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Abstract:
Ageing is a process in which the characteristics of a Structure, System or Component (SSC) gradually change with time or use. Several installations tied to the Norwegian petroleum industry are ageing. They have reached their initial design life, however the respective are still producing hydrocarbons. Continued operations of the facilities are favorable of both economic- and safety perspectives.

Under these premisses, the process of choosing the optimal strategy for ageing equipment becomes essential. In this Master Thesis, a Decision Model applicable for a structure, system or component to determine this strategy, is presented. An introduction to the available strategies are given, in order to set the background for developing such a model regarding ageing equipment.

A Decision Model is than developed in order to easily determine the most optimal strategy for the equipment in question. The model is a tool to evaluate the different strategies against each other, concerning different parameters. These parameters are Obsolescence, Organizational Matters and Technical Challenges. However, the main focus of this report will be given to the material degradation, the technical condition, with necessary assumptions concerning obsolescence and organizational issues taken.

Keyword:
Ageing
Strategies
Decision Model

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MASTER THESIS
for
M.Sc. student Therese Mogstad
Department of Marine Technology

Spring 2011

Decision Models related to Ageing and Life Extension

(Beslutningsmodeller relatert til aldring og levetidsforlengelse)

Ageing is a process in which the characteristics of a Structure, System or Component (SSC) gradually change with time or use. Several installations tied to Norwegian petroleum industry are older than, or approaching, the designed operating life limit. Continued operation is favourable from safety and economic perspectives. Gassco is responsible for safe and efficient transport of gas from the Norwegian Continental Shelf (NCS) to European countries, and operates the integrated gas transport system including the two major Norwegian gas processing facilities, Kårstø and Kollsnes. Gassco is working with MARINTEK to develop and implement models and processes to manage ageing equipment in a safe and cost efficient manner. This M.Sc. thesis shall be written in relation to the Gassco Ageing Management Programme. The thesis includes the following tasks:

1. With basis in the project thesis:
   (a) Identify and elaborate the different strategies that can be implemented for ageing equipment. This should not be limited to purely maintenance strategies, but also include other strategies (e.g. re- investments, modifications, change of operational conditions, inventory strategies, etc.)
   (b) For the different strategies identify and discuss associated parameters and identify the largest cost contributors.
2. (a) Develop a model for determination of optimum strategy for ageing equipment. The model should include the different aspects of ageing (material degradation, obsolescence, organisational).
   (b) With the Fire Water Pump system, or part of this system, as case, recommend strategies that should be implemented to ensure continued operation for a period until 2025. For the matter of ageing and example calculations, focus on material degradation, but make necessary assumptions concerning obsolescence and organisational issues.

The work should be carried out in close cooperation with MARINTEK. 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: 17^{th} January 2011

Completion date: 14^{th} June 2011

Handed in:Trondheim 06^{th} June 2011

Magnus Rasmussen

Professor

Preface

This report is an individual Master Thesis. The thesis is written at the Norwegian University of Science and Technology (NTNU) as a part of a 5 year profession study in Marine Technology with specialization in Marine Operations and Maintenance. The thesis is the result of one semester of work, extending from January to June 2011.

The aim of this Master Thesis is to develop a Decision Model, which can be used as a tool to implement the correct strategy regarding ageing equipment. This is important for the operators of oil and gas facilities to continue safe and economic beneficial operation.

Special thanks will be given to the people contributing to the completion of the thesis. Professor Magnus Rasmussen has been supportive through the process, guiding me in the right direction. Torgeir Brurok and Harald Rødseth have been my invaluable mentors throughout the entire project, guiding and helping me to reach the goal.

Trondheim, Norway
June 6, 2011

Therese Mogstad

Abstract

Ageing is a process in which the characteristics of a Structure, System or Component (SSC) gradually change with time or use. Several installations tied to the Norwegian petroleum industry are ageing. They have reached their initial design life, but the respective are still producing hydrocarbons. Continued operations of the facilities are favorable of both economic- and safety perspectives.

Under these premisses, the process of choosing the optimal strategy for ageing equipment becomes essential. In this thesis, a Decision Model applicable for a structure, system or component to determine this strategy, is presented. An introduction to the available strategies are given, in order to set the background for developing such a model regarding ageing equipment. The strategies found most suitable are:

- Replacement
- Modification
- Change of Maintenance Strategy
- Change of Operational Conditions
- Overhaul
- Continue as usual

Associated cost parameters are than discussed, while this will be an important factor when comparing the different strategies with each other in order to find the optimal ageing strategy. Table 1 shows the largest identified cost parameters related to the strategies.

Strategies	**Associated Cost Parameters**
Replacement	Downtime, Investment, Personnel
Modification	Downtime, Labor, Investment of spare parts
Change of Maintenance Strategy	Personnel, Consumables, Training
Change of Operational Conditions	Loss in production and revenue
Overhaul	Replacement parts, site to perform overhaul
Continue as usual	Increase in maintenance costs

Table 1: Associated Cost Parameters related to the strategies in Section 2.1

A Decision Model is than developed in order to easily determine the most optimal strategy for the equipment in question. The model is a tool to evaluate the different strategies against each other, concerning different parameters. These parameters are *Obsolescence*, *Organizational Matters* and *Technical Challenges*. However, the main focus of this report will be given to the material degradation, the technical condition, with necessary assumptions concerning obsolescence and organizational issues taken.

The first step of the model is to determine eventual rules and regulations, which can exclude some of the optional strategies in order to minimize the further analyses. Thereafter, the parameters are analysed in parallel to make room for ongoing discussions to minimize the calculations needed to determine the optimal strategy.

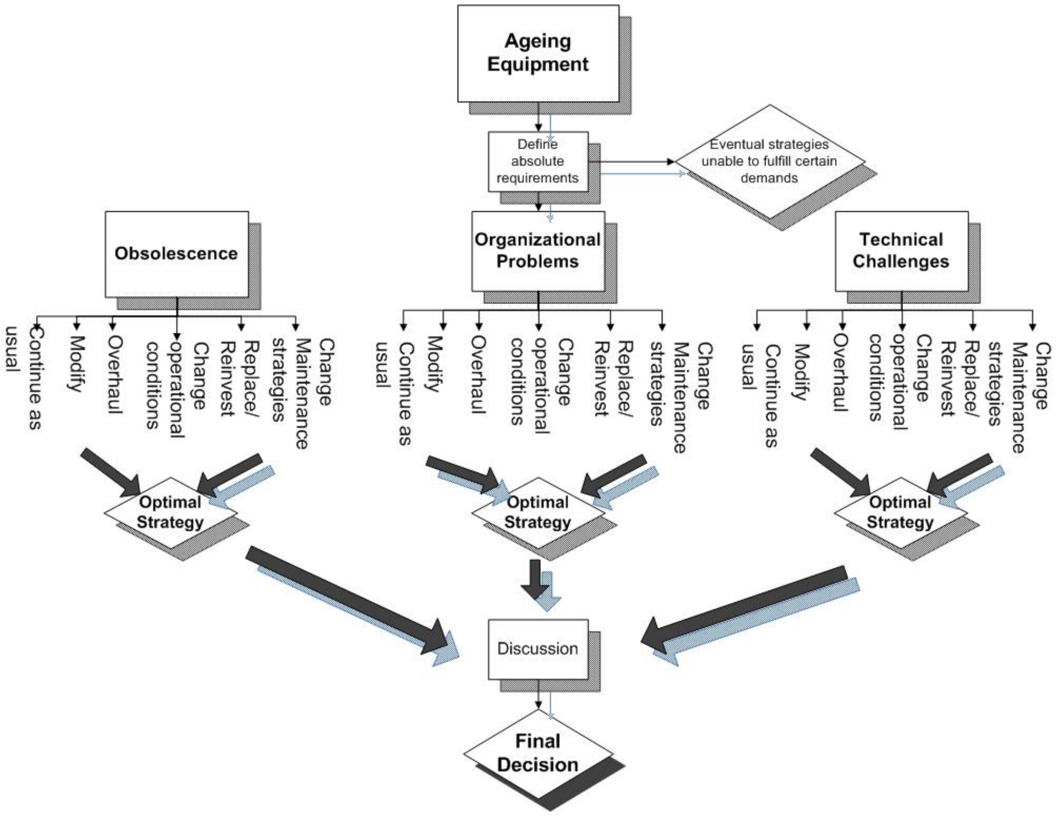

Figure 1: Superior Model

The final decision will be based on costs related to the strategies, and the ageing strategy returning most cost-beneficial is considered the most optimal.

A real case, the Fire Water Pump system at Gas Facility A, is used to illustrate how the Decision Model can be implemented to determine which strategy to choose regarding ageing equipment. This is a large and complex system, and the focus of this thesis will be on the Air-Starting system, one of six subsystems of the Fire Water Pump system. The most important step of the technical analyses is the Weibull Analysis, which for the Air-Starting system shows signs of ageing. The strategies of Continuing as Usual, Modification and Change Operational Conditions are early defined as non-applicable, and the optional strategies appears to be Replacement, Overhaul and Change of Maintenance Strategy. Costs related to these strategies are discussed and the most optimal strategy proves to be a replacement of the air-compressor.

Limitations related to the model and the uncertainties related to the use of OREDA data are discussed in the thesis.

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1 Introduction

The purpose of this report is to develop an overall Decision Model for determination of the optimal strategy for ageing equipment. Furthermore, the thesis will show benefits and costs of the strategies available for ageing equipment.

1.1 Background

The facilities at the Norwegian Continental shelf are ageing and several of the installations have reached their original designed life period. They are, however, still able to operate and it is both in the Norwegian Governments and the operators interest to continue safe and economic operation. Thus, strategies and decisions have to be made regarding ageing of old equipment.

1.2 Objectives

The overall objective of this Master Thesis is to develop a Decision Model suitable for ageing equipment. This model will optimize the work regarding ageing equipment by determining the optimal strategy to implement, with focus on cost. This is done through 4 main objectives:

- Identification and elaboration of different strategies applicable to ageing equipment
- Identification and discussion of associated cost parameters to the strategies
- Development of a decision model for determination of optimal strategy for ageing equipment
- Implementation of the model to a real case problem

1.3 Structure of Report

Section 2 identifies and elaborates different strategies that can be implemented for ageing equipment.
Section 3 discusses the associated cost parameters to the strategies from Section 2. An introduction to the Life Cycle Cost is also given.
Section 4 describes the developed model for determination of optimum strategy for ageing equipment.
Section 5 describes the Fire Water Pump System at Gas Facility A.
Section 6 implements the model to the real case, Fire Water Pump system at Gas Facility A, focusing on the Air-Starting system.
In *Section 7* and *Chapter 8* the result from use of the model is discussed.
Section 9 provides the reader with a conclusion.

1.4 Limitations & Assumptions

Limitations of this thesis is concerned with limited data for the system in question. Assumptions regarding costs are made to show the use and applicability of the model. The estimated parameters are carefully described.

2 Ageing of Equipment

Ageing failure: Failure whose probability of occurrence increases with the passage of calendar time. (Standard Norge, 2010)

All types of equipment can be susceptible to ageing. Ageing equipment is equipment for which there is evidence or likelihood of significant deterioration and damage taking place since new, or for which there is in- sufficient information and knowledge available to know the extent to which this possibility exists. (COMAH, 2010)

Ageing of processing facilities and terminals at Gas Facility A, is an important consideration for regularity and safety when prolonging the useful life of oil and gas (O&G) installations. Operating Company's goal is to operate it's facilities with high levels of regularity and safety. Including ageing aspects in existing maintenance management loops is intended to secure their technical integrity and provide a sound basis for determination of ageing strategies.
(Operating Company A, 2008)

In addition to technical deterioration of equipment, it is also important to evaluate the obsolescence and organizational deterioration of ageing in order to obtain a complete picture of the ageing problem. This is further elaborated in Section 4, developing the Decision Model.

2.1 Strategies for Ageing Equipment

"A strategy is optimal when it is applicable and can cost-effectively prevent failures or predict the timing of necessary refurbishment". (IAEA, 2007)

Detection of ageing effects should occur before there is a loss of structure or component intended functions, and in order to deliver an effective "ageing strategy" it is important to understand:

- the current status and data confidence for each of the facility assets
- the history, "life-stage" of the asset and its projected trajectory
- the potential failure mode and the risks this imposes to the business (revenue, cost, HSE, reputation etc)
- mitigation options and cost

(Transfield Worley Services, 2007)

Ageing equipment is less efficient, harder to maintain, less flexible and more labor intensive. The outdated equipment also puts the entire facility at risk, and the importance of actions regarding ageing equipment is therefore high. There are different strategies operators can implement when the equipment is ageing and following is a description of the most relevant strategies, which the further developed Decision Model will be based on.

2.1.1 Replacement

Replacement is, by definition, when an equipment takes the place of another that is broken, inefficient or no longer working or yielding as what is expected.

A replacement is an option in situations where ageing is a major factor, or where system expansion/reconfiguration to support increased power or load demand is required. With a total replacement, new equipment using higher-rated technology is installed, removing the problems of ageing. The life-cycle timer is turned back to zero and new equipment are designed to perform well for a new, defined period. A further benefit is that new equipment is more reliable with higher safety considerations. Disadvantages of this strategy can be problems regarding long delivery time, downtime when removing and installing the equipment, staff training and new spare parts. (Stephens, 2009)

Replacement usually fall into two categories:

1. Replacement of equipment that deteriorates with time
2. Replacement of items that fail in service

The first category is concerned with determining the optimum point in time at which the item should be replaced. At some age, a replacement of equipment is more economic beneficial than continuing operation of the old equipment with an increasing operating cost. At that age, the saving from the use of new equipment compensates more than the initial cost of the equipment.

The second category is related to circumstances in which the item breaks down and a replacement is necessary while the equipment can no longer operate as planned.
(S.Eilon, J.R.King and D.E. Hutchinson, 1966)

If the company decides on replacing the equipment, there are different policies which can be implemented:

- Equipment is replaced on scheduled basis, whether failed or not
- There is no testing nor maintenance action of the equipment, and it is replaced on failure
- Equipment is maintained or tested on scheduled basis and replaced when found faulty
- Operation of degraded components is continued in order to postpone the replacement until a convenient moment

(IAEA, 2000)

Which policy to choose is dependent of the equipments reliability, safety significance and accessibility. Considering equipment particularly exposed for ageing, spare parts availability and obsolescence are of high importance. It is also important to optimize the time to perform a replacement, which is at the time when the total costs of providing and safely maintaining the asset of service are minimized over a defined period. (IAEA, 2000)

There have been several previous examples of replacements at Gas Facility A. In 2009 they received consent for installation of two new crossovers from the Water X inlet and the Water XX inlet. The replacements were performed in order to meet the new requirements for export gas sales from Gas Facility A, as well as improve availability at the processing facility. (PSA, 2009)

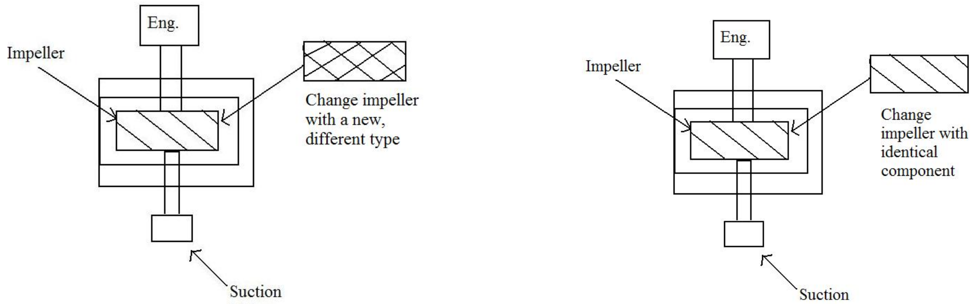
2.1.2 Modification

"A modification is a combination of all technical, administrative and managerial actions intended to **change** one or more functions of an item". (Standard Norge, 2010)

By performing a modification, ageing items are better equipped to meet the required operational standards. In operating production or processing systems, modifications performed on ageing equipment, is firstly to prevent recurrence of the original failure cause, and to ensure that the repair will be resistant and not introduce any further damage. The aim is to achieve higher reliability and a reduction in cost. A modification should be carried out to meet new rules and regulations and appropriate consent should be in order before proceeding with this strategy. (TWI Ltd & Engineering, 2006)

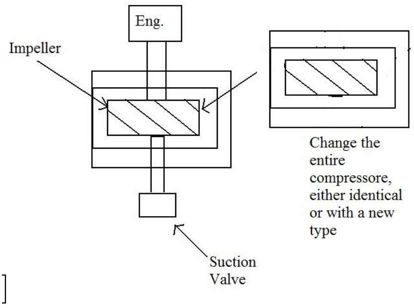
However, modifications changing the equipment or process, can introduce a hazard. Modifications can for instance change the loading on the structure and change the fire and explosion hazard profile. Modifications may also lead to a degradation of the effectiveness in maintaining the integrity in a greater or lesser degree. It is therefore important to have a system, identifying and controlling the changes and make sure of maintaining the integrity of the equipment avoiding degradation due to a modification. As a part of the Gas Facility A Expansion Project 2010 to upgrade the systems at Gas Facility A, in total 21 modifications were performed on existing sublocations/local equipment rooms. This project aims to improve regularity, accessibility and technical safety with the highest HSE standards and goals avoiding any disturbances to normal production.

It is important to distinguish between a replacement and a modification. For instance, considering a centrifugal pump with a broken impeller. If the impeller is changed, that is by definition a replacement of the impeller but a modification or an overhaul (if changed with identical parts) of the pump. However, if it is economical beneficial to change the entire pump, than a replacement of the pump is conducted. This is shown in Figure 2.



[Modification]

[Overhaul]



[Replacement]

Figure 2: Differences of the strategies Replacement, Modification and Overhaul

2.1.3 Change of Maintenance Strategy

A change of maintenance strategy may lengthen production run times, without damaging the equipment. (John Endrenyi and George J. Anders, 2006)

To prevent and reduce further ageing, an optional strategy is to change the existing maintenance strategy. The existing plant or offshore facility are supposed to have a rigorous work order system by which maintenance activities can be scheduled, implemented and recorded. However, to prevent further ageing, one can optimize the strategy by for instance increasing the number of inspections and actions, use new technology or completely change the maintenance strategy.

Maintenance activities should ensure that the installed equipment remains in its qualified condition and provide timely identification of unforeseen ageing mechanisms that may cause equipment degradation. (IAEA, 2007)

Improving reliability means freedom from failures. By improving the reliability of a system through maintenance improvements, one reduces the cost in three ways:

1. One get more time to make product
2. One get more product out
3. One get to keep the earnings the business would have lost from failures

(Sondalini & Witt)

A change of maintenance strategy should result in the equipment being in a better condition than its current state or if it was replaced. However, most often, only limited improvements are performed, and these small improvements of the damaged equipment may result in smaller costs. When concerning limited improvements, these are often based on experience, which is an important part of choosing the optimal strategy.

In september 2007, the Insulation, Scaffolding and Surface treatment (ISS) program was implemented at Gas Facility A. This program aims to reduce and prevent corrosion of the plant. The work focuses on maintaining the surface of piping and tanks as well as replacing insulation and heating cables in selected plant sections. This project is scheduled to run over five-seven years and is an example of implementing new maintenance strategies at the plant. (Operating Company, 2010)

Reliability Centered Maintenance (RCM) is a common method to establish maintenance strategies for all devices in a facility based on internal and external criteria's related to safety, environment, operational and financial matters. This is a process to ensure that assets continue to do what their users require in their present operating context. (Moubray, 1997)

The main tasks for every maintenance strategy is to:

- Decide upon which system/equipment where preventive maintenance is applicable and economic beneficial
- Decide upon intervals (periodically or condition based) for the strategy chosen

(Rasmussen, 2003)

By use of RCM, the intervals and maintenance strategy is determined. More on how to perform a RCM-process is explained in Section 4.5 when implementing the Decision Model to the Fire Water Pump System at Gas Facility A.

Different approaches to Maintenance The different approaches to maintenance discussed in this Master Thesis will take basis in the student's Project Work (Mogstad, 2010). This report will give a quick summary of the various models.

Age- Based preventive Maintenance This model can be implemented to a basic system or a more complex system, in either case, the failures can be seen according to a stochastic process, and it is presumed that historically data is available. Preventive maintenance is performed after t_p hours of operation without failure. If the system should fail prior to t_p hours, corrective maintenance will be performed and preventive maintenance is rescheduled to another t_p operation hours. When maintenance is performed, both corrective and preventive, the system will again obtain an "as-good-as-new" condition.

$$\mathrm{UEC}(\mathrm{t}_p) = \frac{\mathrm{C}_p\mathrm{R}(\mathrm{t}_p) + \mathrm{C}_c\mathrm{F}(\mathrm{t}_p)}{\mathrm{t}_p\mathrm{R}(\mathrm{t}_p) + \mathrm{M}(\mathrm{t}_p)\mathrm{F}(\mathrm{t}_p)}[\frac{\text{cost}}{\text{unit time}}] \tag{1}$$

Constant- Interval Preventive Maintenance The major difference from the previous model is the replacement regime. Instead of setting a critical age to the system, preventive maintenance is performed at pre-determined intervals. This is regardless of the number of intervening failures. Should a failure occur before planned maintenance, corrective maintenance will be performed, and the time until next maintenance will remain as scheduled.

$$\mathrm{UEC}(\mathrm{t}_p) = \frac{\mathrm{C}_p + \mathrm{C}_c\mathrm{H}(\mathrm{t}_p)}{\mathrm{t}_p}[\frac{\text{cost}}{\text{unit time}}] \tag{2}$$

Constant Interval with Minimum Repair This model is almost the same as the previous model. A constant interval is determined, but the amount of repair of an eventual failure is different. If the failure occurs close to the planned maintenance action, only a minimal repair is performed and hopefully the component will survive until the interval has elapsed. An obvious disadvantage of the constant interval model is thus removed.

$$\mathrm{UEC}(\mathrm{t}_p) = \frac{\mathrm{C}_p + \mathrm{C}_{cm}\mathrm{H}(\mathrm{t}_p)}{\mathrm{t}_p}[\frac{\text{cost}}{\text{unit time}}] \tag{3}$$

Opportunity- Based Replacement Model The previous presented models all assumes that preventive maintenance can be executed at any time. This however, is not the case for many systems. Due to time limitations, safety manners and high downtime cost i.e. there may only be opportunity for maintenance when the equipment is down due to failures of other units. In this model, the maintenance is scheduled to be carried out at these opportunities and the cost model will be as shown below.

$$\mathrm{UEC}(\mathrm{t}_p) = \frac{\mathrm{NC}_c + [(1-\lambda l)\mathrm{C}_c + \lambda l\mathrm{C}_p]}{\mathrm{L} + l}[\frac{\text{cost}}{\text{unit time}}] \tag{4}$$

2.1.4 Change of Operational Conditions

"Operational conditions include environmental conditions and physical loads as the equipment experiences during all lifecycle phases. To fully understand failures mechanisms, it is important to know and understand the operational conditions". (Expro Base, 2009)

The operating conditions can affect the ageing process, and periodic evaluation of operational experience may reveal the need to change operational conditions. This can be changes in temperature, pressure, flow velocity or system loading to mention some adjustments. Change of such parameters can reduce the wear and ageing deterioration. Notice though, these adjustments will result in conditions outside the original design and careful preparations have to be made. A change of the operational conditions can lead to a higher risk of damage and a loss in production. If there is no buffer regarding such losses, it can lead to severe financial losses. (IAEA, 2000)

In 1988, a laboratory was founded as an accredited laboratory for the testing and calibration of dry gas meters. The Laboratory is situated as Gas Facility A's nearest neighbor and has become known worldwide due to it's unlimited access to high-pressure natural gas and condensate. At the Laboratory, Operating Company A is able to find the optimal operating condition, to increase the production as well as reduce the ageing. (Offshore Technology, 2009)

2.1.5 Overhaul

To conduct an overhaul is to make necessary repairs on the equipment and restore the item in question to a serviceable condition. (The Free Dictionary, 2009)

In order to increase the life period for a system or component exposed to ageing, an optional strategy is to perform an overhaul of the item. By changing parts of the equipment with an identical component, the equipment can extend its life period and has, by definition, went through an overhaul. An overhaul has therefore the benefit of interchangeability using identical devices, making installation easy. Downtime is kept at a minimum, and no structural modifications or additions should be necessary.

However, there are to this as to every strategy, disadvantages. If an overhaul is conducted in the constant-failure rate region of its life period, an overhaul might do very little, if anything, to restore the equipment to a like-new condition. An overhaul can at this point be a waste of money because of lack in knowledge of which parts to restore nor the proper time to initiate an overhaul. Another risky aspect of an overhaul is to push the equipment back to the infant mortality condition and there are also no benefits as increase in safety levels, new technology, increased system or load capabilities and there is a marginal extension in service life. Errors concerning incorrect installation can also occur when performing an overhaul, and it should therefore always be satisfactory supervised. As described earlier, it is important to notice that there is a thin line between an overhaul and a modification.

Examples regarding overhauls at Gas Facility A, will be based on the history of mobile cranes. Such cranes, used on Operator A's facility, shall have a general maintenance overhaul in accordance with the design parameters from the manufacturer. If data for design criteria not are available, a maintenance overhaul should be carried out and documented every ten years. (Operator A, 2006)

2.1.6 Continue as usual

It may not always be necessary to perform an action against ageing equipment. Equipment showing signs of ageing can still be able to perform as required through it's planned life cycle, and the optional strategy to Continue operation as usual should be chosen. This strategy assumes that current maintenance practices are continued and failure rates will gradually increase commensurate with progressive ageing. There should also be well established that the equipment will be able to meet new and forthcoming demands and regulations. An option similar to this strategy is to continue as usual for a defined period, and than reevaluate the decision.

2.2 Inventory Optimization

"Inventory optimization is the derivation of stocking levels throughout the supply planning network based upon service level input". (Snapp, 2010)

Ageing equipment has a greater need for spare parts available at the site, and every above described strategies should have a discussion regarding an optimization of the level of spares. The organizations today faces new challenges, concerning rising storage and transportation costs, increasing service or mission requirements and an ageing infrastructure that is reaching its capacity limits. To work around these problem, one should optimize the inventory of spares.

2.3 Summary & Discussion

Six different strategies to implement in order to prevent further ageing of SSC's have now been discussed. In order to give a quick summary, the pros and cons of each strategy will be shown in Table 2.

	Pros	**Cons**
Replacement	A permanent elimination of the ageing problem	Expensive due to investment- and down-time cost
Modification	Ageing equipment is better equipped to meet the required operational standards	Hazards due to changing of the loading and structure, degradation of effectiveness in maintaining the integrity of the plant. This is also typically a costly alternative
[Change of Maintenance Strategy]	More time to produce, more product and revenue and the equipment resulting in an improved condition	Complex to integrate a completely new system, costly
Change of operational conditions	Less wear and corrosion on the ageing equipment. A strategy, which is easy to implement	Hazards due to change of conditions outside the original design. Loss in revenue due to loss in production can occur
Overhaul	Increases the life period of the equipment by changing only the parts exposed to ageing	Can push the equipment back to infant mortality condition due to lack of knowledge of the ageing problem
Continue as usual	No expenses to implement a new strategy	The equipment may experience more severe signs of ageing as time elapses

Table 2: Summary of Strategies to reduce an ageing problem

3 Associated Cost Parameters

In the process of identifying the optimal strategy concerning ageing equipment, the cost of implementation is the conclusive parameter. Various stakeholders value different criteria's regarding cost.

1. Profit
   For the owners, maximum profit is always the most important factor and will pave the way concerning choice of strategies.
2. Regularity
   The customers main focus is regularity in production.
3. Safety
   Petroleum Safety Authority's highest concern when making a decision regarding ageing equipment, is safety.

In this Section, associated parameters and identification of the largest cost contributers for the strategies from Section 2, will be discussed. A number of economic factors needs to be taken into account when determining the economic life of equipment. Examples can be the cost of acquisition of new plant or machinery, the scrap or resale value of the old equipment, the maintenance cost of keeping the equipment in functioning order and the downtime cost. Further, technical changes in the design and performance of new equipment are also of prime importance.
(S.Eilon, J.R.King and D.E. Hutchinson, 1966)

Discussing associated costs regarding the oil and gas industry is very much about *what* is done *where*. For the labor costs, for instance, the price of personnel will vary a lot from where the operation is performed and how complex it is. An operation performed at Gas Facility A, onshore Norway, is more expensive than hiring personnel in Arabia but less expensive than performing the action offshore Norway. This is shown in Table 3, where the costs vary from low (L) to high (H).

What?	**Where?**	**Cost level**
Simple	Onshore Norway	M
	Offshore Norway	H
	Arabia	L
Big/Complex	Onshore Norway	H
	Offshore Norway	HH
	Arabia	L/M

Table 3: Variation of Costs

The same will apply to the investment cost as well as other associated cost parameters to the ageing strategies. The investment cost can vary from very high to as low as to be negligible, dependent of the equipment. To replace the entire fire water pump system for instance, will be a costly affair while changing a sensor will have no impact on the budget. It is therefore important to analyse what and where when discussing the associated cost parameters.

3.1 General costs

In addition to specified costs related to the strategies in Section 2, which will be further discussed through this Section, some costs are more general, and will be given a short introduction here. These costs will affect every strategy at some level, however, they are hard to predict and will vary a lot from case to case.

3.1.1 Storage Cost

"The cost associated with inventory storage facilities, such as material handling equipment and personnel. It does not include the costs of holding inventory due to insurance, scrap, etc". (Term Wiki, 2010)

3.1.2 Transportation Cost

"By definition, transport cost is the costs involved in relaying goods to and from a plant, including payments to transport firms for their services and any cost incurred by a plant in using and maintaining its own equipment". (Answers.com, 2011)

3.1.3 Administration Cost

"An administration cost is an expense incurred in controlling and directing an organization, but not directly identifiable with financing, marketing, or production operations. Salaries of senior executives and costs of general services (such as accounting, contracting, and industrial relations) fall under this heading. Administrative costs are related to the organization as a whole as opposed to expenses related to individual departments. Also called administrative expenses". (Business Dictionary, 2011)

3.1.4 Costs of spares

"A spare related to an item, is a copy of the item itself". Initial spares and inventory costs includes the acquisition of major units to support organizational maintenance and parts to provide the intermediate level of maintenance. To each of the described strategies, there should be a spare part discussion, while this matter will influence both the technical and economical environment owing to the fact that it is influencing both the unavailability and the cost of storing the spare parts. An optimal decision concerning spare parts, are influenced by several external and system-related parameters:

- *The item's position and function in the system*
  The unavailability of an item can lead to severe downtime costs or just a small, negligible cost dependent on the importance of the equipment
- *The operational situation of the plant*
  The consequence of downtime is also influenced by the operational situation. E.g. will politically imposed production limitations make production downtime up to a certain limit of no economic consequence
- *Oil Price*

- *Frequency of resupply*
  How often is it possible to receive spare parts, and how long will it take for spares to arrive if critical parts are stored at another location?
- *Maintainability properties*
  How the area are designed, influences the amount of work required for performing the work associated with a maintenance task

One should notice that these parameters change over time, and a decision should be reconsidered every so often. The associated cost elements are used to calculate the expected annual cost C_T

$$C_T = C_i + C_p + f \cdot ((1 - p_s)c_n + p_s \cdot c_s \tag{5}$$

The variables are defined as follows:
C_r=Expected total annual maintenance cost
C_i=Annual capital cost for spares and storage facilities
C_p=Annual rush action preparedness cost (if used)
c_n=Cost per action, normal conditions
c_s=Cost per action when spare shortage occurs
p_s=Probability of spare shortage at system supply store
f=Expected number of tasks per year (failure rate)
If no spares are held, both C_i and p_s, is equal to zero.

(Driftslogistikk, 2010)

3.2 Replacement cost

Replacement cost is defined as : ”The amount it would cost to replace an asset at current prices. If the cost of replacing an asset in its current physical condition is lower than the cost of replacing the asset so as to obtain the level of services enjoyed when the asset was bought, then the asset is in poor condition and the firm would probably not want to replace it”.
(Investor Words, 2011)

If the optimal ageing strategy is found to be replacement of equipment, either to prevent obsolescence or to replace failed items, it is necessary to predict replacement costs and the determination of the most economical replacement policy. The following costs should be considered:

- **Downtime cost when replacing**
  Equipment, which is down when it should be operating, restricts the amount of products that is deliverable on the market, and is the oil and gas industry’s number one enemy. This is the most obvious and often largest cost contributor when the equipment is replaced. If the item in question is an important part of the operation and leads to a stop in production when replaced, it can turn out very expensive. Listed below are some of the costs to calculate when determining the actual downtime cost.
  - Employee Productivity
    - Annual revenue of the company divided on number of employees.
  - System Restoration Cost
    - Total Labor Hours required to replace lost data and restore system times the hour cost of restoration.
  - Lost Employee Production Cost
    - percentage of employees (excluding systems staff) that are unproductive during downtime
  - Lost Sales Opportunity Cost
    - Estimated number of sales lost due to outage
  - Lost Customer and Damaged Reputation Cost
    - Number of customers lost due to system failure
  - Loss due to planned maintenance
  - Loss due to unplanned maintenance

  (Sudora, 2010)
- **Investment cost**
  Investment cost is a significant cost contributor when implementing the replacement strategy for ageing equipment. As a part of a company’s financial responsibility, it should always be able to demonstrate that it has the adequate capital to finance replacement of equipment for the next twenty years. The following answers can determine the technical condition of a system and determine the amount one should have in capital to replace system components.
  - How old is the piece of equipment?
  - How long should the equipment function reliably and safely?
  - How much would it cost to replace the equipment

$$\text{The annualized cost } = \frac{\text{Replacement Cost}}{\text{Remaining Useful life}} \tag{6}$$

The annualized cost is the important factor, and the key to determining your systems expected replacement expense. (DEH, 2009)

- **Scrap Value**
    - The market or sale price of the material content of a scrap (accounting).
    - The recovery value of an abandoned or damaged property (insurance).

  ”An assets scrap value derives from the intrinsic value of it’s underlying parts”.
  (The Free Dictionary, 2009)

  One should therefore consider the value of the material of the equipment, which may be resold for other uses. However, the money earned from scrap value will normally be much lower than the price of new equipment.

- **Cost of personnel and training of personnel**
  The cost and size of the crew is also important regarding replacement of equipment. The cost of personnel training includes the initial cost of training operators and maintenance technicians, developing new, necessary skills. A significant cost contributor is the lost employee productivity, and this cost can be measured in terms of the salaries, wages and benefits of idled people

  The following is a quick formula for estimating hourly downtime labor costs:

$$\text{Hourly Labor Cost} = \text{P} * \text{A} * \text{C} \tag{7}$$

  Where:
  P = number of people affected
  A = average percentage they are affected
  C = average employee cost (salaries or wages + benefits)
  (Information Management, 2009)

3.3 Modification Costs

Performing a modification of ageing equipment, means changing essential parts with new, and preferable better, parts. A modification of ageing equipment can therefore cause high initial costs, and temporarily remove the equipment from service. The operation of a modification will thereby cause a downtime cost with the same cost parameters as described in Section 3.2. In addition, spares specifically designed for the equipment can be made redundant when changing essential parts and an investment cost due to new parts will arise. Labor and administration costs will also become large contributors to the costs of this strategy, and the calculations will also here be the same as in Section 3.2. Thus, modification of ageing equipment can be a costly affair, and the operation should therefore be designed economically and efficiently by replacing only the needed components for further safe operation of the equipment. The largest cost contributor is undoubtedly the downtime cost.

3.4 Maintenance Costs

To maintain the best possible functional and technical conditions are becoming more and more demanding, by the equipment in operation being exposed to ageing in terms of wear and corrosion. As shown in Figure 3, the maintenance cost will increase with time.

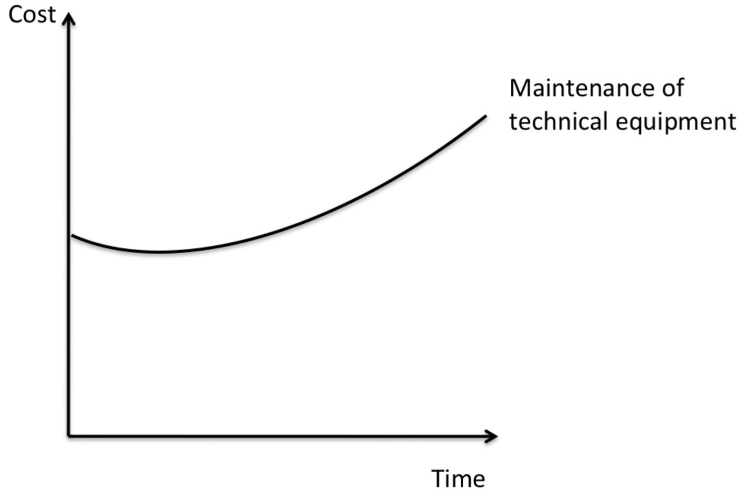


Figure 3: Development of Maintenance Costs

Maintenance costs typically includes cost of labor and parts to perform repairs and it is normal to differ between two types of maintenance costs, *Direct Cost* and *Indirect Cost*. Direct maintenance costs is defined as budgeted costs, affecting the cash flow of the organization. Indirect maintenance cost is defined loss-related costs as well as opportunity costs, affecting the profit of the organization.

The most important cost parameters associated with improved maintenance, are listed below:

- Downtime Cost
- Costs of own and external crew
- Cost of training tradesmen and operators in new and better skills
- Spare parts and consumables costs
- Buildings and storage costs
- Transportation costs
- Administration and documentation costs

(Sondalini & Witt) & (Forsvaret, 1996)

The costs defined above should serve as a basis when analysing the replacement strategy, and the largest cost contributors from the list are the cost of downtime and storage cost. Though it is important to notice that the costs will vary a lot for each case analysed and this only serves as an indicator of expected high costs.

3.5 Cost of Changing Operational Conditions

To change the operational conditions of ageing equipment, is an easy and cost-beneficial strategy. There is no occurrence of downtime, neither investment or storage costs for new equipment.

However an important cost aspect to remember choosing this strategy, is the possibility of a reduction in production and thereby a loss in revenue. It should therefore be properly calculated if there is enough buffer for such losses. It should also be stressed that to change the operational conditions, is regarded causing a higher risk of damage and careful considerations should be taken. The largest cost contributor to this strategy is therefore considered as loss in revenue due to a loss in production.

3.6 Overhaul costs

The overhaul costs depends on selected technology, time in service and technical condition. This is often an economically beneficial ageing strategy, while the exchanged parts are identical to the old ones and often already exists in stock. However, as a rule of thumb, one should not spend more than 60% of replacement cost for the first overhaul and not more than 30% of replacement cost for the consecutive overhaul. (Plant Services, 2011)

Common cost parameters to this strategy are labor costs, cost of replacement parts and the cost of a site to perform the overhaul. These costs will increase with the age of equipment.

An important cost-aspect of the overhaul strategy, is the increase in the production throughput the new equipment can bring. This should be considered as an additional benefit that offsets the cost of removing the old equipment. (eHowMoney, 2011)

For determination of the cost of an overhaul, the following should be defined:

1. Determine the present realizable salvage value of the equipment. This value is determined by examining the condition of the equipment
2. Request quotes for the cost to overhaul the equipment, and use the average cost to estimate the cost to overhaul the equipment
3. Define if there is a cost of removing the damaged or outdated equipment
4. Subtract the total cost to overhaul from the present realizable salvage value of the item. The result is the complete overhaul cost

3.7 Cost of Continuing as usual

If the decision falls upon the ageing strategy, continuing as usual, the costs will also remain as before in the short term. Considering a longer period, the equipment may experience an increase in failures, and new strategies can turn out more expensive than implementing them at first. This should be taken into considerations before choosing upon this alternative, and the largest cost parameter for this strategy will therefore be the anticipated increase of maintenance costs.

3.8 Summary & Discussion

Various cost parameters have now been discussed in relation to the alternative strategies to implement on equipment exposed to ageing. As discussed at the beginning of the section, it is important to see the costs in relation to what needs to be done and more importantly, where the action is performed, while the costs will vary from place to place. In Table 4, the most significant costs related to the ageing strategies are summarised.

Strategies	**Associated Cost Parameters**
Replacement	Downtime, Investment, Personnel
Modification	Downtime, Labor, Investment of spare parts
Change of Maintenance Strategy	Personnel, Consumables, Training
Change of Operational Conditions	Loss in production and revenue
Overhaul	Replacement parts, site to perform overhaul
Continue as usual	Increase in maintenance costs

Table 4: Associated Cost Parameters related to the strategies in Section 2.1

The largest cost contributor will unprecedented be the cost of downtime. To shut down the production can lead to a severe economical loss for the operators.

3.8.1 Limitations

While some alternatives can turn out *economically* beneficial, there might be other constraints and limitations that will make them less attractive and even unsuitable. This can be rules and regulations which may exclude some of the strategy options and it is therefore important to always be familiar with the latest rules and regulations. This will be emphasized in the Decision Model in Section 4.

3.9 Life Cycle Cost

The Life Cycle Cost (LCC) is mostly determined by which ageing strategy applied. Choosing the wrong strategy may lead to unnecessary costs and extend the costly downtime. The optimal strategy should therefore be both applicable and cost-efficient. Conducting such an LCC analysis in the early stage of a project, may limit the available input data and use of various cost- estimating techniques may become handy.

The whole-life cost is calculated using the formula:

$$\begin{aligned} \text{LCC} = \text{Capital Cost} + \text{Present worth of Operation and Maintenance costs} \\ -\text{Present worth of Salvage value} \end{aligned} \tag{8}$$

The capital cost includes the initial capital expense for equipment, engineering and installation. Regardless of how the project is financed, the cost is always considered a single payment occurring at the beginning of the year. The capital cost, are in other words, the total cost needed to bring the project to a commercially operable status.

Maintenance costs are the sum of all yearly operational and maintenance costs. Fuel or equipment replacement costs are not included, the costs include such items as an operator's salary, inspections, insurance, property tax, and all scheduled maintenance.

The salvage value of a system is its net worth in the final year of the life-cycle period. It is common practice to assign a salvage value of 20 percent of original cost for mechanical equipment that can be moved.

(Olofsson, 2009)

The most important cost contributors to the six strategies in the model, are further discussed in Section 4.6, and these costs will be the basis for determination of the optimal strategy. This strategy will be found by comparing the concurrent costs, and the focus will be at LCCs. The profit, LCP, which is a result of revenue minus costs, will not be further discussed but LCP will always be a result of the calculated LCC. LCP differs from LCC by considering the revenue of an equipment, in addition to to operating and maintenance costs.

4 Decision Model

"A goal is created three times. First as a mental picture. Second, when written down to add clarity and dimension. And third, when you take action towards its achievement"

- Gary Ryan Blair

A decision model provides a framework for monitoring and diagnosis of difficult decisions. A decision model is a tool allowing decision makers to solve their problem by evaluating, rating, and comparing different alternatives and multiple criteria. (RFP Evaluation Center, 2011)

Decision making is dependent upon up-to-date information about the ageing equipment, coupled with knowledge of sensitive non-technical issues. Decision making regarding ageing equipment is hard due to the disparate data sources, the information is not easily obtained and merged. To make a decision, information about technical state or machine health, cost of maintenance activities or loss of production, and non-technical risk factors such as obsolescence and organizational issues, are required. This is what the following Decision Model should contain and considerate in order to determine the most optimal strategy for equipment exposed to ageing.

This Decision Model is a tool that combines different input parameters, which seen individually would support different strategies. Compared to each other, the optimal strategy regarding ageing equipment should be found.

4.1 Basis for developing a Decision Model

The oil and gas industry faces challenges with age-related equipment deterioration. When the equipment has exceeded its original life period, the companies must ask themselves what to do with the ageing equipment. Also, as shown in Figure 4, the equipment will not always function optimal through its planned life cycle. When the equipment fails or show tendencies to fail, an analysis has to be made in order to find the optimal strategy. There are, as discussed in section 2, several ways to approach ageing equipment. The intention of this model is to make the way against an optimal strategy easier.

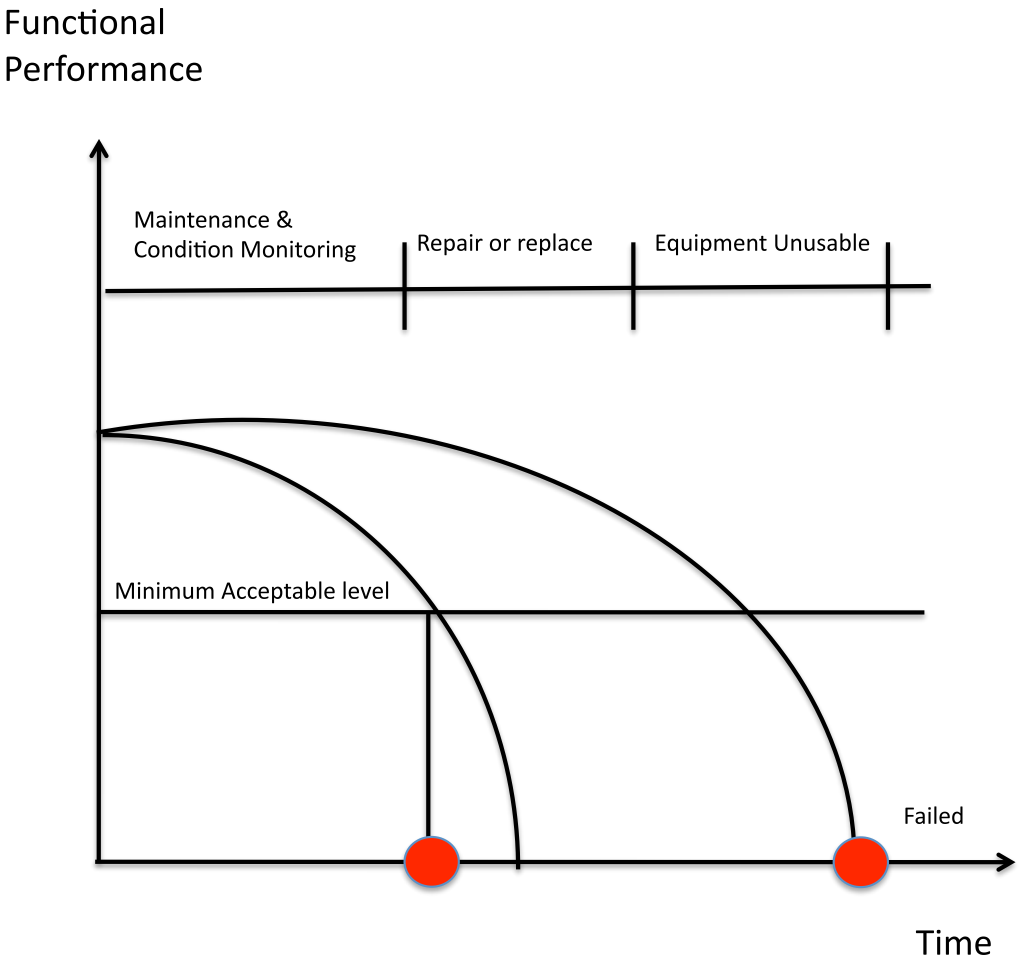


Figure 4: Reliability Figure

4.1.1 Interaction with the environment

The model in this Master Thesis will focus on choosing the optimal strategy based on the equipment's technical condition. Though it is also important to recognize issues as obsolescence and organizational matters and how the results are evaluated. These are matters that will be discussed in the thesis, but note again, the main focus will be on the technical challenges as shown in Figure 5. The challenge and goal is to create a model, which will make room for personal experience in addition to more tangible data as failure rates, costs, etc.

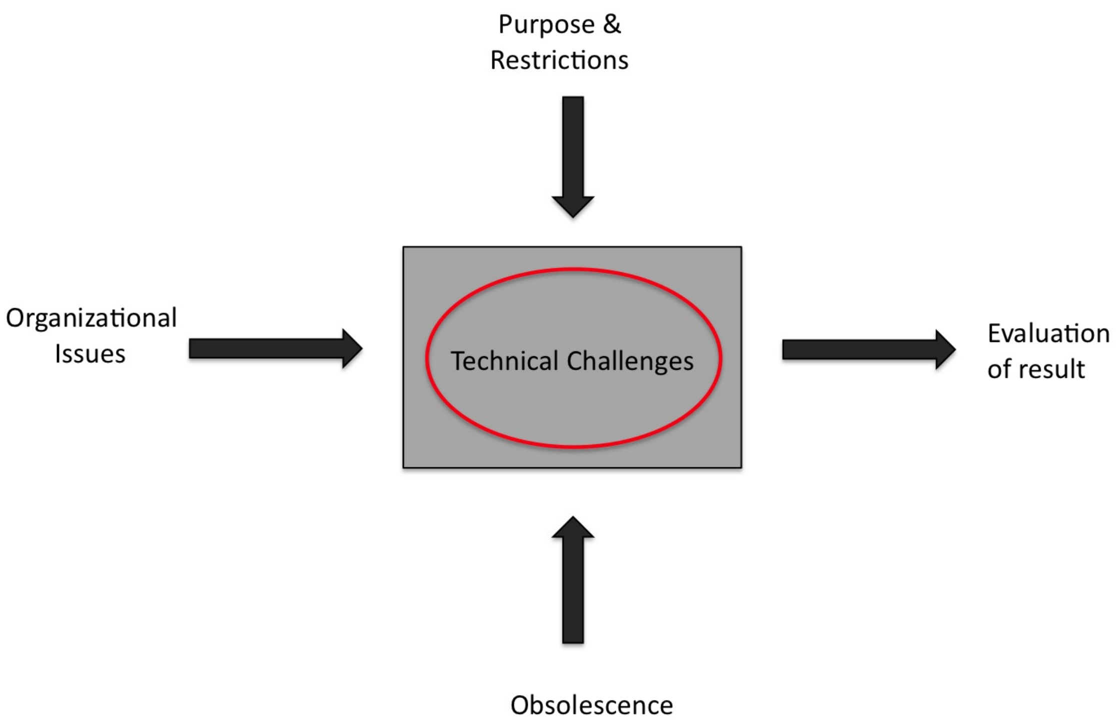


Figure 5: Interaction with the environment

4.1.2 Theory of the model

This model is a tool for selecting the most optimal strategy regarding ageing equipment. By evaluating different parameters with equal denominations one can compare the outcome, and determine the optimal strategy to make the equipment remain operational for a given period. This future performance level must be in accordance with the different stakeholders as discussed in Section 4.6.

4.2 Organizing the model

The Decision Model will be built with basis on the different ageing strategies described in Section 2. Different strategies implemented to ageing equipment will lead to different costs, and the optimal strategy will normally be the one less costly. However, other criteria's and restrictions may influence the decision, such as safety, reliability and availability. It may also be necessary to make several iterations and use multiple strategies to find the optimal solution. The Decision Model is build like a flow chart, describing the different strategies and the steps to take in order to make the correct decision. By looking at obsolescence and organizational issues in parallel with technical challenges, the outcome will be the optimal solution regarding all three parameters.

4.2.1 Problem Description/Objective

Danger of ageing failure

1. Does the hazard of the component failure increase with age?
2. Is the impact of failure more serious than the impact of preventive maintenance?

If the answer to either of these questions are no, the optimal ageing strategy is to replace the equipment in question when failing, using corrective maintenance. If the answer is yes, one should proceed with the further described Decision Model.

As shown in Figure 5, the main focus of the Decision Model will be based on the technical conditions. However, to obtain the complete picture of the ageing problem, this Decision Model shall evaluate the different strategies in concordance to the parameters, Obsolescence, Organizational Problems and Technical Challenges. This can either be done sequentially or in parallel and there are obvious pros and cons of both methods.

For the sequential approach, alternatives which might be considered inapplicable, either regarding cost or other criteria's at an early stage, can still be a good alternative when considering other parameters later in the process. At the pros side, it can save the analyst time and money, being able to exclude strategies at an early stage.

As for the parallel approach, it can be time consuming to consider and analyse every possible strategy when there might be demands that at an early stage can prove a strategy to be inapplicable and be excluded. However, no strategy will be left out before an analysis, and a proper groundwork is done in order to make the correct decision.

To overcome the obstacle of choosing one or the other approach, this model will be a mix of the sequential and parallel approach. As shown in Figure 6, obsolescence, organizational problems and technical challenges are analysed in parallel. Severe limitations, for instance rules and regulations, are defined at the beginning of the model, and will make it easy to avoid analysing inapplicable strategies. The different approaches to each parameter will be explained further separately.

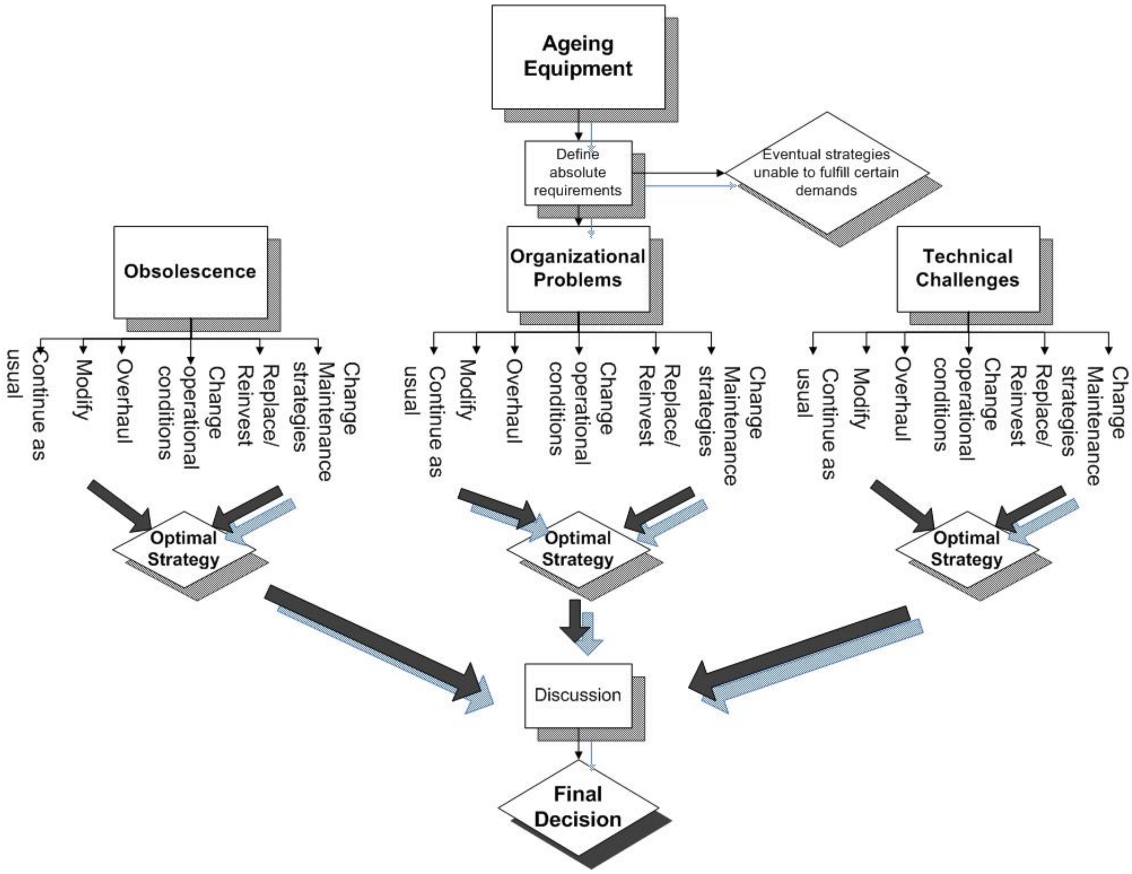


Figure 6: Superior Decision Model

4.3 Organizational Problems

The quality, age of the equipment and its degree of sophistication usually weigh heavily in an organizations productivity. (Prokopenko, 1992)

Organizational problems goes beyond merely making a decision. It also includes finding and formulating the problem, implementing the decision and an audit and review of the results produced.

Competence is key to the management of ageing issues. Suitable competent people need to be employed in inspection and assessment activities, making any necessary judgments about remaining life, defining remediation programs and additional risk reduction, and making assessments in support of life extension. In order to meet the challenging issue of ageing, the organizational problems must be emphasized, and some common organizational issues are listed below:

- *Loss of knowledge*
  There is an increased likelihood of loss of technical knowledge required for safe operation as the installation gets older. Instruction manuals gets outdated and staff with the key experience are no longer available. Change of owner and operator can also cause loss of knowledge.
- *Knowing the limits*
  Concerning ageing equipment, there might be hard to recognise sign and nature of failure if there is no previous experience of running the plant past design life. This can lead to running of equipment not suitable for further operation.
- *Working and living environment conditions*
  Poor conditions in the living environment can lead to low morale, high staff turnover and poor safety climate.

(HSE, 2009)

Other issues, which can occur within an organization:

- *Policies and Procedures*
  Organizations often have formalised policies and procedures, developed to resolve common problems and help the manager in decision making. This can lead to moderate new-thinking and the ”old” strategies being chosen before more suitable strategies.
- *Organizational Hierarchy*
  This refers to the management structure of the organization. Most organizations carry out a level of authority, which impacts the nature of decision an individual can make. This is important to be aware of when a decision is made. Is it the *right* people with the *right* competence making the *right* decision?

When the roles and needs are defined and decided upon, a plan for competence is made, and changes according to documentation, IT-support, training, roles and responsibility and analysis are performed, a strategy can be proved applicable for implementation. The changes are made by on-the-job training and coaching, project meetings and follow ups, and the project of implementing a new strategy should than be evaluated and experiences should be shared.

In accordance to PSA and IAEA, the following standards regarding organizational issues should be met:

If a company are planning to optimize the strategy concerning ageing equipment, it is important not only to examine the strategy itself, but also the management approach, work culture, skill set, motivation of the work force and the effective use of technologies. (IAEA, 2007)

The operator or the party responsible for operating an offshore or onshore facility shall ensure coordination of plans of significance to health, safety and the environment.

The resources necessary to carry out the planned activities shall be made available to project and operational organizations.

(PSA, 2010)

4.3.1 Transfer of Experience

An organization should plan for transfer of skills and knowledge to allow for staff development and turnover. Specific recruitment and training strategies should be developed in order to transfer the necessary knowledge to less experienced staff. This planning should include identification of skills and competencies needed as well as training strategies.

4.4 Obsolescence

Obsolescence is defined as "the inability of an item to be maintained due to the unavailability on the market of the necessary resources at acceptable technical and/or economic conditions". These necessary resources may be a sub-item to restore the item, tools, monitoring or testing devices, documentary resources or skills. While the unavailability of the resources may be due to technological development, market situation, absence of supplier or regulations. (Standard Norge, 2010)

Obsolescence frequently occurs because a replacement has become available that is superior in one or more aspects. The operators are experiencing that many vendors do not longer support warranty and equipment services, or have terminated production of spare parts.

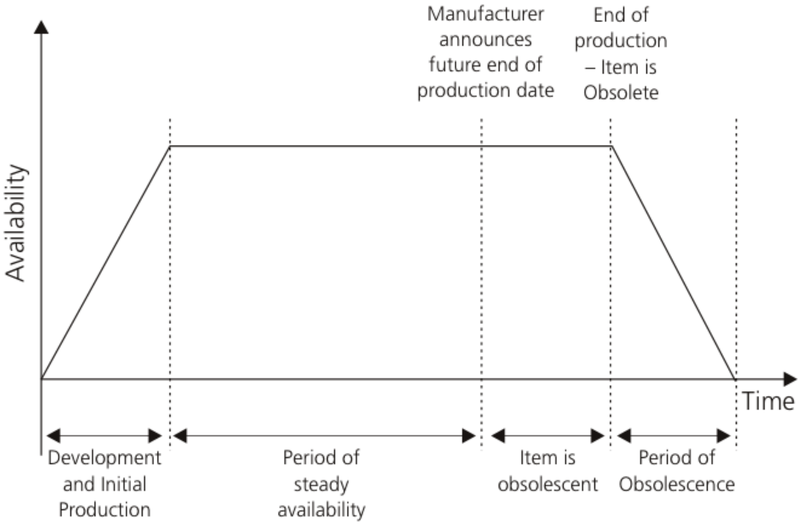


Figure 7: Life Cycle of a Component

Figure 7 shows the life cycle of a component, which becomes obsolete.

When defining and analysing the ageing equipment, it is important to identify if the equipment is exposed to obsolescence and assess the potential level of exposure. By use of the Decision Model shown in Figure 6, the different strategies available will be examined with the limitations and restrictions due to obsolescence in mind. The following aspects must be evaluated for each strategy alternative when investigating obsolescence in connection to ageing:

- *Knowledge*
  What is the knowledge of current standards, regulations and technology?
- *Standards & Regulations*
  Are there any deviations from current regulations and standards?
- *Technology*
  Will the decision alternative provide any problems in terms of lack of spare parts or technical support?

(IAEA, 2000)

If obsolescence is a fact, the questions below should be answered in order to obtain the complete overview of the ageing situation. These questions are prepared by the US Nuclear Power Industry for The Petroleum Safety Authority Norway.

1. Is the SSC still being manufactured and will it be available for at least the next five years?
2. Is there more than one supplier for the SSC for the foreseeable future?
3. Can the plant or outside suppliers manufacture the SSC in a reasonable time?
4. Are there other sources or contingencies available in case of emergency?
5. Is the SSC frequency of failure/year times the number of the SSC's in the plant times the remaining operating life (in years) equal or lower than the number of stocked SSC's in the warehouse?
6. Can the spare part inventory be maintained for at least the next five years?
7. Is the SSC immune to significant ageing degradation?
8. Can newer designs, technology, concepts be readily integrated with the existing configuration?

(US Nuclear Power Industry, 2006)

By applying these set of questions, obsolescence is ranked, and a complete picture of the equipment what regarding obsolescence is made. One should now be able to choose the optimal strategy in terms of obsolescence.

Examples of critical safety equipment, exposed to ageing and obsolescence, are the plant protection system and the associated sensors such as pressure, level and flow transmitters in primary and secondary systems. This equipment is highly exposed to ageing and obsolescence due to the harsh environment in containment, and should therefore receive special attention when evaluating danger of obsolescence due to ageing. (IAEA, 2000)

4.5 Technical Challenges

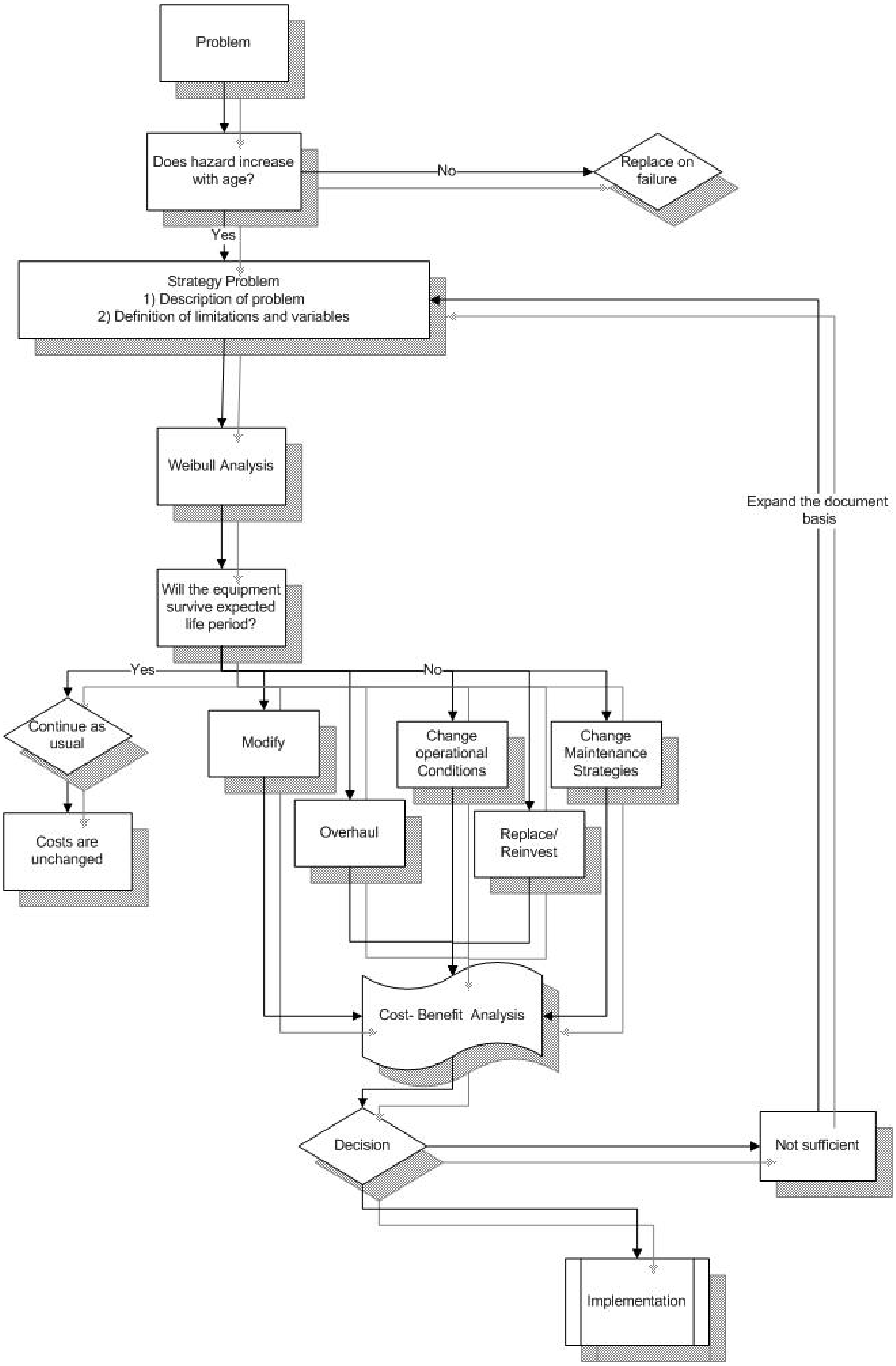


Figure 8: Sketch of the model

4.5.1 Description of Steps

- **Strategy Problem**
  - *Description of Problem*
    At this stage of the model, signs of damage and other indicators to ageing equipment are starting to appear, and the rate of degradation is increasing. The next step is to gather every information available about the equipment. Failure rates, importance of equipment, possibilities for repair, available spare parts etc.
  - *Definition of Limitations & Variables*
    While there may be several strategies to choose between, every strategy may not be suitable for the equipment in question. There may be restrictions concerning safety, cost, rules and regulations, etc. These may exclude some alternatives, and can make the analyses less comprehensive.
- **Weibull Analysis**
  Second step of the technical matter is to perform a Weibull Analysis. A Weibull Analysis matches historical failure and repair data to appropriate Weibull distributions. These distributions represent the failure or repair characteristics of a given failure mode and may be assigned to specific failure models. (Isograph, 2009)

  The advantage of a Weibull Analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. The analysis will be essential in this part of the decision, forecasting failure frequency, needs for spare parts and choosing the optimal maintenance strategy. The analysis consists of three possible outcomes:
  - $\beta < 1$: The rate decreases with time, t. With a β less than one, the distribution is hyper-exponential and one can expect to experience infant mortality failure modes.
  - β =1: If the components are subjected neither to wear nor to ageing, the failure rate is constant and equals an exponential distribution. Expect chance failure modes. This means that the probability of failure is constant regardless of the equipment's age and the reliability is equal with or without maintenance.
  - β >1: The rate increases with time, t. Appropriate ageing strategy should be developed.

After performing a Weibull Analysis, one should know whether the equipment will survive through its expected life period or will fail during this period. If proved able to continue operating as expected, the ageing strategy chosen should be Continue as usual. However, if the analysis predicts failure in recent years, either an improvement of the already existing maintenance strategy should be made or a completely new strategy should be implemented, that being either replacement, overhaul, change of operational conditions or a modification. The next step is than, as shown in Figure 8, to perform a cost-benefit analysis of the alternative strategies. The final decision of the optimal strategy will than be based on the cost of implementation. The discussion towards each strategy is exemplified in Section 6.

4.6 Cost-Benefit Analysis

To survive in the competitive global market of today, it is vital for an organization to optimize its operational costs. The cost of maintaining complex industrial systems is one of the critical factors influencing the enterprise operating costs. Hence, the importance of optimizing the costs of the chosen strategy for ageing equipment is essential and the theory of a cost-benefit analysis is an important aspect.

"A cost- benefit analysis is used to determine how well or poorly a planned action will turn out and is a tool to help to appraise or assess the case for a project or a program. The process involves, whether explicitly or implicitly, weighing the total cost against the total expected benefits of one or more action in order to choose the most beneficial, in a cost perspective, strategy". (Mogstad, 2010)

When evaluating the strategies in context to either organizational, obsolescence or technical matters, it is important to define the potential costs and benefits of the strategies. This cost-benefit analysis will be divided between quantitative and qualitative costs and benefits. Quantitative analysis is made by identifying the initial monetary cost of development, the expected monetary cost of operating and supporting the strategy, and the expected future monetary benefits of implementing the strategy. These costs should be converted to present value form, while the costs and benefits may be accrued at different times. (Leffingwell, 2009)

Equation 9 shows the calculation of Net Present Value, P where p is the interest rate and n is the number of years counting.

$$\mathrm{P} = \mathrm{F}\left[\frac{((1+p)^n - 1)}{p(1+p)^n}\right] \tag{9}$$

The qualitative factors are, in addition to the financial factors, relevant to the decision, however hard to measure in terms of money. These factors can be the effect on employee morale, effect on present and future customers, etc.

For each of the criteria's, a table should be developed, listing potential benefits and potential costs, both quantitative and qualitative. In Table 5, 6 and 7, there are listed a number of possible costs and benefits regarding the three parameters obsolescence, organizational and technical matters. These are shown as an example and guidance.

Type	**Potential Costs**	**Potential Benefits**
Quantitative	• wages for additional crew needed • training of personnel • administration costs	• reduced personnel cost from a reduction in staff
Qualitative	• increased employee dissatisfaction due to fear of change	• relationships with and commitment to suppliers • effect on present and future customers

Table 5: Cost-benefit, Organizational problems

Type	**Potential Costs**	**Potential Benefits**
Quantitative	• investment cost • scrapping • possible rework	• reduced maintenance cost • increase in revenue due to higher production
Qualitative	• technological trends • rules and regulations	• raising of existing, or introduction of a new equipment to entry within your industry to keep competition out of your market

Table 6: Cost-benefit, Obsolescence

Type	**Potential Costs**	**Potential Benefits**
Quantitative	• investment cost if new equipment • maintenance cost • spare parts cost • storage cost • transportation cost	• reduced operating costs • increased revenue from additional production • increased revenue from decreased down time
Qualitative	• new and better equipment, increasing revenue	• positive effect on probability of failures

Table 7: Cost-benefit, Technical issues

4.7 Decision

Having evaluated the strategies in connection to the organizational, obsolescence and technical parameters, it should now be possible to limit the number of alternative strategies due to restrictions, and reduce the calculations needed to determine the optimal strategy. Some of the strategies will be found inapplicable and can be rejected at an early stage due to rules and regulations, while other solutions might be applicable options for instance for the organizational matters, but compared to obsolescence and technical issues, found unsuitable. This is shown in Figure 9. The grey areas represents applicable strategies for each parameter, while the black area demonstrates the strategies applicable to all three categories. These are the strategies that are further evaluated in an economic perspective.

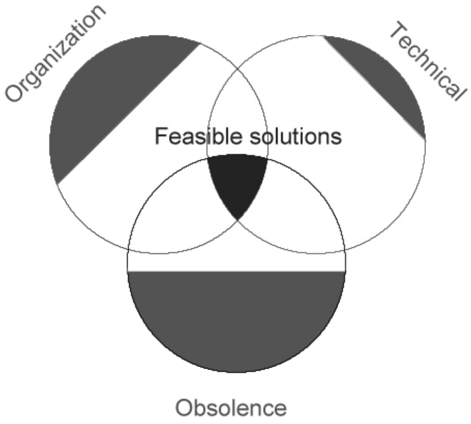
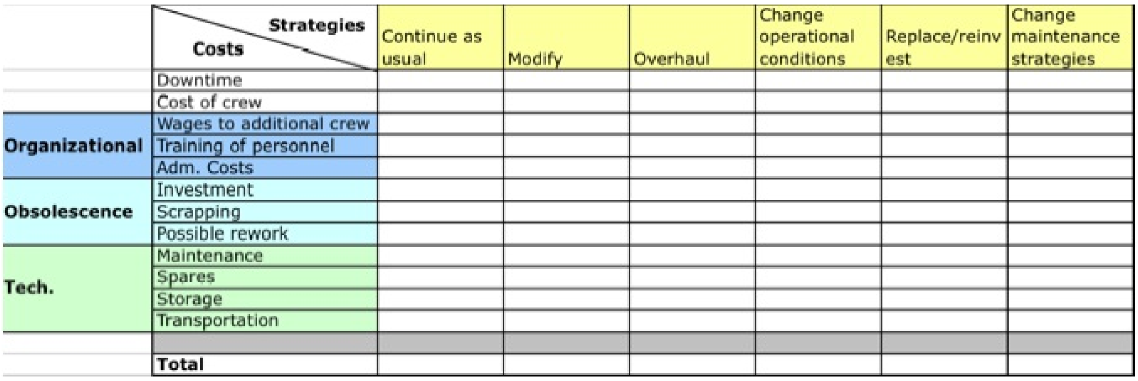


Figure 9: Acceptable solutions

To properly evaluate the strategies proved applicable to the system in question, one have to look at the costs of implementing the strategies. In the end, the life cycle costs will determine which strategy to choose. The next step of the model is therefore to analyse subsequent costs.

In order to find the most optimal strategy, a cost-sheet is developed to make it easy to determine the most cost-effective solution by comparing the different costs of each strategy.



	Strategies **Costs**	Continue as usual	Modify	Overhaul	Change operational conditions	Replace/reinvest	Change maintenance strategies
	Downtime						
	Cost of crew						
Organizational	Wages to additional crew						
	Training of personnel						
	Adm. Costs						
Obsolescence	Investment						
	Scrapping						
	Possible rework						
Tech.	Maintenance						
	Spares						
	Storage						
	Transportation						
	Total						

Figure 10: Cost Matrix

Figure 10 shows the comparable costs, divided into categories concerning organizational, obsolescence and technical matters. The costs in Table 5, 6 and 7 serves as a basis for the most important cost parameters and are included in the spread sheet. However the qualitative costs are hard to define in terms of money, and is not considered in this spread sheet. Some of the alternative strategies will probably already be categorized as non-applicable, and the calculations will be less comprehensive than it may look. The alternative resulting in the lowest cost, will be defined as the most optimal strategy. If the results are very close, additional sensitivity and uncertainty analysis should be performed in order to find the definite optimal solution.

5 Gas Facility A

The Decision Model from Section 4 will be implemented to the Fire Water Pump system, or parts of the system, at Gas Facility A to determine and recommend strategies to ensure continued operation until 2025. This Master Thesis will focus mainly on the technical material degradation, however necessary assumptions regarding obsolescence and organizational issues will also be made. From the Project work, Decision Models Related to Ageing and Life Extension, a general introduction to Gas Facility A and the Fire Water Pump system is provided. (Mogstad, 2010)

5.1 Introduction to Gas Facility A

Gas Facility A plays an important role in the transport and treatment of gas and condensate from different areas on the Norwegian Continental Shelf (NCS).

In 19XX Gas Facility A started to stabilise and fraction the unprocessed condensate arriving from the Area X. On an annual basis, roughly X million tonnes of stabilised condensate is shipped from Gas Facility A by sea. (Operator A, 2009)

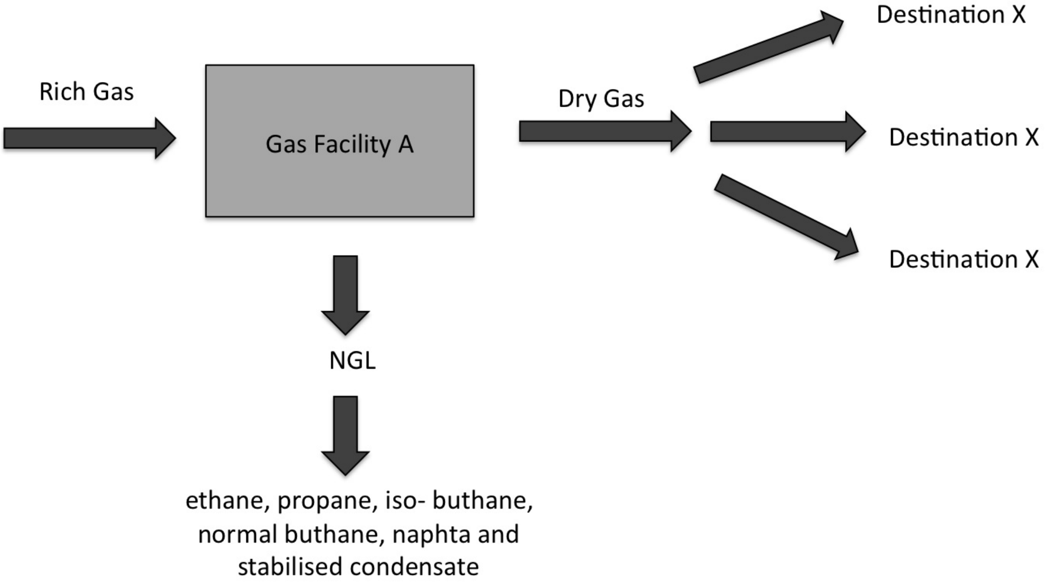


Figure 11: Process at Gas Facility A

Figure 11 describes roughly what happens when rich gas reaches Gas Facility A.

While the plant is ageing, it is important to remain the necessary level of safety and regulations at Gas Facility A.

5.2 Fire Water Pump system

The Fire Water Pump system is a complex system, which is of high importance to Gas Facility A's safety, while the system is essential in preventing escalation if a fire should occur on the plant. Every equipment, from sea pumps to control sensors, have to be in order at any time in case of a fire. Due to ageing, it is necessary to perform analyses to determine how well the system is functioning and for how long it can stay in a satisfactory operative condition.

The current fire water pumps were installed in 19XX during the development of Area XX, and to prevent explosion, fire, freezing and mechanical damage, the ring main is mostly situated underground. The fixed fire systems are installed in areas with high risks of fire and particularly cover equipment containing significant quantities of hydrocarbons. To ensure the integrity of the fire water system "The Gas Facility A Fire Water System Upgrade Project" is proposed by Gas Facility A. This project aim to improve the performance of the system and meet the required demands from Operator A. (Haraldseide, 2010)

5.2.1 Description of system

The Fire Water Pump system consists of the following main components:

- One electric-motor driven pump (70-PA-102A).
- Two diesel-motor driven pumps (70-PA-102B/C).
- Three centrifugal pumps with following characteristic:
  - Nominal capacity = 2000 m3/h at 11.7 bar and 990 RPM.
  - Maximum capacity = 3000 m3/h.
  - Minimum capacity 200 m3/h.
- Engine and pump start, stop and control devices.

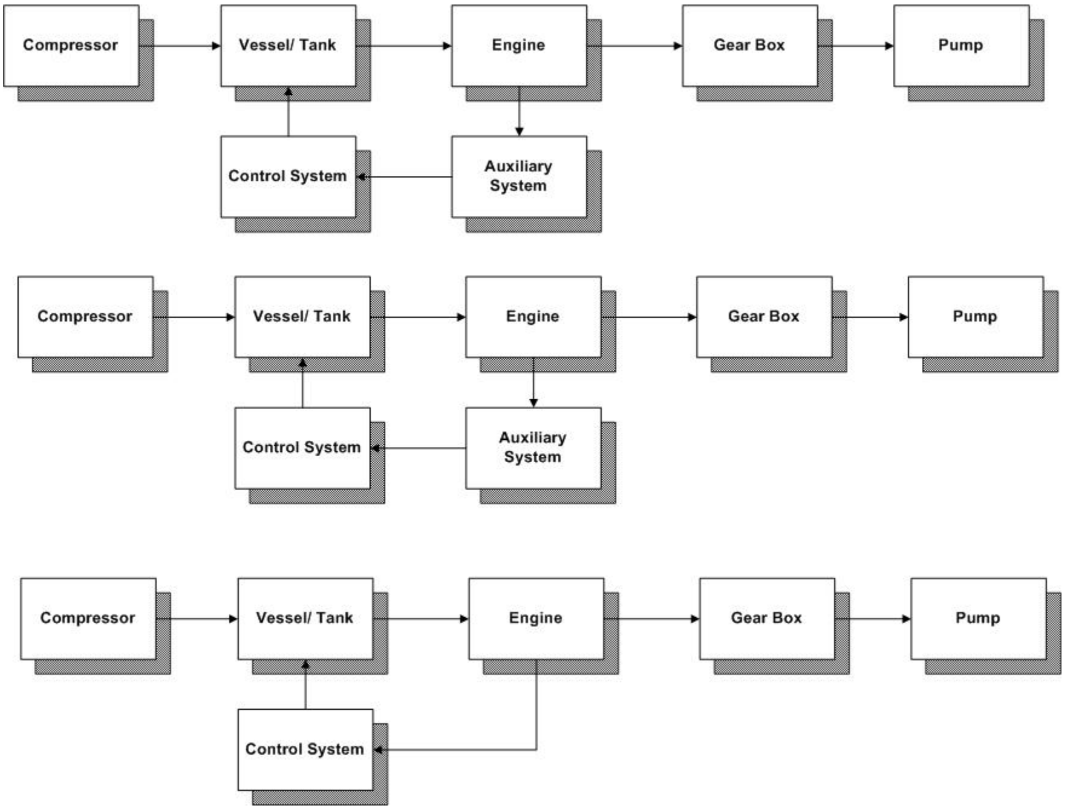


Figure 12: The main Fire Water Pump system

The two main pumps in the system are one diesel-driven pump and one electrical-driven pump. With one additional diesel-driven pump, there is redundancy in the system if the main diesel-driven pump should fail. If the electrical-driven pump should fail at the same time as one of the diesel-driven pumps, there is no back up and the firewater demand will not be fully covered if a fire should arise. Under normal operations the pressure in the ring main is maintained from a connection to fresh water from "Water X", situated 127 meters above sea water level. When the pressure in the ring main drops below 11,7 barg, the fire water pumps starts automatically. These are connected to the Seawater pool XX.

The seawater intake is situated at 80 meters depth close to Water XX in Water XXX. The capacity of the two pumps is 8000m3 /hour, and the seawater is transported into two basins, X and XX . The system of interest, the Fire Water Pump system, is collecting water from the Basin XX.

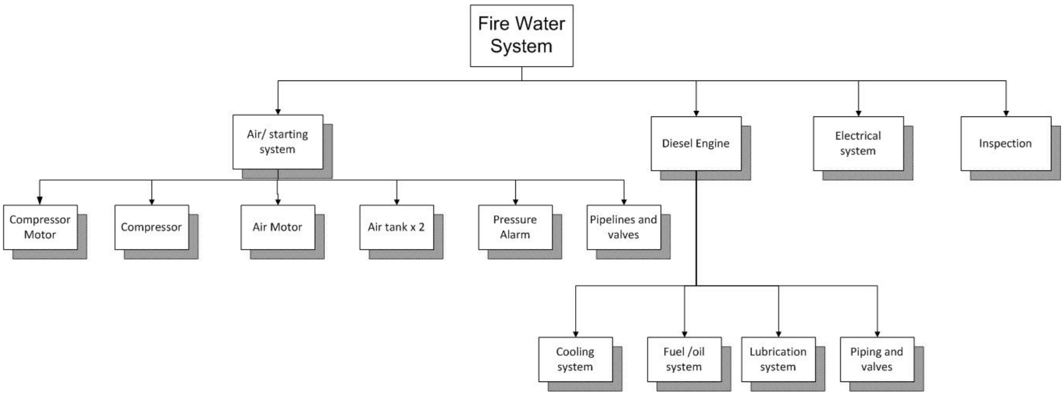


Figure 13: Fire Water Pump system

As shown in Figure 13, the Fire Water Pump system consists of four independent subsystems. This Master Thesis will focus on the Air-Starting system for implementation of the Decision Model.

6 Implementing the Model

To retain the safety at Gas Facility A, analyses of the Fire Water Pump system exposed to ageing, will be performed in order to determine the optimal strategy for the system and to show the use and benefits of the Decision Model from Section 4. An introduction to the history of maintenance planning at Gas Facility A will be given first.

During the first years of maintenance planning, corrective maintenance was conducted much more frequently than today. The focus of maintaining the equipment in an operational condition was higher, and there were less focus on the actual need for maintenance and the following consequences of these frequent maintenance actions. This has changed over the years and after implementation of the PM program, reducing the number of break-downs and performing risk-criticality analyses, are now in focus.

Today the maintenance philosophy at Gas Facility A is based on a mix of Program Based Maintenance (PBM) and Condition Based Maintenance (CBM). The maintenance philosophy is founded in the Operator A document WR0154 that is valid for all Operator A operated assets. This leads to several different approaches to the equipment at the same industrial asset.

A priority list, stating the key objectives of operation, maintenance and modification at Gas Facility A, is established:

1. HSE integrity
2. Regularity of production
3. Optimization of operational and maintenance cost/unit cost
4. Maintenance performance

Gas Facility A has set a target of a plant turnaround every sixth year, shutting down the entire plant for a period of 2-3 weeks. Due to lost production both at Gas Facility A and the O&G producers, reliant at Gas Facility A to process their gas, this is a costly affair. The goal is therefore to reduce this period. (Økland, 2009)

6.1 Air-starting system

Due to the Fire Water Pump System being a complex and large system, the further analyses will focus on the subsystem, Air-Starting System, its function and its components.

The Air-Starting system at Gas Facility A is a double air-starting system with air-reservoirs and one electric driven starting air compressor including connections for air supply. (Operator A, 1984)

It is a highly safety critical system, which have a so-called hidden function. That means this system is not performing an action itself, but is starting the components that will prevent an eventual fire. The system consists of:

- One starting air compressor, 2.-stage with built in inter- and after cooler
- Two starting air tanks with a capacity of 750 l. and 3000 kPa
- Two pressure alarms starting each tank
- Alarm starting compressor
- Air motor with a rating of 4,8 kW

The compressor provides pressure in the air tanks, and the tanks are designed to obtain this pressure in an event of the compressor failing. Start system 1 consists of one air tank, which starts the system by air injection to the cylinders. If this system should fail, start system 2, the second air tank will start the air engine by air injection directly on the crankshaft. (Operator A, 1984)

The maintenance plan for the air-starting system is to maintain the equipment every 8th year. The last inspection was performed by Operator A in 2009. Originally this inspection was planned for 2012, but was conducted in advance due to other maintenance activities. The inspections showed, similar to the inspection in 2004, a thin layer of 1,0 mm corrosion in the air-starting tanks. Thus, no development of corrosion over the last six years. (Operator A, 2011)

With basis in this inspection, it is assumed that the air-starting tanks are not of high risk concerning exposure to ageing.

6.2 Definition of requirements

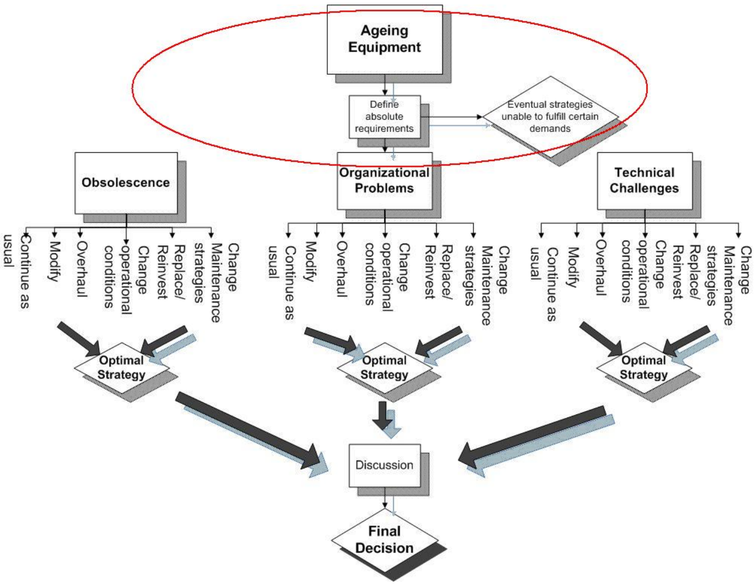


Figure 14: Stage of the Model

To save time and money, it is important to perform necessary research to find eventual regulatory requirements and/or restrictions, which can exclude strategies. As this system is a part of the Fire Water Pump system, there are specified restrictions from PSA, NORSOK and IACS to follow. These will be categorized as in the model by organizational, obsolescence and technical matters.

6.2.1 Requirements regarding Organizational matters

Before decisions are made, the responsible party shall ensure that issues related to health, safety and the environment have been comprehensively and adequately considered. The decision criteria shall be based on the stipulated objectives, strategies and requirements for health, safety and the environment, and shall be available prior to making decisions.

Necessary coordination of decisions at various levels and in different areas shall be ensured so that no unintended effects arise.

Assumptions that form the basis for a decision, shall be expressed so they can be followed up. (PSA, 2010)

Decision Making regarding organizational matters always include uncertainty and risk. Humans have bounded rationality – we do not know all of the consequences of our actions. Sometimes a policy organizational decision making can lead to an externality, or unintended side effect. These externalities can be positive or negative.

6.2.2 Requirements regarding Obsolescence

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

The resources necessary to carry out the planned activities shall be made available to project and operational organizations.

The operator or the party responsible for operating an offshore or onshore facility shall ensure coordination of plans of significance to health, safety and the environment. (PSA, 2010)

Requirements specific to obsolescence is mainly concerning to check the availability of spare parts in the near future.

6.2.3 Requirements regarding Technical Challenges

The International Association of Classification Society (IACS) states that:

The Fire Water Pump system should be functional at any time, also when performing maintenance and it should secure sufficient supply of water to fire protection. The Fire Water Pump system should always be independent of other systems. (IACS, 2010)

From NORSOK Standard, the following are defined: Permanently manned facilities shall have firewater supply from fire pumps or other independent supply to ensure sufficient capacity at all times, regardless of whether parts of the supply are out of service. The fire water system shall be designed such that a pressure stroke does not make the system or parts of the system inoperative. (NORSOK STANDARD S-001N, 2000)

And from PSA: On facilities where fire water is supplied from fire pumps, the pumps shall start up automatically in the event of a pressure drop in the fire main and upon confirmed fire detection. Fire pumps shall also be capable of being manually activated from the central control room and at the propulsion unit. Propulsion units for fire pumps shall be equipped with two independent starting arrangements. Automatic disconnection functions shall be as few as possible. Firewater piping shall be designed and placed such that a sufficient supply of firewater is ensured to any area on the facility. (PSA, 2010)

More specific technical requirements to the air-starting system: Each start engine should have a manual shut-off valve or-switch between the starter and starting battery/air bank. Each motor shall have two independent starting systems. IACS rules state: In order to protect starting air mains against explosion arising from improper functioning of starting valves, the following must be fitted.

1. An isolation non-return valve or equivalent at the starting air supply connection to each engine.
2. A bursting disc or flame arrester in way of the starting valve of each cylinder for direct reversing engines having a starting manifold OR at the supply inlet to the starting air manifold for non reversing engines. The system may also be provided with a relief valve.

(IACS, 2011)

Regarding technological challenges, the focus will relay on failure statistics and weibull analysis. It is important to achieve a complete overview of the problem, and this is the first step against a conclusion for the most optimal strategy regarding ageing equipment.

6.3 Exclusion of Strategies

In accordance to the requirements listed above, the ageing strategy to change the operational conditions, is inapplicable. The pressure in the air tanks have to contain the correct pressure and there is no room for changing the operational conditions. The five remaining strategies are, at this stage, considered applicable to the air-starting system.

The further analyses will start with the technical issue, while this is the main focus of the thesis.

6.4 Technical Analysis

Having identified the restrictions regarding the air-starting system, the further procedure of the Decision Model is to perform a technical analysis of the system. The parallel approach to the decision making, makes it possible to perform the analyses regarding organizational issues and obsolescence at the same time and exchange results along the process.

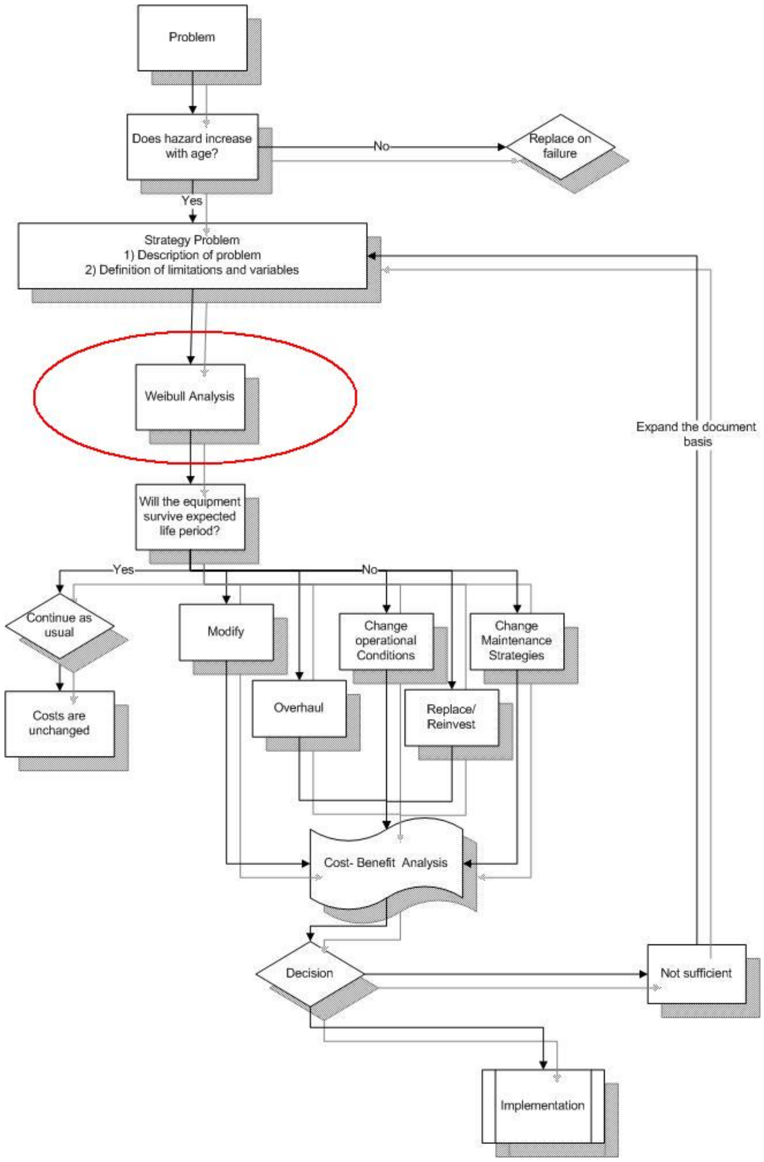


Figure 15: Whereabouts at the model

6.4.1 Weibull Analysis

The first part of the technical analysis, is to perform a Weibull Analysis. By looking closer at the failure rates of the system, one is able to predict whether the failures will increase with age, decrease with age or not be subject to neither wear nor to ageing by investigating its β - value, as described in Section 4. The failure rates for this system is found in Operating Company's database and from general data found in the OREDA database. This is a database, which purpose is to collect and exchange reliability data among the participating companies. (SINTEF, 2009)

Component	**Failure rate / 10^6 hours**
Starting Air Compressor	22,45.
Air Motor	5,24
Pressure Alarm	0,30

Table 8: Failure Rates

Based on calculations in Excel, the β- and α- values returns as:
β= 2,6
α= 395902
The calculations can be seen in Appendix A.

With the Weibull Analysis resulting in a β >1, the failure rate will increase with time, t, and an appropriate ageing strategy should be developed. The Weibull Analysis also makes it possible to exclude one other strategy, continue as usual, while the system failures clearly will increase with age.

6.5 Finding the Optimal Ageing Strategy

The next step of the Decision Model, when β is greater than one, is to decide upon which ageing strategy to choose. A general requirement for the strategies is that they shall be precise and applicable for all equipment they are connected to. It is therefore preferable that one has multiple precise strategies rather than fewer but more general strategies. In order to obtain a complete picture of the degree of ageing, a useful tool is the RCM-process described in Section 2.1.3.

Steps to carry out a RCM

1. *Gather information*
   Starting a RCM-process requires essential information about the ageing equipment. To gather all necessary information, the maintenance and operational personnel should cooperate and develop a RCM-team. Appropriate understanding of the equipment in question's failures and failure mechanisms are essential.

2. *Identification and Classification*
   The data are than sorted into predetermined groups for the system in question. The offshore industry has systemized this grouping in a Tag.no system. The drawback of this system is the different approaches to definition of the groups between companies. This makes the work of building experience harder.

3. *Identification of important equipment and its possible failures*
   The main purpose of this phase is to identify the significant units for preventive maintenance. A FMECA and Risk Assessment is performed.

4. *Preventive Maintenance tasks*
   After identification of the most critical parts of the system, establishment of maintenance strategy and intervals is possible.

1. Gather Information

In order to gather the necessary information, the RCM-method starts with answering the seven questions below in order:

- *What is the item supposed to do and its associated performance standards?*
  The Air-Starting system is a very important subsystem of the Fire Water Pump system. Its function is to be a power source used to provide initial rotation to start the engines, starting the fire-water pumps. The air-starting motor should consist of two independent starting systems. Further can be read in Section 6.2
- *In what ways can it fail to provide the required function?*
  The most common failures for the Air-Starting system are failures to either start or function on demand for the compressor, motor or pressure alarm. Another critical failure, which have occurred, is too low pressure in the starting air tanks. This will be a very critical failure.
- *What are the events that causes each failure?*
  The events that causes the described failure modes, are failures in the control unit or instrument pressure. It can also be a result of too much vibration to the system components.
- *What happens when each failure occurs?*
  If these failures occurs, the outcome can be fatal. The Air-starting system is performing a so called hidden function, starting the engines that will prevent an eventual failure. If the pressure in the air-tanks are too low, it might not be able to start the engines, starting the fire water pumps. If the compressor is not working as required, the pressure again, can become too low. If the alarm is not in function, the low pressure might not be discovered.
- *What systematic task can be performed proactively to prevent, or to diminish to a satisfactory degree, the consequences of the failure?*
  To make sure every component of the system is in order, regular check-ups should be performed. Eventual new pressure alarms could be installed. More frequent maintenance tasks. , Etc.
- *What must be done if a suitable preventive task cannot be found?*
  The entire system must be replaced.

During the operation phase for the equipment, RCM is applied to reevaluate/update the existing maintenance strategies. This means, evaluating relations between corrective and preventive maintenance, maintenance- and inspection intervals, level of spare parts, etc. (Rasmussen, 2003)

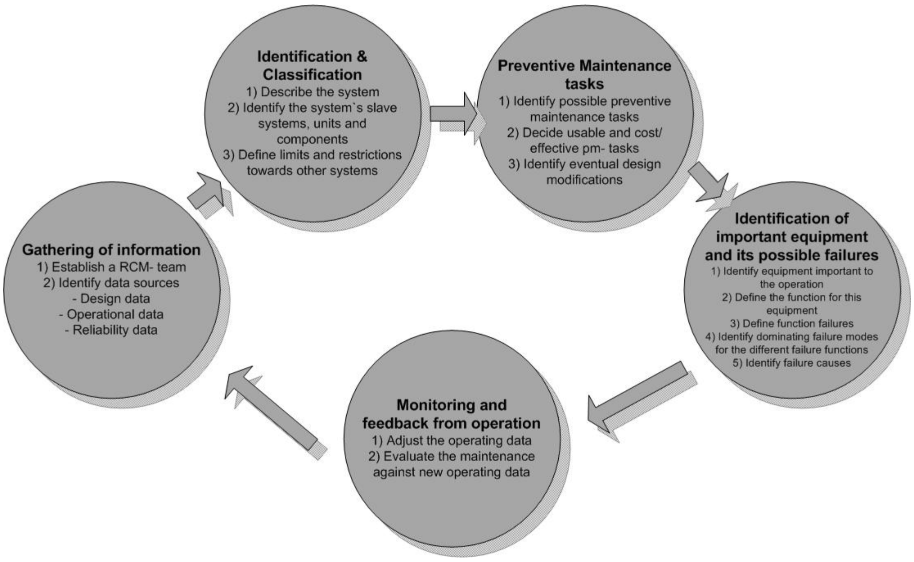


Figure 16: RCM Process

2. **Identification & Classification** The identification of important equipment and components are made in the Project Work (Mogstad, 2010), and the following information about the air-starting system is taken from that work.

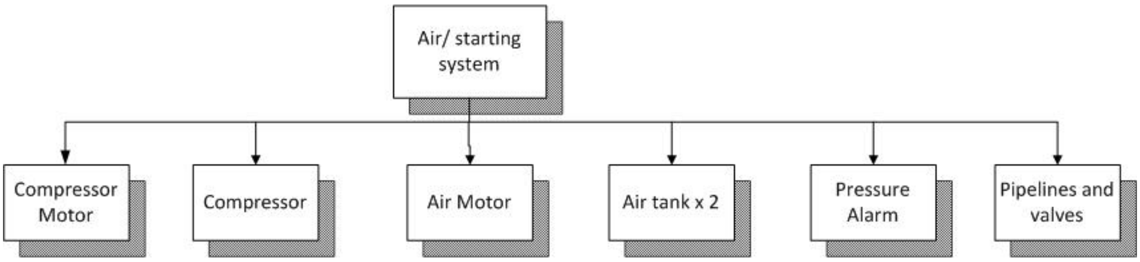


Figure 17: Air-Starting system

The air tanks are already considered not important due to its low degradation and not being exposed for corrosion. The remaining equipment of the air-starting system are further analysed.

3. **Identification of important equipment and its possible failures**
   In order to identify the important equipment and its possible failures, a FMECA is performed. More about the background and philosophy of this method is described in Appendix F, taken from the student's Project Thesis.

   The first step of a FMECA is to define the system structure. This is shown in Figure 13, where the components are organized in a tree-diagram. The Fire Water Pump system consists of six subsystems, and to avoid overwhelming calculations, this master thesis will be limited to describe subsystem 1, the Air-Starting system shown in Figure 17. The information regarding failure rates from the questions above, are then organized in Table 9 to obtain a complete overview of the system.

Component	**Failure Mode**	**Failure Cause**	**Failure rate / 10^6 hours**	**MTTR**
Starting Air Compressor	Fail to start on demand	Control unit, instrument, pressure	22,45	25
Air Motor	Fail to start on demand	Control unit, other	5,24	7,2
Pressure Alarm	Fail to function on demand	Vibration	0,30	10

Table 9: Failure Rates

Some of the data in Table 9 are collected from Operating Company's database, those data were mainly concerning the compressor failing to start, which will be a critical failure. The other data were hard to obtain from Operating Company's database, and are collected from the OREDA database.

Further in a FMECA, it is important to rank the severity of the potential failure modes. The severity is defined as the worst potential effect of the failure considered on the system level. The severity of the failures of the Air-Starting system is ranked as in Table 10:

10	Catastrophic	Failure results in major injury or death of personnel
7-9	Critical	Failure results in minor injury to personnel, personnel exposure to harmful chemicals or radiation, or fire or release of chemical to the environment
4-6	Major	Failure results in a low level of exposure to personnel or activates facility alarm systems
1-3	Minor	Failure results in minor system damage but does not cause injury to personnel, allow any kind of exposure to operational or service personnel or allow any release of chemicals into the environment.

Table 10: Severity Ranking

In case of a fire, which will be the outcome if the initial components of the fire prevention system fail, the severity class is catastrophic. Because of the redundancy in the system, however, some components can fail without causing a fire.

To investigate whether or not the system is acceptable and to identify feasible improvements to the systems in order to reduce risk, the FMECA should be reviewed according to risk.

RPN- Method The Risk Priority Number is defined as:

$$\mathrm{RPN} = \mathrm{S} * \mathrm{O} * \mathrm{D} \tag{10}$$

The variables are defined as follows:
S= the rank of the severity of the failure mode
O= the rank of the occurrence of the failure mode
D= the rank of the likelihood that the failure will be detected before the system reaches the end-user. The assumption is that the cause has occurred.

To estimate the rank of occurrence during one year, 24 hours per day of operation, the failure rate is utilized. D is an estimate.

The calculated RPN's have no value or meaning themselves. It is a common agreement amongst experts that larger RPN-values normally indicate more critical failure modes, however this is not always the case. RPN numbers may be identical and one component have a severity ranking of 10 while the other one has a severity ranking of 5. In these cases severity is given the most weight when assessing risk.

Component	O	S	D	RPN
Starting Air-Compressor	0,20	8	0,8	1,28
Air Motor	0,046	8	0,9	0,33
Pressure Alarm	0,0026	10	0,2	0,0052

Table 11: Risk Ranking

As for the air starting system the severity is high for every component and an eventual failure could be catastrophic. However, when looking exclusively at the RPN-value, the compressor stand out as the most critical component of the system. It should be stressed that the reason for the compressor resulting with the highest RPN-values can be because this is the only equipment with correct data collected from Operator A. Even though, with basis in this information, the further process of finding the most suitable strategy will focus on the compressor.

4. **Preventive Maintenance Tasks**
Developing preventive maintenance tasks or procedures for a plant or facility without a solid plan will result in inconsistent and unreliable procedures. Because it is important to document the development process, build-in consistency, and develop a good understanding of expected results, the planning of preventive maintenance task is essential. The process towards finding this strategy will be further discussed in Section 6.6.

Spare parts discussion Number and location of spares should be identified. A well known and used tool for this, is LISA, The Logistic Investments and Support Analysis software. This software is a collection of models to be used in the evaluation of parameters related to the logistics support system of an installation. The aim is to optimize maintenance and support related decisions in such a way that cost of the designated maintenance- and support resources balances the downtime cost for the supported system. (NTNU, 2009)

6.5.1 HL 2/77 Compressor

The compressor, which is most likely to be exposed for ageing, is a 2. Stage air-cooled compressor with built in inter- and after cooler. Its capacity is 17m^3/ h and it has a working capacity of 30 barg. The manufacturer is the norwegian company Sperre, which has produced compressors for 40 years.

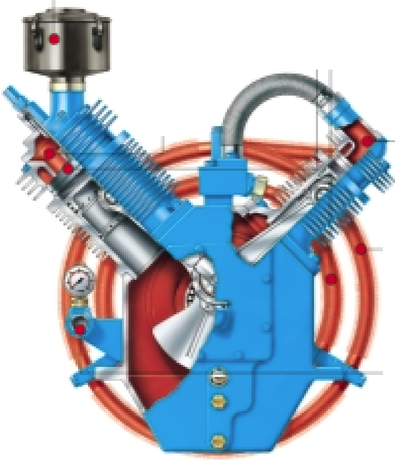


Figure 18: Piston and piston rings

Both pistons are made from an aluminum alloy and the compression and oil scraper rings are made of high-grade cast iron. There is a manually operated valve lifter for unloading the LP suction valve on top of the LP cylinder head.

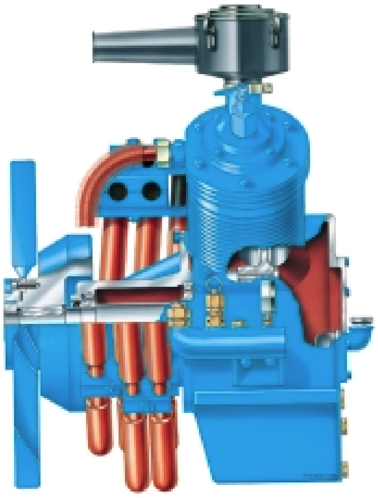


Figure 19: Fittings

The Sperre standard supply includes safety valves and pressure gauges for both stages and the finned HP and LP cylinders are made of cast iron. The finned cylinder heads are also made of cast iron. The crankshaft and connection rods are made of nodular iron, while the counterweights are integrated in the crankshaft and the crank and gudgeon bearings are needle bearings. The information is taken from the Sperre Compressor Data sheet shown in Appendix C.

Typical actions to maintain a compressor are cleaning, NDT, individual component dimensional inspection, rotor unstack, repair, replacement of impeller, diffusers, IGV's, rods, rings, shafts or shaft components or assembly of rotors and machines.

The further work of the Decision Model will focus on the compressor and finding its optimal ageing strategy.

With Sperre being a company with long experience and a good reputation with a 30 years warranty for it's products, the modification strategy will also be excluded. It seems unsuitable to modify the compressor instead of replacing the entire compressor or perform an overhaul with identical components when they exist. The further cost-benefit estimates will therefore include the three ageing strategies, replacement, overhaul and change of maintenance strategy. Nevertheless, the use of the decision model and appropriate discussion is exemplified.

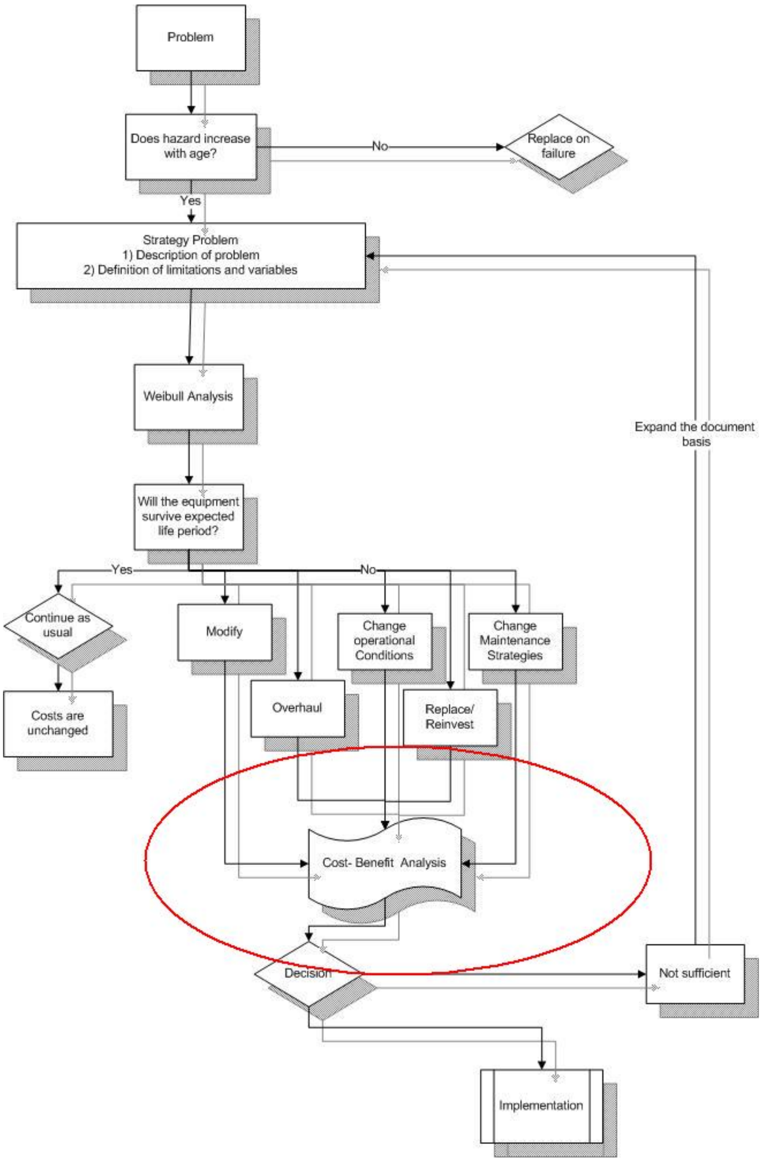


Figure 20: Stage of the model

6.6 Technical Costs

The costs regarding the technical issue falls into the following categories:

- Maintenance
- Spares
- Storage
- Transportation

Investment cost of spares and storage costs will be decisive in this context. How many spares should be in stock and how much storage space is needed? Where is the storage situated and how long time will it take to transport the storage? Those are crucial questions to determine when analysing and implementing a new strategy.

Replacement Replacement of equipment regarding technical issues are mostly concerned with the cost of new equipment in terms of spares as well as the other costs listed above. It is a thin line between overhaul and replacement, and the costs related to replacement are in this case considered the same as for the overhaul, where the price of maintenance kits are discussed.

Change of Maintenance Strategy In Section 2, four different approaches to improved maintenance are discussed.

1. Age- Based preventive Maintenance
2. Constant- Interval Preventive Maintenance
3. Constant Interval with Minimum Repair
4. Opportunity- Based Replacement Model

The benefit of preventive maintenance is the cost-effectiveness, flexibility, energy savings, reduced failure and increased component life. However, the disadvantages of this maintenance philosophy is the still danger of critical failures to occur, it is labor intensive and it includes performance of unneeded maintenance. Further is a discussion regarding costs for the different strategies, focusing on the technical related costs.

Age-Based Preventive Maintenance is performed after t_p hours regardless of failures prior to this interval. This is thereby a cost-efficient strategy in the way that the intervals are rescheduled after unforeseen maintenance actions. The demand for spare parts is on the other hand high, while the necessary equipment should always be in stock. The initial spare parts costs are therefore high, however, the expensive "spare parts needed right away" - cost is reduced. Further is this is labor-intensive strategy, and the maintenance cost in general is high.

Constant-Interval Preventive maintenance is cost-beneficial to the degree that there are few surprises and well planned maintenance actions. However the costs can be unnecessary high if the planned actions are performed without there really being a need for maintenance and preventive actions being conducted with short interval after a corrective maintenance action.

Constant Interval with minimum repair is usually less expensive than the previous strategy, the discussion is how well the equipment will function with only minimum repair. The costs are reduced when failure occurs by limiting the performed repair, hoping it will survive until the planned interval has elapsed.

To perform maintenance on an opportunity based schedule is less time consuming, while the equipment already is down, and may be less costly if failures are prevented to a satisfactory degree. However, the probability of failures occurring outside these opportunities are high and can cause costly operations.

In context to costs regarding technical issues, it is hard to predict tangible costs due to non-existing data concerning this matter. The above discussion serves as a guidance to the pros and cons for the alternative strategies.

Overhaul Sperre offers a wide range of Maintenance Kits to provide the necessary equipment, see Appendix D. To, for instance, overhaul the rod and rings, one need the Gasket Kit (4120) and Connecting Rod (1424MK) kit. The Gasket Kit includes all flat gaskets, O-rings, sealing rings and valve gaskets and the Connecting Rod kit includes a connecting rod with small- and big-end bearings, oil scoop with set screw.

The price is \$ 2000 for the Gasket Kit and \$ 13,000 for the Connecting Rod Kit with an interest rate of 10 %.

$$\text{NPV} = 80.000 \left[\frac{((1+0,1)^{10}-1)}{0,1(1+0,1)} \right] = \text{NOK}1,159,085,- \tag{11}$$

Based on Net Present Value, the price of these spares will be NOK 1,159,085,-.

6.7 Organizational Analysis

Due to the parallel approach of finding the optimal strategy to implement to the system, the results of the technical analysis will also be leading when evaluating the organizational and obsolescence issues. This means, the organizational issues will be related to the compressor and the three remaining optional strategies.

Costs related to organizational matters are based on Table 5.

- *Wages for additional crew*
  As for the matter of actions regarding the compressor, the personnel at the plant are considered sufficient for performing the necessary operations, and there is neither need nor cost for additional crew.
- *Training of personnel*
  The personnel are also considered well enough trained and familiar with the equipment that training of personnel is not required.
- *Administration Costs*
  Since maintenance of the compressor already is a well established action, the administration costs are considered negligible.

From Figure 10, the costs regarding organizational issues will therefore only concern additional costs due to wages of the existing staff.

Replacement The extra costs due to additional manpower when performing a replacement of the equipment, is estimated to become NOK 4800,-. This is calculated from a need for three man with an hourly wage of NOK 200,- for eight hours.

Change of Maintenance Strategy In Section 2, four different approaches to improved maintenance are discussed.

1. Age- Based preventive Maintenance
2. Constant- Interval Preventive Maintenance
3. Constant Interval with Minimum Repair
4. Opportunity- Based Replacement Model

As for the organizational part of implementing a new or changing the existing maintenance strategy, there are certain aspects that will affect the maintenance performance. The key of finding the optimal strategy is planning. This is the first step against an improved strategy and a process, which should continue till the end of the process. The second most important aspect is control. When in control one should have the complete overview of the following:

- All relevant variables operational in the specific maintenance environment
- The relationships between the variables
- Action has been taken to optimize the desired outputs, by focusing on the inputs to each process.

Control can be measured qualitatively to the degree that there are no surprises.

(Ellis, 2009)

If planning and control have been established, one can proceed to the system integration. This must be performed beyond the maintenance boundaries. Trust, teamwork and cooperation are key-words to succeed with implementation of a new strategy.

As described in Section 6.6, there are pros and cons regarding cost and availability for the different approaches to maintenance. The organizational costs concerns wages to crew and other necessary administration and it is hard to predict which of the discussed options that will come out most cost-beneficial. As few as possible maintenance actions are preferable, still keeping the ageing under control.

Overhaul An overhaul of the compressor requires less workforce, and will therefore make a less item of expenditure. It is estimated, with basis in information from Sperre, see Appendix E, that the job will take three hours. With an hourly wage of NOK 200,- and a need for 3 workers, the total cost of this overhaul will become NOK 2400,-.

6.8 Obsolescence

With basis in information from Sperre, the possibility of obsolescence of necessary spare parts are considered as low. Sperre is offering different maintenance kits and is providing a guarantee to produce spare parts for at least 30 years after buying one of their products.

The questions regarding obsolescence in Section 4, will here be elaborated to the degree that they are relevant.

- *Knowledge* The knowledge is assumed to be high among the personnel at Gas Facility A regarding the compressor. Since this compressor is still in production, there will also be competent personnel from the manufacturer available if necessary.
- *Standards & Regulations* Since the installation of the compressor, there has not been established new rules and regulations regarding the compressor, which could cause obsolescence.
- *Technology* In terms of problems related to lack of spare parts or technical support, the compressor is well served and the probability of obsolescence is low. The structure and components are still being manufactured by the producer.

Due to lack of information about the stock level at Gas Facility A, it is hard to estimate wether or not there is an acceptable level of spares in storage or other sources or contingencies available. However, the compressor has proved not to be immune to significant ageing degradation and newer designs and concepts are probably already on the market, ready to replace the existing compressor if that should be necessary. The costs related to obsolescence for the different strategies are investment, scrapping and possible rework.

Replacement Considering obsolescence, replacement costs includes investment cost of a compressor. With basis in information from Sperre, a new compressor will cost NOK 60.000,-. With an estimated life period of ten years with an interest rate of 10%, the net present value of the compressor is:

$$\mathrm{NPV} = 60.000 \left[\frac{((1+0,1)^{10} - 1)}{0,1(1+0,1)} \right] = \mathrm{NOK}869.314,- \tag{12}$$

Scrapping value of a compressor exposed to ageing, will be low and insignificant to the budget.

Possible rework is also neglected due to the assumption that this is a well established procedure and rework will not be necessary.

Change of Maintenance Strategy The discussion will be the same as for the technical issue in Section 6.6.

Overhaul As for overhauls, Sperre offers different sets of maintenance kits. For the sake of the calculations, the preferred maintenance interval is estimated to 5.000 hours and the action includes overhaul of valves, piston ring, air cleaner, clutch discs and bearings.

$$\mathrm{NPV} = 9.500 \left[\frac{((1+0,1)^{10} - 1)}{0,1(1+0,1)} \right] = \mathrm{NOK}137,641,- \tag{13}$$

The price for this overhaul kit is NOK 137,641,-.

7 Results & Discussion

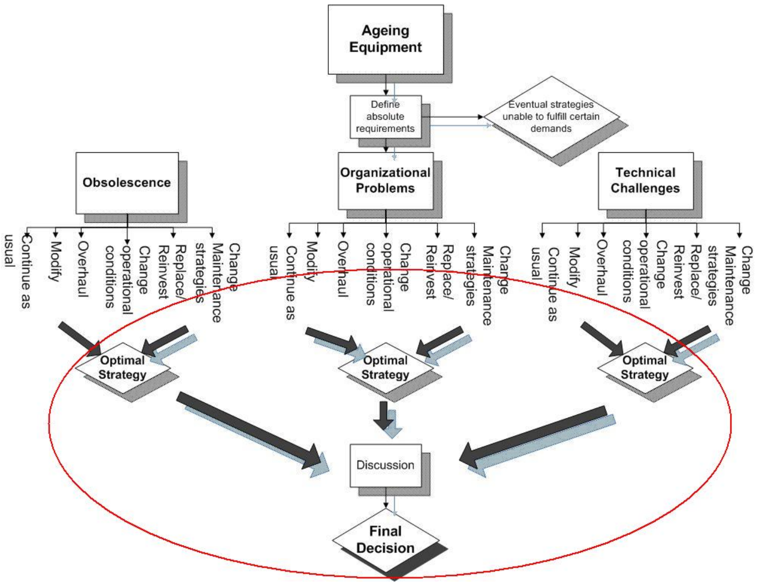
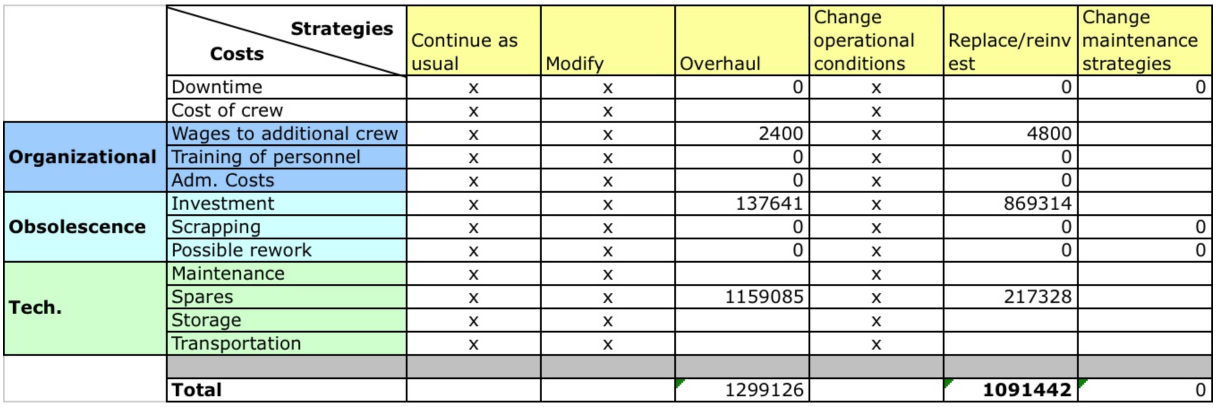


Figure 21: Point of the Decision Model

7.1 Results

The spreadsheet from Section 4.6 is now filled with the associated identified cost parameters.



	Strategies Costs	Continue as usual	Modify	Overhaul	Change operational conditions	Replace/reinvest	Change maintenance strategies
	Downtime	x	x	0	x	0	0
	Cost of crew	x	x		x		
Organizational	Wages to additional crew	x	x	2400	x	4800	
	Training of personnel	x	x	0	x	0	
	Adm. Costs	x	x	0	x	0	
Obsolescence	Investment	x	x	137641	x	869314	
	Scrapping	x	x	0	x	0	0
	Possible rework	x	x	0	x	0	0
Tech.	Maintenance	x	x		x		
	Spares	x	x	1159085	x	217328	
	Storage	x	x		x		
	Transportation	x	x		x		
	Total			1299126		**1091442**	0

Figure 22: Result

Due to lack of data, the strategy to change the maintenance strategy, is provided with a discussion, but without actual cost parameters. The most optimal ageing strategy is therefore considered to be a replacement of the compressor. This strategy turns out to be less expensive than an overhaul of the compressor, however the margins are subtle. The costs concerning the analysed strategies are considered fairly accurate with basis in information from the manufacturer, Sperre and the result can be considered adequate. The downtime cost is considered zero, while it is assumed that the required pressure in the air-tanks will remain constant during the replacement, not forcing any system to be out of order. This is also a requirement from PSA.

It is important to stress that the point of implementing the Decision Model to the Air-Starting system is to show the model's functionality and degree of applicability and due to lack of data, not necessarily find the correct optimal strategy. The Decision Model is designed to be able to either analyse a complete system, a structure or a single component exposed to ageing. For the case of the air-starting system, the model starts to analyse the entire system and then breaks down the different components, before defining the most critical component exposed to ageing as the compressor. The data available for the system are limited, and this is partially the reason for breaking down the system as described. To analyse each component of the system without sufficient data is a complicated and time consuming affair.

The data used in this Master Thesis are found in Operating Company A's database, OREDA and the most significant costs are collected from the manufacturer Sperre. The missing data and costs are estimated and the result should be evaluated thereafter. Even though accurate data have limited the implementation of the model, the student still consider the result as adequate and that the steps and organization of the model have been shown in a proper way.

7.2 Remarks to the Decision Model

The Decision Model presented in this Master Thesis, aims to provide strategic decision support for a wide range of oil and gas operators. When that is said, it should be stressed that there are aspects of the Decision Model that could be improved. This chapter aims to briefly discuss some of the shortcomings in the model and suggest improvements that would further strengthen the model as a strategic decision support tool.

7.2.1 Failure Rates

The technical outcome of the model is based on failure rates and the Weibull Analysis. The data used in this Master Thesis is found in Operating Company A's database and OREDA. The data from OREDA are general data and not specific failure rates for the actual system at KPP. This may lead to imprecise answers and to improve the model, a system to collect the correct data should be implemented. This is discussed further in Section 8.1.

7.2.2 Pricing of Equipment

The Decision Model is implemented to the Air-Starting system and the system is broken down to concerning the compressor and the costs related to this component. Sperre has provided the student with adequate information about pricing of new components as well as maintenance kits, and these costs are therefore considered authentic. Costs of different maintenance strategies are discussed back and forth in order to enlighten the most essential pros and cons of the strategies. However, to provide the reader with accurate data concerning this strategy has proved to be a difficult task.

7.2.3 Decision Making

An important note to the outcome of this Decision Model is the influence of experience of the crew. This makes the decision partly subjective, differing from who is part of the decision making and should be taken into account before making the final decision.

8 Conclusion

"*It is indeed a curious (and unfortunate) fact that, in today's world of modern technology, one of the least understood phenomena about our marvelous machines is how and why they fail.*

- Anthony M. Smith & Glenn R. Hinchcliffe

As in every industry, the oil and gas industry is driven by money. Ageing is a critical factor for systems operating in harsh environment and can cause high costs for the operator and customer. Proper strategies regarding ageing equipment are therefore an important issue for the existing facilities in order to be able to continue operation from both a safety and economic perspective.

The Decision Model presented in this Master Thesis is intended to make the way towards an optimal strategy regarding ageing equipment easier. Evaluating different strategies in relation to Organizational, Obsolescence and Technical issues in parallel makes the calculations less comprehensive and makes room for subjective opinions and discussion throughout the process.

Implementation of the Decision Model for the Fire Water Pump System at Gas Facility A, shows the steps of the model, even though the lack of data limits correct calculations. Based on these calculations, the optimal ageing strategy is to replace the air-compressor. However, notice though, that to perform an overhaul is also a recommended strategy, resulting only NOK 200,000 more expensive than the recommended replacement.

8.1 Further Work

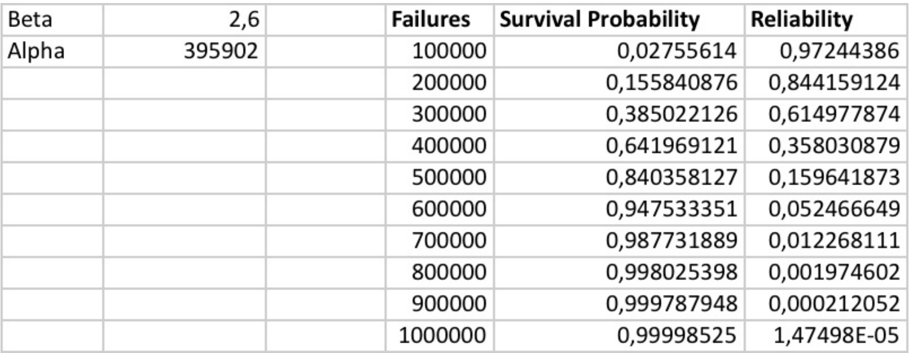
The quote of Smith & Hinchcliffe grasps the essence of decision making related to ageing equipment. If all necessary data were collected and categorized, the job of determining the optimal strategy to reduce ageing, would be a much simpler matter.

Optimization of the Decision Model developed in this Mater Thesis should therefore focus on implementing and develop a tool to collect the data needed to determine the optimal strategy regarding ageing equipment. The oil and gas industry is special when it comes to lack of standard equipment. Each field has it's own custom- made system due to the variation of oil and gas dependent on where the field is situated. This makes the task of constructing a general model for ageing equipment difficult and a discussion of the importance of such customized systems for new plants and fields should be made.

There should also be developed a tool to make it easier to calculate the qualitative costs, this is specially concerning the organizational and obsolescence related issues. A sensitivity analysis should than be performed in order to evaluate further which one is the optimal ageing strategy.

Appendices

A Weibull Data



Beta	2,6		**Failures**	**Survival Probability**	**Reliability**
Alpha	395902		100000	0,02755614	0,97244386
			200000	0,155840876	0,844159124
			300000	0,385022126	0,614977874
			400000	0,641969121	0,358030879
			500000	0,840358127	0,159641873
			600000	0,947533351	0,052466649
			700000	0,987731889	0,012268111
			800000	0,998025398	0,001974602
			900000	0,999787948	0,000212052
			1000000	0,99998525	1,47498E-05

B Weibull Results

SAMMENDRAG (UTDATA)

Regresjonsstatistikk	
Multippel R	0,95888871
R-kvadrat	0,919467558
Justert R-kvadrat	0,907962924
Standardfeil	0,264863676
Observasjoner	9

Variansanalyse

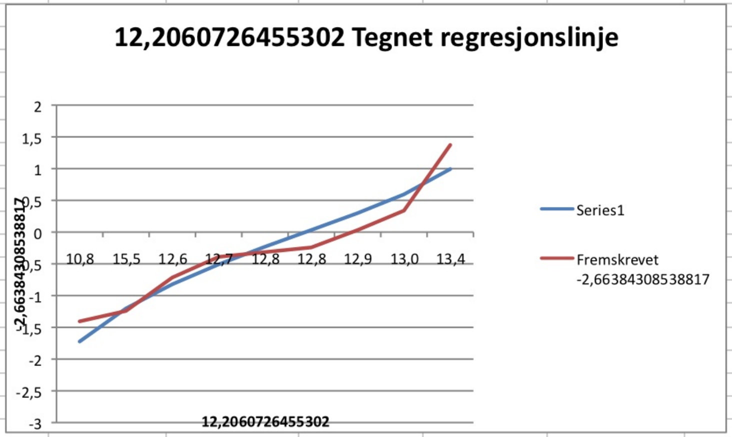
	fg	SK	GK	F	Signifkans-F
Regresjon	1	5,606713809	5,606713809	79,92149191	4,45567E-05
Residualer	7	0,49106937	0,070152767		
Totalt	8	6,097783179			

	Koeffisienter	Standardfeil	t-Stat	P-verdi	Nederste 95%	Øverste 95%	Nedre 95,0%	Øverste 95,0%
Skjæringspunkt	-33,48647879	3,714881741	-9,014143955	4,22235E-05	-42,27077824	-24,70217933	-42,27077824	-24,70217933
12,20607265	2,598494747	0,290663201	8,939882097	4,45567E-05	1,911185493	3,285804001	1,911185493	3,285804001

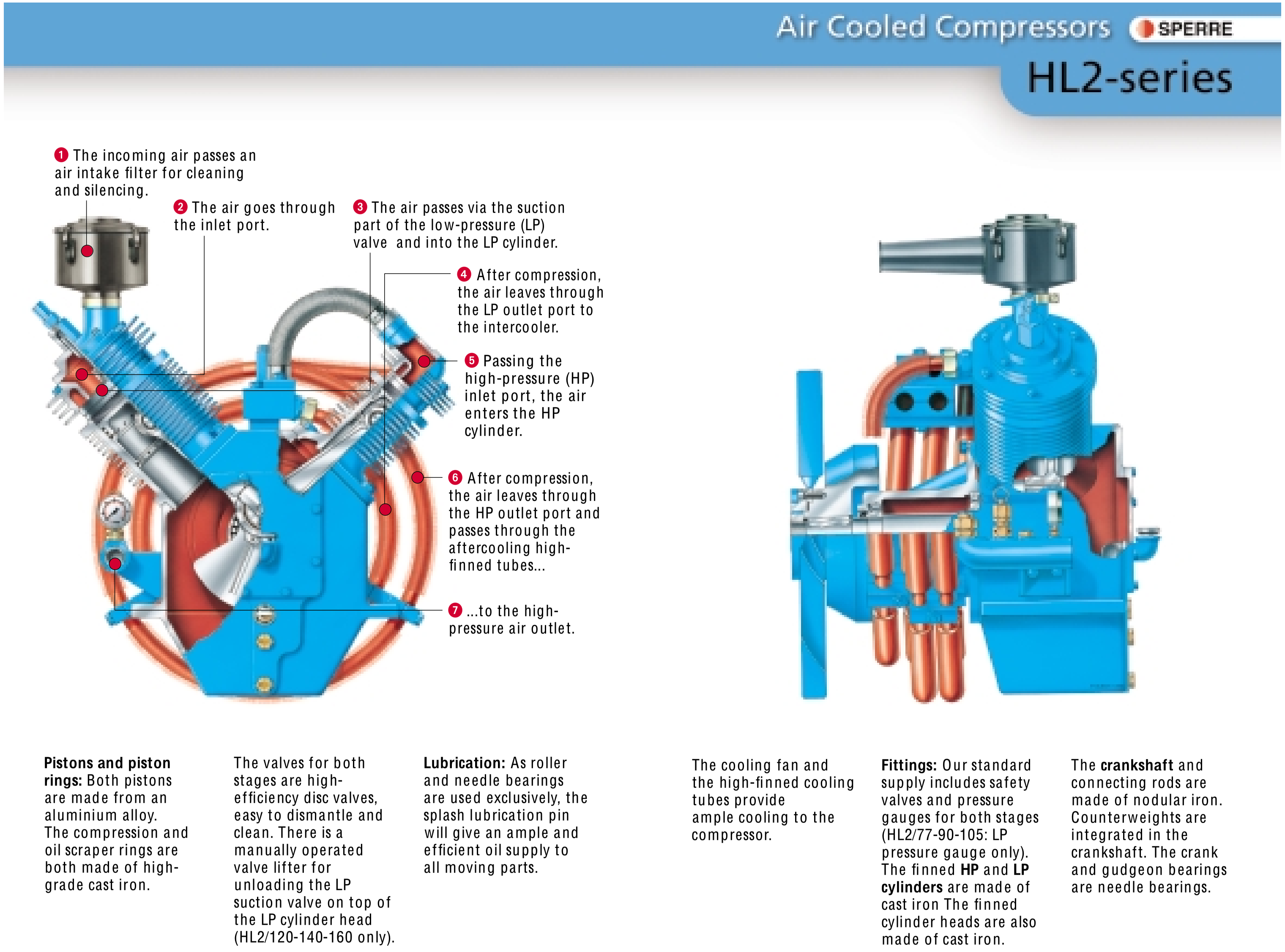
Beta =	2,598494747
Alpha =	395092,6961

AVVIK (UTDATA)

Observasjon	Fremskrevet -2,66384308538817	Residualer
1	-1,405892462	-0,317370688
2	-1,241722418	0,039699303
3	-0,715464182	-0,106202334
4	-0,390228412	-0,118366982
5	-0,31490445	0,084539005
6	-0,241702574	0,274627536
7	0,032076173	0,266956759
8	0,338134772	0,255842445
9	1,372413973	-0,379725044



C Sperre Compressor Data



Air Cooled Compressors SPERRE

HL2-series

❶ The incoming air passes an air intake filter for cleaning and silencing.

❷ The air goes through the inlet port.

❸ The air passes via the suction part of the low-pressure (LP) valve and into the LP cylinder.

❹ After compression, the air leaves through the LP outlet port to the intercooler.

❺ Passing the high-pressure (HP) inlet port, the air enters the HP cylinder.

❻ After compression, the air leaves through the HP outlet port and passes through the aftercooling high-finned tubes...

❼ ...to the high-pressure air outlet.

Pistons and piston rings: Both pistons are made from an aluminium alloy. The compression and oil scraper rings are both made of high-grade cast iron.

The valves for both stages are high-efficiency disc valves, easy to dismantle and clean. There is a manually operated valve lifter for unloading the LP suction valve on top of the LP cylinder head (HL2/120-140-160 only).

Lubrication: As roller and needle bearings are used exclusively, the splash lubrication pin will give an ample and efficient oil supply to all moving parts.

The cooling fan and the high-finned cooling tubes provide ample cooling to the compressor.

Fittings: Our standard supply includes safety valves and pressure gauges for both stages (HL2/77-90-105: LP pressure gauge only). The finned **HP** and **LP** **cylinders** are made of cast iron The finned cylinder heads are also made of cast iron.

The **crankshaft** and connecting rods are made of nodular iron. Counterweights are integrated in the crankshaft. The crank and gudgeon bearings are needle bearings.

D Sperre Spare-Part and Maintenance Kits, HL2/77

Valuable
technical information

SPARE-PART & MAINTENANCE KITS
Model HL2/77

SPERRE's kits of genuine spare-parts include the wear parts you must change when you overhaul the compressor. For example, if you replace a valve, it is strongly recommended to replace the valve gaskets at the same time. With a spare-part kit available, all necessary parts are at hand together with clear installation instructions.

For model HL2/77 following kits are available:

Description	Part No	Content of kit
Gasket kit	4120	All flat gaskets, O-rings, sealing rings, and valve gaskets.
Crankshaft	1403MK	Crankshaft with all bearings, flywheel key and nut, Seeger-rings, endplate and screw.
Valve LP	3036MK	Valves and necessary copper rings and/or gaskets.
Valve HP	3037MK	Valves and necessary copper rings and/or gaskets.
Overhaul kit – LP valve	3036MK2	Valve plate and gaskets.
Overhaul kit – HP valve	3037MK2	Valve springs, plates and gaskets.
Piston LP	3354MK	Piston, gudgeon pin with Seeger-rings and piston rings.
Piston HP	3352MK	Piston, gudgeon pin with Seeger-rings and piston rings.
Connecting rod	1424MK	Connecting rod with small- and big-end bearings, oil scoop with set screw.
Cylinder LP	1135MK	Cylinder with gaskets, stud bolts/nuts and fittings.
Cylinder HP	1133MK	Cylinder with gaskets, stud bolts/nuts and fittings.
Overhaul kit Routine B	7934	All parts needed for 5000-hours' maintenance: Overhaul kits for valves complete with gaskets and guide rings, piston rings, connecting rod bearings, gudgeon pins, Seeger rings, gaskets and ventilator.
Overhaul kit Routine C	7964	All parts needed for 10 000-hours' maintenance: Same as kit B, plus complete valves, crankshaft bearings and seal ring.

Maintenance kits:

- All necessary parts at hand when you need them
- With clear installation instructions enclosed

Genuine Sperre parts give you peace of mind at sea!

Sperre Industri AS
Tel +47 70 16 11 00
Fax +47 70 16 11 10
E-mail:industri@sperre.com

Sperre Rotterdam BV
Tel +31 180 463 299
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Sperre Asia PTE LTD
Tel +65 763 63 00
Fax +65 763 18 11
E-mail:asia@sperre.com

Sole suppliers of
genuine spare parts

E Information from Sperre Industry AS

Hei igjen Therese,

En Sperre HL2/77 Startlufts kompressor med alt utstyr og klassesertifikat koster ca. NOK 60.000,-

For å gjøre vedlikehold av kompressorene enkelt for brukerene, har vi laget vedlikeholdsett med nødvendige reservedeler og installasjonsveiledning for hver service rutine. Vi har også laget en CD med digital informasjon om vedlikeholdsrutinene som skal gjøre det enkelt å legge informasjonen inn i Planned Maintenance Systemet(PMS) på båtene. Dette programmet forteller operatørene hvilken service som er nødvendig basert på antall driftstimer.

Vedlikeholdsettene består av Ventiloverhalingsett som brukes ca. hver 2.500 timer. Disse koster Ca. NOK 4.000,- Jobben tar ca. 2 timer.

Videre har vi 5.000 timers sett som inneholder ventil overhalingsett, stempelringsett, luftfilter, koblingslameller og lager. Pris ca. NOK 9.500,- Jobben tar ca. 3 timer.

Til slutt har vi 10.000 timers sett som inneholder alle slitedeler i kompressoren inklusiv komplette ventiler og lager til veivaksel. Pris ca. NOK 12.500,- Jobben tar ca. 7 timer.

Sperre har alltid alle reservedeler til kompressorene vi leverer på lager. Vi har lager i Singapore , Rotterdam og på Ellingsøya i Norge. Vi har også et slagskontor med reservedelslager i Shanghai China.

Vi lover kundene våre å ha reservedeler på lager i minst 30 år etter at vi har sluttet å produsere de forskjellige kompressor modeller.

Sender med vår Ettersalgsbrosjyre som vedlegg, og håper du har fått svar på dine spørsmål!

Du vil også finne ytterligere informasjon på vår hjemmeside; http://www.sperre.com/

Vil du vite mer må du gjerne ta kontakt!

Lykke til med masteroppgaven!

Vennlig hilsen,
Sperre Industri AS
Arnstein Kvernevik
Ettersalgssjef
Mob. +47 928 66337
Tel/Fax: +47 70161153/70161110
http://www.sperre.com

F FMECA

Failure Mode, Effects and Criticality Analysis were one of the first systematic techniques for failure analyses and is still the most widely used reliability analysis technique in the initial stages of product development. This is a technique, which facilitates the identification of potential problems in either design or process, by examining the lower level failures and how they can affect an entire system. In connection with this analysis, recommended actions or compensations are made to reduce the likelihood of the problems occurring. This is also a useful tool to make action plans to mitigate the risk if the problem should occur. The FMECA is a result of two steps:

- Failure Mode and Effect Analysis (FMEA)
- Criticality Analysis (CA)

A FMECA can depend on a combination of function and hardware, just the function or only the hardware. (Rausand, 2005)

By use of a FMECA, there are both advantages and disadvantages. It is a systematic establishment of relationship between failure causes and effects, and an important tool to point out individual failure modes for corrective actions in the design process. However, it does not consider combined failures and it usually provides an optimistic estimate of reliability. The FMECA also requires an extensive use of labour and considers a large number of trivial cases. It should therefore be considered using other analytical data as well.