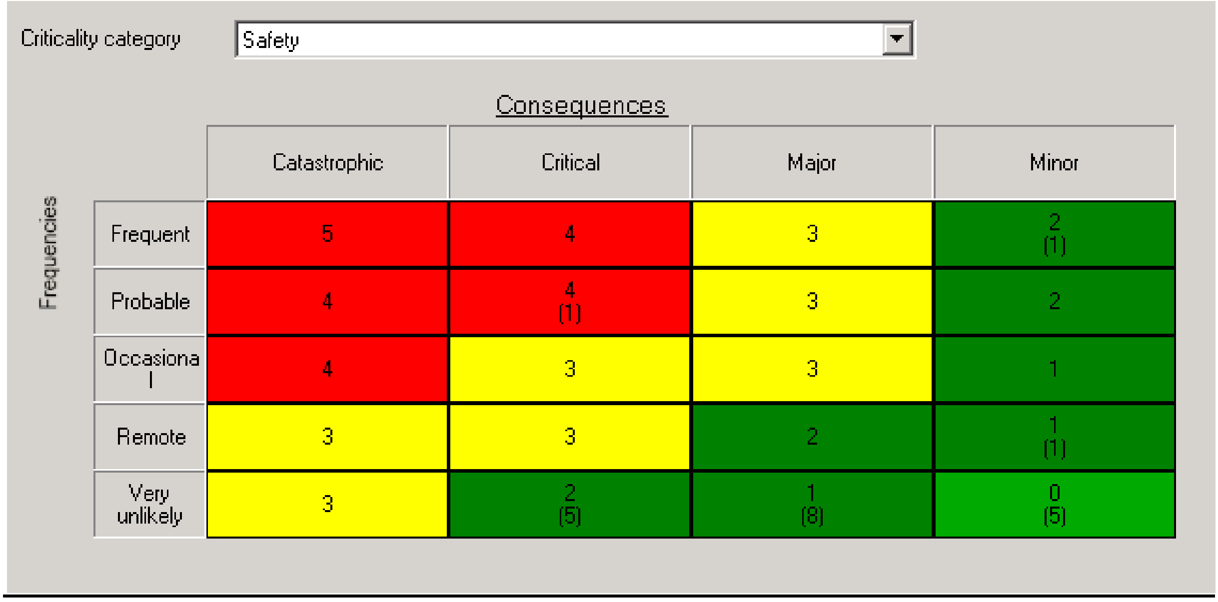
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2 (1)
Probable	4	4 (1)	3	2
Occasional	4	3	3	1
Remote	3	3	2 (1)	1
Very unlikely	3	2 (6)	1 (9)	0 (3)



Criticality category: Environment

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2 (1)
Probable	4	4 (1)	3	2
Occasional	4	3	3	1
Remote	3	3	2	1 (1)
Very unlikely	3	2 (6)	1 (9)	0 (3)

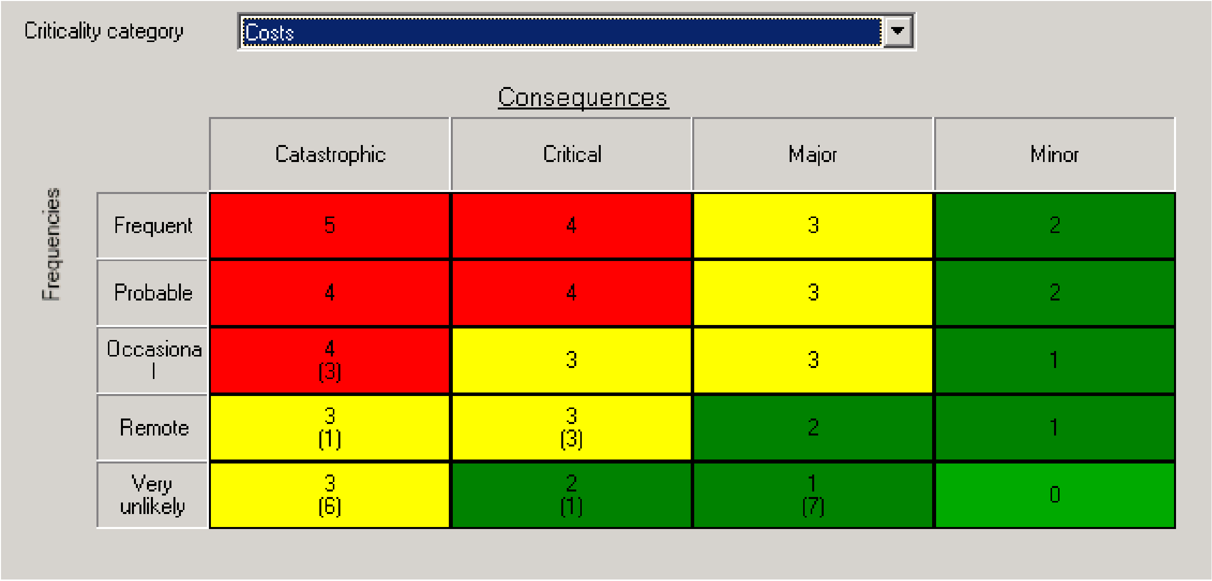


Criticality category: Safety

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2 (1)
Probable	4	4 (1)	3	2
Occasional	4	3	3	1
Remote	3	3	2	1 (1)
Very unlikely	3	2 (5)	1 (8)	0 (5)

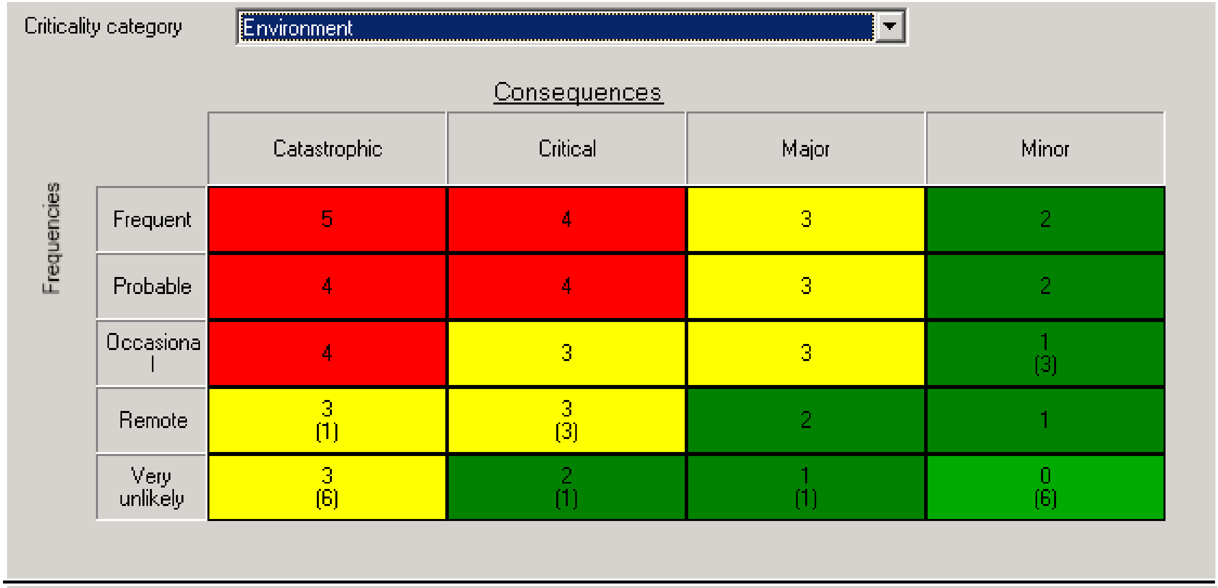
Risk matrices: Cooling



Criticality category: Costs

Consequences

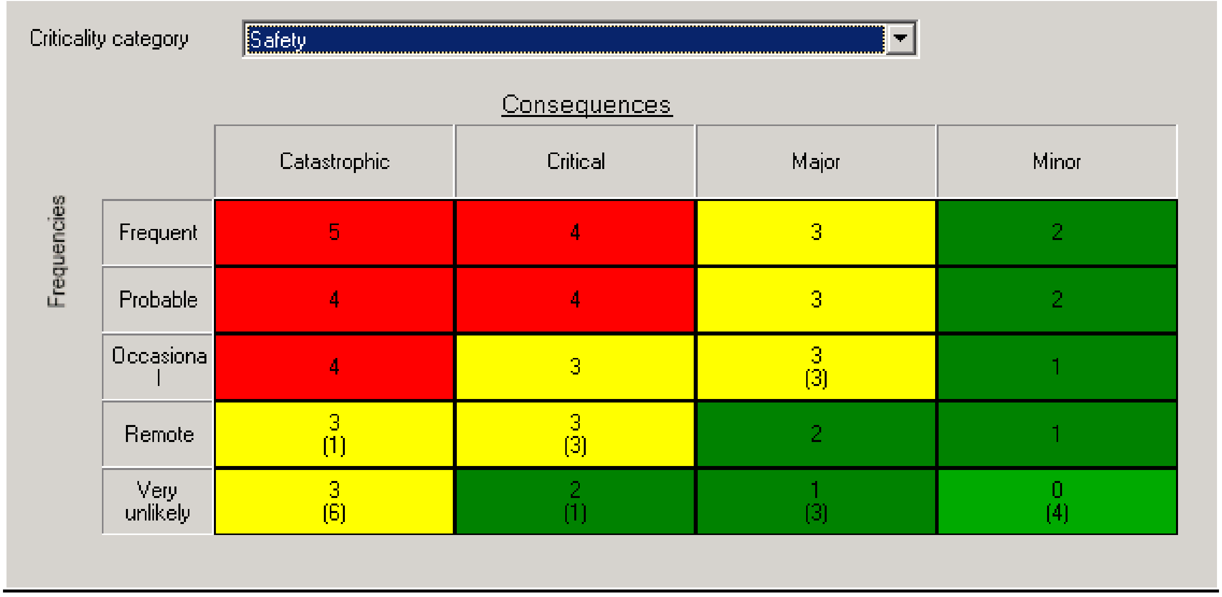
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2
Probable	4	4	3	2
Occasional	4 (3)	3	3	1
Remote	3 (1)	3 (3)	2	1
Very unlikely	3 (6)	2 (1)	1 (7)	0



Criticality category: Environment

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2
Probable	4	4	3	2
Occasional	4	3	3	1 (3)
Remote	3 (1)	3 (3)	2	1
Very unlikely	3 (6)	2 (1)	1 (1)	0 (6)

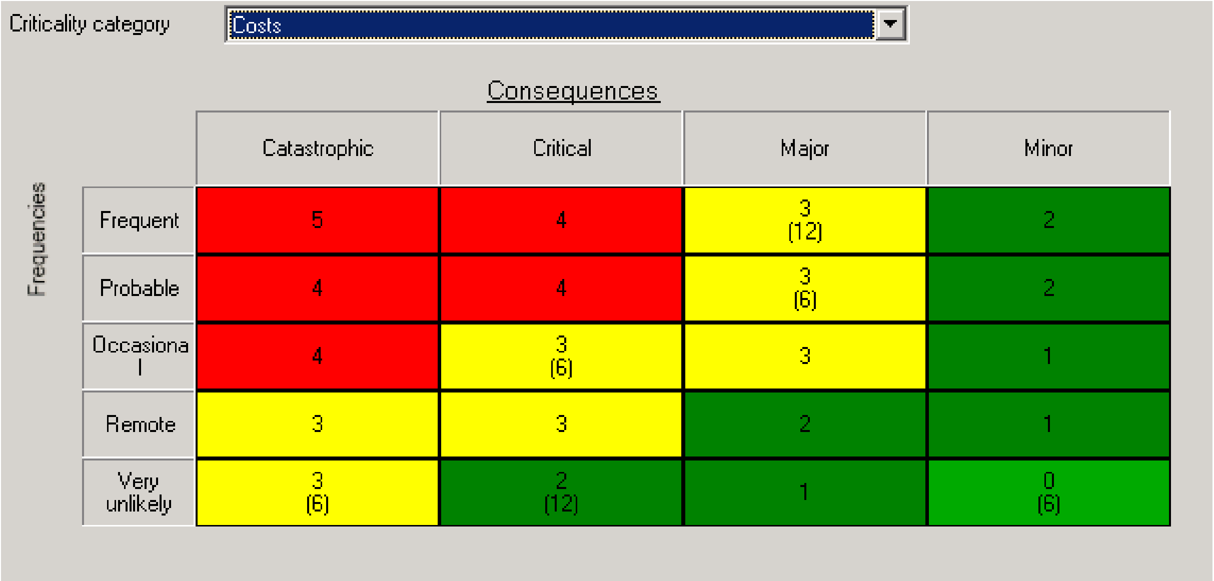


Criticality category: Safety

Consequences

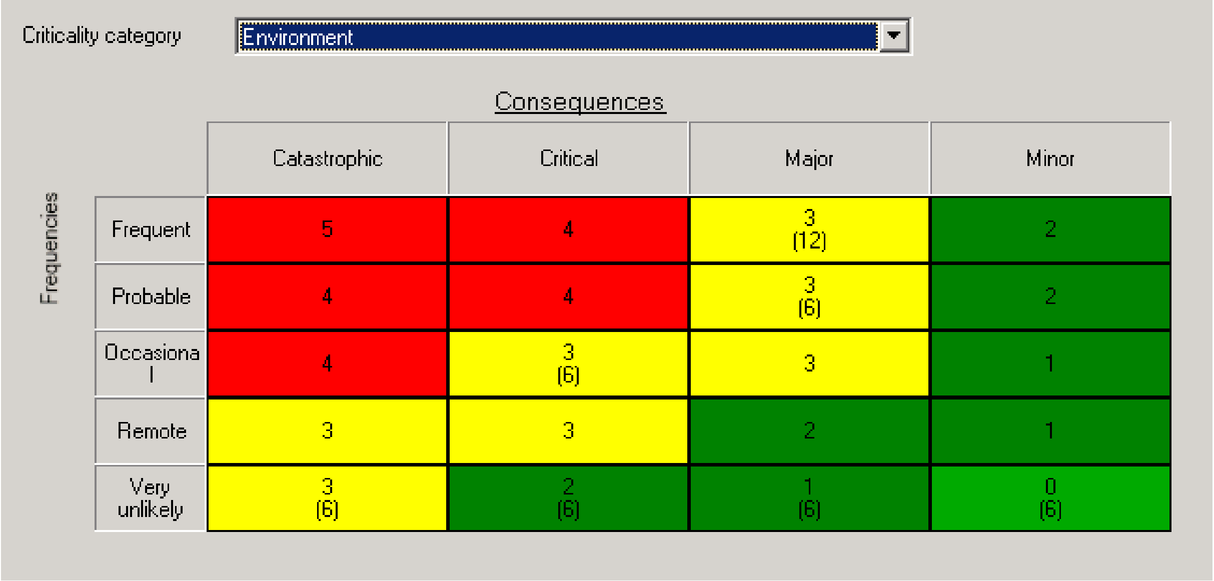
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3	2
Probable	4	4	3	2
Occasional	4	3	3 (3)	1
Remote	3 (1)	3 (3)	2	1
Very unlikely	3 (6)	2 (1)	1 (3)	0 (4)

Risk matrices: Pumping


Criticality category: Costs

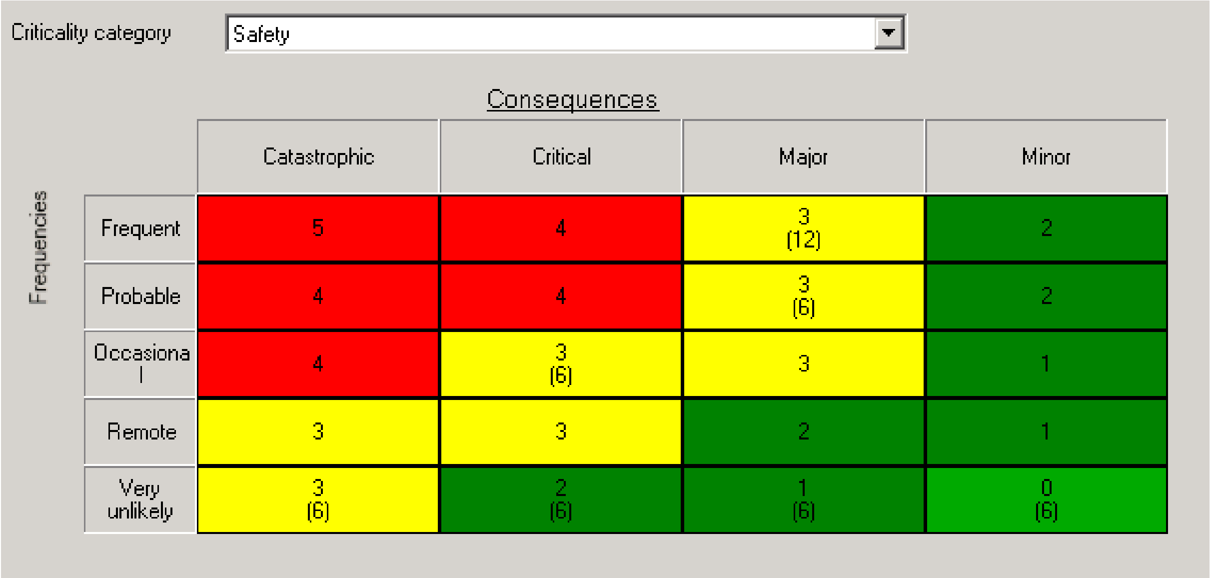
Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (12)	2
Probable	4	4	3 (6)	2
Occasional	4	3 (6)	3	1
Remote	3	3	2	1
Very unlikely	3 (6)	2 (12)	1	0 (6)


Criticality category: Environment

Consequences

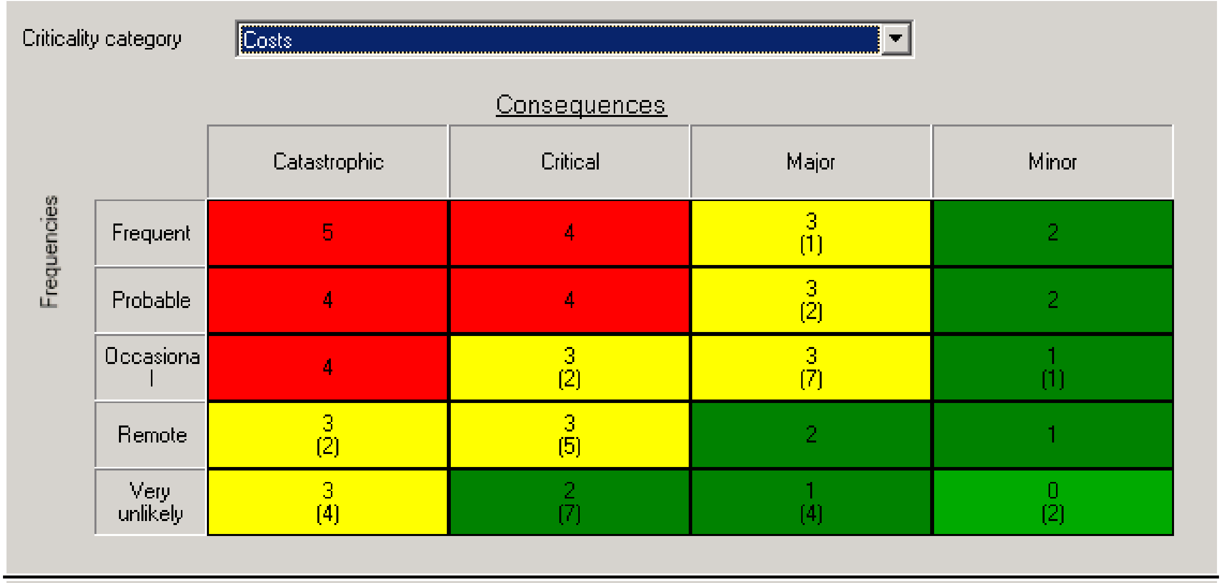
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (12)	2
Probable	4	4	3 (6)	2
Occasional	4	3 (6)	3	1
Remote	3	3	2	1
Very unlikely	3 (6)	2 (6)	1 (6)	0 (6)


Criticality category: Safety

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (12)	2
Probable	4	4	3 (6)	2
Occasional	4	3 (6)	3	1
Remote	3	3	2	1
Very unlikely	3 (6)	2 (6)	1 (6)	0 (6)

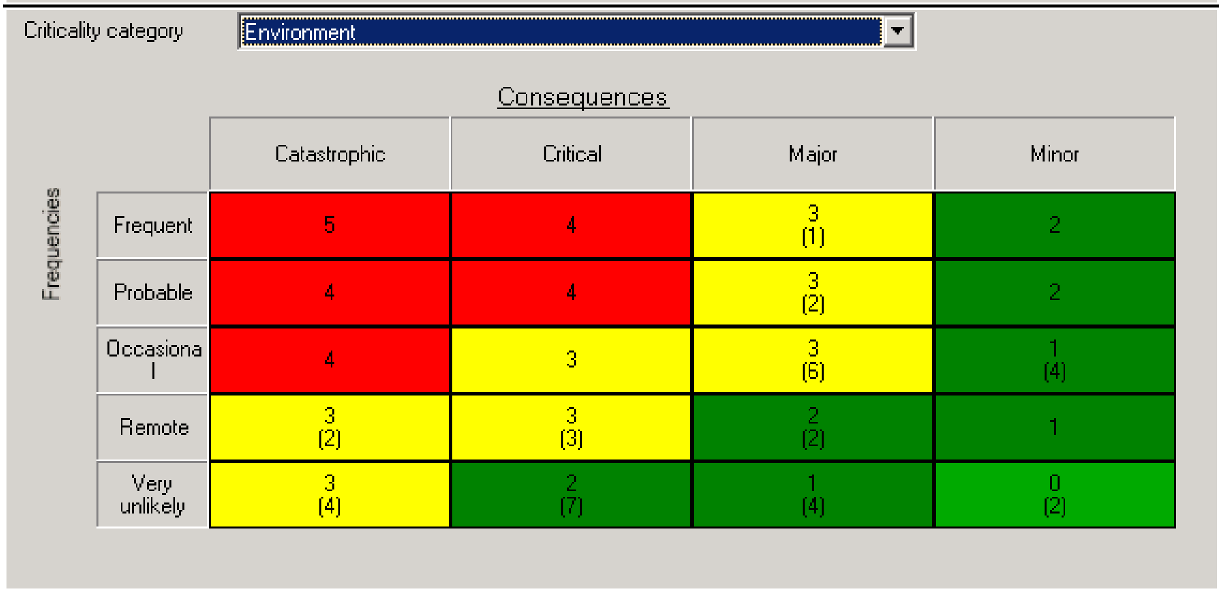
Risk matrices: Separation



Criticality category: Costs

Consequences

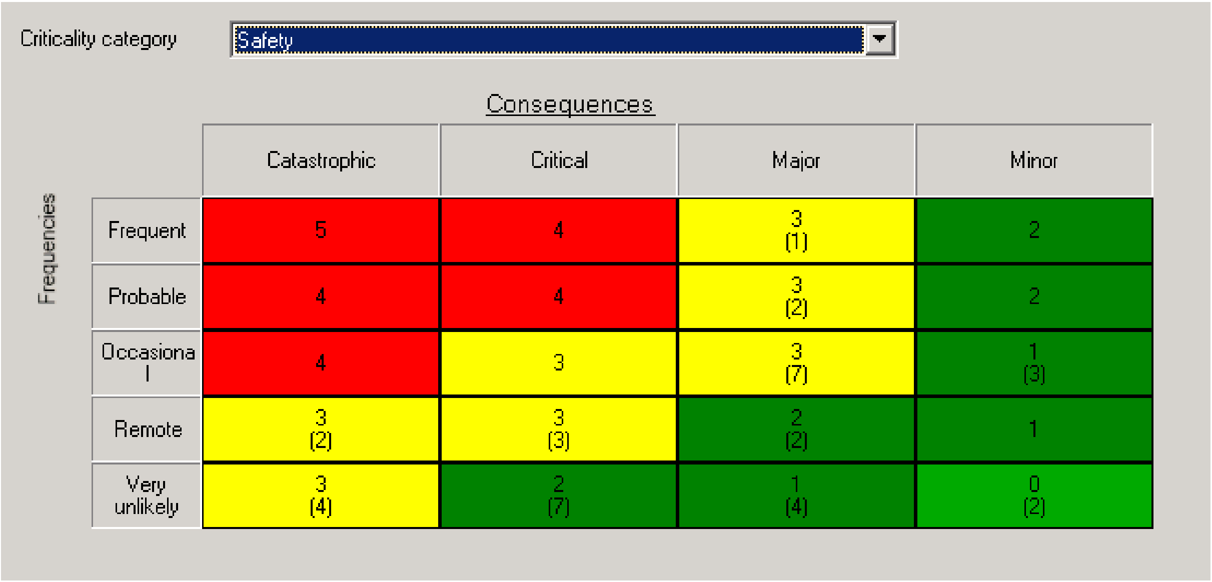
Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (1)	2
Probable	4	4	3 (2)	2
Occasional	4	3 (2)	3 (7)	1 (1)
Remote	3 (2)	3 (5)	2	1
Very unlikely	3 (4)	2 (7)	1 (4)	0 (2)



Criticality category: Environment

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (1)	2
Probable	4	4	3 (2)	2
Occasional	4	3	3 (6)	1 (4)
Remote	3 (2)	3 (3)	2 (2)	1
Very unlikely	3 (4)	2 (7)	1 (4)	0 (2)



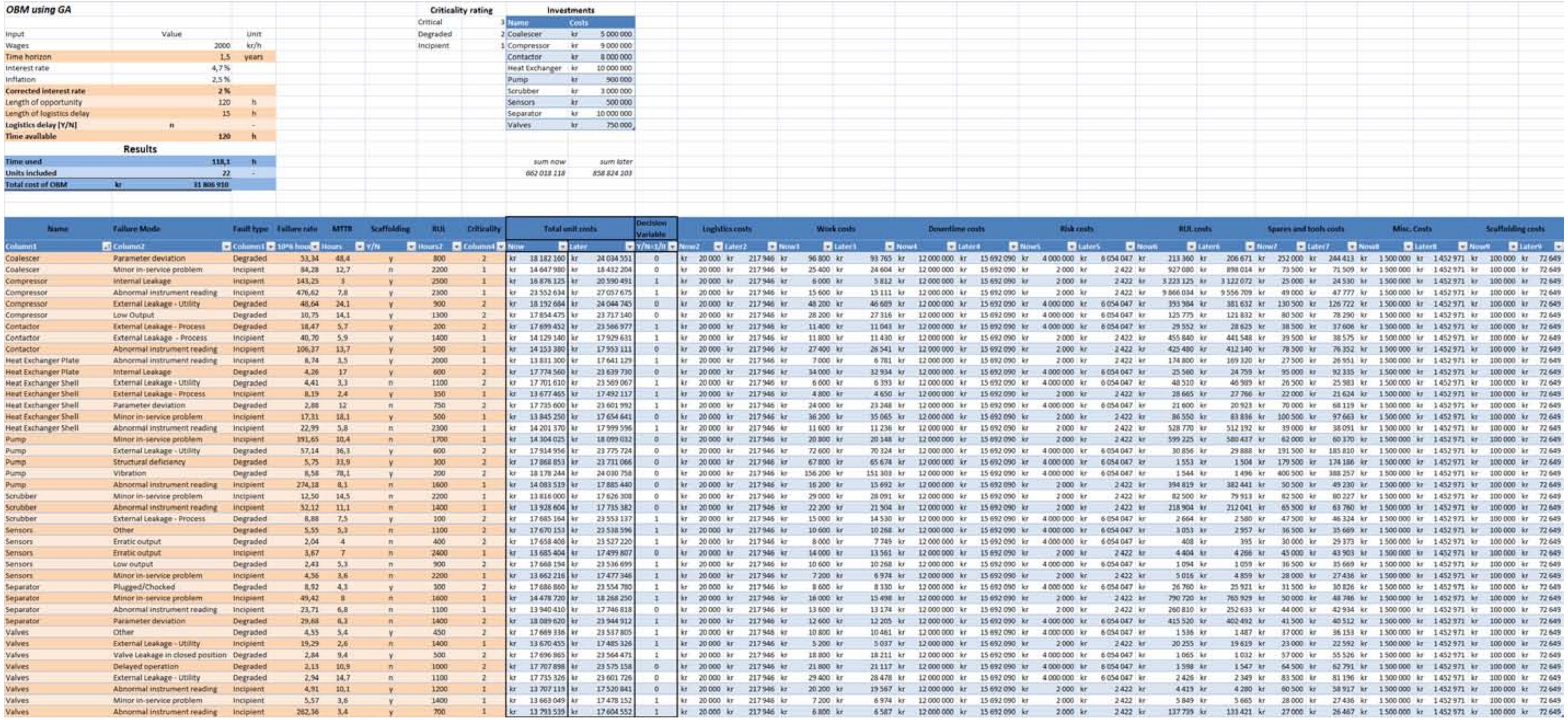
Criticality category: Safety

Consequences

Frequencies	Catastrophic	Critical	Major	Minor
Frequent	5	4	3 (1)	2
Probable	4	4	3 (2)	2
Occasional	4	3	3 (7)	1 (3)
Remote	3 (2)	3 (3)	2 (2)	1
Very unlikely	3 (4)	2 (7)	1 (4)	0 (2)

Appendix 4: CD with OBM model.

Appendix 5: OBM model



OBM using GA

Input	Value	Unit
Wages	2000	kr/h
Time horizon	1,5	years
Interest rate	4,7 %	
Inflation	2,5 %	
Corrected interest rate	**2 %**	
Length of opportunity	120	h
Length of logistics delay	15	h
Logistics delay [Y/N]	n	-
Time available	**120**	**h**

Results

Time used		**118,1**	**h**
Units included		**22**	-
Total cost of OBM	**kr**	**31 806 910**	

Criticality rating

Critical	3
Degraded	2
Incipient	1

Investments

Name	Costs	
Coalescer	kr	5 000 000
Compressor	kr	9 000 000
Contactor	kr	8 000 000
Heat Exchanger	kr	10 000 000
Pump	kr	900 000
Scrubber	kr	3 000 000
Sensors	kr	500 000
Separator	kr	10 000 000
Valves	kr	750 000

sum now	*sum later*
662 018 118	*858 824 103*

Name	Failure Mode	Fault type	Failure rate	MTTR	Scaffolding	RUL	Criticality	Total unit costs		Decision Variable	Logistics costs		Work costs		Downtime costs		Risk costs		RUL costs		Spares and tools costs		Misc. Costs		Scaffolding costs	
Column1	Column2	Column1	10^6 hours	Hours	Y/N	Hours2	Column4	Now	Later	Y/N=1/0	Now2	Later2	Now3	Later3	Now4	Later4	Now5	Later5	Now6	Later6	Now7	Later7	Now8	Later8	Now9	Later9
Coalescer	Parameter deviation	Degraded	53,34	48,4	y	800	2	kr 18 182 160	kr 24 034 551	0	kr 20 000	kr 217 946	kr 96 800	kr 93 765	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 213 360	kr 206 671	kr 252 000	kr 244 413	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Coalescer	Minor in-service problem	Incipient	84,28	12,7	n	2200	1	kr 14 647 980	kr 18 432 204	0	kr 20 000	kr 217 946	kr 25 400	kr 24 604	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 927 080	kr 898 014	kr 73 500	kr 71 509	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Compressor	Internal Leakage	Incipient	143,25	3	y	2500	1	kr 16 876 125	kr 20 590 491	1	kr 20 000	kr 217 946	kr 6 000	kr 5 812	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 3 223 125	kr 3 122 072	kr 25 000	kr 24 530	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Compressor	Abnormal instrument reading	Incipient	476,62	7,8	y	2300	1	kr 23 552 634	kr 27 057 675	1	kr 20 000	kr 217 946	kr 15 600	kr 15 111	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 9 866 034	kr 9 556 709	kr 49 000	kr 47 777	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Compressor	External Leakage - Utility	Degraded	48,64	24,1	y	900	2	kr 18 192 684	kr 24 044 745	0	kr 20 000	kr 217 946	kr 48 200	kr 46 689	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 393 984	kr 381 632	kr 130 500	kr 126 722	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Compressor	Low Output	Degraded	10,75	14,1	y	1300	2	kr 17 854 475	kr 23 717 140	0	kr 20 000	kr 217 946	kr 28 200	kr 27 316	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 125 775	kr 121 832	kr 80 500	kr 78 290	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Contactor	External Leakage - Process	Degraded	18,47	5,7	y	200	2	kr 17 699 452	kr 23 566 977	1	kr 20 000	kr 217 946	kr 11 400	kr 11 043	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 29 552	kr 28 625	kr 38 500	kr 37 606	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Contactor	External Leakage - Process	Incipient	40,70	5,9	y	1400	1	kr 14 129 140	kr 17 929 631	1	kr 20 000	kr 217 946	kr 11 800	kr 11 430	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 455 840	kr 441 548	kr 39 500	kr 38 575	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Contactor	Abnormal instrument reading	Incipient	106,37	13,7	y	500	1	kr 14 153 380	kr 17 953 111	0	kr 20 000	kr 217 946	kr 27 400	kr 26 541	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 425 480	kr 412 140	kr 78 500	kr 76 352	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Plate	Abnormal instrument reading	Incipient	8,74	3,5	y	2000	1	kr 13 831 300	kr 17 641 129	1	kr 20 000	kr 217 946	kr 7 000	kr 6 781	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 174 800	kr 169 320	kr 27 500	kr 26 951	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Plate	Internal Leakage	Degraded	4,26	17	y	600	2	kr 17 774 560	kr 23 639 730	0	kr 20 000	kr 217 946	kr 34 000	kr 32 934	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 25 560	kr 24 759	kr 95 000	kr 92 335	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Shell	External Leakage - Utility	Degraded	4,41	3,3	n	1100	2	kr 17 701 610	kr 23 569 067	1	kr 20 000	kr 217 946	kr 6 600	kr 6 393	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 48 510	kr 46 989	kr 26 500	kr 25 983	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Shell	External Leakage - Process	Incipient	8,19	2,4	y	350	1	kr 13 677 465	kr 17 492 117	1	kr 20 000	kr 217 946	kr 4 800	kr 4 650	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 28 665	kr 27 766	kr 22 000	kr 21 624	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Shell	Parameter deviation	Degraded	2,88	12	n	750	2	kr 17 735 600	kr 23 601 992	1	kr 20 000	kr 217 946	kr 24 000	kr 23 248	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 21 600	kr 20 923	kr 70 000	kr 68 119	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Shell	Minor in-service problem	Incipient	17,31	18,1	y	500	1	kr 13 845 250	kr 17 654 641	0	kr 20 000	kr 217 946	kr 36 200	kr 35 065	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 86 550	kr 83 836	kr 100 500	kr 97 663	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Heat Exchanger Shell	Abnormal instrument reading	Incipient	22,99	5,8	n	2300	1	kr 14 201 370	kr 17 999 596	1	kr 20 000	kr 217 946	kr 11 600	kr 11 236	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 528 770	kr 512 192	kr 39 000	kr 38 091	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Pump	Minor in-service problem	Incipient	391,65	10,4	n	1700	1	kr 14 304 025	kr 18 099 032	0	kr 20 000	kr 217 946	kr 20 800	kr 20 148	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 599 225	kr 580 437	kr 62 000	kr 60 370	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Pump	External Leakage - Utility	Degraded	57,14	36,3	y	600	2	kr 17 914 956	kr 23 775 724	0	kr 20 000	kr 217 946	kr 72 600	kr 70 324	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 30 856	kr 29 888	kr 191 500	kr 185 810	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Pump	Structural deficiency	Degraded	5,75	33,9	y	300	2	kr 17 868 853	kr 23 711 066	0	kr 20 000	kr 217 946	kr 67 800	kr 65 674	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 553	kr 1 504	kr 179 500	kr 174 186	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Pump	Vibration	Degraded	8,58	78,1	y	200	2	kr 18 178 244	kr 24 030 758	0	kr 20 000	kr 217 946	kr 156 200	kr 151 303	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 544	kr 1 496	kr 400 500	kr 388 257	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Pump	Abnormal instrument reading	Incipient	274,18	8,1	n	1600	1	kr 14 083 519	kr 17 885 440	0	kr 20 000	kr 217 946	kr 16 200	kr 15 692	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 394 819	kr 382 441	kr 50 500	kr 49 230	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Scrubber	Minor in-service problem	Incipient	12,50	14,5	n	2200	1	kr 13 816 000	kr 17 626 308	0	kr 20 000	kr 217 946	kr 29 000	kr 28 091	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 82 500	kr 79 913	kr 82 500	kr 80 227	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Scrubber	Abnormal instrument reading	Incipient	52,12	11,1	n	1400	1	kr 13 928 604	kr 17 735 382	0	kr 20 000	kr 217 946	kr 22 200	kr 21 504	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 218 904	kr 212 041	kr 65 500	kr 63 760	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Scrubber	External Leakage - Process	Degraded	8,88	7,5	y	100	2	kr 17 685 164	kr 23 553 137	1	kr 20 000	kr 217 946	kr 15 000	kr 14 530	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 2 664	kr 2 580	kr 47 500	kr 46 324	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Sensors	Other	Degraded	5,55	5,3	n	1100	2	kr 17 670 153	kr 23 538 596	1	kr 20 000	kr 217 946	kr 10 600	kr 10 268	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 3 053	kr 2 957	kr 36 500	kr 35 669	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Sensors	Erratic output	Degraded	2,04	4	n	400	2	kr 17 658 408	kr 23 527 220	1	kr 20 000	kr 217 946	kr 8 000	kr 7 749	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 408	kr 395	kr 30 000	kr 29 373	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Sensors	Erratic output	Incipient	3,67	7	n	2400	1	kr 13 685 404	kr 17 499 807	0	kr 20 000	kr 217 946	kr 14 000	kr 13 561	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 4 404	kr 4 266	kr 45 000	kr 43 903	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Sensors	Low output	Degraded	2,43	5,3	n	900	2	kr 17 668 194	kr 23 536 699	1	kr 20 000	kr 217 946	kr 10 600	kr 10 268	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 094	kr 1 059	kr 36 500	kr 35 669	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Sensors	Minor in-service problem	Incipient	4,56	3,6	n	2200	1	kr 13 662 216	kr 17 477 346	1	kr 20 000	kr 217 946	kr 7 200	kr 6 974	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 5 016	kr 4 859	kr 28 000	kr 27 436	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Separator	Plugged/Chocked	Degraded	8,92	4,3	y	300	2	kr 17 686 860	kr 23 554 780	1	kr 20 000	kr 217 946	kr 8 600	kr 8 330	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 26 760	kr 25 921	kr 31 500	kr 30 826	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Separator	Minor in-service problem	Incipient	49,42	8	n	1600	1	kr 14 478 720	kr 18 268 250	1	kr 20 000	kr 217 946	kr 16 000	kr 15 498	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 790 720	kr 765 929	kr 50 000	kr 48 746	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Separator	Abnormal instrument reading	Incipient	23,71	6,8	n	1100	1	kr 13 940 410	kr 17 746 818	0	kr 20 000	kr 217 946	kr 13 600	kr 13 174	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 260 810	kr 252 633	kr 44 000	kr 42 934	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Separator	Parameter deviation	Degraded	29,68	6,3	n	1400	2	kr 18 089 620	kr 23 944 912	1	kr 20 000	kr 217 946	kr 12 600	kr 12 205	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 415 520	kr 402 492	kr 41 500	kr 40 512	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Other	Degraded	4,35	5,4	y	450	2	kr 17 669 336	kr 23 537 805	1	kr 20 000	kr 217 946	kr 10 800	kr 10 461	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 536	kr 1 487	kr 37 000	kr 36 153	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	External Leakage - Utility	Incipient	19,29	2,6	n	1400	1	kr 13 670 455	kr 17 485 326	1	kr 20 000	kr 217 946	kr 5 200	kr 5 037	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 20 255	kr 19 619	kr 23 000	kr 22 592	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Valve Leakage in closed position	Degraded	2,84	9,4	y	500	2	kr 17 696 865	kr 23 564 471	1	kr 20 000	kr 217 946	kr 18 800	kr 18 211	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 065	kr 1 032	kr 57 000	kr 55 526	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Delayed operation	Degraded	2,13	10,9	n	1000	2	kr 17 707 898	kr 23 575 158	0	kr 20 000	kr 217 946	kr 21 800	kr 21 117	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 1 598	kr 1 547	kr 64 500	kr 62 791	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	External Leakage - Utility	Degraded	2,94	14,7	n	1100	2	kr 17 735 326	kr 23 601 726	0	kr 20 000	kr 217 946	kr 29 400	kr 28 478	kr 12 000 000	kr 15 692 090	kr 4 000 000	kr 6 054 047	kr 2 426	kr 2 349	kr 83 500	kr 81 196	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Abnormal instrument reading	Incipient	4,91	10,1	y	1200	1	kr 13 707 119	kr 17 520 841	0	kr 20 000	kr 217 946	kr 20 200	kr 19 567	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 4 419	kr 4 280	kr 60 500	kr 58 917	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Minor in-service problem	Incipient	5,57	3,6	y	1400	1	kr 13 663 049	kr 17 478 152	1	kr 20 000	kr 217 946	kr 7 200	kr 6 974	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 5 849	kr 5 665	kr 28 000	kr 27 436	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649
Valves	Abnormal instrument reading	Incipient	282,36	3,4	y	700	1	kr 13 793 539	kr 17 604 552	1	kr 20 000	kr 217 946	kr 6 800	kr 6 587	kr 12 000 000	kr 15 692 090	kr 2 000	kr 2 422	kr 137 739	kr 133 421	kr 27 000	kr 26 467	kr 1 500 000	kr 1 452 971	kr 100 000	kr 72 649

Appendix 6: OBM answer reports

Answer report from scenario 1:

Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/1/2010 1:11:44 PM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 02 Seconds
Iterations: 0
Subproblems: 5
Incumbent Solutions: 1509

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM n	858 824 102,63	10 272 062,85

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	1	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	1	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	1	Normal
PU_d2	PU_d2	0	1	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	1	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used n	119,9	$B$14<=$B$12	Not Binding	0,1

Answer report from scenario 2:

Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/1/2010 1:27:16 PM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 01 Seconds
Iterations: 0
Subproblems: 9
Incumbent Solutions: 702

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM y	858 824 102,63	71 474 244,08

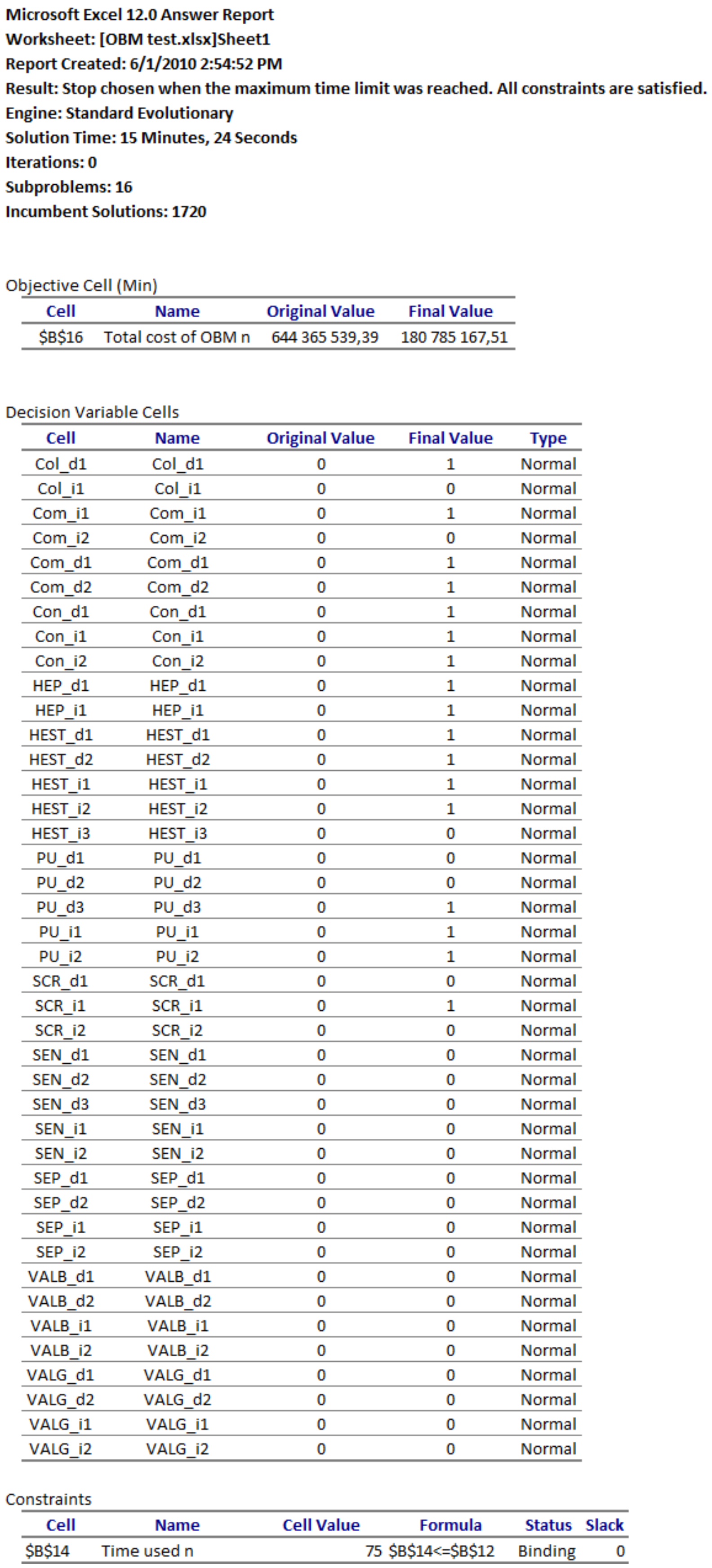
Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	1	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	1	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	1	Normal
PU_d2	PU_d2	0	1	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used y	104,9	$B$14<=$B$12	Not Binding	0,1

Answer report form scenario 3:



Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/1/2010 2:54:52 PM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 24 Seconds
Iterations: 0
Subproblems: 16
Incumbent Solutions: 1720

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM n	644 365 539,39	180 785 167,51

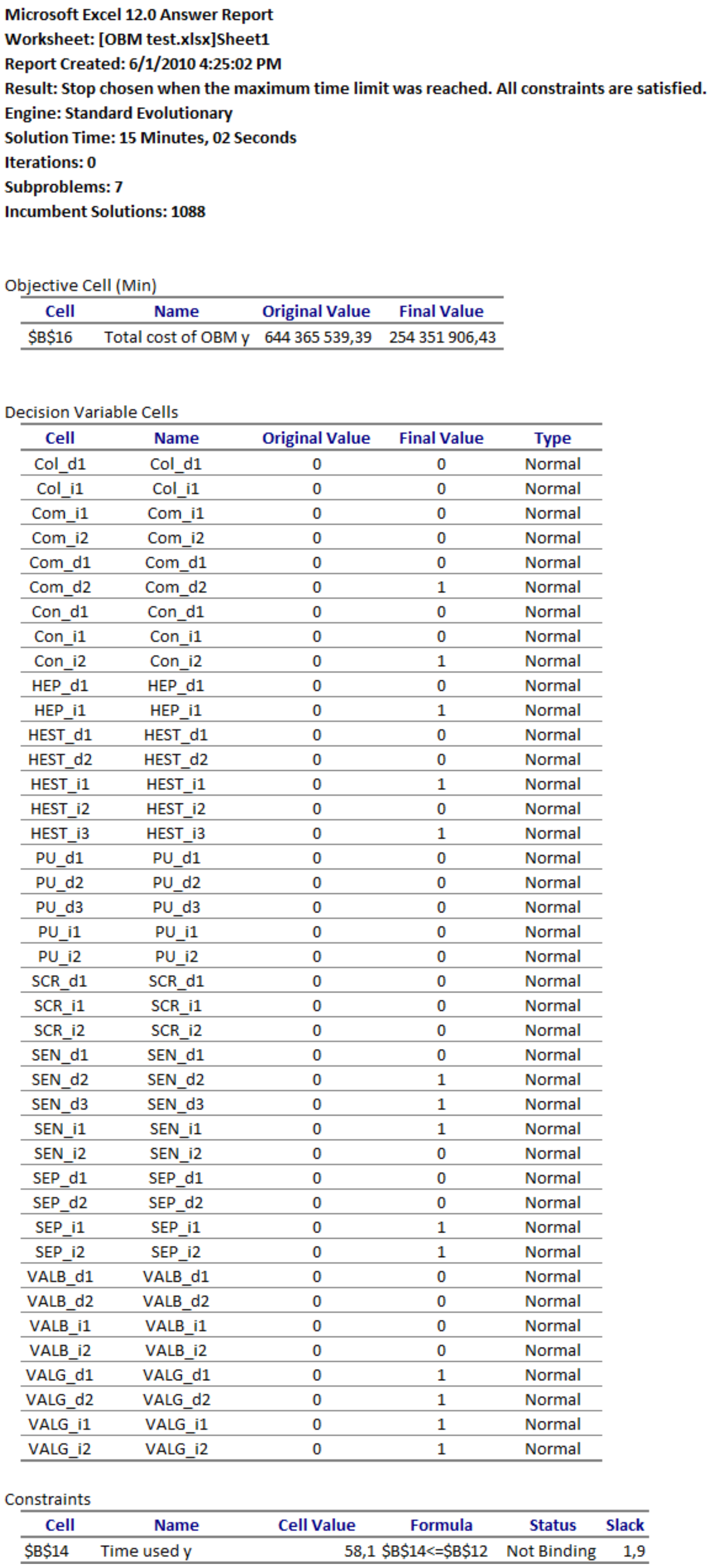
Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	1	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	1	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	1	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	1	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	1	Normal
PU_i1	PU_i1	0	1	Normal
PU_i2	PU_i2	0	1	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	1	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	0	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used n	75	$B$14<=$B$12	Binding	0

Answer report from scenario 4:



Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/1/2010 4:25:02 PM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 02 Seconds
Iterations: 0
Subproblems: 7
Incumbent Solutions: 1088

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM y	644 365 539,39	254 351 906,43

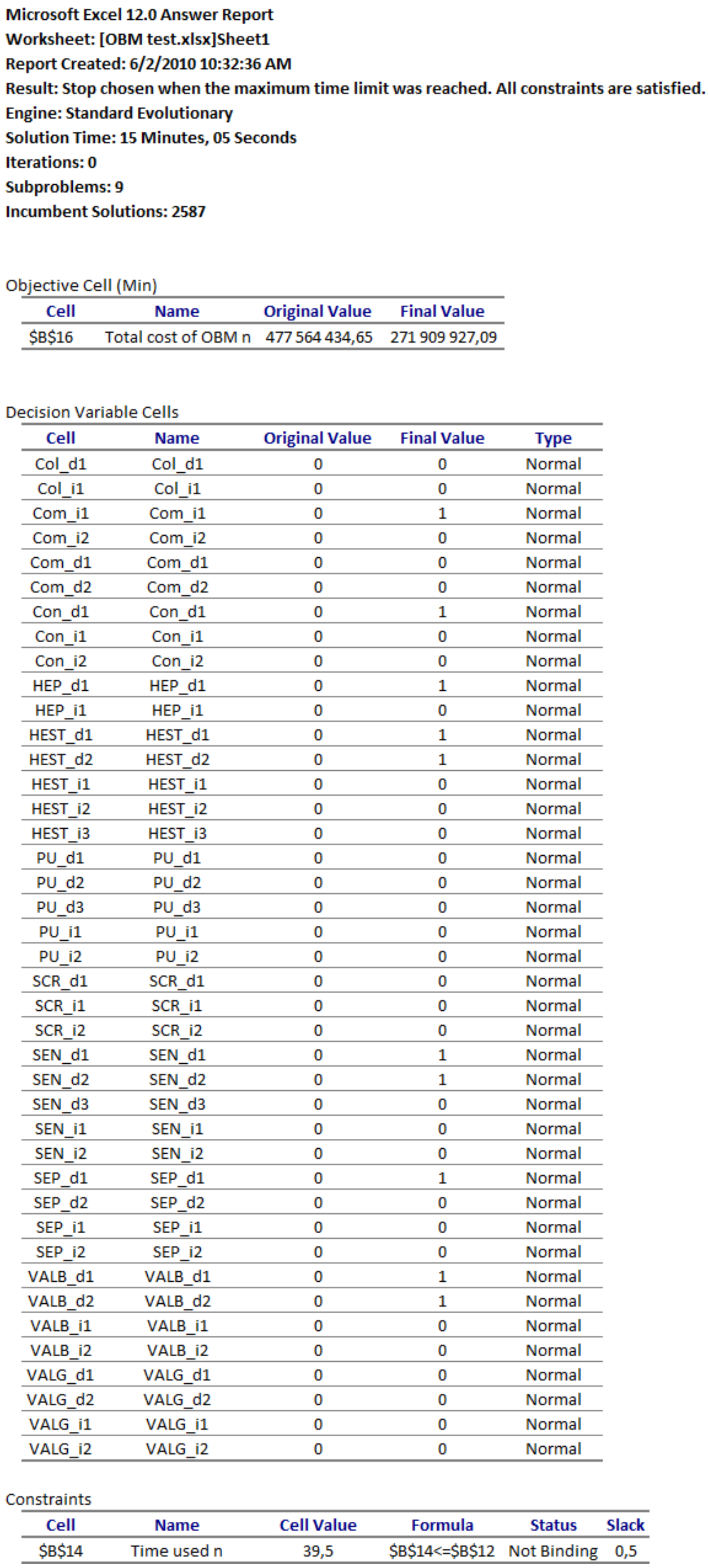
Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	0	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	1	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	1	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	1	Normal
HEST_d1	HEST_d1	0	0	Normal
HEST_d2	HEST_d2	0	0	Normal
HEST_i1	HEST_i1	0	1	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	1	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	0	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	1	Normal
SEN_i1	SEN_i1	0	1	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	0	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	1	Normal
SEP_i2	SEP_i2	0	1	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	0	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	1	Normal
VALG_d2	VALG_d2	0	1	Normal
VALG_i1	VALG_i1	0	1	Normal
VALG_i2	VALG_i2	0	1	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used y	58,1	$B$14<=$B$12	Not Binding	1,9

Answer report from scenario 5:



Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/2/2010 10:32:36 AM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 05 Seconds
Iterations: 0
Subproblems: 9
Incumbent Solutions: 2587

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM n	477 564 434,65	271 909 927,09

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	0	Normal
Con_d1	Con_d1	0	1	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	0	Normal
HEP_d1	HEP_d1	0	1	Normal
HEP_i1	HEP_i1	0	0	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	0	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	1	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	1	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	1	Normal
VALB_d2	VALB_d2	0	1	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used n	39,5	$B$14<=$B$12	Not Binding	0,5

Answer report from scenario 6:

Microsoft Excel 12.0 Answer Report
Worksheet: [OBM test.xlsx]Sheet1
Report Created: 6/2/2010 11:28:44 AM
Result: Stop chosen when the maximum time limit was reached. All constraints are satisfied.
Engine: Standard Evolutionary
Solution Time: 15 Minutes, 14 Seconds
Iterations: 0
Subproblems: 8
Incumbent Solutions: 11981

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$B$16	Total cost of OBM y	477 564 434,65	333 048 876,55

Decision Variable Cells

Cell	Name	Original Value	Final Value	Type
Col_d1	Col_d1	0	0	Normal
Col_i1	Col_i1	0	0	Normal
Com_i1	Com_i1	0	1	Normal
Com_i2	Com_i2	0	0	Normal
Com_d1	Com_d1	0	0	Normal
Com_d2	Com_d2	0	0	Normal
Con_d1	Con_d1	0	0	Normal
Con_i1	Con_i1	0	0	Normal
Con_i2	Con_i2	0	0	Normal
HEP_d1	HEP_d1	0	0	Normal
HEP_i1	HEP_i1	0	0	Normal
HEST_d1	HEST_d1	0	1	Normal
HEST_d2	HEST_d2	0	1	Normal
HEST_i1	HEST_i1	0	0	Normal
HEST_i2	HEST_i2	0	0	Normal
HEST_i3	HEST_i3	0	0	Normal
PU_d1	PU_d1	0	0	Normal
PU_d2	PU_d2	0	0	Normal
PU_d3	PU_d3	0	0	Normal
PU_i1	PU_i1	0	0	Normal
PU_i2	PU_i2	0	0	Normal
SCR_d1	SCR_d1	0	0	Normal
SCR_i1	SCR_i1	0	0	Normal
SCR_i2	SCR_i2	0	0	Normal
SEN_d1	SEN_d1	0	1	Normal
SEN_d2	SEN_d2	0	1	Normal
SEN_d3	SEN_d3	0	0	Normal
SEN_i1	SEN_i1	0	0	Normal
SEN_i2	SEN_i2	0	0	Normal
SEP_d1	SEP_d1	0	1	Normal
SEP_d2	SEP_d2	0	0	Normal
SEP_i1	SEP_i1	0	0	Normal
SEP_i2	SEP_i2	0	0	Normal
VALB_d1	VALB_d1	0	0	Normal
VALB_d2	VALB_d2	0	1	Normal
VALB_i1	VALB_i1	0	0	Normal
VALB_i2	VALB_i2	0	0	Normal
VALG_d1	VALG_d1	0	0	Normal
VALG_d2	VALG_d2	0	0	Normal
VALG_i1	VALG_i1	0	0	Normal
VALG_i2	VALG_i2	0	0	Normal

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$14	Time used y	24,9	$B$14<=$B$12	Not Binding	0,1