NTNU
Norwegian University of Science and Technology
Department of Marine Technology

M.Sc.THESIS

Title: **Condition Monitoring of Offshore O&G Separator – Cost-Benefit Evaluations and Presentation of Information**	**Delivered:** 6/9/2010 **Availability:** OPEN
Student: Jørgen Houmstuen	**Number of pages:** 102

Abstract:

This thesis introduces and analyses the following condition monitoring methods for a first stage production separator:

- Neutron backscatter
- Acoustic monitoring (active/passive/ultrasonic)
- Gamma monitoring
- Microwave monitoring
- IR thermometry

The methods are analyzed and evaluated in a cost-benefit analysis. Different models for cost estimation are presented along with estimations of the benefits. To perform the cost-benefit analysis a model has been developed and implemented in a spreadsheet. The method yielding the highest net benefit for the lifetime of the case separator was a combined passive acoustic and IR monitoring solution.

To maximize the utilization of condition monitoring data it is important that it is presented to decision makers as information aggregated up to a useful level. As the amount of condition monitoring data increases automatic aggregation and filtration of information is becoming more important to limit the operational costs. Technical condition indexing (TCI) is presented as a method to automate this process. An example of how condition monitoring data can be utilized using TCI is given complete with the implementation of the measurements in the TCI software TeCoMan.

Keyword:

Separator
Condition monitoring
Cost-benefit analysis

Advisor:

Professor Magnus Rasmussen

Address:
NTNU
Department of Marine Technology
N-7491 Trondheim

Location
Marinteknisk Senter
O. Nielsens vei 10

Tel. +47 73 595501
Fax +47 73 595697

Faculty of Engineering Science and Technology
Department of Marine Technology

MASTER THESIS
for
M.Sc. student Jørgen B. Houmstuen
Department of Marine Technology
Spring 2010

Condition Monitoring of Offshore O&G Separators - Cost-Benefit Evaluations and Presentation of Information.

(Tilstandskontroll av offshore O&G separatorer - LCC (livssyklus) evaluering og presentasjon av resultater.)

Within the Center for Integrated Operations in the Petroleum Industry (IO Center) there is an interest for implementation of Non-Intrusive Inspection (NII) methods for Condition Monitoring of topside static equipment. Implementation of CM methods will potentially reduce the operational and revenue losses associated with offshore operations. However, it is crucial that the cost of implementing methods is justified by the benefits of doing so. In addition, the CM information must be understandable and efficiently communicated to the decision makers in order to execute appropriate maintenance actions in due time.

The M.Sc. thesis therefore includes the following tasks with an offshore production separator as case:

1. CM methods:
    a. Identify and describe the different applicable CM methods for the case equipment.
    b. For the identified methods describe how the CM data is presented today, and indicate improvements to the way this is done.
2. Technical Condition Indexing (TCI):
    a. Do a literature survey and describe the principle behind TCI as a means for presenting technical condition to decision makers.
    b. Establish a TCI model and hierarchy for the case equipment, in particular taking into account use of CM data from the different methods.
3. Cost-benefit modelling:
    a. Do a literature survey and identify/describe model(s) for Life Cycle Cost (LCC) analysis.

b. Develop a model for cost-benefit assessments of the various CM methods for the case equipment, and evaluate the different CM methods by use of the model.
c. Based on the outcome of Point 3b) make the necessary adjustments to the TCI model and hierarchy presented in Task 2.

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

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

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

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

Starting date: 18th January 2010
Completion date: 11th June 2010
Handed in:

Trondheim 18th January 2010.

Magnus Rasmussen

Professor

Master Thesis

Marine Technology

Jørgen Houmstuen

9/6/2010

Condition Monitoring of Offshore O&G Separators – Cost-Benefit Evaluations and Presentation of Information

Preface

This thesis is the result of my M.Sc. study at the Norwegian University of Science and Technology, Department of Marine Technology with the topic Condition monitoring of O&G separators – Cost-Benefit evaluations and presentation of data. The M.Sc. thesis was done in cooperation with Marintek and Shell.

Considerable amount of time has been spent trying to quantify both the costs and benefits related to condition monitoring to get realistic results in the cost-benefit analysis. The values of these costs and benefits are often well kept company secrets, but thanks to helpful hints the values used in this thesis should not be too far from the truth.

I would like to thank professor Magnus Rasmussen (NTNU), Torgeir Brurok (Marintek), Harald Rødseth (Marintek) and Graham Baird (Shell) for their help with this thesis. Without your help, guidance and insight I would not have been able to put this thesis together.

Trondheim 6/9/2010

____

Jørgen Houmstuen

Summary

A large portion of the avoidable operational cost for an offshore oil and gas producing facility can be traced back to maintenance costs and downtime related to maintenance issues. Correct use of condition monitoring (CM) data can greatly reduce these costs by giving an accurate early warning of equipment degradation. Static equipment is usually not well covered by condition monitoring equipment today. This thesis introduces and evaluates the following methods for CM of a first stage separator:

- Neutron backscatter
- Acoustic monitoring (active/passive/ultrasonic)
- Gamma monitoring
- Microwave monitoring
- IR thermometry

The methods are evaluated using a cost-benefit analysis. Different estimation methods for the values in the cost-benefit analysis have been introduced, the cost-benefit analysis performed here relies on deterministic estimation. To perform the analysis the model has been implemented in an Excel spreadsheet.

CM method	Net benefit [NOK]	Net Benefit / LCC ratio
IR	73 511 000	15,19
Gamma	4 691 000	0,21
Neutron Backscatter	4 151 000	0,18
Ultrasonic	11 078 000	1,21
Microwave	37 287 000	3,21
Passive acoustic	13 475 000	2,84
IR+PA	76 305 000	9,09

The method yielding the best net benefit for the lifetime is the combination of IR and passive acoustic monitoring. Using only IR gives the highest net benefit / LCC ratio, in other words the highest benefits compared to the costs. Sensitivity analysis shows that the greatest uncertainty of the calculation is the consequences of accidents and incidents. Economic variables like interest, inflation and oil price have minor influence on the results.

To maximize the utilization of the CM data it is important that it is presented to decision makers as information aggregated up to a useful level. As the amount of CM data increases automatic aggregation and filtration of information is becoming more important to limit the operational costs. Technical condition indexing (TCI) is presented as a method to automate this process. An example of how CM data from the selected IR and passive acoustic monitoring solution can be utilized using TCI is given complete with the implementation of the measurements in the TCI software TeCoMan.

Contents

Table of figures

Table of tables

List of abbreviations

ALARP	As low as reasonable practicable
CAPEX	Capital expenditures
CBS	Cost Breakdown Structure
CDF	Cumulative distribution function
CM	Condition Monitoring
ECAM	Electronic Centralized Aircraft Monitoring
FMECA	Failure mode, effect and criticality analysis
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Infra Red
LCC	Life Cycle Cost
LRUT	Long Range Ultrasonic Testing
NDT	Non-Destructive testing
NPV	Net Present Value
OPEX	Operational expenditures
OREDA	Offshore Reliability Data Handbook
PA	Phased Array Ultrasonics
REMR	Repair Evaluation Maintenance Rehabilitation Research Program
TCI	Technical Condition Indexing
TCO	Total Cost of Ownership
TeCoMan	Technical Condition Manager (Software package)

1 Introduction

A large portion of the avoidable operational cost for an offshore oil and gas producing facility can be traced back to maintenance costs and downtime related to maintenance issues. The major cost is revenue loss due to unnecessary maintenance shutdowns and extended maintenance downtime due to lack of preparation. Correct use of condition monitoring (CM) data can greatly reduce these costs by giving an accurate early warning of equipment degradation.

Modern facilities have often got a comprehensive condition monitoring system for rotating equipment. The coverage of condition monitoring systems for static equipment is however not as good, static equipment is usually subject to other maintenance strategies. With recent development in technology and general cost reduction of technology condition monitoring of more static equipment may be economically feasible. Condition monitoring may also lower the risk of incidents and accidents putting both personnel and environment at risk.

This thesis will try to shed some light on condition monitoring of static equipment using a gravity-based separator as a case. The separator is introduced along with descriptions covering how it fails followed by descriptions of condition monitoring methods capable of detecting these failures. To implement these methods they must yield a net benefit over the residual lifetime of the platform. This is analyzed in a cost-benefit analysis; a spreadsheet- based cost-benefit model has been developed and used to analyze the presented condition monitoring methods.

Once the condition monitoring data has been acquired it must be presented to decision makers to aid in the decision making process. A description of how this is done is presented along with suggestions to how this may be improved. Special attention is given to technical condition indexing as a method to present the condition monitoring data. The method is introduced and the condition monitoring solution giving the best overall net benefit based on the cost-benefit analysis has been implemented in the TeCoMan software as an example of how condition monitoring data may be presented.

2 Introduction to Condition Monitoring and Separators

Condition based maintenance is based on quantitative information about the current condition of the components. This information is gathered by sensors. If the gathering is continuous and not involving human interaction it is called *Online Condition Monitoring*. If the gathering is periodic and involves human interaction is required it is called *Offline Condition Monitoring.*

Online condition monitoring has the highest investment cost; the results and savings in operational costs must justify the high investment cost. Information is automatically gathered into a database and can be accessed later or in real-time. This gives great advantages with respect to fault detection and analysis of operational history. With numerous data points for each parameter it is possible to trend different parameters against each other and find their correlation and see the change in condition instantly. Online monitoring offers the possibility of recording a large number of parameters with negligible use of man-hours, thereby reducing the need for workers on site.

Offline condition monitoring offers much of the same advantages of online monitoring, but with fewer data points it harder to detect faults. Trending and correlation between different parameters will also have a larger confidence interval. The data should be stored in a database, and preferably in connection with the online results. Collection of data for offline monitoring can be as simple as a worker recording readouts from instruments onto a paper based form. Today an offline data collector is often used. The data collector is basically a small portable computer storing data from either sensors mounted on the component or from its own sensors. Pre-mounted sensors are used when access to the measuring point is restricted, often due to worker safety. Otherwise sensors from the data collector are preferable, the investment cost is reduced to one set of sensors for the whole plant, and sensor replacement is easy.

Condition monitoring is used when the component is expected to have a wear out fault distribution and measurable parameters to monitor this exist. Condition monitoring is especially useful for components without a clearly established expected lifetime and for components with high replacement cost. Accurate measurement of the condition combined with experienced analysts makes prediction about remaining lifetime possible.

2.1 Separator

A separator can clearly benefit from condition monitoring; it is extremely expensive and there are measurable parameters to monitor the degradation and detect failures.

The separator type chosen for further investigation in this thesis is a first stage production separator located at the Draugen platform in the Norwegian Sea. This specific separator will be used for analysis and examples throughout the thesis. The outcome of the discussions and analysis will however be applicable to most gravity separators and vessels. The model created for cost-benefit analysis is applicable for all condition monitoring methods. The purpose of the first stage separator in this system is to separate oil, gas and water.

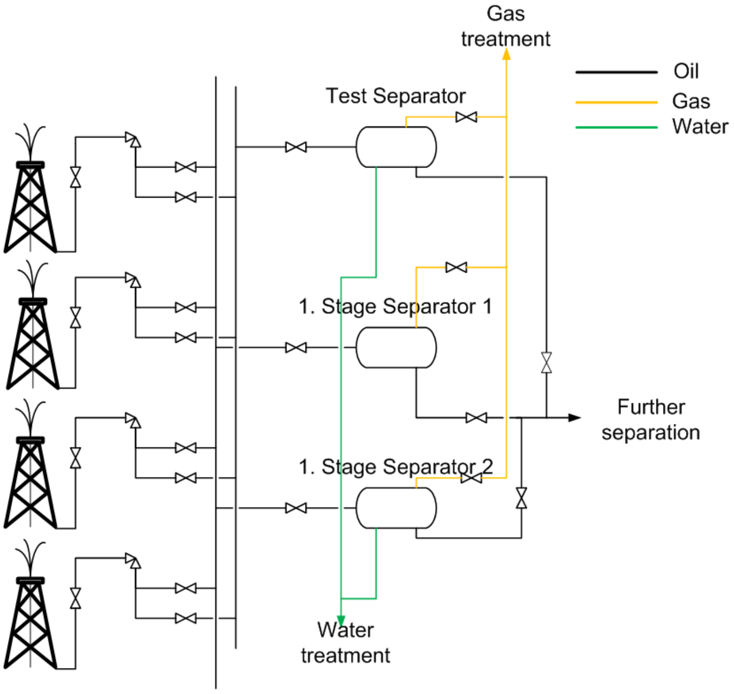


Figure 1 - Separator and the system

The first stage production separator is connected to the high pressure manifold as shown in Figure 1. The pressure from the well is reduced by the production chokes before the production manifold and separator. The typical operational pressure of the separator is 5-15 bars while the typical temperature is between 0 °C and 70 °C. The typical retention period, that is the time the fluids spend inside the separator, is around 5 minutes. The separator analyzed in this thesis has a total volume of approximately 120 m^3, the length is over 12 meters and the diameter is approximately 3.5 meters. The design max flow rate is more than 200 000 bbl/d. The separator is constructed from high quality steel.

2.1.1 Separator internals

Inside a separator there are several internal components that aid in the separation process. A brief introduction into the most common will be given here along with an illustration of a separator. All separators do not have all of these internals, and there are several different designs trying to accomplish the same task. The separator used for further analysis has a schoepentoeter at the inlet, gas demister, weir plate, sand system and vortex breakers at the outlets.

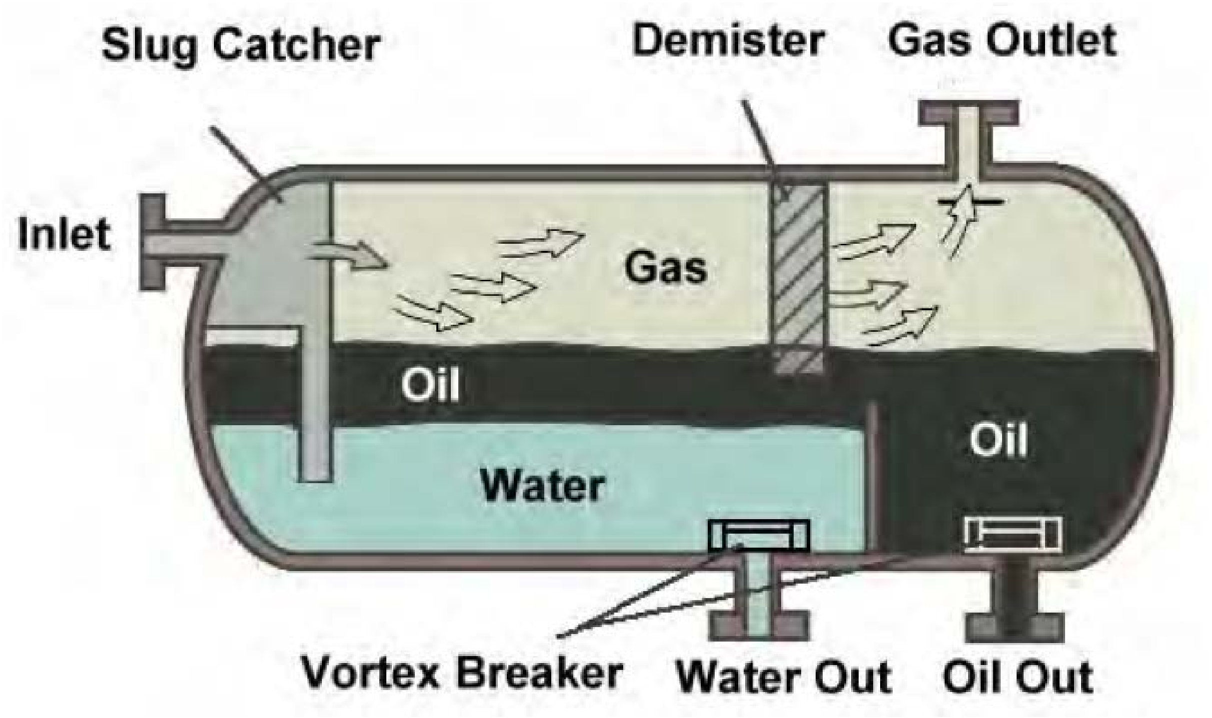


Figure 2 - Production separator (Devold, 2009)

Inlet cyclone:	Hydro cyclone placed at the inlet of the separator for especially demanding inlet conditions. Gives an initial crude separation of the fluids whilst decreasing foam buildup. (Ascom Separation, 2010)
Slug Catcher:	Situated at the inlet to reduce the effect of slugs (large gas bubbles or liquid plugs)
Schoepentoeter:	Inlet device designed to reduce the momentum of the inlet flow and perform a first separation.
Vortex breaker:	Situated at the liquid outlets to reduce the effect of vortices. This protects the liquid table inside the separator and ensures that only the separated liquid is allowed to exit through the outlet.
Gas demister:	Situated at the gas outlet to prevent mist and droplets in the gas, essentially a filter that prevents mist and droplets to pass.
Sand system:	Nozzles situated at the bottom of the water area of the separator. By introducing pressurized water sand will be carried by the water and can be drained out. This allows for sand removal without interfering with the production.
Weir:	Steel plate mounted in the separator to separate water from oil.

2.2 Separator Failures and consequences

Failures concerning a large oil and gas separator may have large consequences to the environment, to safety and to the overall economy of the plant. A large production separator contains substantial amounts of hazardous hydrocarbons under pressure, and the volume flow is high. Because of this any incident related to a separator has the potential to turn into a disaster. To analyze the different failures and their potential consequences an FMECA analysis has been performed.

2.2.1 FMECA introduction

FMECA (Failure mode, effect and criticality analysis) is a systematic approach to analyzing failures criticality and the effect of these events. Failure modes are preferably kept in a standardized format describing the failure, cause, effect and detection method of the failure. For the FMECA performed here the detection method is left out, as it will be thoroughly investigated in chapter 3. Important parameters such as criticality, severity and failure rate should also be included. The FMECA approach can be summarized in the following way:

- Define the system
- Construct a function hierarchy
- Identify failure modes
- Assign effects to failure modes
- Assign severity categories to effects
- Enter other relevant information (detection methods, failure rates, etc)
- Create a report highlighting critical failures

2.2.2 Definitions

The system selected for this FMECA is limited to a single production separator as described in chapter 2.1. To assess the different failures it is necessary to have a set of definitions regarding consequences and frequencies of the failures and a risk matrix combining this information. The definitions used in this thesis are given in the following tables.

Frequency classes	Quantification
Very unlikely	Once per 1000 years or more rarely
Remote	Once per 100-1000 years
Occasional	Once per 10-100 years
Probable	Once per 1-10 years
Frequent	More often than once per year

Table 1 - Frequency classes

Consequence	Safety	Environment	Production
Catastrophic	Complete plant meltdown	Large uncontrollable spillage > 100 m3	Complete plant shutdown
Critical	Injury to personnel, death to personnel in close proximity	Spillage < 100 m3	Risk of downtime, severely reduced capacity
Major	Injury to personnel in close proximity	Spillage < 10 m3	No downtime, reduced capacity
Minor	No safety risk	No spillage	No downtime, negligible capacity reduction

Table 2 - Consequence classification

		Consequence			
		Minor	Major	Critical	Catastrophic
Frequency	Frequent	4	5	6	7
	Probable	3	4	5	6
	Occasional	2	3	4	5
	Remote	1	2	3	4
	Very unlikely	0	1	2	3

Table 3 - Risk matrix

2.2.3 Failure modes

Failure mode is defined as the effect which a failure is observed on a failed unit (SINTEF Industrial Management, 2002). To perform an FMECA it is necessary to have good knowledge of the different failure modes. The major challenge is getting adequate information regarding the failure rate; failure statistics is usually considered a company secret and therefore not published. This thesis relies on a single source of information; the Offshore Reliability Data handbook (OREDA) which is a collection of failure statistics from several oil companies. OREDA groups its failure modes into three main severity categories shown in Table 4. The two most common failure modes for each category are presented in Table 4. The failure modes used in OREDA are unfortunately not the same as the ones used in research of condition monitoring methods. The FMECA will only use the failure modes defined in OREDA.

Severity Class	Definition	Most common FM
Critical	A failure which causes immediate and complete loss of a system's capability of providing its output	Abnormal instr. rd. Ext. Leak. P medium
Degraded	A failure which is not critical, but prevents the system from providing its outputs within specifications. Such a failure would usually, but not necessarily, be gradual or partial, and may develop into a critical failure in time	Abnormal instr. rd. Plugged / Chocked
Incipient	A failure which does not immediately cause loss of a system's capability of providing its output, but which, if not attended to, could result in a critical or degraded failure in the near future	Abnormal instr. rd. Minor in-service problems

Table 4 - Failure mode severity categories

The problem with abnormal instrument readings is a major concern, without instruments there is little knowledge about what's going on inside the separator. Instrument problems are the most common in all categories, thereby the most common problem overall. Looking further into the data presented in OREDA regarding maintainable items versus failure mode for separators the following insight into the distribution of instrument failures can be obtained:

Instrument	Percent
Flow	12
General	1
Level	80
Pressure	5
Temperature	1

Table 5 - Instrument failure distribution

From this table it is clear that the most common instrument to have a problem is the level measuring instrument(s). OREDA also states that failures regarding instruments accounts for almost 60 % of the total recorded failures.

As earlier described a separator of this size contains large amounts of hydrocarbons that should stay inside the separator at all times. Inside the separators these hydrocarbons are warm and pressurized; any leaks may therefore lead to disaster. The second most common critical failure mode is external leakage of the process medium, and this account for 8 % of the total recorded failures.

2.2.4 Failure causes

Most failures related to separators originate inside the separator. This means that they are undetectable by traditional visual inspection unless the separator is shut down. The inside of a separator contains numerous part already described. All these internal parts may fall /break off and thereby significantly reduce the performance of the separator. All these internals are fixed to the separator wall and may therefore induce fatigue problems to the wall or other mechanical problems. The internal wall itself may corrode or erode. Erosion will typically be a problem if there is large sand production, sand production will typically change during the lifetime and thereby change the erosion problem. Large sand production will also increase the risk of being plugged or chocked. If the sand production is large sand may enter the gas demister and continue into other part of the system. In addition to the internal wall corrosion the external wall may of course also corrode. This is easy to detect if the separator has no isolation, if a separator has isolation it is not possible to detect external corrosion visually without removing the isolation.

2.2.5 Effect of failure

The effect of failures is usually described in a qualitative manner in an FMECA analysis, grouped into categories as shown in Table 4**.** For the further use of the FMECA analysis in a cost-benefit analysis it is necessary to also have a quantitative assessment of the effects of the different failure modes. The average effect of the different failure modes has been obtained using engineering judgment and is shown in Table 6. These assessments are used as a basis for the qualitative assessment scheme used to get the overall criticality.

Failure mode	Spill [m3]	Deaths	Injuries	Downtime [hrs]
Critical				
Abnormal instrument reading	5	0,2	0,5	12
External leakage process medium	40	0,2	1	48
Plugged / Choked	5	0,2	0,5	48
Degraded				
Abnormal instrument reading	0	0,1	0,2	12
External leakage process medium	10	0,1	0,5	24
Plugged / Choked	5	0,1	0,2	24
Incipient				
Abnormal instrument reading	0	0	0	0
External leakage process medium	1	0	0	12
Parameter deviation	0	0	0	1
Plugged / Choked	0	0	0	12

Table 6 - Average quantitative failure effect

2.2.6 FMECA result

The outcome of the FMECA analysis is presented in Figure 4. The color coding reflects the limit set in Table 3, green is ok, yellow is just below the limit and red signifies an unacceptable high criticality. As seen in Figure 4 there are four failure modes with an unacceptable high criticality and several failure modes that are just below the limit. Even though most failure modes are below the set criticality limit this does not mean that nothing should be done to improve their criticality. The criticality of these failure modes below the limit should be lowered to a level "as low as reasonably practicable" (ALARP). The ALARP principle states that a safety or risk reducing measure should be implemented unless there is a large difference in the cost of implementation and the expected benefits. This is illustrated in Figure 3 and is assessed in a cost-benefit analysis in chapter 8.

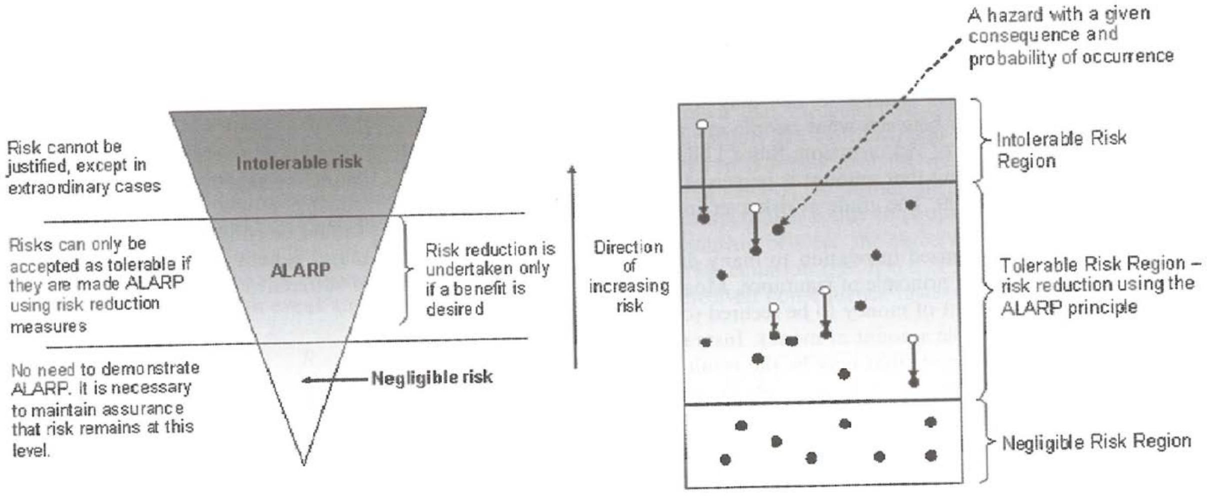


Figure 3 - ALARP principle (Kristiansen, 2004)

Failure mode effect and criticality analysis

Function: Separate oil/gas/water

Equipment: Separator

Failure mode	Failure Cause or mechanism	Failure rate [per 10^6 Hr]	Effect on system	Resulting state	Criticality		
					Safety	Environment	Production
Abnormal instrument reading	Instrument / sensor failure	14,03	critical	Shutdown	5	4	5
External leakage	Corrosion /Erosion	9,55	critical	Shutdown	4	4	4
Plugged / choked	Improper design / Excessive sand and scale	4,05	critical	Shutdown	4	3	4
Abnormal instrument reading	Instrument / sensor failure	24,96	degraded	Degraded	3	4	4
External leakage	Corrosion / Erosion	15,61	degraded	Shutdown	4	4	5
Plugged / choked	Improper design / Excessive sand and scale	29,68	degraded	Degraded	3	4	5
Abnormal instrument reading	Instrument / sensor failure	252,3	incipient	Degraded	4	4	4
External leakage	Corrosion / Erosion	23,71	incipient	Degraded	3	4	4
Parameter deviation		21,26	incipient	Degraded	3	3	3
Plugged / choked	Improper design / Excessive sand and scale	15,42	incipient	Degraded	3	3	4

Figure 4 - FMECA result

3 CM and non-intrusive inspection of separators

Currently most separators are subject to periodic inspection to determine their internal condition. Inspection may give a good insight in the condition at the inspection, but the condition at any other time is however unknown. Most failures are related to the internal conditions of the separator, and do therefore require either an inspection or equipment capable of monitoring inside the separator during operation.

There is no simple solution to the condition monitoring or inspection dilemma. No method will detect all failures, so a combination of methods may be the optimal solution. To decide which method or combination of methods to implement a thorough cost-benefit analysis is required. A good cost-benefit analysis requires good knowledge of the alternatives and their possibilities. The major condition monitoring possibilities will be introduced here with comments. A cost-benefit analysis assessing the methods presented here is presented in chapter 8.

3.1 Neutron backscatter

Neutron backscatter uses a sealed radioactive source next to a detector. Fast neutrons are emitted, passes through the separator wall and into the separator. Inside the separator the fast neutrons interact with hydrogen and some neutrons are reflected back as slow neutrons. The reflection is measured by the detector. This method measures the level of hydrogen presence. Since oil, water and gas have different level of hydrogen their individual level can be measured by changing the position of the instrument. This can be done manually or by mounting the instrument on a rail making the process fully automated. This method is mainly suitable for level measurement and has a limited scanning depth. Accurate readings are only obtainable within 10 to 13 cm (Scanning Technologies, 2007). It is therefore recommended that the total thickness of the wall and other objects separating the scanning equipment from the process fluids should be limited to maximum 7.5 cm. This limitation is a major inconvenience when it comes to large scale oil and gas separators. These separators operate under considerable pressure and are often fire insulated making the total wall thickness more than 7.5 cm. Strips of the fire insulation may be removed for testing (Baird, 2010), this makes periodic manual testing possible for these separators. The cost of each individual test will however increase, and automation will not be possible.

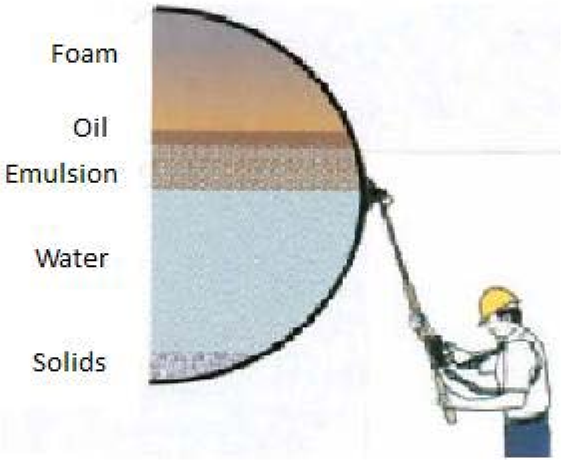


Figure 5 - Neutron backscatter (Thunem, 2007)

3.2 Acoustic monitoring

There are two different types of acoustic monitoring, passive and active. Passive monitoring is based on pure listening, while active is based on sending out sound and listening for the result. A basic method of passive acoustic monitoring is to listen for sounds using your own ear. If a machine makes more sound or new sounds something has happened. A well known example of active acoustic monitoring is active sonar. Active sonar sends out a sound (well known “ping” from submarines in movies) and waits for the reflected sound. Changes in the reflection will indicate changes in the equipment. Ultrasonic monitoring is a type of active acoustic monitoring.

3.2.1 Passive monitoring

Passive acoustic monitoring can be defined as vibration monitoring of higher frequencies, typically frequencies above 25 kHz (Hunt, 2006). Several processes and transients send out vibrations in the high frequencies. Among the conditions detectable described in (Hunt, 2006) changes in flow conditions are the relevant one for separators. Laboratory tests confirm that it is possible to detect sand, loose objects and objects falling down (Brurok, 2009). According to (Hou, Hunt, & Williams, 1998) passive acoustic monitoring is well suited for monitoring flow conditions in a hydro cyclone. During tests it was possible to detect inlet pressure, solid concentration and mass flow rate with usable accuracy. This means that passive acoustic monitoring of the inlet of a separator will give useful information about the current process conditions. If the sensors are placed externally background noise must be filtered out or accounted for. Test carried out at Herøya in 2004 and 2005 confirms that externally mounted sensors are well suited to detect changes in flow and changes in the internal conditions. Interpretation of the acoustic data may however be a challenge. (Thunem, 2007)

Passive acoustic monitoring is in use today on the oil and gas industry for several tasks, among them is valve monitoring. One example of this is V-Maps system delivered by Score Group which detects valve leaks by listening for the acoustic emission of a leak. The severity of the leak is automatically assessed based on the acoustic emissions.

3.2.2 Ultrasonic monitoring

Ultrasonic monitoring is commercially in use for numerous applications today. Most of the use today is inspection based; an inspector manually scans the part. There are several different types of ultrasonic testing in use, and they are under continuous development. Two methods of interest for separator monitoring will be briefly introduced here.

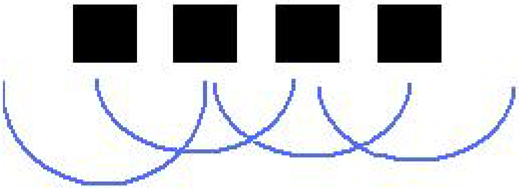


Figure 6 - Phased array ultrasonic's

Phased Array Ultrasonic (PA) has several applications in NDT (Non-Destructive Testing) of steel and also in medicine. The most common use in medicine is to picture the heart. PA utilizes an array of ultrasonic transducers that act coordinated after predetermined patterns. When the transducers act coordinated it is possible to detect a large amount of failures previously undetectable by ultrasonic testing. PA can detect loss of material, discontinuity of material and change of acoustic response of material (caused by degradation process). PA requires a clean surface to work, and it is only able to test the area where the transducer is located. These drawbacks make automation of the method hard.(Skogstrand, 2008)

Long Range Ultrasonic testing (LRUT) is a new and revolutionary method for piping inspection. LRUT manages to scan 60 meters of pipe under typical condition from a single transducer position; under ideal condition up to 350 meters is possible(Plant Integrity Ltd, 2009). This capacity makes LRUT suitable for constant automated monitoring. LRUT technology was originally developed for piping inspection, but recent research confirms that there is no problem applying the technology to vessels (Kleiner, et al., 2005). This contradicts the recommendations given by DNV in (DNV, 2007). LRUT should therefore be applicable to separator monitoring. LRUT differs from traditional ultrasonic testing by transmitting the waves along the component, not through it. This is done by attaching a ring (Figure 7) around the component with the transducers. These rings are commercially available in several sizes, and with the possibility of connecting several rings to create one larger size is not a problem. For piping inspection the largest cost may in certain cases be getting access to the pipe that is buried underground. The LRUT ring assembly is therefore in commercial use sometimes permanently fixed to the pipe and buried underground. This is useful for separators where the LRUT ring assembly could be placed permanently under the fire insulation.

Figure 7 - Long range ultrasonic testing equipment (Scanning Technologies, 2007)

3.3 Gamma monitoring

Gamma monitoring is based on the physical fact that different materials absorb gamma radiation at different levels; different phases of the same material do also absorb radiation at different levels. Utilizing these properties gamma radiation measurements can detect the level of gas/foam in the separator, as well as the presence of metal objects. When the wall thickness is known it can be accounted for and thereby provide the average density of the internal process medium.

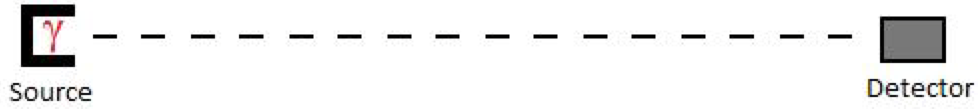


Figure 8 - Gamma monitoring

To measure gamma absorbance both a source of gamma radiation and a detector is needed (Figure 8). The source and detector has to be properly aligned to accurately measure the radiation. The source and detector are placed on opposite sides of the separator scanning through it. Both the source and detector are shielded with lead to prevent an increase in background radiation and keep the results accurate. Gamma scanning is normally not affected by the wall of insulation and is not limited by the same limitations in range as neutron backscatter measurements. The result of a gamma scan is an average density value of the scanned area. Changes of the internal conditions will result in a change in density and will thereby be detected (Scanning Technologies, 2007).

Using a single source placed below a separator it is only possible to detect the liquid level accurately for a large production separator. Using multiple sources and detectors it is possible to accurately detect the level of oil / gas /water / sand and the presence of metal objects. Further extending this thought it is also possible to detect the lack of metal equipment. This will make it possible to detect if internals have been damaged or are out of position. Laboratory tests confirm that gamma scanning of the separator floor is well suited for detection of sand/scale, missing parts and foreign objects (Brurok, 2009). Gamma monitoring is well suited for automation and the equipment is widely commercially available. (Thunem, 2007)

One major concern with gamma monitoring is the introduction of radioactive sources. These sources may become a serious hazard in an emergency situation. If the source and detector is placed inside the separator to measure the internal conditions the radiation level needed is low, and the risk of radioactive injuries are kept low. If the source and detector are placed externally a much higher level of radiation is needed. Permission from The Norwegian Radiation Protection Authority will definitively be needed; the risk of injuries related to radioactivity in an emergency will be present (Thunem, CORD-TT and CORD-SEP: Condition monitoring of Production Separators, 2007).

3.4 Microwave monitoring

Microwaves are per definition electromagnetic waves. The definition of the microwave band is not standardized in literature, IEC standard 60050 (IEC, 2009) and IEEE standard 100 (IEEE, 2000) defines it as 1 GHz and upwards while (Barton & Leonov, 1998) defines it as 3 – 300 GHz. This is a wide definition including several frequency bands in use today, like UHF and SHF used for TV, cell phones, radar, WLAN and numerous other services. The wide use of electromagnetic waves in the microwave spectra makes the definition of microwave based monitoring wide.

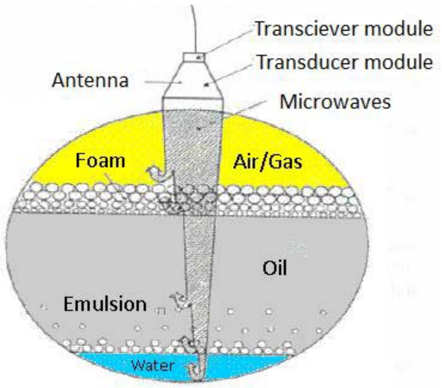


Figure 9 - Microwave monitoring (Thunem, 2007)

SINTEF Telecom and Informatics performed lab tests in the early 1990s investigating the use of microwaves in separators. They proved that microwaves can be used to detect the interfaces between gas, oil and foam using commercially available tank measuring equipment. Microwaves were also able to penetrate through the oil and reflect of the bottom (Thunem, 2007). This proves that microwaves can be used to detect the levels inside the separator, and thereby detect possible instrument failures.

Except for HF and VHF radar frequency bands all other radar frequencies fall within the microwave frequency spectra. Radar technology has widespread use and is well developed, and is still under development. (Edgcombe, 2008) discusses the recent advances in through wall radar sensing and progress in this area is being made as the cost of signal processing equipment is declining. These radars can see through 40 cm of reinforced concrete, the possibilities of seeing through solid steel is not directly discussed. With the discussion of other materials it is however reasonable to assume that the radar should be placed internally. These antennas will be able to produce a 3D image of the internals of the separator. This method would be able to detect if equipment is present or not, as well as the level of sand in the separator. It will not be able to give a more detailed assessment of the internal equipment.

3.5 IR Thermometry

IR thermometry utilizes the fact that all objects with a temperature above 0 Kelvin emit radiation in the infrared specter. Thermal cameras detecting this heat radiation is widely commercially available and is used for numerous tasks. Among the tasks related to separator monitoring is other sorts of process monitoring like vessel level monitoring and vessel degradation monitoring.

IR thermometry can be used to detect the level of solids in a separator. Stationary solids will usually loose more heat to the surroundings than fluids. During typical operating conditions the temperature of the solids are 30° C while the temperature of the gas/liquid phase is 85° C (Thunem, 2007). Cracks, corrosion, erosion and other damages to the wall of the vessel will show up on an IR image provided that it is possible to create thermal contrast by changing the temperature of the object. Modern thermal cameras have sensitivity better than 80 mK which makes it possible to detect internal levels without removing the insulation. Internals directly attached to the separator wall are extra isolators and will be detectable from the outside. This requires that the internals are directly attached without insulation to the wall, and will only give information about the presence of the internals. (Holme, 2010)

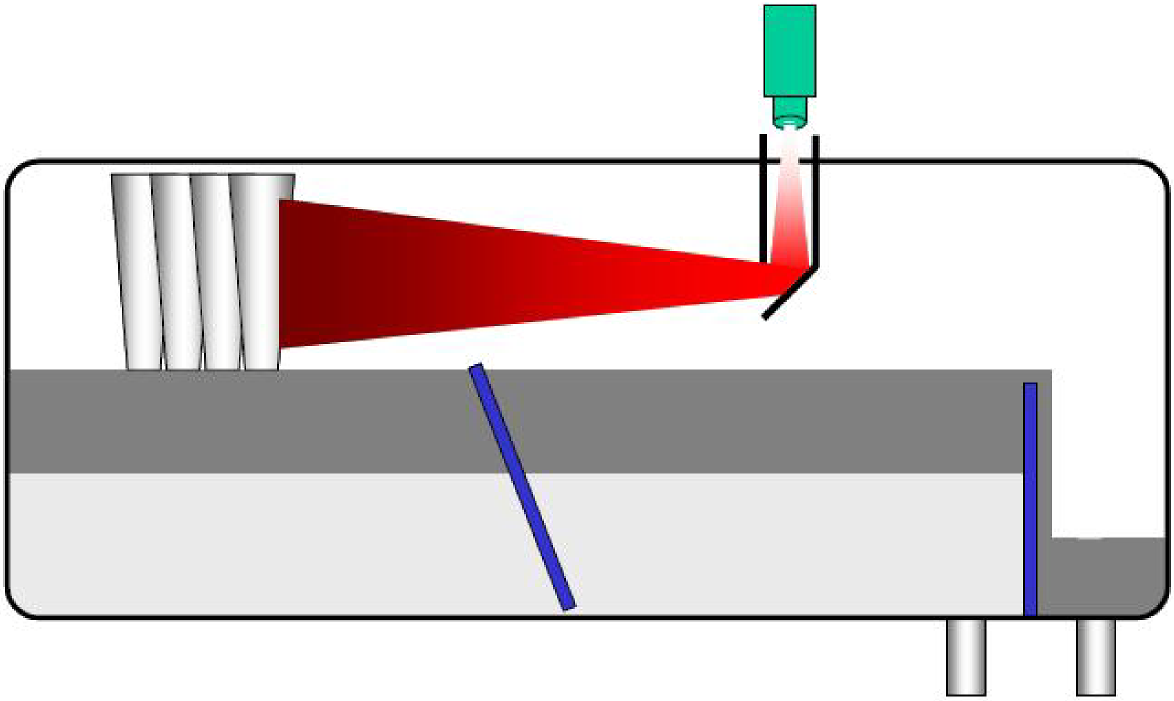


Figure 10 - IR thermometry possibilities (Thunem, 2007)

Positioning the IR sensor so it can see directly at the internals will make it possible to detect changes in the condition of these elements. This can be done by putting the sensor internally or by putting it externally as shown in Figure 10. Detection of the condition of the internals by mounting the sensor as shown will require modification to the separator; this is not required for any other use of IR technology. For automation purposes some sort of modification to the surroundings is necessary; the sensor requires power and has to be mounted to something. The amount of modification depends on the current infrastructure surrounding the separator.

3.6 CM methods overview

An overview of the detection capabilities of the methods described is given in Table 7. The failures described here are typical failure descriptions found in research reports and articles. Unfortunately these descriptions are not used in failure statistics, at least not in public failure statistics. For the further use in this thesis the failure detection capabilities are an interpretation of the description of the different methods adapted to the selected monitoring solutions. This is further presented in chapter 9.1.

	Neutron Backscatter	Passive acoustic	Ultrasonic	Gamma	Microwave	IR
Internals presence detection		X		X		X
Internals condition		x				x
Wall defects			X	X		X
Level measurement	X			X	X	X
Foam detection	X			X	X	

Table 7 - CM overview

4 Presentation of CM data

After having collected information about the current condition of equipment it is important to utilize this data in the best way possible. Collection, processing and analyzing data is expensive, efficient utilization is vital to maximize the overall plant profit. To utilize the data efficiently it is important to remember who actually needs the information, and what information do they require.

Information about the current condition of equipment is ultimately required by decision makers to aid in the decision making process. In this process detailed knowledge is not necessarily desirable, information like “corrosion level is at 50 % of the allowed level” is better than a complete table of all corrosion measurements in millimeters. With an ever growing amount of information available aggregating this data up to a useful level is becoming more and more important. Automating the process is vital to reduce man-hour need and improve efficiency.

4.1 Presentation today

Several of the condition monitoring methods presented here is used today as tools for periodic inspections. The inspection interval is often long, resulting in a small amount of data. The inspection data is presented in reports from the inspection campaign and stored in an inspection database for historic analysis and trending. The results from the inspection are manually compared to the performance standard set in SAP or other enterprise resource planning software. If the performance standard is not met a notification is raised and further action is taken. (Grønseth, 2010)

Today’s presentation of condition data for the methods presented here requires a substantial amount of labor. For a limited amount of inspection data this is an adequate solution, but with the implementation of more monitoring methods other solutions should be assessed. Automated online monitoring solutions may create large amounts of data every day, as a comparison the inspection interval of production separators may be up to 12 years. Today data is aggregated up to a useful level for decision makers in reports that are made manually. Manual processing of data will always involve the risk of human error, and with a larger amount of data to process the probability of having a human error will increase.

4.2 Future improvements

With an increasing amount of condition data available something must be done to limit the amount of labor put in to the analysis and aggregation of data. The data collected must be readily available to persons needing it, this also includes external experts.

When the data is collected it should be aggregated up to a usable level without human interaction. Ideally the system should be capable of filtering out information and only present the significant information to decision makers. This will greatly reduce the workload for decision makers whilst still keeping a good overview of the overall system condition. An example of a system doing this is the ECAM (Electronic Centralized Aircraft Monitoring) system in use in all newer Airbus aircrafts. The system monitors all aircraft systems and alerts the decision makers (the pilots) about any abnormalities and suggests further actions to correct this,

```
ENG DUAL FAILURE
-ENG MODE SEL.......IGN
-THR LEVERS........IDLE
OPTIMUM RELIGHT SPD.280
-FAC 1......OFF THEN ON
.IF NO RELIGHT AFTER 30S
-ENG MASTERS.OFF 30S/ON
```

Figure 11 – ECAM (Bachian, 2009)

as illustrated in Figure 11 where the red text describes the failure and the blue text describes the actions required. The system also shows the new aircraft limitations with the failures. ECAM automatically classes the failures by importance from level 1 to level 3, in event of several failures the most important is presented first. The ECAM system uses different warnings for the different levels like flashing light and warning tone.(Winglet Media, 2010) For a condition monitoring system this may be replaced by automated e-mails, text-messages and phone calls. The implementation of automatic aggregation and presentation of information has significantly contributed to a reduced workload for the crew of modern aircrafts. Where old aircrafts required a crew of 3 new aircrafts only require a crew of 2. The simplification of the work environment is illustrated in Figure 12 showing the difference between the old Boeing 707 and the newer Airbus A340. Both aircrafts are large long-range commercial passenger aircrafts with 4 engines. The goal of future improvements to the presentation of condition monitoring data must be to achieve the same level of simplification and reduction in workload.

Figure 12 - Airbus A340 vs. Boeing 707 cockpit (AviationExplorer.com)(Flicr.com)

To create a fully automated system like the ECAM system it is necessary to have a completely automated data gathering system. This is not always economically feasible, or necessary from and operational point of view. Failures involving a separator is often less time-critical than failures involving a passenger aircraft in-flight. To decide if the data should be collected automatically or with human interaction a cost-benefit analysis must be performed. If a solution involving manual collection of data is selected possibilities of using a data collector similar to the ones used for vibration measurements should be explored. The data collector will collect and store the data until it is connected to the condition monitoring system where it will upload the data. The data will then be treated in the same way as the automatically collected data.

Once the data is collected, analyzed and assessed by the system it is important that the data it is available to those needing it. This is not limited to decision makers or in-house experts; it should be easy to give access to external resources like manufacturers and vendors. To ease the process both with respect to internal and external resources, all information should be gathered in one common system. The common system should be web-based and not have any computer requirements other than a standard web-browser and internet access.

5 Technical Condition Indexing

Technical condition indexing (TCI) is a method that aims to collect all relevant data about the condition of an item or a system and use it to quantify the overall condition. The definition of TCI is given as the degree of degradation relative to design condition (Nystad & Rasmussen, Prognostics of Technical Condition Index for an aging repairable system, 2006). This gives decision makers an easy overview of the current condition without having to analyze any data, or understand how the system works on a detailed level. This can be used for several applications, in the oil industry and in other areas.

With an increasing amount of data and knowledge available from increasing amounts of condition monitoring systems it is becoming more and more important to utilize this data in the best way possible. The TCI process is done as a hierarchy starting with establishing the low level subcomponents TCI based on measurements or other knowledge about the condition. Using already established rules and guidelines the TCI's of the subcomponents are combined into the TCI's of components which in turn is combined into the overall unit TCI. Using a numerical TCI scale this can be programmed into a computer and immediately show the change in condition.

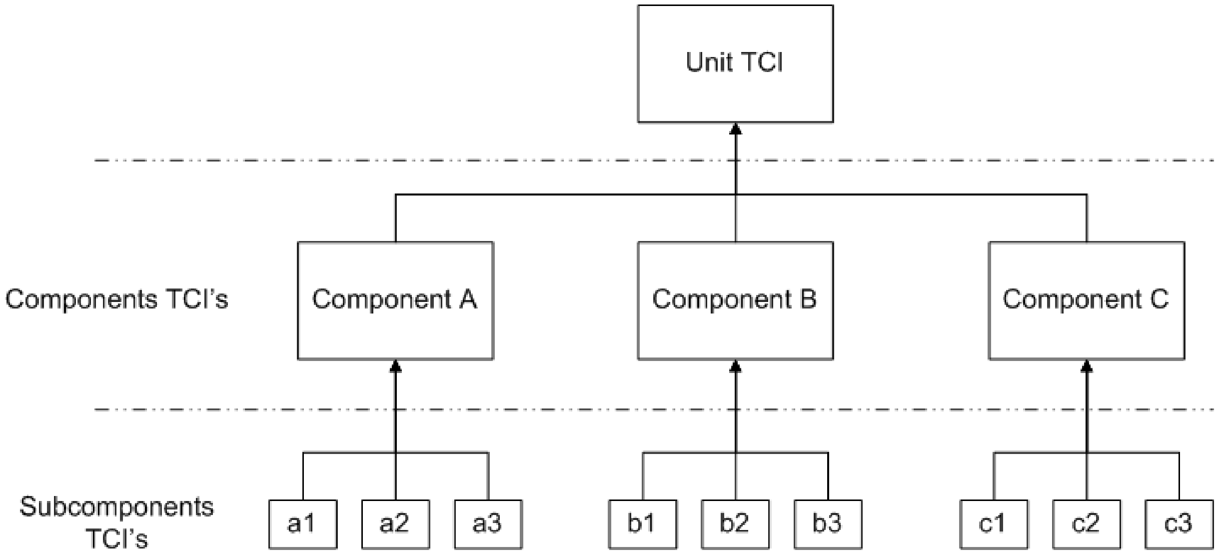
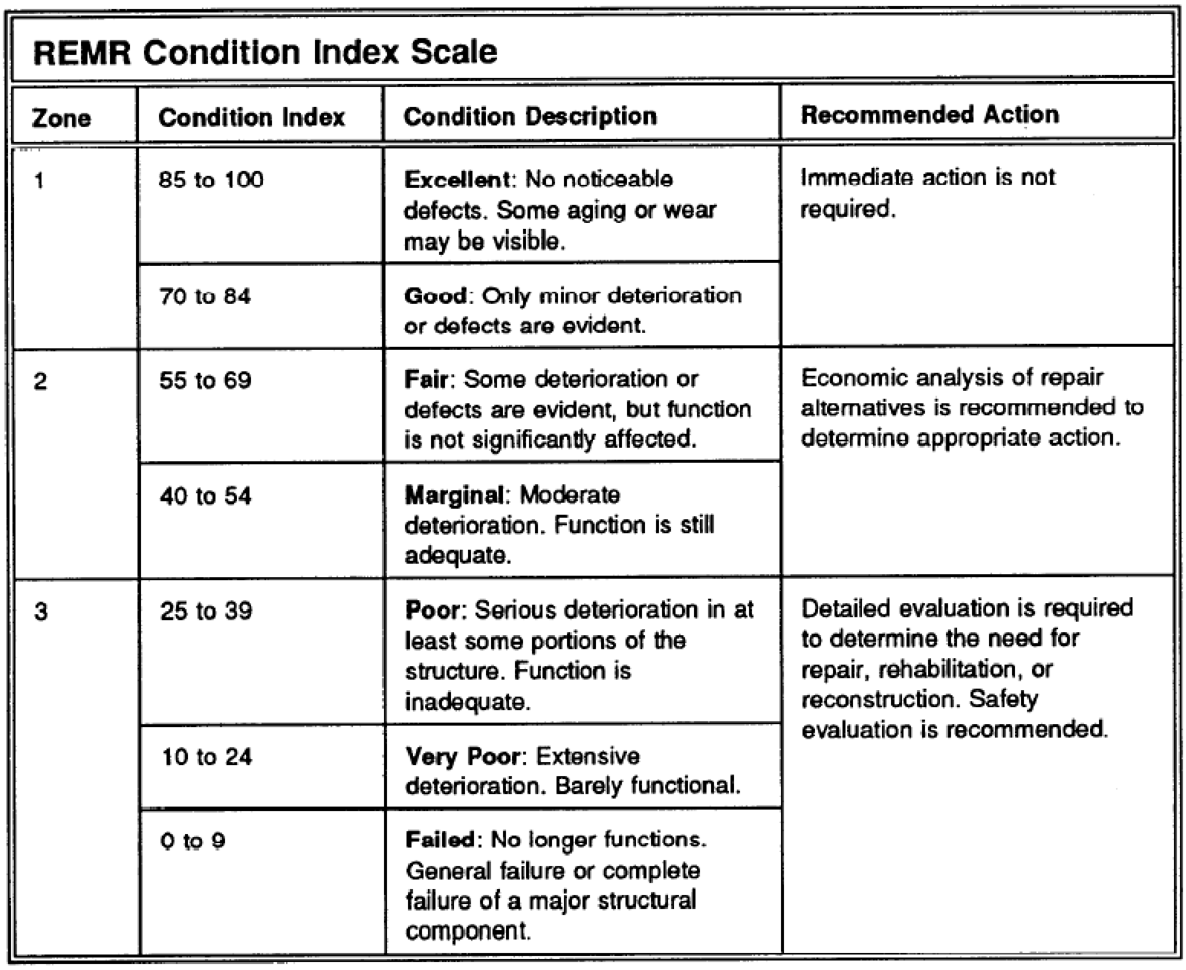


Figure 13 - TCI Hierarchy

5.1 REMR CI Scale

The Repair, Evaluation, Maintenance and Rehabilitation (REMR) research program was performed by the U.S. Army Corps of Engineers from 1984 to 1998 to extend the life of ageing U.S. infrastructure. Among the subjects investigated during this research program was the definition of a condition index (CI) scale.

The REMR CI scale ranges from 0 to 100 where 0 indicates complete failure and 100 indicates perfect condition. The scale is further divided into three “action” zones as shown and described in Figure 14**.** Although this program was aimed at infrastructure in the U.S. the CI scale created gives valuable insight into the details of a condition index scale. The scale may be used as it is, or be modified to better suit the offshore environment.(US Army Corps of Engineers, 1996)



REMR Condition Index Scale

Zone	Condition Index	Condition Description	Recommended Action
1	85 to 100	**Excellent**: No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 to 84	**Good**: Only minor deterioration or defects are evident.	
2	55 to 69	**Fair**: Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 to 54	**Marginal**: Moderate deterioration. Function is still adequate.	
3	25 to 39	**Poor**: Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
	10 to 24	**Very Poor**: Extensive deterioration. Barely functional.	
	0 to 9	**Failed**: No longer functions. General failure or complete failure of a major structural component.	

Figure 14 - REMR CI scale

5.2 Transforming information into TCI

To calculate the overall TCI it is necessary to start at the lowest component level where information about the condition exists. This information must then be transformed into the TCI of the subcomponent using either a transfer function or a set of rules. The information may come from several sources, examples includes: condition monitoring data, notifications and process data.

5.2.1 Transfer function

An example of a transfer function is given in Figure 15. This fictional example is for the wall of a vessel with an original wall thickness of 35 mm and a corrosion allowance of 5 mm. In this example the transfer function is linear, in real life this may not always be the case. Transfer functions are ideal for automatically collected data where the function is defined in the computer system and the TCI is automatically calculated. Using already set alarm limits as a basis for creating the transfer function most of the work involved is already done.

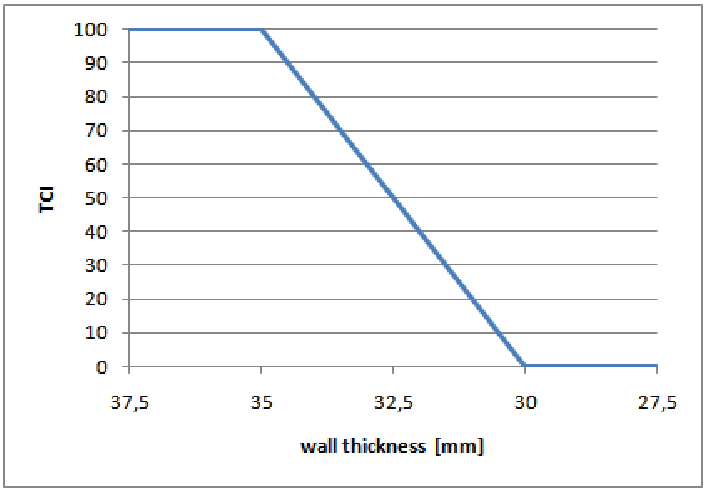


Figure 15 - TCI transfer function

5.2.2 Non-quantitative measurements

Some information about the condition of equipment is qualitative. To increase the accuracy of the TCI it is desirable to also include this information in the assessment. This can be done manually by categorizing the current condition according to predetermined guidelines; an example is given in Table 8. The accuracy of these inputs relies on the accuracy of the personnel and that the personnel share a common understanding of the definitions.

External corrosion	TCI
None	100
Minor	90
Major	60
Unacceptable	10

Table 8 - TCI transfer table

5.2.3 Combining measurements

When a single subcomponent has several different measurements these measurements are all taken into account when calculating the subcomponents TCI. The different TCI's are weighted according to their importance. There are several formulas in use to calculate the combined TCI. These formulas are applicable both for combining several measurements and for aggregating the TCI of several subcomponents into the TCI of a higher level component. Examples of formulas in use are (Nystad, 2008) :

1. Weighted sum: $TCI = 100 - \sum_{i=1}^{n}(100 - TCI_i) * w_i , \sum_{i=1}^{n} w_i = 1$
2. Penalty aggregation: (similar to the weighted sum, but the sum of the weights is permitted to be different from 1. If the calculated TCI is less than zero it is set equal to zero.
$$TCI = 100 - \sum_{i=1}^{n}(100 - TCI_i) * w_i , \sum_{i=1}^{n} w_i \neq 1$$
3. Worst case: $TCI = MIN_{i=1}^{n} TCI_i$

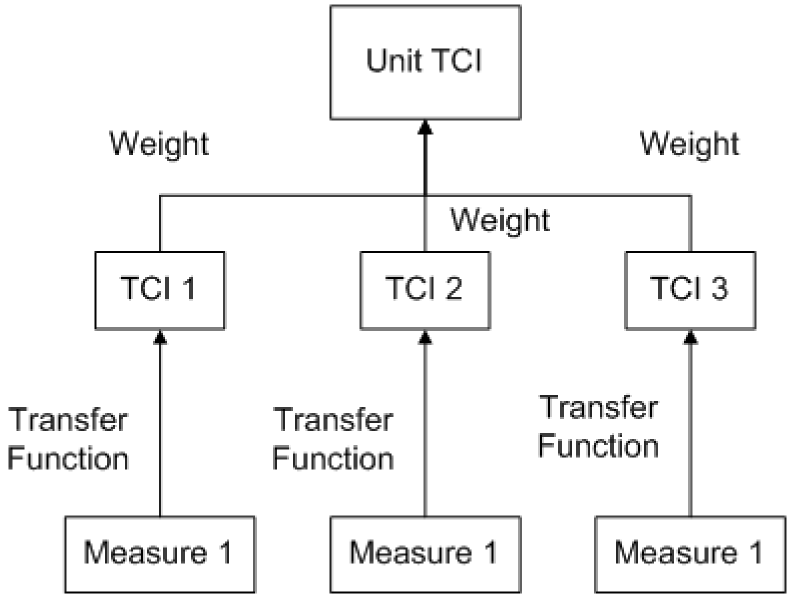


Figure 16 - Aggregation of TCI

5.3 Separator TCI hierarchy

A general separator TCI hierarchy is presented in Figure 17. It includes all the investigated condition monitoring methods and shows how they can be utilized to calculate an overall TCI. This TCI does not include any weighting of the individual measurements or failures. The TCI divides the separator into four major function areas that are further subdivided and aims to include all relevant knowledge available to create the best overall TCI possible. A TCI hierarchy covering the best condition monitoring methods according to the cost-benefit analysis is further presented in chapter 6.

The hierarchy presented here is equipment focused. It will show the TCI of the individual components and aggregate it up to the overall equipment TCI. There are other ways to look at the technical condition of a system or parts of a system. It is for example possible to create a performance focused hierarchy that combines information about efficiency and degradation to calculate the overall equipment performance. For the production separator analyzed here it is believed that the equipment focused hierarchy will yield the most relevant information to decision makers and planners.

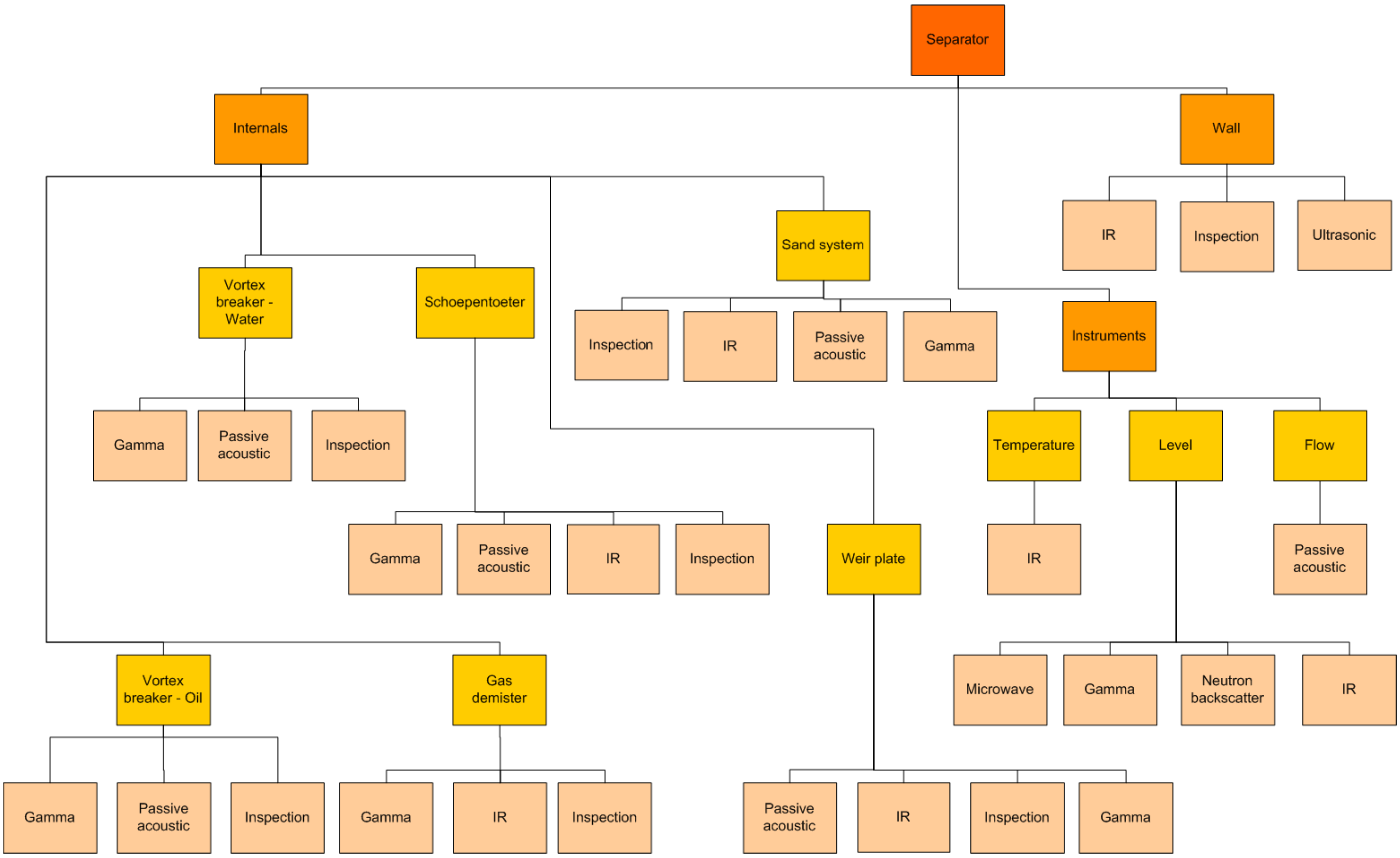
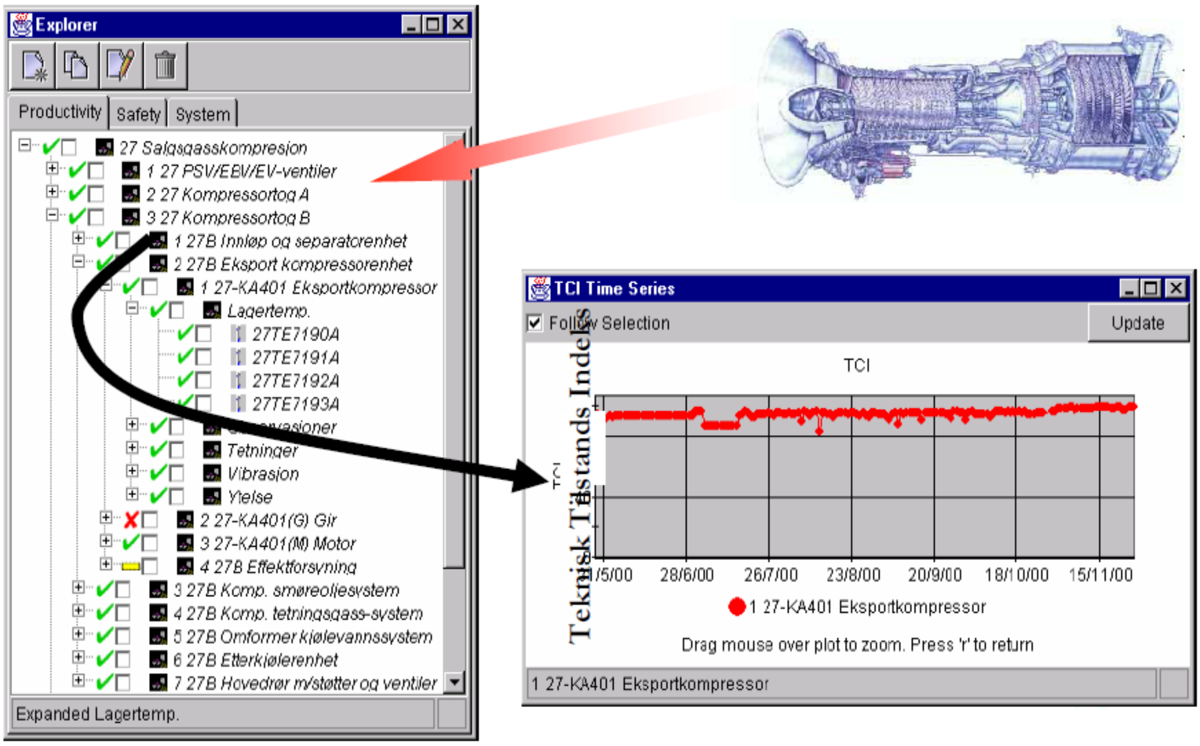


Figure 17 - TCI hierarchy for separator

5.4 Presentation to decision makers

Once the data is collected and the TCI hierarchy is complete it is important to present the findings in an easily understandable way to decision makers. This can be done by color-coding the different equipment after their condition. The REMR CI scale (Figure 14) has three main zones, using this as a reference and applying traffic light colors anyone is immediately able to recognize the condition and focus on problem areas. For a more detailed overview a graph showing the TCI development over time could be produced. It is important that the presentation highlights the problem areas and gives easy access to the individual subcomponents in the hierarchy. All of this is done in the TeCoMan software developed in cooperation between Marintek, Statoil and Forsmark Kraftgrupp AB, shown in Figure 18. This software is further presented using the separator as a case in chapter 6.



- ✓ ☐ 27 Salgsgasskompresjon
  - ✓ ☐ 1 27 PSV/EBV/EV-ventiler
  - ✓ ☐ 2 27 Kompressortog A
  - ✓ ☐ 3 27 Kompressortog B
    - ✓ ☐ 1 27B Innløp og separatorenhet
    - ✓ ☐ 2 27B Eksport kompressorenhet
      - ✓ ☐ 1 27-KA401 Eksportkompressor
        - ✓ ☐ Lagertemp.
          - ✓ ☐ 27TE7190A
          - ✓ ☐ 27TE7191A
          - ✓ ☐ 27TE7192A
          - ✓ ☐ 27TE7193A
        - ✓ ☐ Observasjoner
        - ✓ ☐ Tetninger
        - ✓ ☐ Vibrasjon
        - ✓ ☐ Ytelse
      - ✗ ☐ 2 27-KA401(G) Gir
      - ✓ ☐ 3 27-KA401(M) Motor
      - ☐ 4 27B Effektforsyning
    - ✓ ☐ 3 27B Komp. smøreoljesystem
    - ✓ ☐ 4 27B Komp. tetningsgass-system
    - ✓ ☐ 5 27B Omformer kjølevannssystem
    - ✓ ☐ 6 27B Etterkjølerenhet
    - ✓ ☐ 7 27B Hovedrør m/støtter og ventiler

Expanded Lagertemp.

Figure 18 - TCI presentation in TeCoMan (Technoport, 2007)

6 Separator TCI in TeCoMan

The TeCoMan software package consists of several components as shown in Figure 19. The software package is an example of a modern way of automatic aggregation of condition monitoring data up to a useful level for decision makers with easy access and effective presentation. An example of how the case separator may be implemented in the TeCoMan package is given here along with examples of how the information will be presented to decision makers.

The TeCoMan application transfers the measurements into TCI's and stores them in the TeCoMan database. The TeCoCalc application can calculate relevant parameters based on information from TeCoMan application and server, and send it back to it. The TeCoView applet is a java applet that presents the information stored in the TeCoMan database to the end user. This applet can present the information on the internet or on the company intranet depending on the configuration. Being a java applet it is platform independent.

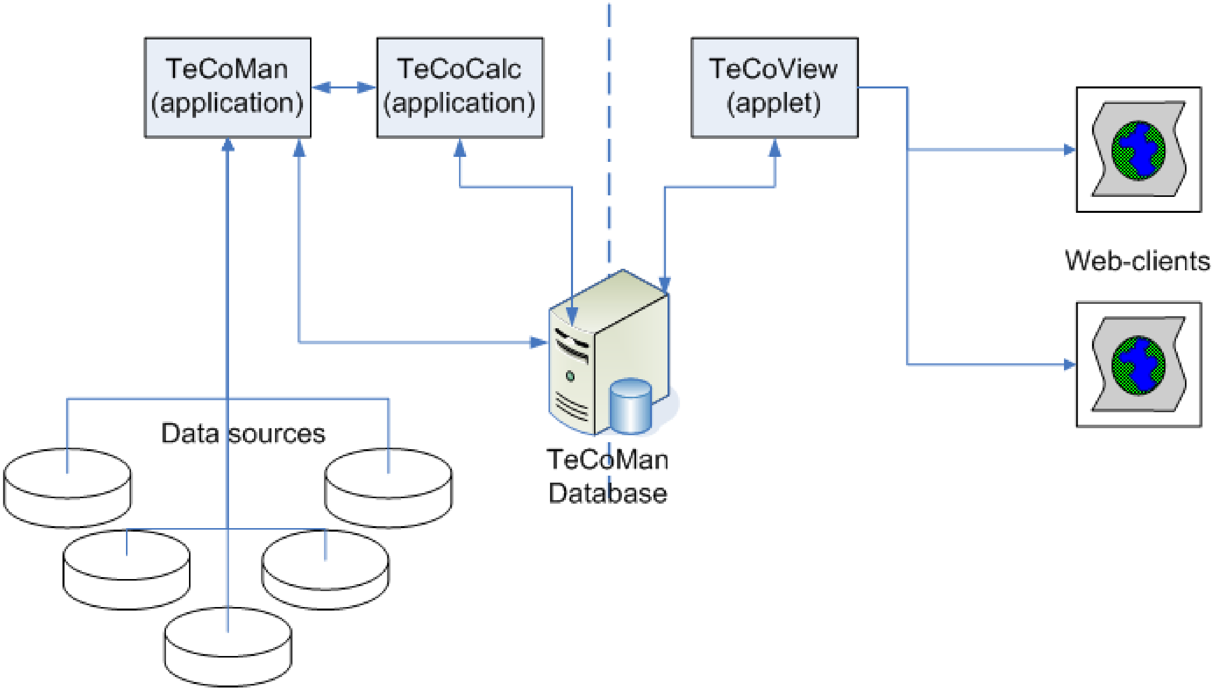


Figure 19 - TeCoMan software package

6.1 Importing data

Data can be gathered from numerous sources commonly used in the industry like SAP and PI. Other formats include xml and csv files in addition to data from various databases. This should ensure compatibility with existing condition monitoring solutions and make it possible to easily integrate TeCoMan. For the further use in this thesis a simple csv-file (comma separated value) has been used. An extract of this input file is shown in Appendix 1.

6.2 TCI Hierarchy

The hierarchy implemented in TeCoMan is presented in Figure 20. The resulting system hierarchy as seen in TeCoMan is presented in Figure 21. This hierarchy is complete with weighting of the individual components and aggregation methods. The condition monitoring equipment included is the best solution according to the cost-benefit analysis in chapter 9; a combination of IR and passive acoustic monitoring.

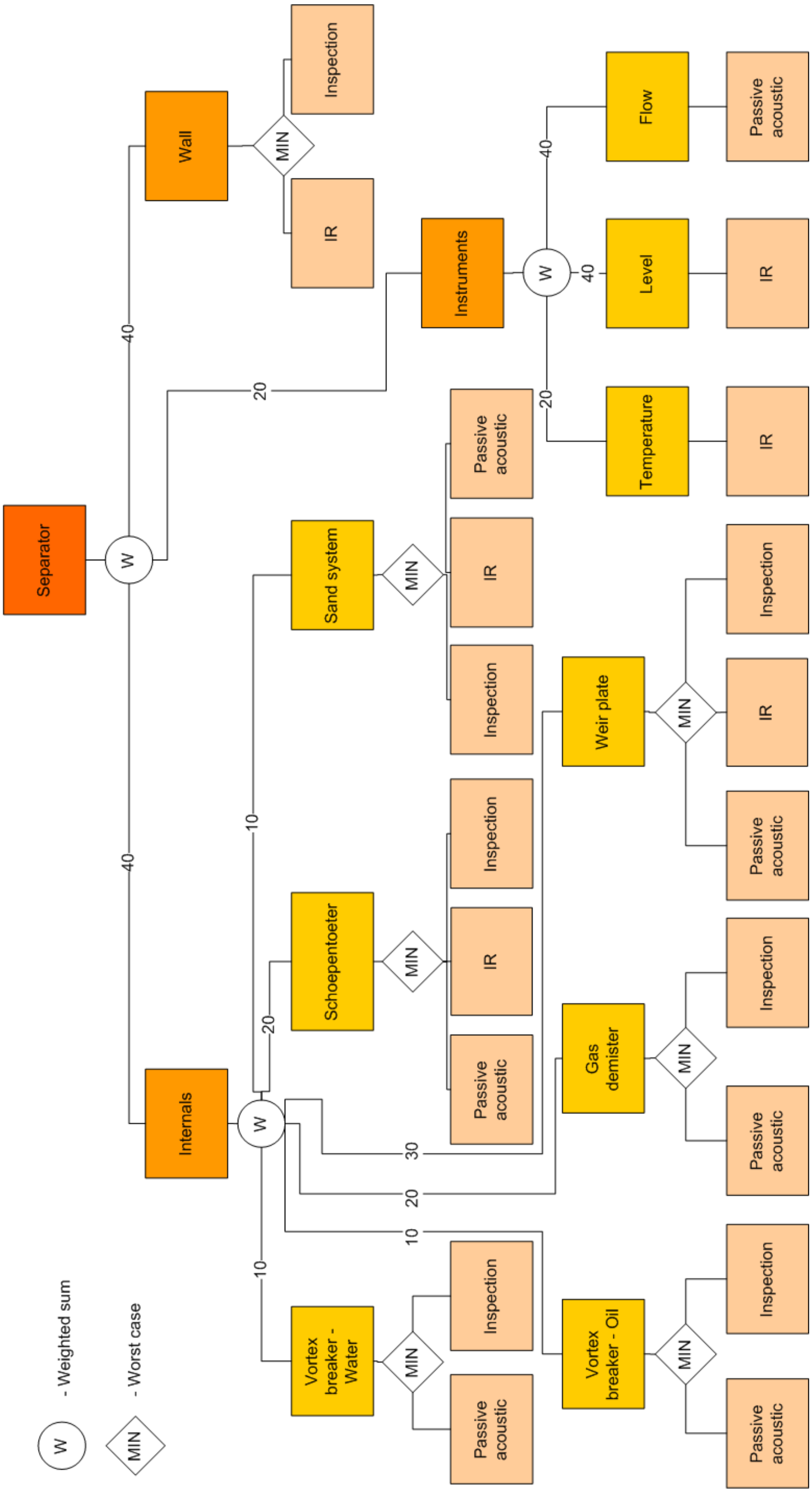
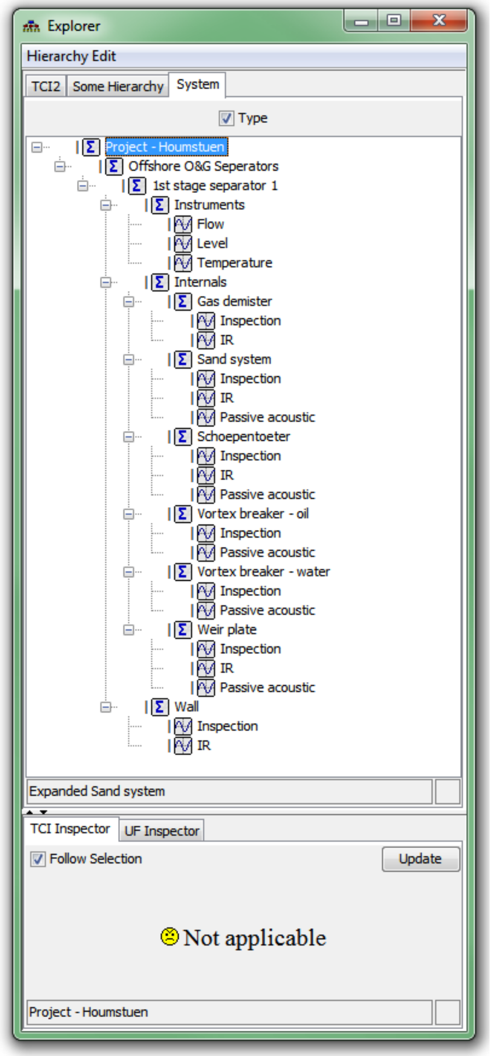


Figure 20 - TCI hierarchy for TeCoMan



- Project - Houmstuen
  - Offshore O&G Seperators
    - 1st stage separator 1
      - Instruments
        - Flow
        - Level
        - Temperature
      - Internals
        - Gas demister
          - Inspection
          - IR
        - Sand system
          - Inspection
          - IR
          - Passive acoustic
        - Schoepentoeter
          - Inspection
          - IR
          - Passive acoustic
        - Vortex breaker - oil
          - Inspection
          - Passive acoustic
        - Vortex breaker - water
          - Inspection
          - Passive acoustic
        - Weir plate
          - Inspection
          - IR
          - Passive acoustic
      - Wall
        - Inspection
        - IR

Expanded Sand system

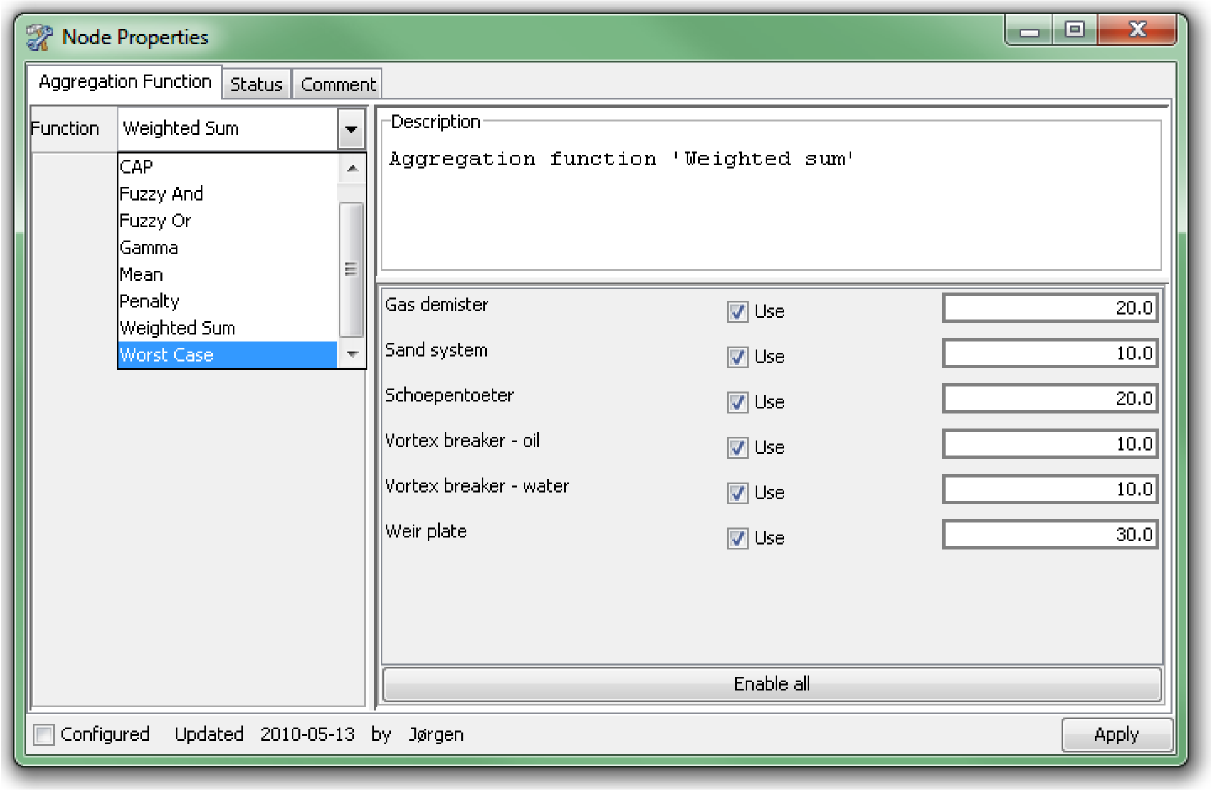
Not applicable

Project - Houmstuen

Figure 21 - System hierarchy in TeCoMan

6.3 Aggregation

The aggregation equations used in this thesis are the weighted sum and worst case equation. The worst case equation is used were several measurements are measuring specific item. Weighted sum is used to combine the TCI of different components into the TCI of a higher component in the hierarchy. TeCoMan offers a wide range of aggregation methods, and new methods may be implemented. It is also possible to only include selected measurements in the aggregation. When deciding which aggregation method that should be used it is important to make sure that a given TCI reduction at a low level is reflected in a correct way throughout the hierarchy.



Function: Weighted Sum

Description

`Aggregation function 'Weighted sum'`

Gas demister	☑ Use	20.0
Sand system	☑ Use	10.0
Schoepentoeter	☑ Use	20.0
Vortex breaker - oil	☑ Use	10.0
Vortex breaker - water	☑ Use	10.0
Weir plate	☑ Use	30.0

☐ Configured Updated 2010-05-13 by Jørgen

Figure 22 - TeCoMan aggregation

An example of how the same reduction of TCI at a low level may be aggregated to different higher level values is shown in Figure 23 where the weir plate inside the separator reaches a TCI of 0 from the IR measurement. With the original weighted sum aggregation the aggregated TCI of the internals is 70. With a gamma aggregation and a gamma value of 2.0 the aggregated TCI of the internals is 49. If the worst case aggregation had been used the internals TCI would be aggregated to 0. As shown the choice of aggregation method greatly influences the TCI. The selected aggregation method must be able to transform the change in low level TCI to a correct change in higher level TCI according to the selected TCI scale.

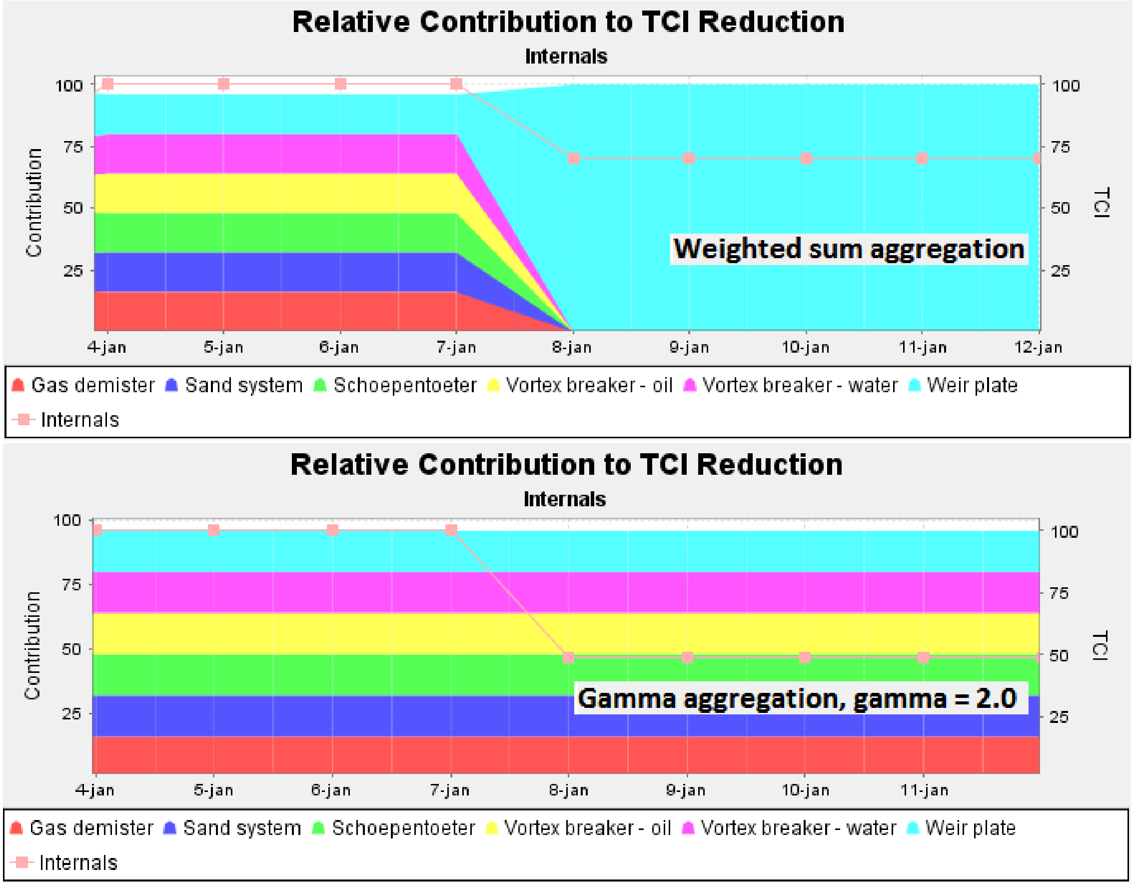


Figure 23 - Different aggregation methods

6.4 Weighting

For the aggregation of TCI using the weighted sum it is necessary to assign weights to the elements involved in the aggregation. The weights are shown in Figure 20 and are based on engineering judgment. The change of TCI at higher levels is obviously effected by the weight assigned, it is important to ensure that a critical failure at a low level results in an appropriate TCI at higher level.

6.5 Transfer functions

Two examples of the transfer functions implemented in TeCoMan are given here with the wall as a case. All other transfer functions are given in Appendix 2. TeCoMan offers a range of built in transfer functions in addition to the possibility of creating fully customized user functions.

6.5.1 IR

The transfer function is based on a corrosion allowance of 1 mm. The TCI reaches 0 at 2 mm degradation; it is assumed that the risk of wall rupture is unacceptable at this level. It is assumed that the IR software can convert measurements to wall loss in millimeters automatically based on knowledge about the process inside the separator and knowledge about the separator itself.

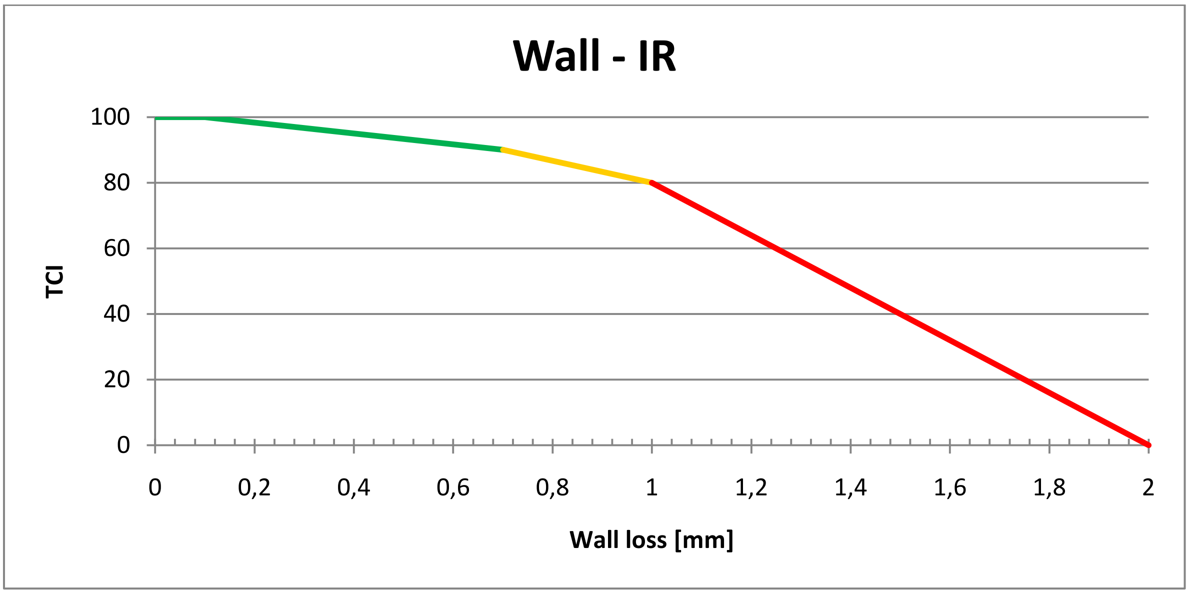


Figure 24 – Transfer function: wall - IR

6.5.2 Inspection

For the inspection of the separator wall it is assumed that only visual inspection is performed. The following descriptions should be used in the reports of the inspections. The quality of the input from inspections rely on the crew performing the inspection, particularly that they have a common understanding of the definitions in the table.

Signs of corrosion / erosion	TCI
Not visible	100
Barely visible	85
Clearly visible	50
Major	0

Table 9 - TeCoMan transfer function: wall - inspection

6.6 TeCoMan TCI Scale

TeCoMan uses a three-level TCI scale that is fully customizable, different components can have different scale definitions. The TCI scale has been defined equal for all components in this thesis with these definitions: 100-90 – green, 90-80 – yellow, below 80 – red. This is indicated in the transfer functions and reflected in the TCI reduction rate.

6.7 TeCoMan presentation to decision makers

The information generated by TeCoMan is presented to decision maker's trough the java-applet TeCoView. TeCoView offers the same full insight into all levels of the TCI as TeCoMan including transfer functions, aggregation and raw measurements, but is not able to make changes. If configured TeCoMan has the ability to automatically generate reports and send them by e-mail. These reports may contain both graphical presentation of the conditions and automated comments. The reports are fully customizable, the content and layout depends entirely upon the configuration. As a general guideline reports should contain only necessary information and as accurate comments as possible.

6.7.1 Graphical presentation

TeCoMan displays the hierarchy with color coding representing the calculated TCI and set TCI scale. The TCI and change in TCI can be displayed in several different ways highlighting contributing components and the change over time. This is shown in Figure 25 where the sand system is experiencing minor problems and the schoepentoeter is experiencing large problems. The same situation is covered by the hierarchy in Figure 26. Expanding the hierarchy it is easy to locate the source of the degradation of the separator. By selecting the components in the hierarchy it is possible to view the change in TCI over time as a table, in addition to different graphic representations.

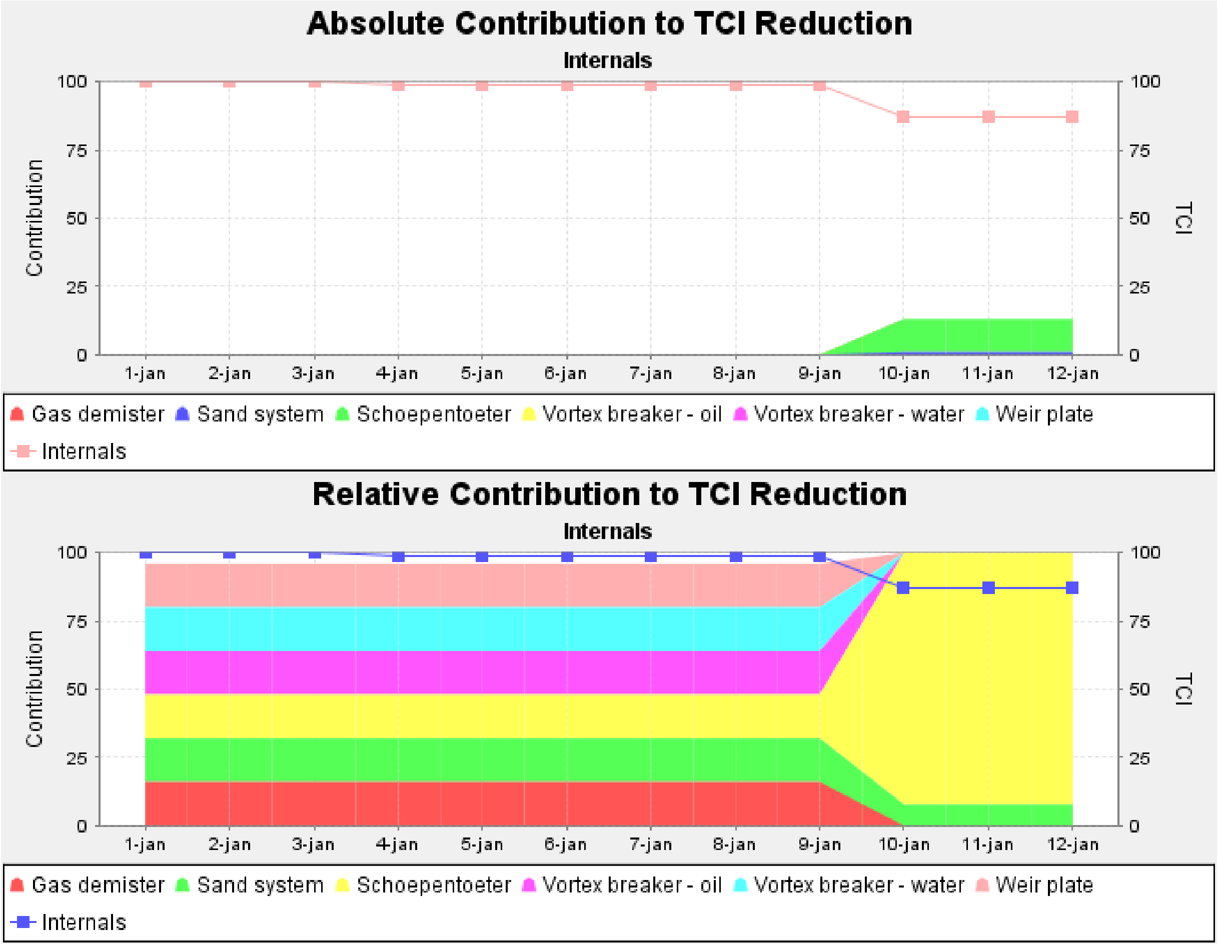
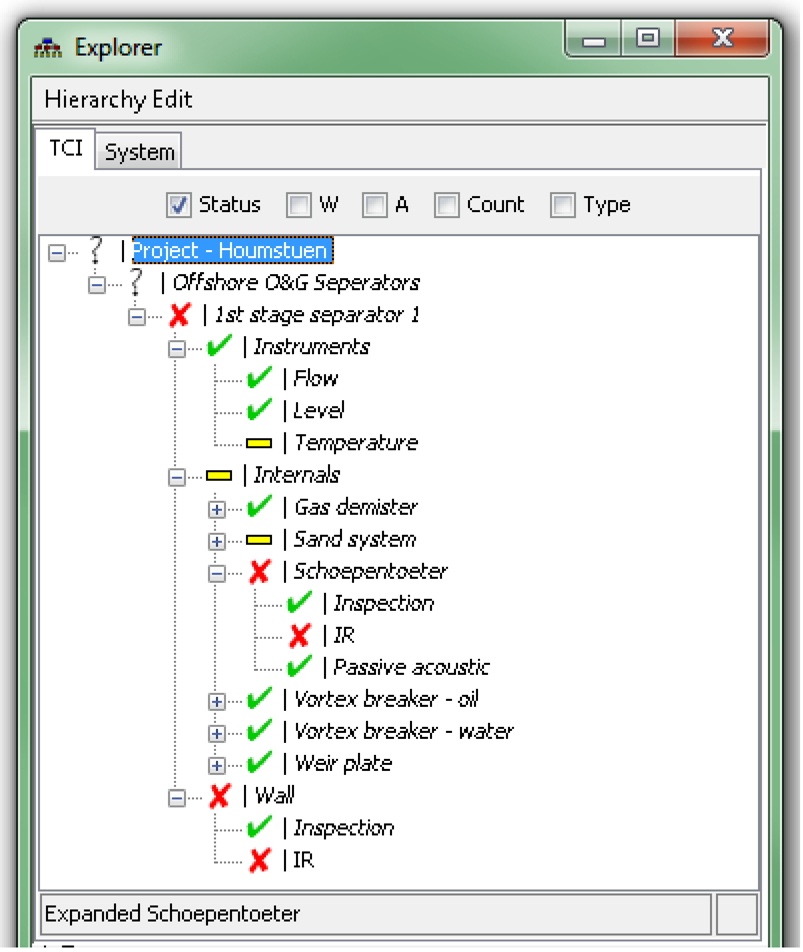


Figure 25 – TeCoMan TCI presentation



☑ Status ☐ W ☐ A ☐ Count ☐ Type

Expanded Schoepentoeter

Figure 26 – TeCoMan TCI hierarchy

6.7.2 Comments

If comments are implemented into TeCoMan they can be presented at an alarm or warning stage. An example of a comment shown when the specific fuel oil consumption of a main engine is too high is:

> *SFOC too high, possible causes:*
> - *Check relationship between max pressure (too low) and exhaust temperatures (too high)*
> - *Error in readings/instruments for: power, rpm, density, heat value or fuel flow volume*
> - *Check guidelines for main engine performance test*
> - *Fuel flow meter needs calibration, check date when last calibrated*
> - *Incorrect VIT settings*

These comments may serve as automated fault diagnostics, suggest further actions and identify new operational limits. An example of this is to lower the maximum allowed pressure for the separator in case of wall corrosion. This introduces the functionality of the ECAM system as discussed in chapter 4.2 and will reduce the probability of having an accident before the defect is corrected. New operational limits may also keep the separator operating until it can be repaired instead of shutting it down once the failure is detected. This may significantly lower the downtime associated with failures. Implementation of comments for different failures is time consuming and must be weighed against the benefit of the comments.

7 Life cycle cost

Life cycle costs (LCC) are all cost associated with a system, unit or other object for the whole duration of its life and creation (US Department of Energy, 1997). LCC is also referred to as Total Cost of Ownership (TCO) or Whole-life cost approach. LCC analysis for offshore projects commonly involves the following cost areas:

- Planning
- Procurement
- Installation
- Operation
- Decommissioning
- Scrapping
- Depreciation

These cost areas are further broken down into a cost breakdown structure (CBS) giving a more detailed overview of the costs involved. An example of a complete CBS is given in Figure 27.

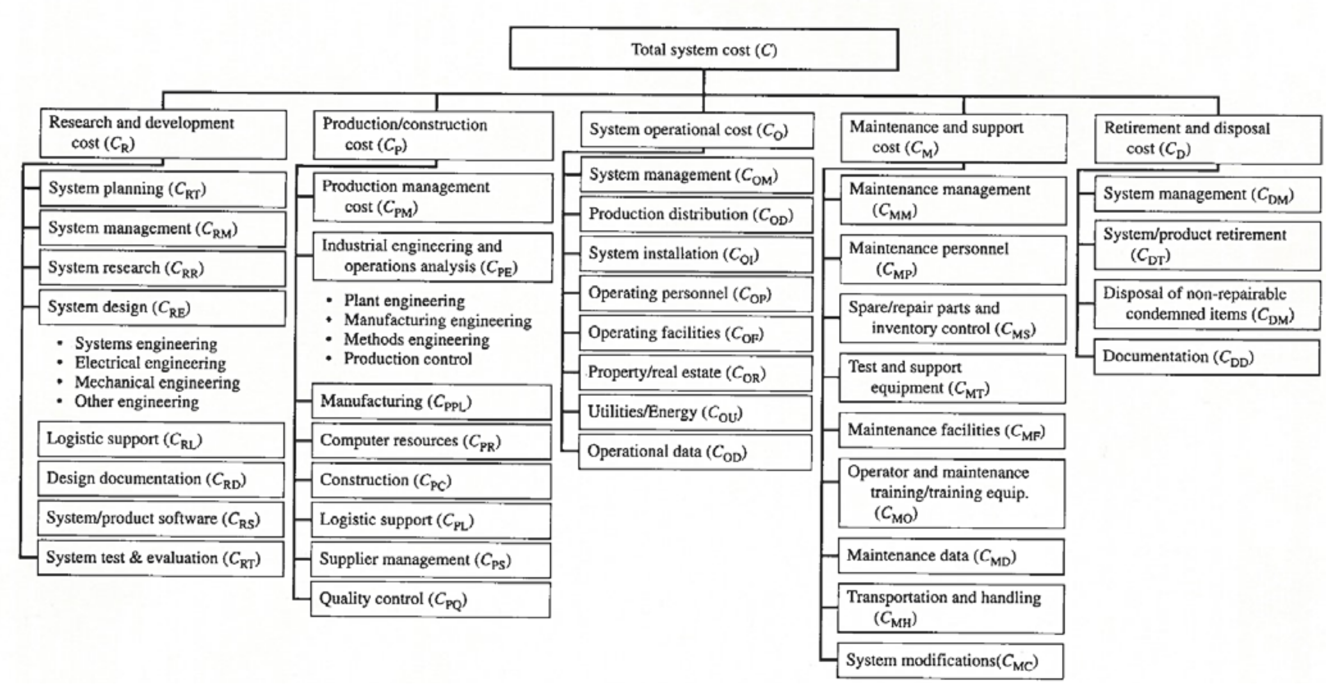


Figure 27 - Cost Breakdown Structure (Blanchard, Logistics Engineering and Management, 1998)

7.1 Common errors

LCC is a key factor in the decision making process of an oil and gas producing facility and it is therefore important to know the most common errors in LCC analysis so they can be avoided. (US Department of Energy, 1997) lists the following errors as the most common in LCC analysis:

- Omission of data
- Lack of a systematic structure or analysis
- Misinterpretation of data
- Wrong or misused estimating techniques

- A concentration of wrong or insignificant facts
- Failure to assess uncertainty
- Failure to check work
- Estimating the wrong items
- Using incorrect or inconsistent escalation data

7.2 LCC formula

There are numerous different LCC models that share the same goal of trying to estimate the total life cycle costs as accurately as possible. All of them can be described with the following formula: (Bai, 2001)

$$\begin{aligned}
&Total(NPV) = Capex(NPV) + Opex(NPV) + Riskex(NPV)\\
&Capex = The\ capital\ expenditure\ or\ initial\ investment\\
&Opex = The\ operational\ costs, both\ planned\ and\ unplanned\\
&Riskex = The\ risk\ expenditure\\
&NPV = Net\ Present\ Value
\end{aligned}$$

This is a common initial CBS covering all areas of interest. The different components of the formula are themselves a result of a large number of individual costs as described in a detailed CBS. The difference between the LCC models is how this equation is solved. The choice of model is important and one may opt to use several models for different costs. Available knowledge is often a decision maker. The knowledge varies with the current phase of the project, as illustrated in Figure 28 (Blanchard & Fabrycky, 1991).

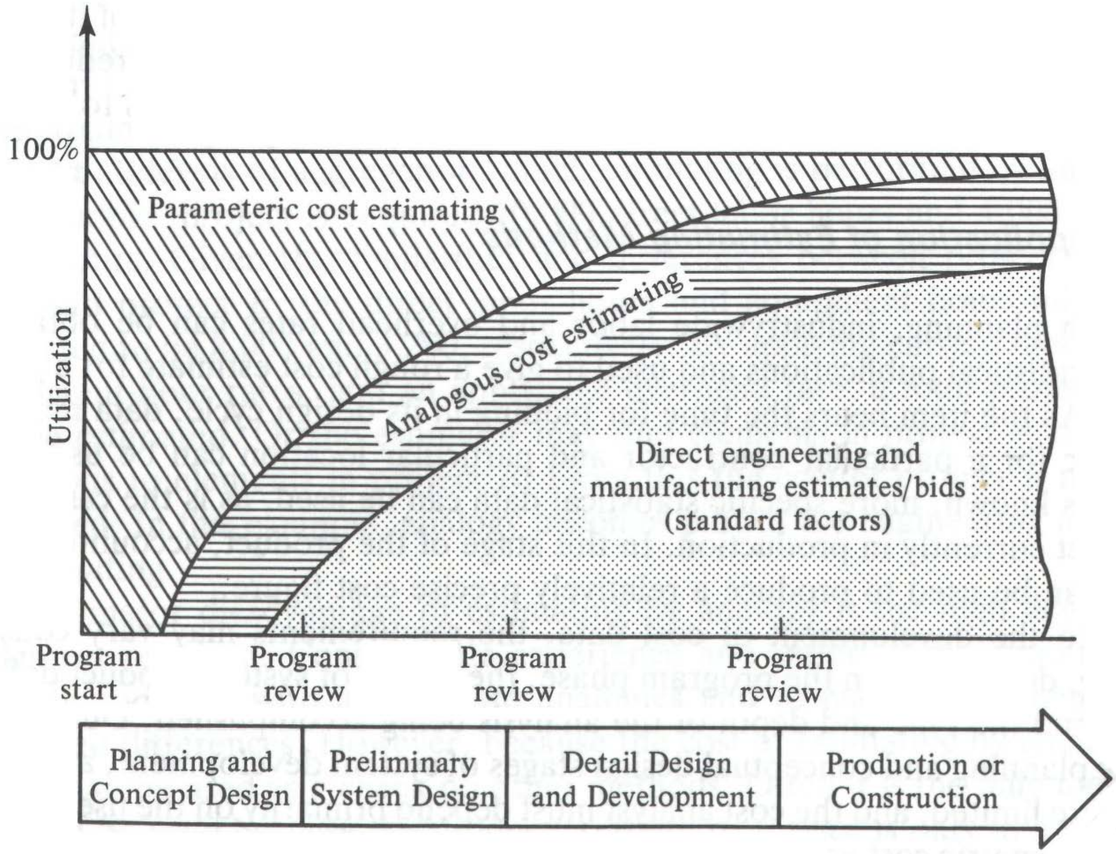


Figure 28 - Project phase vs. cost estimating model (Blanchard & Fabrycky, 1991)

7.2.1 Deterministic models

A deterministic approach to solving the LCC problem involves identifying and estimating all costs based on historic data and past events. There are several different deterministic methods in use, and one LCC analysis may utilize one or more of these for different costs.

7.2.1.1 Engineering procedures

Cost estimating by engineering procedures is a detailed estimate on a low-level. This requires a complete design and detailed knowledge about this design. Each component, task and need is specified and estimated in detail. Costs are specified at the lowest level and summed up to get the total cost. This requires a large work effort and a complete overview of every task involved. Tasks not known by the engineer will not be taken into account. Some tasks are factored in as a percentage of other tasks, for example rework is often added as a percentage of the total work estimated. This means that small errors created at a low level will result in a large error over all.

7.2.1.2 Analogy

If cost data for previous equal project does not exist it is possible to estimate by analogy. The cost of estimating by analogy is low, and can therefore be used to check estimates made by other methods. Aircraft companies bidding on missile programs in the 1950s used analogies between aircraft and missiles in their estimation. The estimates were adjusted for differences in size, engines and performance (Blanchard & Fabrycky, 1991). In shipbuilding estimating by analogy is widely used. A shipyard knows the approximate building cost of a hull based on the steel weight of the hull from previous builds. The estimation is adjusted for complexity, represented by the degree of single- and double-curved areas (Hagen, 2008).

A large drawback with the analogy estimates is the adjustments made to the estimate. These adjustments are based on the judgment of the analyst and greatly influence the outcome of the estimate. To make a good quality estimate by analogy a high degree of experience and knowledge is needed.

7.2.1.3 Parametric method

Parametric estimation uses functional relationships between changes in cost and changes of the cost driving factors. These functional relationships may be anything from graphical curve fitting to multiple correlation analysis. This may be done on a high level or on a more detailed level. For shipbuilding estimation it is possible to get an early price estimate knowing only the gross tonnage and type of vessel (Levander, 2006). For a more detailed estimate later in the project phase a more detailed parametric approach may be used. A more detailed parametric estimate will involve more parameters, for example engine size, speed, volume and so forth. This is based upon statistics and the quality of the estimate relies on the quality of the statistic used. An important pitfall that must be avoided is to include obsolete information; statistics for single-hull tankers is now obsolete since all new tankers must be double-hulled, using single-hull statistics for cost estimation will be a source of error.

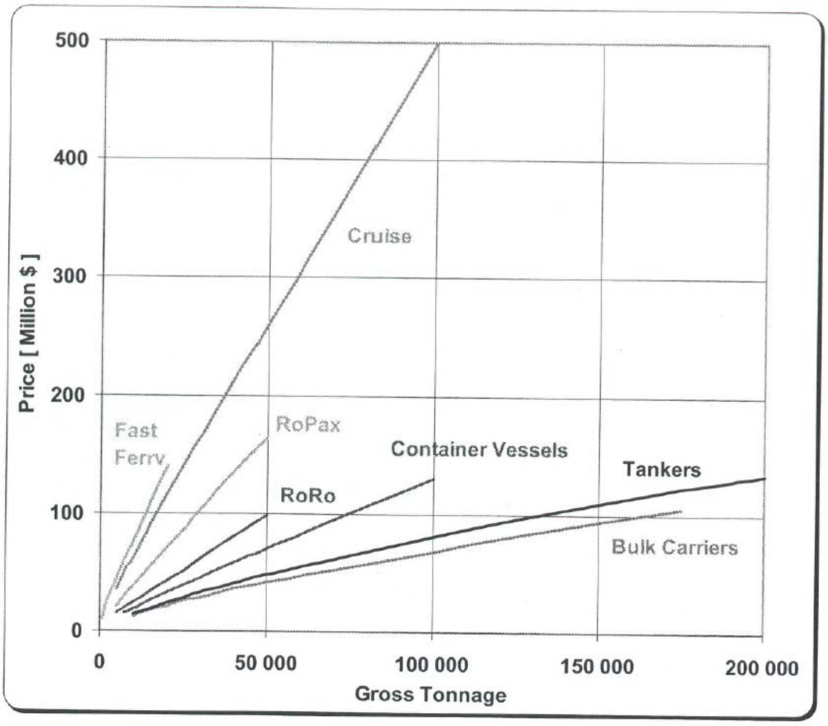


Figure 29 - Parametric ship cost estimation (Levander, 2006)

7.2.2 Probabilistic models

A probabilistic approach to solving the LCC problem identifies costs and develops a probability distribution for each cost using statistical data. The goal is to develop a cumulative distribution function (CDF) of the total LCC. The CDF can then be used to calculate the confidence interval for the LCC. This gives valuable input to decision makers, they can clearly see the probability of the project LCC being within the budget. All estimates are estimates, not a definitive number. It is easy to forget this fact, but providing a CDF makes it unforgettable.

To perform a probabilistic estimate it is necessary to provide a complete CDF for each cost that is considered to vary. Several costs in projects can be considered fixed or be estimated with sufficient accuracy to not influence the total outcome. These fixed costs are added to the CDF after the statistical analysis has been done to contribute to the overall CDF. Unfortunately several of the costs that vary are correlated; this means that the central limit theorem cannot be used to say that the overall CDF is normally distributed (Touran, Probabilistic Cost Estimating with Subjective Correlations, 1993). In addition to the distribution and parameters for each cost the correlation coefficients between the costs also has to be provided. Research with actual building cost data has shown that it is crucial to include correlation in simulations to get an accurate estimate of the variance. This research also shows that the best probability distribution for building costs in almost all cases is the lognormal distribution, followed by the beta distribution (Touran & Wiser, 1992).

If enough statistical data is available and this data is analyzed properly the outcome of a probabilistic cost estimate is a very good basis for LCC evaluation. The drawback of probabilistic estimation is the requirement of statistical data and the high amount of work involved with the analysis of this data.

7.3 Net Present Value

One dollar today is not worth the same as one dollar one year from today. Money earns interest over time while inflation decreases the purchasing power over time. To create a useful LCC analysis it is important to take this into account in the analysis. This is done by converting the value of future income and costs into the value of money today. The net present value (NPV) or net present worth of a future amount of cash is given as:

$$NPV = \frac{R_t}{(1+i)^t}$$

$$R_t = Amount\ of\ cash$$

$$t = time$$

$$i = interest\ rate$$

The interest used in this formula is the combined effect of interest and inflation per time unit. To combine interest and inflation the following formula is used:

$$i = \frac{1+p}{1+f} - 1$$

$$p = interest\ rate$$

$$f = inflation$$

This introduces the problem of estimating future interest rate and inflation. This decision is important and may contribute significantly to the outcome of an LCC analysis.

8 Cost-Benefit Model

In order to apply any changes to a commercially run facility the benefits of the change must outweigh the cost. The cost-benefit analysis aims to assess the overall economic result of a purposed investment and to compare different investment alternatives. Costs are calculated according to a chosen LCC model and compared to the benefits. The model developed here with assumptions and estimates is focused on evaluating condition monitoring methods for offshore oil and gas separators, but is applicable for other evaluations with minor modifications.

8.1 LCC Model

The LCC model presented here aims to include all major costs for a condition monitoring system for the entire lifetime. The individual costs are estimated using a deterministic approach. The details of the estimations are given for the individual costs.

8.1.1 Cost breakdown structure

The CBS used for the further analysis in this thesis is presented in Figure 30. Included in this CBS are the major cost drivers for implementation and operation of condition monitoring equipment, costs that have been assessed as minor and insignificant have been left out.

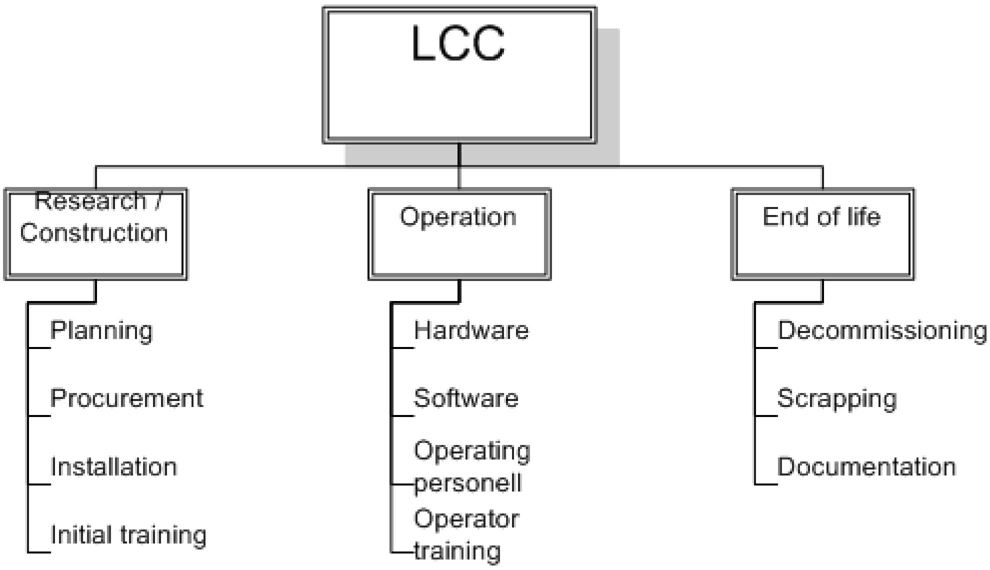


Figure 30 - CBS condition monitoring of separator

8.1.2 Research / Construction

The research and construction cost include all costs from the initial research into condition monitoring and up to the installation is finalized and the equipment is tested. This cost will include both labor and the procurement of equipment.

8.1.2.1 Planning

The planning costs include all cost from initial surveys, assessment of possible solutions and selection of a solution. Planning costs in this model is limited to the cost directly billed to the oil company. Vendors internal costs are not included if they are not specifically billed as planning costs. Planning cost also cover the cost associated with the planning of the installation.

Planning costs have been estimated as onshore man-hours. The amount varies with the individual methods, as a general guideline the following quantity of man-hours is used for further calculations in this thesis:

- 500 man-hours for well known non-radioactive technology
- 750 man-hours for less known non-radioactive technology
- 1000 man-hours for any technology containing radioactivity

The higher amount of planning for radioactive technologies reflects the extra cautions that have to be taken when introducing radioactive components.

8.1.2.2 Procurement

Procurement costs are the direct costs of procuring the selected condition monitoring system. The major procurement cost is the actual cost of the selected equipment and software. The software cost is estimated at 300 000 NOK for well known technologies. Signal cables and electric cables are covered under installation costs.

Procurement costs also include the logistic cost of getting the components to the installation site. Equipment is transported onshore to the supply-base. From the supply-base it is transported offshore with a supply vessel. It is assumed that the equipment is of limited size and weight and that it will be transported by an already scheduled supply vessel. The total logistic cost is assumed equal for all solutions and is estimated at 0.5 MNOK based on calculations in Appendix 3.

8.1.2.3 Installation

Installation costs includes all cost related to the installation of the equipment and necessary support infrastructure, except for planning which is covered under planning. This includes electrical and signal cables (if applicable) and the documentation of this infrastructure. Equipment not permanently mounted only requires brackets or other marking for the measurement point; it does not require any cables. It is assumed that the equipment being analyzed here is installed during an already planned shutdown of the platform if shutdown is required for the installation. No extra downtime costs are therefore included in the installation costs. Changing this will make a major impact to the installation cost.

A major installation cost for condition monitoring equipment is signal and power cables. This is only applicable for permanently installed solutions. For this thesis the overall cost of one cable is estimated at 200 000 NOK everything included, regardless of type. The use of cables can be limited by using wireless signal transmission and on-site energy generating units.

The cost of the initial configuring of the system is included in the installation cost. This cost is estimated at 0.5 MNOK for all condition monitoring methods.

8.1.2.4 Initial training

To be able to utilize the selected condition monitoring equipment it is important to ensure that the operators and analysts understand the possibilities and limitations from day 1. To achieve this it is necessary to have a comprehensive initial training program involving offshore operators and onshore analysts. The cost of this program will depend upon prior knowledge of the technology and software. IR imaging is frequently used to monitor electrical installations and will therefore require less training than a previously unknown technology like neutron backscatter. If the method is unknown and advanced it is necessary to send in-house analysts to external training facilities. The cost of courses at these specialized training facilities is high, but if they lead to a better understanding and use of the equipment the cost is justified. Online condition monitoring solutions will require less training than offline solutions because of the different number of personnel involved in the daily operation. The cost of training offshore crew is higher than onshore crew; the man hour cost is higher offshore and all three shifts must receive the training.

As a reference guideline for offline solutions the estimated number of training hours suggested by the Norwegian Association for Non-Destructive Testing is used (ndt.no, 2010). The estimation is given for level 1 and level 2 operators, per operator. For further use it is assumed that two members of each shift should be trained to level 2, meaning that a total of 6 offshore workers will receive the training.

8.1.3 Operation

The operational costs are all costs associated with the daily operation of the system as well as the maintenance costs. It includes costs for operating personnel and yearly training of personnel.

8.1.3.1 Software

Unless other information is available from suppliers of software the costs estimated in this model for software maintenance and enhancements per year will be a percentage of the software investment cost. (Solartron Instruments, 1994) suggest 25 % of the investment cost for yearly software related costs.

8.1.3.2 Hardware

Unless other information is available from suppliers of hardware the costs estimated in this model for hardware maintenance and enhancements per year will be a percentage of the hardware investment cost. As suggested in (Solartron Instruments, 1994) 10 % of the investment cost will be the estimate for yearly hardware related costs.

8.1.3.3 Operating personnel

Operating personnel includes costs for personnel involved with data collection, analysis, interpretation and management. The personnel cost for data collection will vary with the chosen data collection strategy, on-line measurements will not have any personnel cost for data collection while periodic offline measurements will have a cost directly related to the measurement interval. Data analysis cost and interpretation cost is assumed equal for all data regardless of monitoring method and collection strategy. Automated analysis and aggregation may greatly reduce these costs. Managing personnel will also contribute to the operating costs. For simplicity it is assumed that the managing costs of periodic offline measurements is twice as high as managing cost for online measurements because of the different labor requirement for data collection.

8.1.3.4 Operator training

Operator training is modeled as a continuous yearly cost because of the continuous changing in personnel during the life time of a unit experienced by most companies. Operators also require recurrency training to keep their knowledge up to date and to be updated on software changes during the lifetime of the equipment. The yearly cost of operator training is estimated as 20 % of the initial training cost.

8.1.4 Downtime cost

An important part in cost-benefit analysis for offshore equipment is the downtime cost. The downtime cost for oil and gas facilities is extremely high. For the downtime cost calculations in this thesis the following assumptions has been made:

- Downtime cost is limited to revenue loss due to decreased production
- Production is in the plateau period
- Production lost during the plateau period is regained at the end of the plateau period (in the first year)
- The oil and gas prices are constant for the whole production period

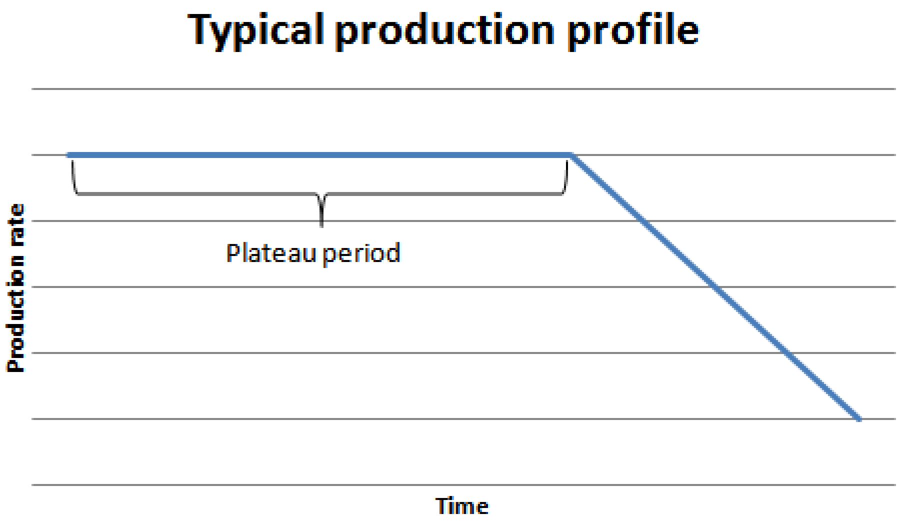


Figure 31 - Typical production profile

A formula for calculating the revenue loss associated with unplanned downtime and deferment of production over the lifetime of subsea equipment is given in (van der Vet & Rasmussen, 2004). Modifying the formula to only account for one incident the revenue loss can be stated as:

$$Revloss = \frac{PR * V}{(1+r)^t} - \frac{PR * V}{(1+r)^{m+1}}$$

$PR = Oil\ price$
$V = Volume\ of\ lost\ production$
$r = Interest\ rate$
$t = Time\ of\ production\ los$
$m = Remaining\ plateau\ time$

Expanding the equation to account for all losses during the reminder of the unit lifetime it becomes (van der Vet & Rasmussen, 2004):

$$Revloss = PR * \sum_{t=1}^{m} \frac{F(t) * V(t)}{(1+r)^t} - \frac{PR * \sum_{t=1}^{m} V(t)}{(1+r)^{m+1}}$$

$F(t) = probability\ of\ production\ loss$

For the years after the plateau period it is assumed that lost production is regained immediately after the downtime. This implies that downtime after the plateau period will not result in revenue loss. The exact same formula is used for the downtime cost related to loss of gas production with the lost volume and the price of gas. The prices and production rates used in this thesis is given in Table 10.

Oil production rate	50000	barrels/day
Gas production rate	300000	Sm^3/day
Gas price	0.5	USD / Sm^3
Oil price	50	USD / barrel

Table 10 - Production rates and prices for oil and gas

8.1.5 End of life

At the end of the life cycle all equipment needs to be decommissioned and scrapped. For the cost evaluations in this thesis it is assumed that all equipment will be scrapped at the end of life, the equipment has zero resale value. The end of life for the equipment is defined as the end of life for the platform. The logistic cost related to the transportation cost of the equipment at the end of life is considered to be substantially lower than the logistic cost at time of installation, the marginal cost of transporting the CM equipment at the end of life is small.

8.1.5.1 Decommissioning

Decommissioning costs are defined as the costs directly related to the removal of the condition monitoring equipment from service. This includes both the planning and physical removal and dismantling of the equipment. Large cost drivers for decommissioning costs are the presence of materials regulated by environmental regulations and the presence of radioactive materials. As an estimate the decommission cost is estimated equal for all monitoring solutions, except for those solutions containing radioactive materials. Costs for these solutions have been estimated as ten times as high.

8.1.5.2 Scrapping

Scrapping costs are all costs from the equipment have been removed from the facility until it has been disposed of. Scrapping costs depends on the quantity and type of material to be scrapped. Special care and consideration must be taken when disposing radioactive materials and other harmful materials, this will increase the cost. Materials not covered by environmental regulations today may be covered by regulations in the future; this has not been taken into account.

8.1.5.3 Documentation

The decommissioning and scrapping of condition monitoring equipment will involve the disposal of material controlled by various environmental regulations. This includes electronic equipment and for some technologies even radioactive parts. Considerations should be taken at the design stage to avoid the use of materials that will increase the scrapping cost. For all technologies not involving radioactive materials the documentation cost is estimated at 2 MNOK (Baird, 2010). For technologies involving radioactive materials the documentation cost will be significantly higher than for other methods, for this thesis it is estimated as ten times as high.

8.2 Benefits

A previously mentioned any changes to a commercially run facility has to be justified, the benefits has to outweigh the costs. To assess this it is necessary to quantify the benefits of implementation of new condition monitoring methods before they are installed. Accurately identify and assess all benefits in advance is a difficult task that requires good insight into the different technologies and experience with the equipment type. The main benefits of installing more condition monitoring equipment will be given a general presentation here with suggestions to how they may be quantified in a general matter for a separator. A pitfall that must be avoided is to count the same benefit twice.

8.2.1 Reduction of maintenance and inspections

When the actual condition is known at all times the maintenance schedule can be optimized to only include required maintenance. This means that the maintenance intervals on average will be longer while the number of corrective maintenance actions will decrease. The obvious benefit from this is the savings from unnecessary planned maintenance actions and reduction in downtime caused by corrective maintenance actions. With other preventive maintenance policies there is still some remaining useful life left in the equipment when maintenance is performed, condition monitoring makes it possible to use this otherwise wasted life.

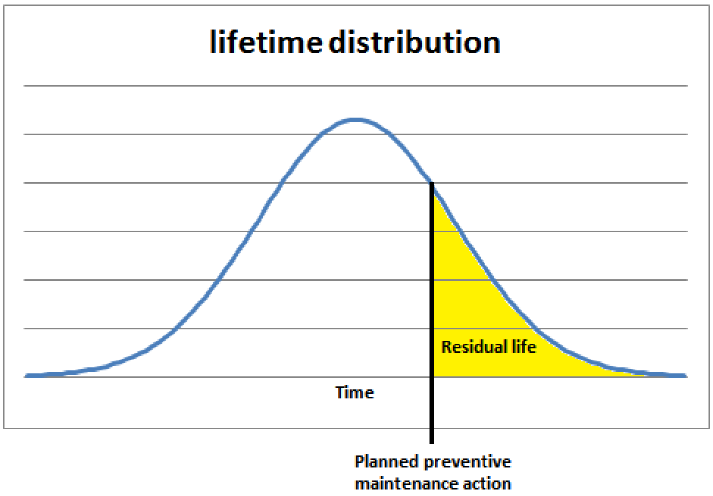


Figure 32 - Lifetime distribution

If the condition monitoring program is non-intrusive and believed to be of high enough quality inspections can be removed from the maintenance program all together. To get this benefit it is necessary to have a comprehensive condition monitoring program covering all aspects previously covered by inspections.

Maintenance and inspections often cause problems of its own. Equipment taken out for preventive maintenance may be worse off than before the maintenance action, common causes include (Rasmussen, 2002) :

- Faulty procedures
- Wrong adjustments
- Bad parts
- Damage done during maintenance action

For rotating equipment surveys have shown that 70 % of the failures are introduced by maintenance activities (Solartron Instruments, 1994). Inspections may also lead to damage and problems, not detecting faults or falsely identifying faults. Fewer maintenance and inspection actions without a decrease of condition knowledge are therefore beneficial. The separator investigated in this thesis undergoes only limited maintenance and inspection. It is constructed to last for the entire lifetime of the platform. Quantification of the reduced maintenance and inspection benefit has therefore been left out of this thesis. This benefit is largest if the lifetime of the platform is extended, condition monitoring will allow the separator to continue operation past its original design life.

8.2.2 Increased reliability and availability

Increased real-time knowledge about the current equipment condition makes it possible to maintain equipment before it fails. Periodic preventive maintenance is based on statistics and experience and will always include the risk of failure before maintenance. This risk is not completely removed by condition monitoring, there is always the probability of a failure developing undetected, but it is greatly reduced. The probability of a failure being detected in advance is either extracted from statistics or assumed using engineering judgment. Getting reliable statistics for condition monitoring methods is often hard, suppliers will often be optimistic and other companies are not sharing their knowledge. The probability of detecting a failure for the different methods is further discussed in chapter 9.1.

Availability is defined as the fraction of the total time the unit is operational. The availability will be affected by failures, maintenance actions and inspections requiring shutdown. All these factors should be reduced with a proper condition monitoring program. These elements induce several costs of their own, but the main cost at an oil and gas producing facility is the cost associated with downtime.

8.2.3 Reduced environmental risk

With fewer incidents and accidents the risk of environmental impact decreases. The benefit can be shown by performing an FMECA analysis for the system with and without the condition monitoring equipment being evaluated. To perform the analysis it is necessary to either know or estimate the impact of condition monitoring to the individual failure modes.

The environmental impact is caused by oil spills. The cost of an oil spill consists of several components, the major one is the cost of cleaning up the oil. The cost of cleaning up oil depends on several factors, among them are: type of oil, location, region, cleanup method and so forth. To estimate the cost of an oil spill at the Norwegian continental shelf a formula introduced in (Etkin, 2000) has been used:

$$\begin{aligned}
C_{li} &= r_i l_i C_N \\
C_{li} &= Cost\ per\ unit\ spilled \\
r_i &= regional\ modification\ modifier \\
l_i &= local\ location\ modifier \\
C_N &= C_n * modification\ factors \\
C_n &= general\ cost\ per\ unit\ spilled\ in\ nation
\end{aligned}$$

Unfortunately (Etkin, 2000) does not state r_i and l_i explicitly. It has therefore been assumed that they are covered by the other modification factors provided. Using the factors stated in Table 11 and using a net present value calculation together with a NOK/USD exchange rate of 6 the cost of 1 m^3 of oil spill is approximated as 50 000 NOK.

Cost factor		Modifier
Oil type	crude	0.55
Spill size	<34 tonnes	2
Location type	offshore	0.46
Primary cleanup	mechanical	0.92
Shoreline oiling	0-1 km	0.47
Cn	20.77	USD/liter

Table 11 - Oil spill cost factors

Oil companies are usually fined by the Norwegian government after oil spills. There is no official price per cubic meter set by the government for oil spills, but looking at old fines it is possible to estimate an approximate level of these fines. Both Shell and StatoilHydro (now Statoil) were fined for oil spills in 2007. The spills were of different size, but the fine was approximate 5 000 NOK/m^3 for both of them (Lundeberg, 2008)(Hatleskog, 2010). The total cost of oil spill is therefore set as 55 000 NOK/m^3.

8.2.4 Increased safety

As a natural consequence of a lower incident and accident rate the safety record of the plant will improve. Increased condition monitoring should also, as previously mentioned, lead to fewer maintenance and inspection actions. Each action carries a safety risk, and with a reduced number of total actions the total safety risk will be reduced.

To quantify the benefit of the increased safety it is necessary to look at the FMECA analysis and compare the reduction in failure rates for the different failure modes to the safety assessment. In addition it is necessary to obtain the safety records of maintenance and inspection actions to calculate safety risk per action which is used to quantify the benefit of fewer actions.

The quantification also requires a monetary value on accidents. Putting a price on a human life is a sensitive topic with very little public information available. To perform a complete cost-benefit analysis and justify the investment it is necessary to quantify the price of a human life. This is done by various parts of the Norwegian government for planning purposes. The Norwegian Directorate of Health states a value between 15 and 18.3 MNOK (Sælensminde, 2006). The Norwegian Ministry of Transport and Communications has in their work with the National Transport Plan found several sources within the government that put a value on a human life in case of an accident. These cost vary between 17 and 20.15 MNOK, the highest number is set by both The Norwegian Public Roads Administration and The Norwegian Costal Administration (Norwegian Ministry of Transport and Communications, 2006). As the costal administration is closest related to the offshore industry this value is used for fatalities. For non fatal accidents there were several values depending on source and severity of the injury. As an approximation for the calculations the cost of one injury is set as 10 MNOK regardless of severity.

8.2.5 Company reputation

The oil and gas industry is continuously watched by environmentalists, governments and media, all looking for the next incident or accident. Accidents involving personnel or harming the environment is a serious threat to the reputation of a company. Operating in the western world it is impossible to keep such incidents and accidents hidden from the media and the public. Quantifying the monetary value of not having an incident with respect to company reputation is hard, but looking at the overall estimated reputation value of a major company it is clear that this is an important area. The monetary value of the reputation impact of an accident for an oil company is not public information and must be estimated for the calculations in this thesis.

The reputation of a company is made up of several parts illustrated in Figure 33. Visibility in the media is illustrated as a negative factor of the corporate reputation. Large accidents in the Norwegian offshore industry get huge attention in the media and will thereby reduce the value of the company reputation. The reputation value of some selected oil companies is given in Table 12 . (Fombrun, 1996)

Company	Value (billion 1993 USD)
Exxon	69,0
Amoco	25,8
Mobil	25,7
Chevron	24,4
Atlantic Richfield	18,7
Texaco	15,9

Table 12 - Company value (Fombrun, 1996)

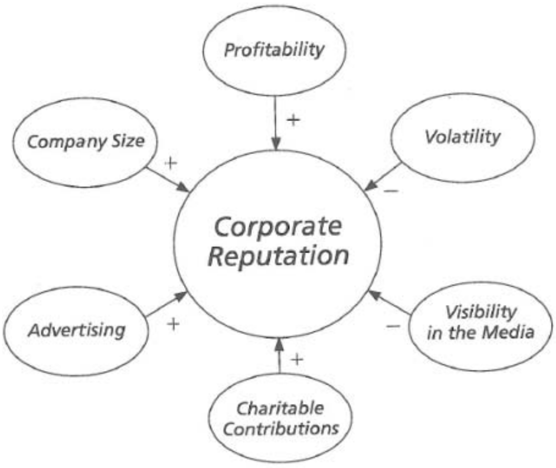


Figure 33 - Corporate reputation (Fombrun, 1996)

The failures assessed in this thesis are grouped in three categorizes after their severity. To simplify the estimation the reputation loss is assumed to be dependent of only the severity class and linearly dependent of the number of accidents. The values of an accident in each class are given in Table 13.

Incident category	Reputation loss [NOK / incident]
Critical	5 000 000
Degraded	200 000
Incipient	10 000

Table 13 - Reputation loss

8.3 Net present value assumptions

To perform an analysis over the lifetime of the equipment it is necessary to predict the future interest and inflation rate. The selected interest and inflation rate is used in the net present value calculation, as described in chapter 7.3.

The inflation rate used in this thesis is 2.5 percent per year. This is based on (Gjedrem, 2003) :

> *The operational target of monetary policy as defined by the Government is inflation of close to 2½ per cent over time. The target is symmetrical - it is equally important to avoid an inflation rate that is too low, as it is to avoid an inflation rate that is too high. The inflation target provides an anchor for economic agents' expectations concerning future inflation. It provides an important basis for choices concerning saving, investment, budgets and wages. Households, businesses, public entities, employees and employers can base decisions on the assumption that inflation in Norway will be 2½ per cent over time.*

Predicting future interest is not as straight forward as predicting future inflation. The interest is used as a tool in monetary policy to control the inflation, among others. As a conservative assumption the yearly interest rate is set to 10 % based on the expectations in Figure 34. As seen in the figure there is a great level of uncertainty regarding future interest. 10 % is believed to be a conservative assumption, but it should be noted that the interest rates has been higher at other points in history. The interest rate presented is the key policy rate of Norges Bank (Norway's central bank); the actual financing interest from financing institution is somewhat higher.

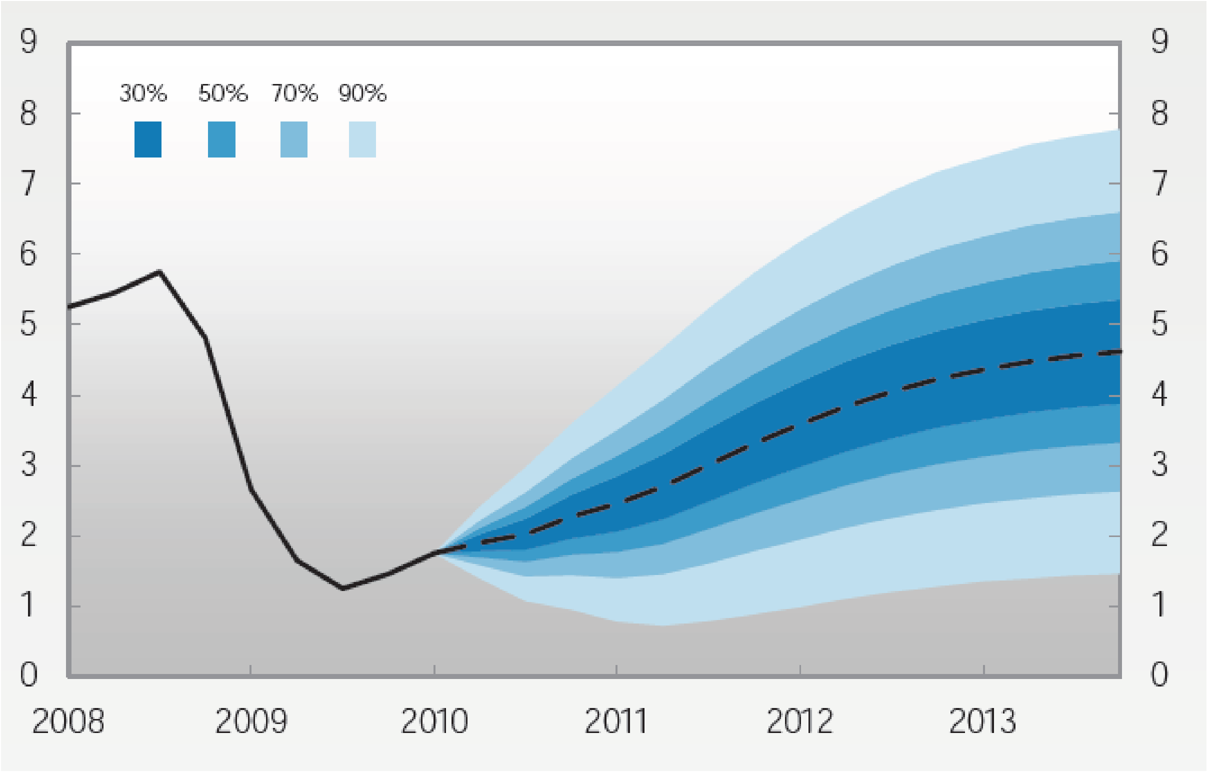


Figure 34 - Future predicted interest rate with confidence interval (Norges bank, 2010)

The final assumption needed for the net present value is the remaining lifetime of the installation. For this thesis the remaining life has been set to 15 years. A current trend for offshore installations is that the lifetime is extended way beyond the original design lifetime. This is not taken into consideration here. Any lifetime extension will increase the value of an investment in condition monitoring equipment.

9 Cost-benefit calculations

To perform cost-benefit calculations a spreadsheet has been developed using the previous stated assumptions and inputs for the calculation of benefits and LCC. The spreadsheet is included on the attached CD in both xls and xslx format. Further assumptions also needed, they are presented here.

The current situation is set as zero for all calculations. All changes are calculated relative to the current situation. The cost-benefit analysis for the current condition gives a result of zero. All calculations giving a positive overall answer is financially feasible according to this model, and all solutions giving a negative overall answer is not feasible.

9.1 Probability of detection

To assess the reduction of failures experienced by installing condition monitoring equipment it is necessary to quantify the probability of detecting a failure with the selected equipment. A failure is defined as detected only if it is detected early enough to be prevented. If no other information is available the probability of detecting a failure that is detectable by the selected monitoring solution is set to 0.9 for online monitoring and 0.5 for offline monitoring. The resulting probability of detection for the different monitoring methods used in the cost-benefit analysis is given in Table 14.

	Detection probability					
Failure mode	Passive acoustic	Ultrasonic	Gamma	Microwave	IR	Neutron backscatter
Critical						
Abnormal instrument reading	0,108	0	0,4	0,72	0,729	0,4
External leakage process medium	0	0,5	0	0	0,8	0
Plugged / Choked	0,5	0	0,5	0,9	0,8	0,5
Degraded						
Abnormal instrument reading	0,108	0	0,4	0,72	0,729	0,4
External leakage process medium	0	0,5	0	0	0,8	0
Plugged / Choked	0,5	0	0,5	0,9	0,8	0,5
Incipient						
Abnormal instrument reading	0,108	0	0,4	0,72	0,729	0,4
External leakage process medium	0	0,5	0	0	0,8	0
Parameter deviation	0,3	0	0,4	0,9	0	0,4
Plugged / Choked	0,5	0	0,5	0,9	0,8	0,5

Table 14 - Detection probability

9.1.1 Abnormal instrument reading

For abnormal instrument reading there are several different types of instruments that can be the cause. Failure distribution for instruments has been given in Table 5 and is utilized to get the overall probability of detecting abnormal instrument reading for the individual monitoring solutions as shown in Table 15. The detection of instrument failure in the general category has not been explored as it is unclear what the exact definition of this category is.

		Monitoring detection probability					
Instrument failure distribution		Passive acoustic	Ultrasonic	Gamma	Microwave	IR	Neutron Backscatter
Flow	0,12	0,9	0	0	0	0	0
General	0,01	0	0	0	0	0	0
Level	0,80	0	0	0	0,9	0,9	0,5
Pressure	0,05	0	0	0	0	0	0
Temperature	0,01	0	0	0	0	0,9	0
	sum	0,108	0	0	0,72	0,729	0,4

Table 15 - Instrument failure detection probability

9.2 CM solutions

The selected condition monitoring solutions will be presented here, complete with all assumptions and costs used in the cost-benefit analysis that is specific for the individual solution.

9.2.1 IR

The IR solution analyzed here is an automatic continuous online monitoring method. The cost of cameras vary greatly, from 30 000 NOK and up to several hundred thousand depending on range of detection and resolution.(Holme, 2010) For this usage it is estimated that the camera costs 100 000 NOK.

During the lifetime of the equipment it is assumed that the software and hardware cost follow the assumptions set in chapter 8.1.3. Operational costs are set as 10 man-hours / year offshore and 100 man-hours / year onshore. The initial training required is estimated as 10 man-hours offshore and 20 man-hours onshore. This is based on the assumption that IR technology is already in use and further training is therefore not necessary. Further supporting this assumption is information from (Holme, 2010) stating that the equipment is easy to use and companies seldom need outside training resources.

At the end of the lifetime the camera is considered as normal electronic waste and treated as such. The marginal cost of scrapping one camera is estimated at 10 000 NOK everything included. The decommissioning cost is estimated at 20 000 NOK.

9.2.2 LRUT Ultrasonic

The ultrasonic solution investigated here is a large LRUT ring mounted beneath the insulation. The investment cost of this solution is high due to the large diameter of the separator and the work involved with removal and refitting of insulation during the installation.

The initial investment cost of the LRUT ring is estimated at 2 MNOK whilst the installation is estimated to require a total of 150 man-hours everything included. Electrical and signal cables are estimated at 600 000 NOK whilst other modifications (brackets, insulation, etc.) is estimated at 500 000 NOK.

The online LRUT solution requires little work once installed; the yearly workload is estimated as 20 man-hours offshore and 50 man-hours onshore. At the end of the platform life the LRUT-ring is treated as electronic waste with a marginal scrapping cost of 30 000 NOK. Decommissioning cost is estimated at 20 000 NOK.

9.2.3 Gamma

The gamma monitoring solution investigated here is an offline manual solution. This solution gives a reduced initial investment cost while the operational costs are higher compared to an online solution.

The cost of the equipment is estimated at 3 000 000 NOK. The offline gamma monitoring solution requires no modification to the infrastructure on the platform and no installation work. The initial training requirement is estimated as 100 hours per worker; 80 hours from (ndt.no, 2010) plus 20 extra hours to comply with radiation regulations. This gives a total initial training requirement of 600 offshore man-hours. In addition it is estimated that the onshore crew requires a total of 50 man-hours initial training.

The operational costs of this solution consist of the labor cost of the offshore crew and the onshore analysis crew. For this offline solution it is estimated that the offshore workload is 200 man-hours / year and 50 man-hours / year in onshore analysis workload.

At the end of the platform life the equipment will be scrapped. The costs are, as previously stated, higher than for other solutions because of the presence of radioactive materials. Based on this the decommissioning cost is set at 200 000 NOK and the scrapping cost at 250 000.

9.2.4 Neutron backscatter

The neutron backscatter solution investigated here is an offline manual solution. This solution is the only possible solution due to the fact that the separators fire insulation has to be removed every time a measurement is taken. This will greatly influence the operational costs as seen in the higher amount of yearly man-hours needed offshore.

The initial training requirement is set equal to the needs of the gamma monitoring giving a total requirement of 600 offshore man-hours and 50 man-hours onshore. The yearly onshore man-hour need for analysis is set to 50 hours. The offshore operation is estimated to take 300 man-hours per year. The high value reflects the extra work required to remove and refit insulation for each measurement.

At the end of the platform life the equipment will be scrapped. The costs are, as previously stated, higher than for other solutions because of the presence of radioactive materials. Based on this the decommissioning cost is set at 200 000.

9.2.5 Microwave

The microwave solution investigated is an online continuous solution. The investment cost of the microwave solution is estimated at 200 000 NOK for hardware and 2 000 000 NOK for software. This is based on the assumption that microwave tank gauges can be used as hardware while some software development is needed to get the best detection probability.

Microwave technology is not commonly used for separator measurements, based on this the initial onshore training is set to 600 man-hours. The onshore initial training is set to 50 man-hours since the solution is online with little offshore work required.

9.2.6 Passive acoustic

The passive acoustic solution investigated here is an online continuous solution. The solution consists of several wireless passive acoustic sensors with energy generating devices. The cost of one wireless sensor with energy generating device is approximately 7 000 NOK, whilst a traditional device costs about 4 000 NOK plus wiring. With the previously discussed cost of wiring a wired solution is not investigated. The devices are glued on to various parts of the separator to minimize installation costs. The sensors are spread out on the separator in order to be able to accurately locate where the acoustic signals originate. One sensor is placed to monitor the inlet condition to be able to predict the risk of plugging / chocking due to increased sand production. The overall equipment need is estimated as four sensors at a total cost of 400 000 NOK including necessary wireless infrastructure. It is assumed that that receiving part of the wireless equipment can be placed at any indoor location not requiring any new cables or connections.

For the initial training it is estimated that the onshore requirement is 50 man-hours and the offshore need is 20 man-hours.

9.3 Initial cost-benefit results

The result from the initial cost-benefit analysis is presented in Table 16. The table describes the net benefit of each solution and in addition a net benefit / LCC ratio showing which solution gives the greatest benefit compared to the investment. Complete calculations are given in Appendix 4.

CM method	Net benefit [NOK]	Net Benefit / LCC ratio
IR	73 511 000	15,19
Gamma	4 691 000	0,21
Neutron Backscatter	4 151 000	0,18
Ultrasonic	11 078 000	1,21
Microwave	37 287 000	3,21
Passive acoustic	13 475 000	2,84

Table 16 - Initial cost-benefit results

The results given here are to be considered as the result of the implementation of one condition monitoring method only. The benefit of implementing two results cannot be obtained by adding together the individual results in the table. Adding two results would possibly count benefits more than once, as described in chapter 7.1 this is a common error that should be avoided as it will lead to overestimating the benefits. To obtain the net benefit of implementing more than one condition monitoring method it is necessary to obtain the joint probability of detecting a failure using the methods simultaneously and enter these new probabilities in to the model along with the correct cost data.

9.3.1 Combining methods

Seeing the results from the single method only analysis it is clear that implementing IR has the greatest benefit. Number two is microwave, but combining these two methods is not a feasible solution since they detect mostly the same failures. Combining IR with passive acoustic measurements is a more reasonable method; passive acoustic measurements cover failures that IR does not cover. IR and passive acoustic have therefore been investigated as a possible solution. All costs for the combined IR and passive acoustic solution are the result of using engineering judgment when adding up the individual costs of the individual methods. The benefits have been obtained by using engineering judgment combining the failure detection capabilities of the individual methods and are presented in Table 17.

Failure mode	
Critical	
Abnormal instrument reading	0.837
External leakage process medium	0.8
Plugged / Choked	0.9
Degraded	
Abnormal instrument reading	0.837
External leakage process medium	0.8
Plugged / Choked	0.9
Incipient	
Abnormal instrument reading	0.837
External leakage process medium	0.8
Parameter deviation	0.3
Plugged / Choked	0.9

Table 17 - Detection probability: IR and passive acoustic

9.4 Overall cost-benefit results

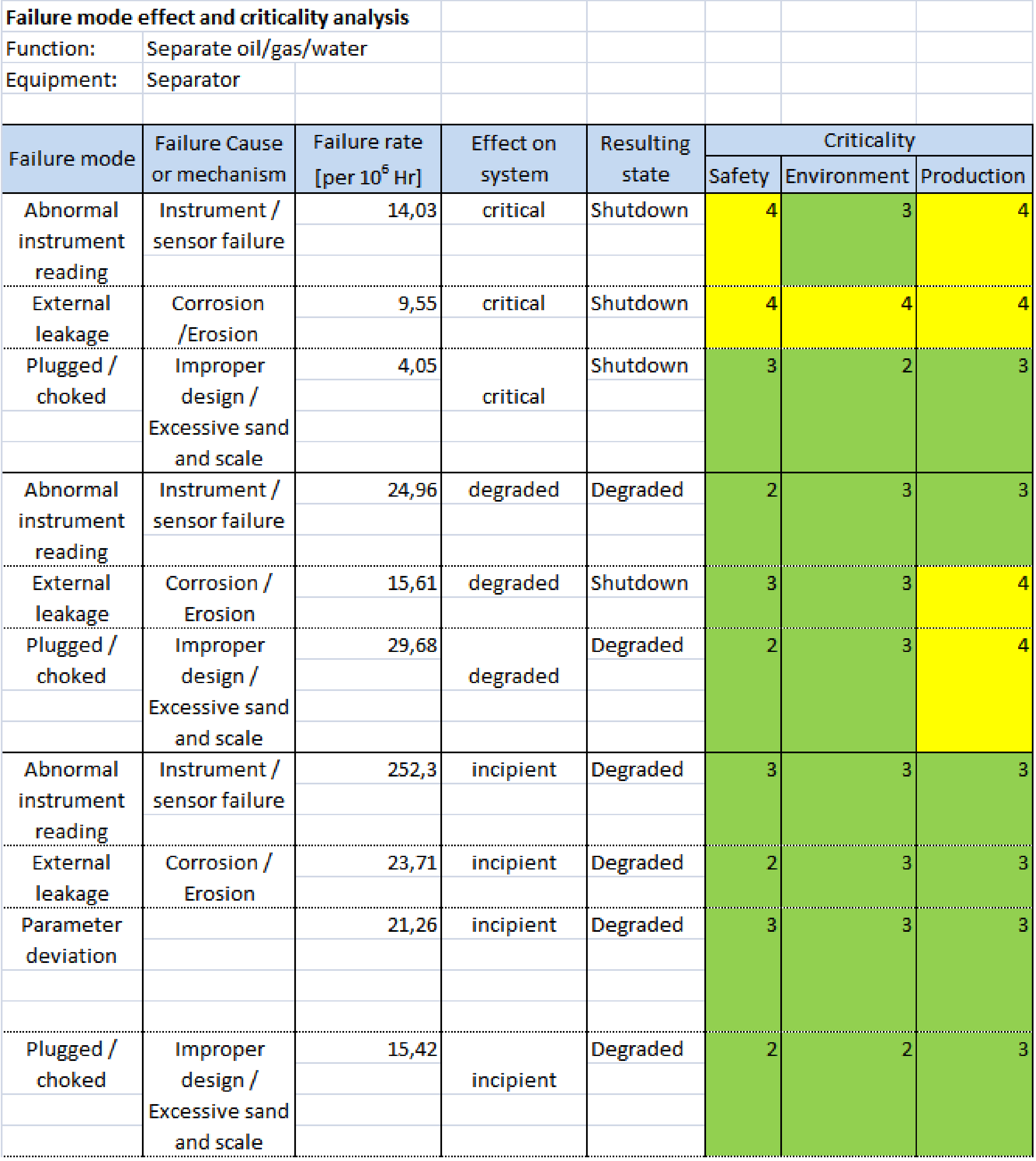
The overall result of the cost-benefit analysis is given in Table 18. As shown the overall benefit increases with combining IR and passive acoustic monitoring at the expense of the net benefit ratio. If the investment budget allows the best solution is the combined IR and passive acoustic, if the budget can only cover one method the best solution is the IR solution.

CM method	Net benefit [NOK]	Net Benefit / LCC ratio
IR	73 511 000	15,19
Gamma	4 691 000	0,21
Neutron Backscatter	4 151 000	0,18
Ultrasonic	11 078 000	1,21
Microwave	37 287 000	3,21
Passive acoustic	13 475 000	2,84
IR+PA	76 305 000	9,09

Table 18 - Cost-benefit results

9.4.1 FMECA with CM solution

To show the effect of implementing the proposed CM solution an FMECA analysis has been performed with the same definitions as in chapter 2.2. This clearly shows the expected improvement of implementing more CM.



Failure mode effect and criticality analysis

Function: Separate oil/gas/water

Equipment: Separator

Failure mode	Failure Cause or mechanism	Failure rate [per 10^6 Hr]	Effect on system	Resulting state	Criticality		
					Safety	Environment	Production
Abnormal instrument reading	Instrument / sensor failure	14,03	critical	Shutdown	4	3	4
External leakage	Corrosion /Erosion	9,55	critical	Shutdown	4	4	4
Plugged / choked	Improper design / Excessive sand and scale	4,05	critical	Shutdown	3	2	3
Abnormal instrument reading	Instrument / sensor failure	24,96	degraded	Degraded	2	3	3
External leakage	Corrosion / Erosion	15,61	degraded	Shutdown	3	3	4
Plugged / choked	Improper design / Excessive sand and scale	29,68	degraded	Degraded	2	3	4
Abnormal instrument reading	Instrument / sensor failure	252,3	incipient	Degraded	3	3	3
External leakage	Corrosion / Erosion	23,71	incipient	Degraded	2	3	3
Parameter deviation		21,26	incipient	Degraded	3	3	3
Plugged / choked	Improper design / Excessive sand and scale	15,42	incipient	Degraded	2	2	3

Figure 35 - FMECA with CM

9.4.2 Comments and further work

The results show that any condition monitoring method is economically feasible using the current assumptions. These results are a result of previous assumptions regarding future oil price, interest, inflation and so on. Some of these parameters have been changed to extreme values and the results are presented in Table 19 and Table 20. This shows that the assumptions regarding the economic future only barely change the outcome of the analysis for methods with a healthy net benefit / LCC ratio. IR and passive acoustic monitoring is economically feasible and the best solution even when the parameters are set to extreme values.

Net Benefit [NOK]					
CM method	**Original**	**40 % interest**	**Oil=1 USD**	**15% inflation**	**5 yr remaining life**
IR	73 511 000	40 115 000	47 230 000	69 493 000	27 750 000
Gamma	4 691 000	6 001 000	-4 552 000	-41 563 000	-13 425 000
Neutron Backscatter	4 151 000	6 395 000	-5 091 000	-44 033 000	-13 235 000
Ultrasonic	11 078 000	5 122 000	4 114 000	2 659 000	277 000
Microwave	37 287 000	20 413 000	20 602 000	25 093 000	11 147 000
Passive acoustic	13 475 000	8 362 000	5 961 000	1 838 000	2 961 000
IR+PA	76 305 000	41 381 000	47 954 000	69 807 000	27 882 000

Table 19 - Economic sensitivity analysis

Net Benefit [NOK]			
CM method	**No reputation loss**	**No injury /accident cost**	**Man-hour cost x 10**
IR	64 236 973	35 594 374	56 676 271
Gamma	1 224 070	-8 498 380	-127 080 029
Neutron Backscatter	684 828	-9 037 623	-143 690 179
Ultrasonic	9 079 616	1 556 367	-9 722 971
Microwave	31 044 102	13 546 684	10 619 469
Passive acoustic	11 783 517	5 467 728	-4 597 729
IR+PA	66 164 108	35 253 851	47 638 914

Table 20 - Sensitivity analysis continued

For further work it is therefore recommended to limit the time spent on improving these inputs. The focus should be on the probability of detecting failures as well as the quantification of the consequences of incidents and accidents. This is believed to be the weakest point of the analysis with the greatest influence. Accurately predicting the consequences of accidents and incident requires detailed statistics and experience that has not been available during the preparation of this thesis. The probability of detecting failures can either be assessed in laboratory experiments or by user statistics. Updating the cost-benefit spreadsheet will immediately show the new and improved results.

10 Conclusion

Separators can benefit from more condition monitoring, and there are several methods available that are capable of detecting a wide range of possible failures. More condition monitoring will lead to a reduced accident and incident rate. This will result in lower environmental risk, increased safety and reduced downtime. The cost-benefit analysis performed in this thesis shows that all condition monitoring methods have a net benefit for the remaining lifetime of the separator used as a case. The best economic solution yielding the highest net benefit is the combined infrared and passive acoustic monitoring solution. This solution covers most of the failures investigated in this thesis and yields a net benefit regardless of the economic future according to the economic sensitivity analysis performed.

Once the condition monitoring data has been collected it must be presented to decision makers as usable information. The aggregation of condition monitoring data into usable information is typically done manually today, looking at other relevant examples this process should be automated to increase efficiency and accuracy. Examples from the reduction of workload experienced in commercial aviation over the past decades is presented, the same reduction of workload should be demanded from new condition monitoring systems. This is possible through the presented technical condition indexing software TeCoMan. This software is capable of combining all relevant information regarding the condition of equipment into an overall condition as well as produce automated reports, warnings and alarms.

11 Bibliography

Ascom Separation. (2010). *Separation Internals*. Retrieved February 9, 2010, from Ascom Separation: http://www.ascomsep.com/index.php?hfst_id=41

AviationExplorer.com. (n.d.). *AviationExplorer.com*. Retrieved March 14, 2010, from AviationExplorer.com: http://www.aviationexplorer.com/cockpit_photos.html

AZoM.com. (2008, June 4). *Battery-Free Wireless Condition Monitoring System Developed by CAP-XX*. Retrieved November 28, 2009, from The A to Z of Materials: http://www.azom.com/news.asp?newsID=12458

Bachian, F. (2009, August 21). *Fsim*. Retrieved March 15, 2010, from Airsimmer Airbus A320 family for Flight Simulator: http://fsim.posterous.com/airsimmer-airbus-a320-family-for-flight-simul

Bai, Y. (2001). LCC modeling as a decision making tool in pipeline design. In Y. Bai, R. Bhattacharyya, & M. McCormick, *Elsevier Ocean Engineering Series, Elsevier, 2001, Volume 3, Pipelines and Risers* (pp. 467-488). Elsevier.

Baird, G. (2010). Condition Monitoring Engineer, Shell. (J. Houmstuen, Interviewer)

Ball, K. (2009). Retrieved November 11, 2009, from Electronics Knowledge Transfer Network (EKTN): http://www.electronics-ktn.com/Portals/0/Content/TAWOP/10-%20Capacitors%20Get%20Ultra-Efficient%20for%20TAWOP%202009.pdf

Barton, D. K., & Leonov, S. A. (1998). *Radar Technology Encyclopedia.* Boston / London: Artech House.

Blanchard, B. S. (1998). *Logistics Engineering and Management.* Upper Saddle River: Prentice Hall.

Blanchard, B. S., & Fabrycky, W. J. (1991). *Life-Cycle Cost and Economic Analysis.* Englewood Cliffs: Prentice Hall.

Brurok, T. (2009). *Condition Monitoring of Oil and Gas Facilities; Avoiding Surprises through proactive Maintenance Management.* Trondheim: Sintef Marintek.

Devold, H. (2009). *Oil and gas production handbook - An introduction to oil and gas production.* Oslo: ABB AS.

DNV. (2007). *Recommended practice DNV-RP-G103, Non-intrusive inspection.* Høvik: DNV.

Edgcombe, J. P. (2008). Latest advances in through-wall radar sensing for security applications. *Sensor Review* , 205-211.

Etkin, D. S. (2000). *Worldwide Analysis of Marine Oil Spill Cleanup Cost Factors.* Winchester, MA: Environmental Research Consulting.

Flicr.com. (n.d.). *Flicr.com*. Retrieved March 14, 2010, from Flicr.com: http://farm4.static.flickr.com/3322/3509651231_1bd8ec578f.jpg

Fombrun, C. J. (1996). *Reputation.* Boston: Harvard Business School Press.

GE Energy. (2009, August). *Products.* Retrieved November 10, 2009, from GE Energy: http://www.ge-energy.com/prod_serv/products/oc/en/downloads/GEA15019.pdf

Gjedrem, S. (2003, December 1). *Norges Bank*. Retrieved March 16, 2010, from The conduct of monetary policy: http://www.norges-bank.no/templates/article____17909.aspx

Grønseth, E. (2010, March 5). Senior Engineer Inspection, Shell. (J. Houmstuen, Interviewer)

Hagen, A. (2008). *Lecture notes,TMR4125 - Building of ships and platforms.* Trondheim: NTNU.

Hatleskog, C. (2010, January 18). *NRK Nyheter*. Retrieved March 17, 2010, from Betaler 25 millioner for oljesøl: http://nrk.no/nyheter/distrikt/rogaland/1.6951553

Holme, G. (2010, February 8). FLIR IR Cameras, Precision Technic Nordic. (J. Houmstuen, Interviewer)

Hou, R., Hunt, A., & Williams, R. (1998). Acoustic Monitoring of Hydrocyclone Performance. *Minerals Engineering* , 1047-1059.

Hunt, T. M. (2006). *The Concise Encyclopaedia of Condition Monitoring.* Oxford: Coxmoor Publishing Company.

IEC. (2009). *IEC 60050 - International Electrotechnical Vocabulary - Details for IEV number 713-06-03*. Retrieved 11 2009, from International Electrotechnical Commission: http://std.iec.ch/iev/iev.nsf/display?openform&ievref=713-06-03

IEEE. (2000). *IEEE 100 The Authoritative Dictionary of IEEE Standards Terms Seventh Edition.* IEEE.

Kent, R. M., & Murphy, D. A. (2000, January). *Health Monitoring System Technology Assesments - Cost Benefit Analysis.* Retrieved February 23, 2010, from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20000021459_2000025393.pdf

Kleiner, D., Edwards, C., Sanderson, R., Kazys, R., Cicenas, V., Raisutis, R., et al. (2005). *Condition monitoring of large oil and chemical storage tanks using Long Range Ultrasonic Testing (LRUT).* London: I Mech E Seminar: Storage Tanks.

Kristiansen, S. (2004). *Maritime Transportation - Safety Management and Risk Analysis.* Trondheim: Butterworth-Heinemann.

Levander, K. (2006). *System Based Ship Design.* Trondheim: NTNU.

Long Range Ultrasonic Technology Group, TWI Ltd. (2007, July). *LRUT.* Retrieved November 2009, from TWI: http://www.twi.co.uk/content/lrut_brochure.pdf

Lundeberg, H. (2008, November 21). *Bellona*. Retrieved March 17, 2010, from Shell får bot etter oljeutslipp: http://www.bellona.no/nyheter/nyheter_2008/shell_far_bot_etter_oljeutslipp

Meland, E. (2009). *Draft: Condition Evaluation of Safety Critical Shut-Down Valves.* Trondheim: NTNU.

ndt.no. (2010). *Norsk Forening for ikke-desktruktiv Prøving*. Retrieved April 26, 2010, from Norsk Forening for ikke-desktruktiv Prøving: http://www.ndt.no

Norges bank. (2010, March 24). *Pengepolitisk rapport 1/10.* Retrieved April 26, 2010, from Norges Bank: http://www.norges-bank.no/Upload/78478/ppr1_10.pdf

Norwegian Ministry of Transport and Communications. (2006). *Norwegian Ministry of Transport and Communications.* Retrieved March 17, 2010, from Transportetatens veiledere i nyttekostnads-analyser: http://www.ntp.dep.no/2006-2015/pdf/NKA_rapport_vedlegg1.pdf

Nystad, B. H. (2008). *Technical Condition Indexes and Remaining Useful Life og Aggregated Systems, PhD thesis.* Trondheim: Norwegian University of Science and Technology.

Nystad, B. H., & Rasmussen, M. (2006). *Prognostics of Technical Condition Index for an aging repairable system.* Trondheim: Norwegian University of Science and Technology, Department of Marine Technology.

Park, C. S. (2004). *Fundamentals of Engineering Economics.* Upper Saddle River: Pearson Education Inc.

Petroleum Safety Authority Norway. (n.d.). *Facilities*. Retrieved November 9, 2009, from Petroleum Safety Authority Norway: http://www.ptil.no/facilities/

Plant Integrity Ltd. (2009, November). *Long Range Ultrasonic Testing*. Retrieved November 13, 2009, from Plant integrity Ltd: http://www.plantintegrity.com/

Rasmussen, M. (2003). *Driftsteknikk Grunnkurs.* Trondheim: Tapir.

Rasmussen, M. (2002). *Operation Technology; Maintenance.* Trondheim: Tapir.

Rasmussen, M. (2007). *Pålitelighets- og tilgjengelighetsbetraktninger for design og drift.* Trondheim: Tapir.

Scanning Technologies. (2007, November 24). *Gamma Scan and Neutron Backscatter*. Retrieved November 28, 2009, from Scanning Technologies: http://www.scanningtech.com/

Schutz, R. (2005). Corrosion of Titanium and Titanium Alloys, Corrosion: Materials. *ASM International* .

SINTEF Industrial Management. (2002). *OREDA - Offshore Reliability Data, 4th edition.* Trondheim: OREDA Participants.

Skogstrand, H. (2008). *Moderne ultralydmetoder for tilstandskontroll av statisk utstyr i produksjon av olje og gass.* Trondheim.

Solartron Instruments. (1994). *Technical Report 27: Cost Benefit Analysis Methods for Condition Monitoring.* Farnborough: Solartron Instruments.

Sælensminde, K. (2006, October 25). *The Norwegian Directorate of Health.* Retrieved March 17, 2010, from Verdsetting av liv, helse og trivsel i samfunnsøkonomiske analyser av folkehelsetiltak: http://www.shdir.no/vp/multimedia/archive/00012/Verdsetting_av_liv___12334a.ppt

Technoport. (2007). *Technoport.* Retrieved February 11, 2010, from http://www.technoport.no/2007/uploads/samarbeid/Condition.pdf

Thorstensen, T. A. (2008). *Lifetime profit modelling of ageing systems utilising information about technical condition.* Trondheim: NTNU.

Thorstensen, T. A. (2001). *Notat kurs TMR4260 Driftsteknikk grunnkurs; RCM-metoden.* Trondheim: Institutt for marint maskineri, NTNU.

Thunem, H. P.-J. (2007). *Condition Monitoring at Petrochemical Installations: Technology Evaluation of Gamma and Thermography.* Kjeller: Institute for Energy Technology.

Thunem, H. P.-J. (2007). *CORD-TT and CORD-SEP: Condition monitoring of Production Separators.* Kjeller: Institute for Energy Technology.

Touran, A. (1993). Probabilistic Cost Estimating with Subjective Correlations. *Journal of Construction Engineering and Management* , 58-71.

Touran, A., & Wiser, E. P. (1992). Monte Carlo Technique with Correlated Random Variables. *Journal of Construction Engineering and Management* , 258-272.

US Army Corps of Engineers. (1996). *The REMR Condition Index: Condition Assessment for Maintenance Management of Civil Works Facilities.* US Army Corps of Engineers.

US Department of Energy. (1997, March 28). *DOE G 430.1-1 Chp 23, Life Cycle Cost Estimate.* Retrieved February 16, 2010, from Department of Energy Directives: https://www.directives.doe.gov/directives/current-directives/430.1-EGuide-1-Chp23/view?searchterm=None

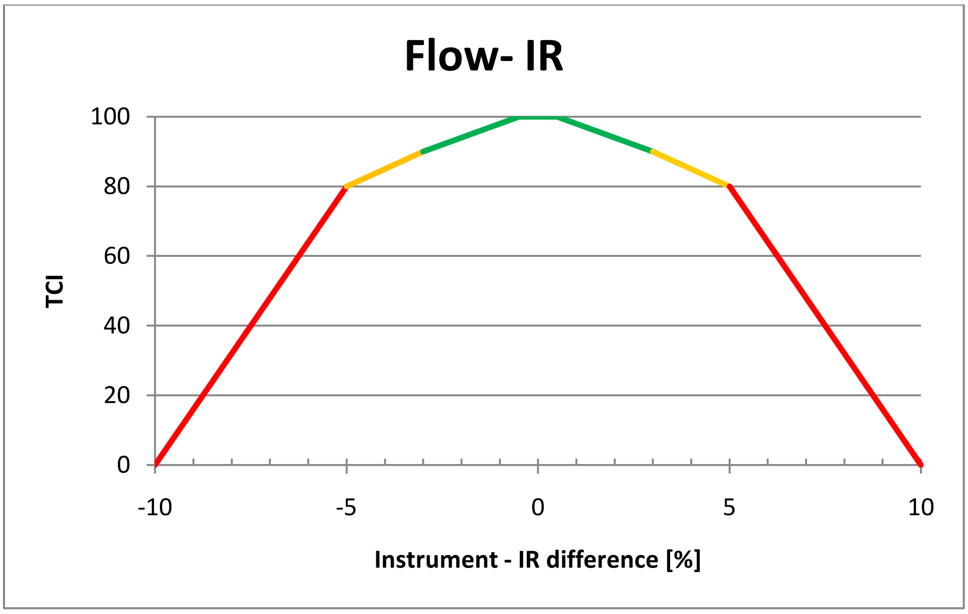
van der Vet, P., & Rasmussen, M. (2004). *Lecture note: Logistics Engineering and Management: Logistic analysis of sub sea operations.* Trondheim: NTNU.

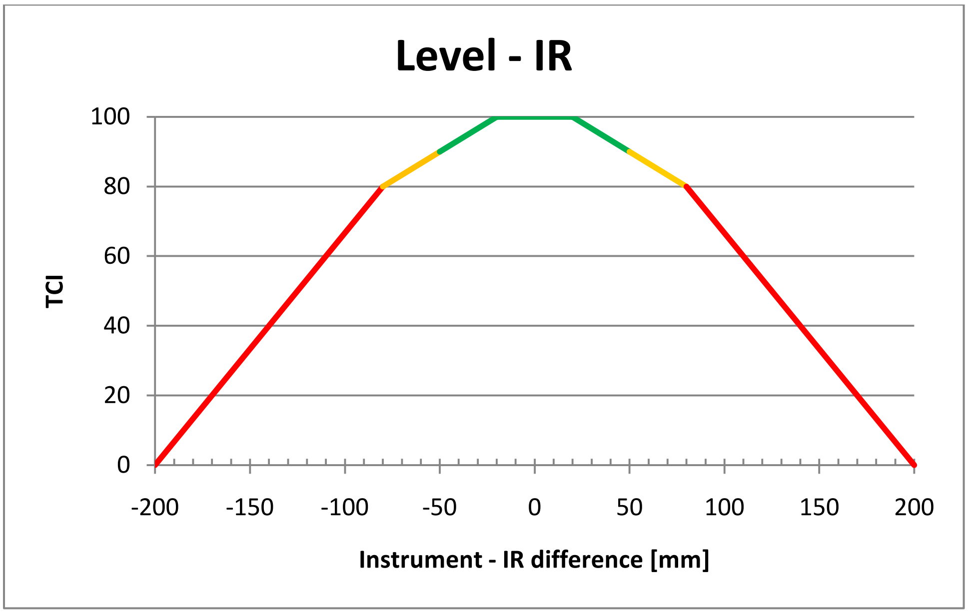
Winglet Media. (2010). *Winglet Media*. Retrieved March 14, 2010, from ECAM Trainer: http://www.winglet.co.uk/solutions/fdt--aet.php

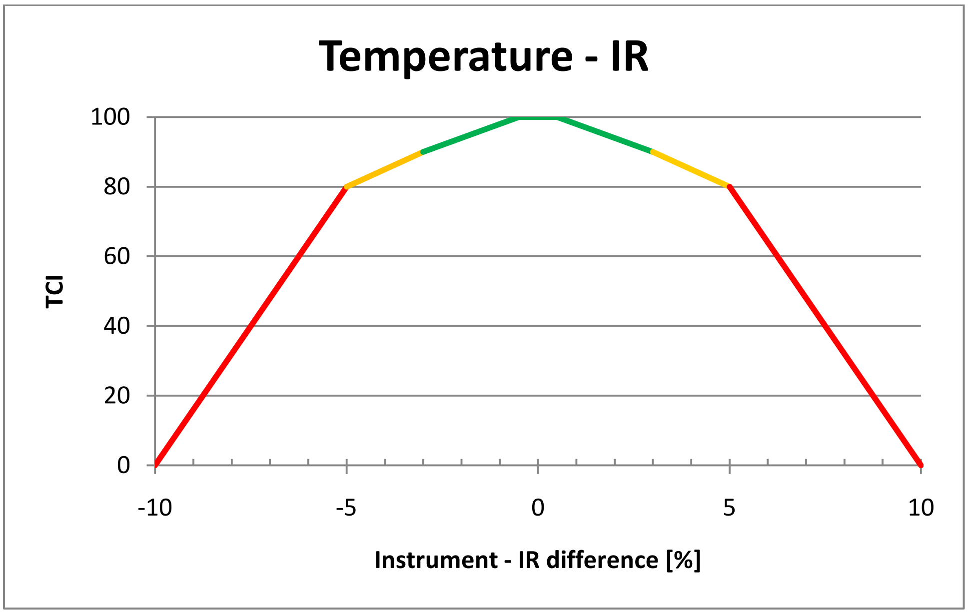
Appendix 1 - TeCoMan input file

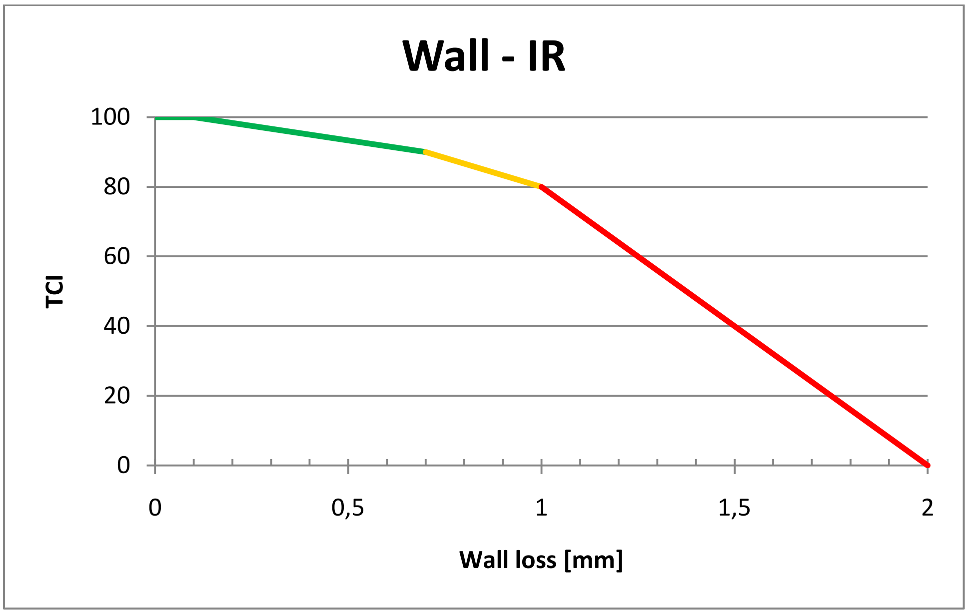
```
01.01.2010;instr_temp;0
02.01.2010;instr_temp;0
03.01.2010;instr_temp;0
04.01.2010;instr_temp;0
05.01.2010;instr_temp;0
06.01.2010;instr_temp;1
07.01.2010;instr_temp;1
08.01.2010;instr_temp;2
09.01.2010;instr_temp;2
10.01.2010;instr_temp;2
11.01.2010;instr_temp;4
12.01.2010;instr_temp;4
01.01.2010;instr_level;1
02.01.2010;instr_level;1
03.01.2010;instr_level;2
04.01.2010;instr_level;2
05.01.2010;instr_level;2
06.01.2010;instr_level;2
07.01.2010;instr_level;2
08.01.2010;instr_level;2
09.01.2010;instr_level;2
10.01.2010;instr_level;1
11.01.2010;instr_level;2
12.01.2010;instr_level;2
01.01.2010;instr_flow;1
02.01.2010;instr_flow;1
03.01.2010;instr_flow;1
04.01.2010;instr_flow;1
05.01.2010;instr_flow;1
06.01.2010;instr_flow;1
07.01.2010;instr_flow;1
08.01.2010;instr_flow;1
09.01.2010;instr_flow;1
10.01.2010;instr_flow;1
11.01.2010;instr_flow;1
12.01.2010;instr_flow;1
```

Appendix 2 - TeCoMan transfer functions






Temperature - IR
TCI
100
80
60
40
20
0
-10
-5
0
5
10
Instrument - IR difference [%]


Wall - IR
TCI
100
80
60
40
20
0
0
0,5
1
1,5
2
Wall loss [mm]

Vortex breaker oil - Passive acoustic

Description	TCI
Normal vortex	100
Enlarged vortex	90
Enlarged vortex - mixing of oil/gas	80
Uncontrolled vortex	0

Vortex breaker oil - Inspection

In place	100
Fixed, but deformed /dislocated	80
Loose / missing	0

Vortex breaker water - Passive Acoustic

Normal vortex	100
Enlarged vortex	90
Enlarged vortex - mixing of water/oil	85
Enlarged vortex - mixing of water/oil/gas	80
Uncontrolled vortex	0

Vortex breaker water - Inspection

In place	100
Fixed, but deformed /dislocated	80
Loose / missing	0

Gas demister - IR

In place	100
Not in place	0

Gas demister - Inspection

In place	100
Fixed, but deformed /dislocated	80
Loose / missing	0

Weir plate - Passive acoustic

Normal	100
Dislocated	0

Weir plate - IR

In place	100
Deformed / dislocated but functioning	80
Deformed / dislocated reduced function	40
Loose / missing	0

Weir plate - Inspection	
In place	100
significant wear	80
Loose / missing	0

Schoepentoeter - IR	
In place	100
Deformed / dislocated - functioning	80
Deformed / dislocated - partly functioning	40
Loose / missing / not functioning	0

Schoepentoeter - Inspection	
In place	100
Insignificant wear / deformation	90
Significant wear / deformation	80
Loose / extreme wear /deformation	0

Schoepentoeter - Passive acoustic	
Normal flow	100
Reduced separation	90

Sand system - Inspection	
In place	100
Slight deformation	90
Nozzles out of alignment	80
Loose / extreme wear /deformation	0

Sand system - IR	
Functioning	100
Partly functioning	80
Not functioning	0

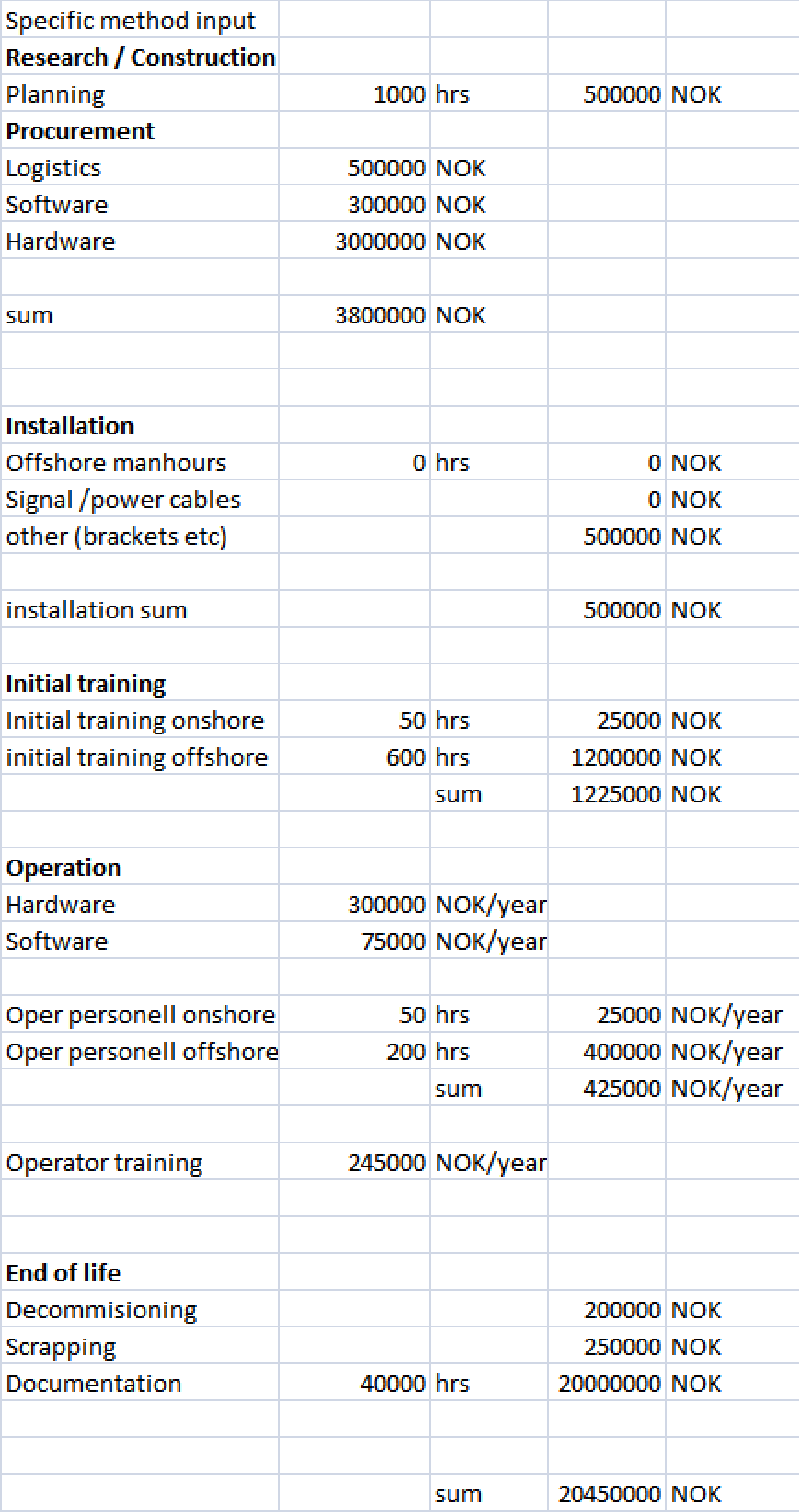
Sand system - Passive acoustic	
Normal nozzle flow	100
Altered flow, sand removed	90
Altered flow, sand inefficiently removed	60
Nozzle flow not removing sand	0

Appendix 3 - Transportation costs

Logistic cost CM equipment		
Distance supply base - offshore	150	km
Transportation cost	6000	NOK /ton km
Weight with packaging	500	kg
Onshore handling	5000	NOK
Offshore handling	10000	NOK
Road transportation cost	50000	NOK
Estimated logistic cost	500000	NOK

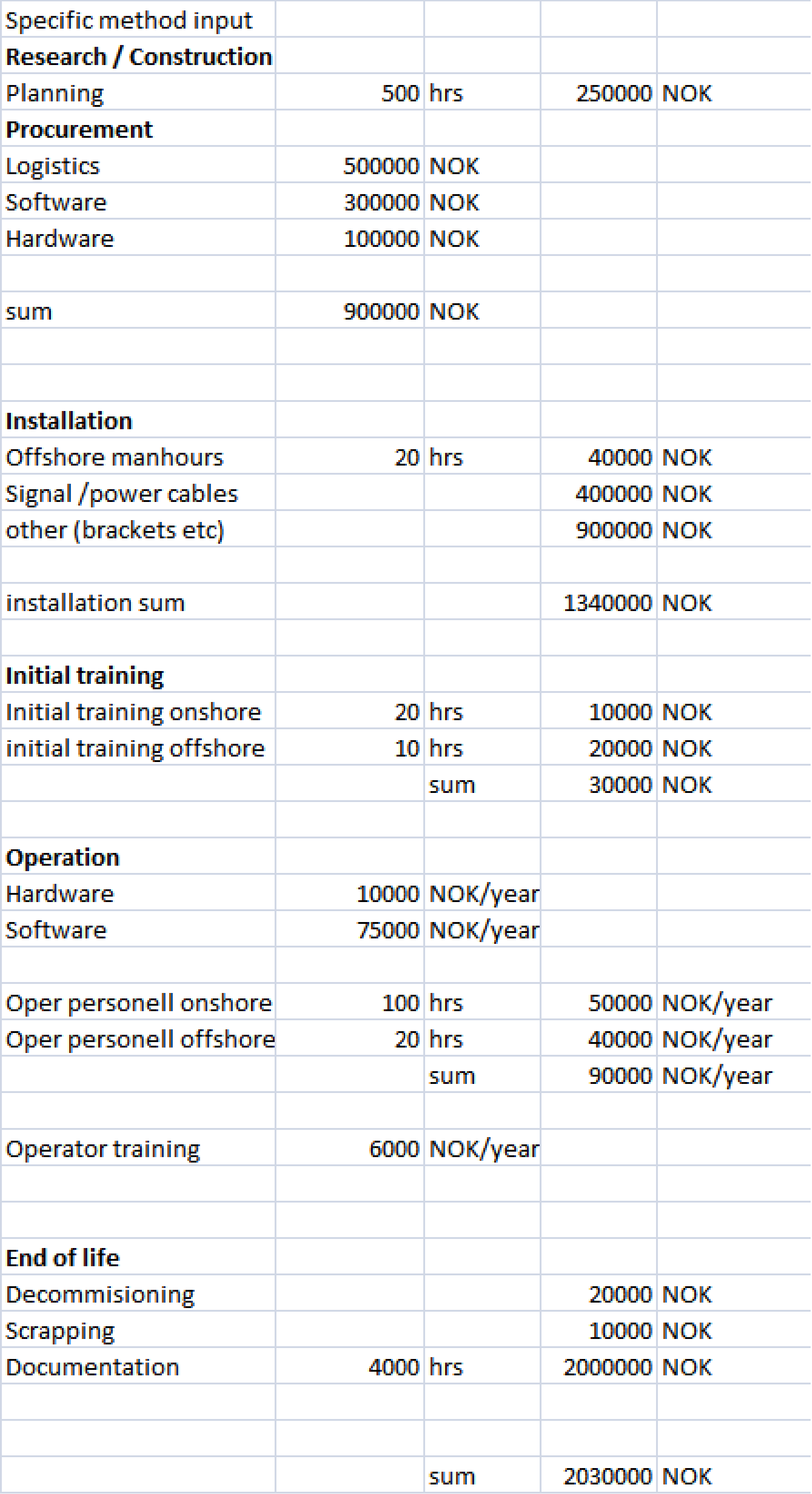
Appendix 4 - Cost-benefit calculations

Gamma						
Costs				**Benefits**		
Research / Construction						
Planning	500000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	3800000	NOK		Reduced environmental risk	54 147	NOK/year
Installation	500000	NOK		Increased safety	1 477 203	NOK/year
Initial training	1225000	NOK		Company reputation	388 253	NOK/year
sum	6025000	NOK				
Operation						
Hardware	300 000	NOK/year				
Software	75 000	NOK/year		Yearly benefits	1 919 603	NOK
Operating personell	425 000	NOK/year				
Operator training	245 000	NOK/year				
sum	1 045 000	NOK/year				
End of life						
Decommisioning	200 000	NOK				
Scrapping	250 000	NOK				
Documentation	20 000 000	NOK				
sum	20 450 000	NOK				
NPV costs						
Research / Construction	6 025 000	NOK				
Operation	9 330 055	NOK				
End of life	7 090 241	NOK		Increased reliability and availability	9 997 041	NOK
LCC	22 445 296	NOK		Lifetime benefits	27 135 800	NOK
Benefits - LCC	4 690 504	NOK				



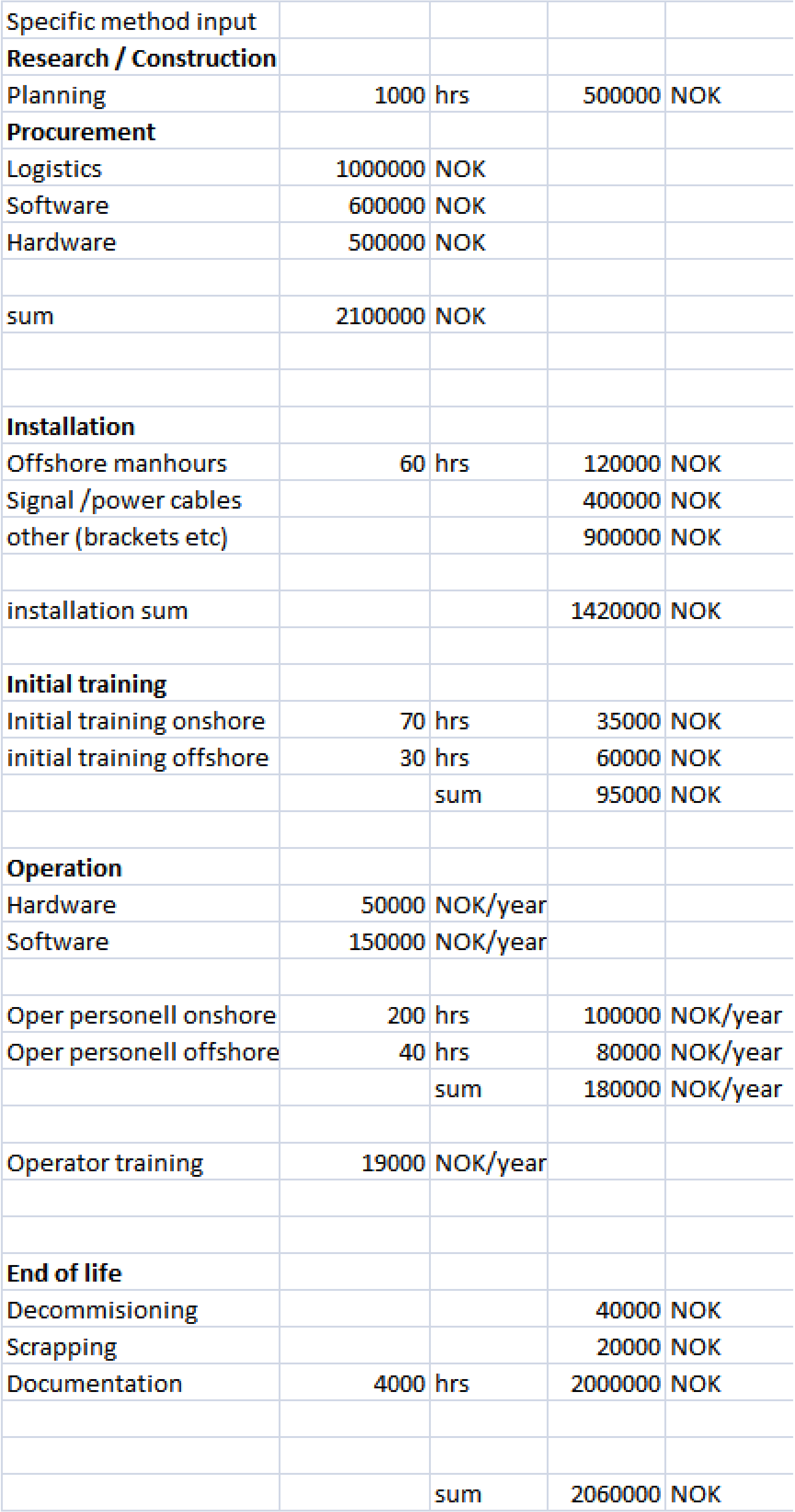
Specific method input				
Research / Construction				
Planning	1000	hrs	500000	NOK
Procurement				
Logistics	500000	NOK		
Software	300000	NOK		
Hardware	3000000	NOK		
sum	3800000	NOK		
Installation				
Offshore manhours	0	hrs	0	NOK
Signal /power cables			0	NOK
other (brackets etc)			500000	NOK
installation sum			500000	NOK
Initial training				
Initial training onshore	50	hrs	25000	NOK
initial training offshore	600	hrs	1200000	NOK
		sum	1225000	NOK
Operation				
Hardware	300000	NOK/year		
Software	75000	NOK/year		
Oper personell onshore	50	hrs	25000	NOK/year
Oper personell offshore	200	hrs	400000	NOK/year
		sum	425000	NOK/year
Operator training	245000	NOK/year		
End of life				
Decommisioning			200000	NOK
Scrapping			250000	NOK
Documentation	40000	hrs	20000000	NOK
		sum	20450000	NOK

IR						
Costs				**Benefits**		
Research / Construction						
Planning	250000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	900000	NOK		Reduced environmental risk	306 187	NOK/year
Installation	1340000	NOK		Increased safety	4 246 812	NOK/year
Initial training	30000	NOK		Company reputation	1 038 736	NOK/year
sum	2520000	NOK				
Operation						
Hardware	10 000	NOK/year				
Software	75 000	NOK/year		Yearly benefits	5 591 736	NOK
Operating personell	90 000	NOK/year				
Operator training	6 000	NOK/year				
sum	181 000	NOK/year				
End of life						
Decommisioning	20 000	NOK				
Scrapping	10 000	NOK				
Documentation	2 000 000	NOK				
sum	2 030 000	NOK				
NPV costs						
Research / Construction	2 520 000	NOK				
Operation	1 616 019	NOK				
End of life	703 823	NOK		Increased reliability and availability	28 426 356	NOK
LCC	4 839 843	NOK		Lifetime benefits	78 350 948	NOK
Benefits - LCC	73 511 106	NOK				



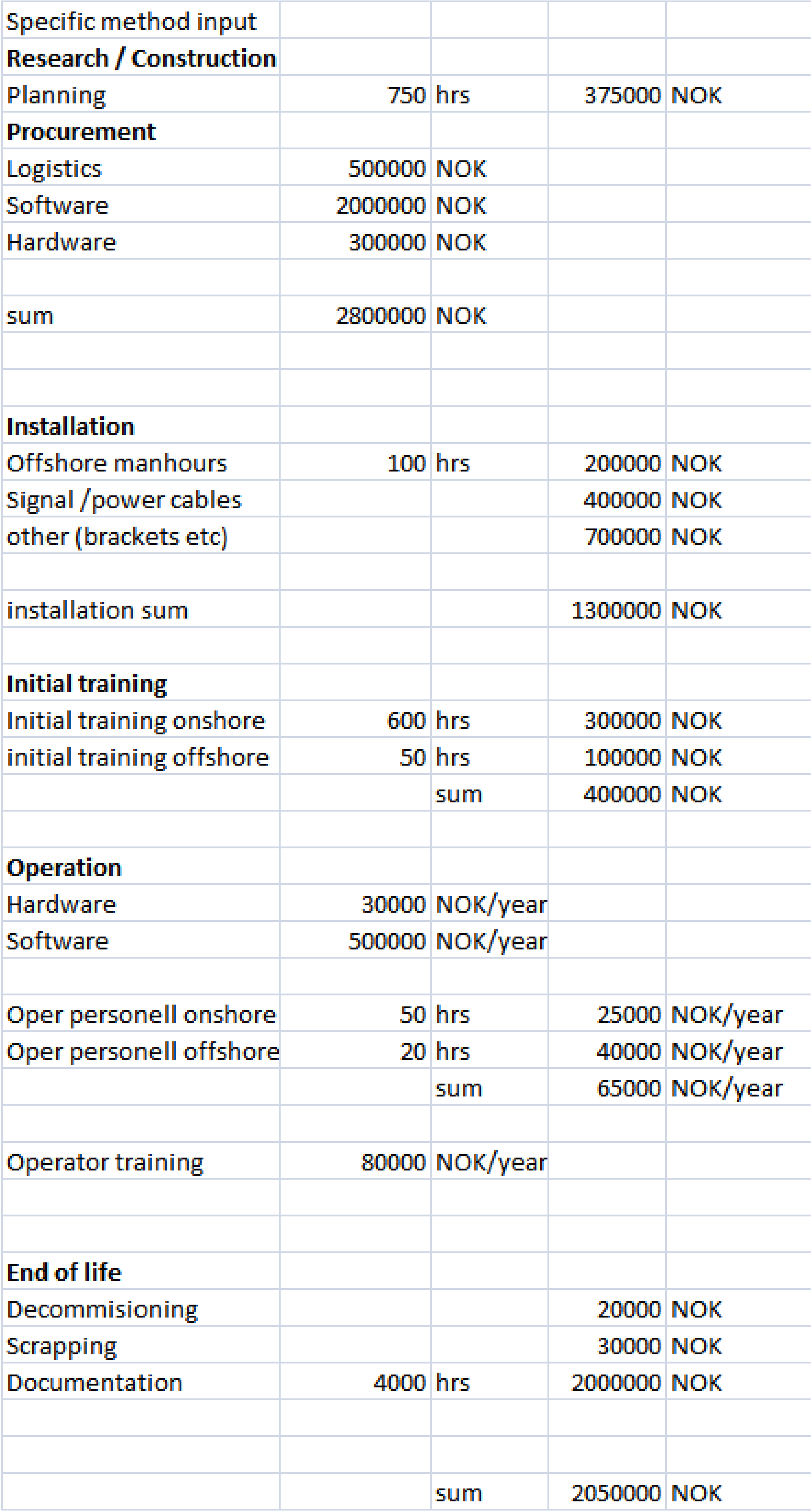
Specific method input				
Research / Construction				
Planning	500	hrs	250000	NOK
Procurement				
Logistics	500000	NOK		
Software	300000	NOK		
Hardware	100000	NOK		
sum	900000	NOK		
Installation				
Offshore manhours	20	hrs	40000	NOK
Signal /power cables			400000	NOK
other (brackets etc)			900000	NOK
installation sum			1340000	NOK
Initial training				
Initial training onshore	20	hrs	10000	NOK
initial training offshore	10	hrs	20000	NOK
		sum	30000	NOK
Operation				
Hardware	10000	NOK/year		
Software	75000	NOK/year		
Oper personell onshore	100	hrs	50000	NOK/year
Oper personell offshore	20	hrs	40000	NOK/year
		sum	90000	NOK/year
Operator training	6000	NOK/year		
End of life				
Decommisioning			20000	NOK
Scrapping			10000	NOK
Documentation	4000	hrs	2000000	NOK
		sum	2030000	NOK

IR						
Costs				**Benefits**		
Research / Construction						
Planning	500000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	2100000	NOK		Reduced environmental risk	317 963	NOK/year
Installation	1420000	NOK		Increased safety	4 597 908	NOK/year
Initial training	95000	NOK		Company reputation	1 135 847	NOK/year
sum	4115000	NOK				
Operation						
Hardware	50 000	NOK/year				
Software	150 000	NOK/year		Yearly benefits	6 051 717	NOK
Operating personell	180 000	NOK/year				
Operator training	19 000	NOK/year				
sum	399 000	NOK/year				
End of life						
Decommisioning	40 000	NOK				
Scrapping	20 000	NOK				
Documentation	2 000 000	NOK				
sum	2 060 000	NOK				
NPV costs						
Research / Construction	4 115 000	NOK				
Operation	3 562 385	NOK				
End of life	714 225	NOK		Increased reliability and availability	30 665 437	NOK
LCC	8 391 609	NOK		Lifetime benefits	84 696 876	NOK
Benefits - LCC	76 305 266	NOK				



Specific method input				
Research / Construction				
Planning	1000	hrs	500000	NOK
Procurement				
Logistics	1000000	NOK		
Software	600000	NOK		
Hardware	500000	NOK		
sum	2100000	NOK		
Installation				
Offshore manhours	60	hrs	120000	NOK
Signal /power cables			400000	NOK
other (brackets etc)			900000	NOK
installation sum			1420000	NOK
Initial training				
Initial training onshore	70	hrs	35000	NOK
initial training offshore	30	hrs	60000	NOK
		sum	95000	NOK
Operation				
Hardware	50000	NOK/year		
Software	150000	NOK/year		
Oper personell onshore	200	hrs	100000	NOK/year
Oper personell offshore	40	hrs	80000	NOK/year
		sum	180000	NOK/year
Operator training	19000	NOK/year		
End of life				
Decommisioning			40000	NOK
Scrapping			20000	NOK
Documentation	4000	hrs	2000000	NOK
		sum	2060000	NOK

Microwave						
Costs				**Benefits**		
Research / Construction						
Planning	375000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	2800000	NOK		Reduced environmental risk	97 465	NOK/year
Installation	1300000	NOK		Increased safety	2 658 965	NOK/year
Initial training	400000	NOK		Company reputation	699 191	NOK/year
sum	4875000	NOK				
Operation						
Hardware	30 000	NOK/year				
Software	500 000	NOK/year		Yearly benefits	3 455 621	NOK
Operating personell	65 000	NOK/year				
Operator training	80 000	NOK/year				
sum	675 000	NOK/year				
End of life						
Decommisioning	20 000	NOK				
Scrapping	30 000	NOK				
Documentation	2 000 000	NOK				
sum	2 050 000	NOK				
NPV costs						
Research / Construction	4 875 000	NOK				
Operation	6 026 590	NOK				
End of life	710 758	NOK		Increased reliability and availability	18 046 265	NOK
LCC	11 612 348	NOK		Lifetime benefits	48 899 024	NOK
Benefits - LCC	37 286 676	NOK				

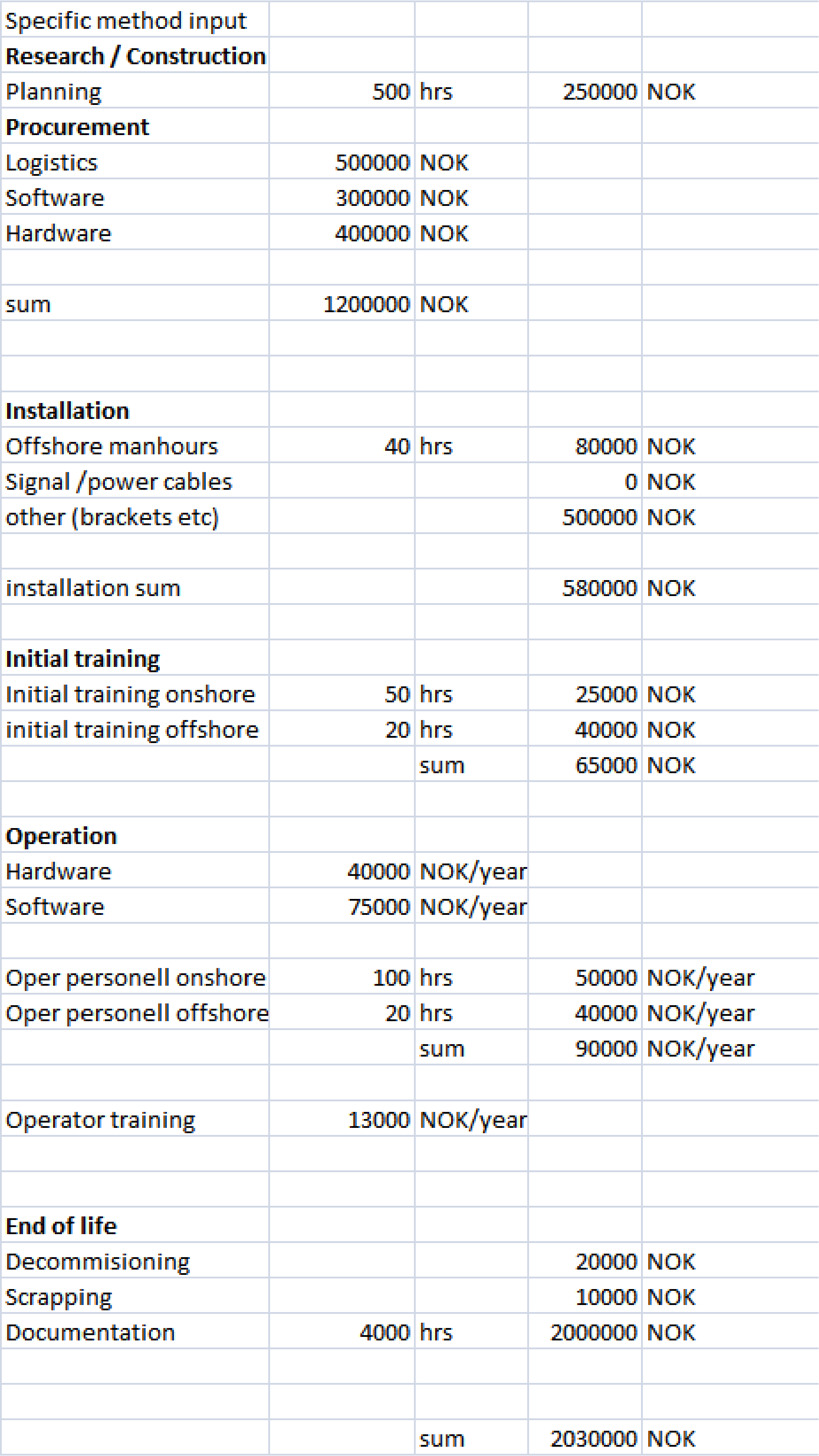


Specific method input				
Research / Construction				
Planning	750	hrs	375000	NOK
Procurement				
Logistics	500000	NOK		
Software	2000000	NOK		
Hardware	300000	NOK		
sum	2800000	NOK		
Installation				
Offshore manhours	100	hrs	200000	NOK
Signal /power cables			400000	NOK
other (brackets etc)			700000	NOK
installation sum			1300000	NOK
Initial training				
Initial training onshore	600	hrs	300000	NOK
initial training offshore	50	hrs	100000	NOK
		sum	400000	NOK
Operation				
Hardware	30000	NOK/year		
Software	500000	NOK/year		
Oper personell onshore	50	hrs	25000	NOK/year
Oper personell offshore	20	hrs	40000	NOK/year
		sum	65000	NOK/year
Operator training	80000	NOK/year		
End of life				
Decommisioning			20000	NOK
Scrapping			30000	NOK
Documentation	4000	hrs	2000000	NOK
		sum	2050000	NOK

Neutron Backscatter						
Costs				**Benefits**		
Research / Construction						
Planning	500000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	3000000	NOK		Reduced environmental risk	54 147	NOK/year
Installation	500000	NOK		Increased safety	1 477 203	NOK/year
Initial training	1225000	NOK		Company reputation	388 253	NOK/year
sum	5225000	NOK				
Operation						
Hardware	200 000	NOK/year				
Software	125 000	NOK/year		Yearly benefits	1 919 603	NOK
Operating personell	625 000	NOK/year				
Operator training	245 000	NOK/year				
sum	1 195 000	NOK/year				
End of life						
Decommisioning	200 000	NOK				
Scrapping	250 000	NOK				
Documentation	20 000 000	NOK				
sum	20 450 000	NOK				
NPV costs						
Research / Construction	5 225 000	NOK				
Operation	10 669 297	NOK				
End of life	7 090 241	NOK		Increased reliability and availability	9 997 041	NOK
LCC	22 984 538	NOK		Lifetime benefits	27 135 800	NOK
Benefits - LCC	4 151 262	NOK				

Specific method input				
Research / Construction				
Planning	1000	hrs	500000	NOK
Procurement				
Logistics	500000	NOK		
Software	500 000	NOK		
Hardware	2000000	NOK		
sum	3000000	NOK		
Installation				
Offshore manhours	0	hrs	0	NOK
Signal /power cables			0	NOK
other (brackets etc)			500000	NOK
installation sum			500000	NOK
Initial training				
Initial training onshore	50	hrs	25000	NOK
initial training offshore	600	hrs	1200000	NOK
		sum	1225000	NOK
Operation				
Hardware	200000	NOK/year		
Software	125000	NOK/year		
Oper personell onshore	50	hrs	25000	NOK/year
Oper personell offshore	300	hrs	600000	NOK/year
		sum	625000	NOK/year
Operator training	245000	NOK/year		
End of life				
Decommisioning			200000	NOK
Scrapping			250000	NOK
Documentation	40000	hrs	20000000	NOK
		sum	20450000	NOK

Passive Acoustic						
Costs				**Benefits**		
Research / Construction						
Planning	250000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	1200000	NOK		Reduced environmental risk	44 278	NOK/year
Installation	580000	NOK		Increased safety	896 797	NOK/year
Initial training	65000	NOK		Company reputation	189 406	NOK/year
sum	2095000	NOK				
Operation						
Hardware	40 000	NOK/year				
Software	75 000	NOK/year		Yearly benefits	1 130 481	NOK
Operating personell	90 000	NOK/year				
Operator training	13 000	NOK/year				
sum	218 000	NOK/year				
End of life						
Decommisioning	20 000	NOK				
Scrapping	10 000	NOK				
Documentation	2 000 000	NOK				
sum	2 030 000	NOK				
NPV costs						
Research / Construction	2 095 000	NOK				
Operation	1 946 365	NOK				
End of life	703 823	NOK		Increased reliability and availability	8 126 520	NOK
LCC	4 745 189	NOK		Lifetime benefits	18 219 776	NOK
Benefits - LCC	13 474 588	NOK				



Specific method input				
Research / Construction				
Planning	500	hrs	250000	NOK
Procurement				
Logistics	500000	NOK		
Software	300000	NOK		
Hardware	400000	NOK		
sum	1200000	NOK		
Installation				
Offshore manhours	40	hrs	80000	NOK
Signal /power cables			0	NOK
other (brackets etc)			500000	NOK
installation sum			580000	NOK
Initial training				
Initial training onshore	50	hrs	25000	NOK
initial training offshore	20	hrs	40000	NOK
		sum	65000	NOK
Operation				
Hardware	40000	NOK/year		
Software	75000	NOK/year		
Oper personell onshore	100	hrs	50000	NOK/year
Oper personell offshore	20	hrs	40000	NOK/year
		sum	90000	NOK/year
Operator training	13000	NOK/year		
End of life				
Decommisioning			20000	NOK
Scrapping			10000	NOK
Documentation	4000	hrs	2000000	NOK
		sum	2030000	NOK

Ultrasonic						
Costs				**Benefits**		
Research / Construction						
Planning	250000	NOK		Reduction of maintenance and inspections	-	NOK/year
Procurement	2800000	NOK		Reduced environmental risk	135 340	NOK/year
Installation	1900000	NOK		Increased safety	1 066 489	NOK/year
Initial training	175000	NOK		Company reputation	223 858	NOK/year
sum	5125000	NOK				
Operation						
Hardware	200 000	NOK/year				
Software	75 000	NOK/year		Yearly benefits	1 425 687	NOK
Operating personell	65 000	NOK/year				
Operator training	35 000	NOK/year				
sum	375 000	NOK/year				
End of life						
Decommisioning	20 000	NOK				
Scrapping	30 000	NOK				
Documentation	2 000 000	NOK				
sum	2 050 000	NOK				
NPV costs						
Research / Construction	5 125 000	NOK				
Operation	3 348 106	NOK				
End of life	710 758	NOK		Increased reliability and availability	7 533 210	NOK
LCC	9 183 863	NOK		Lifetime benefits	20 262 145	NOK
Benefits - LCC	11 078 282	NOK				

Specific method input				
Research / Construction				
Planning	500	hrs	250000	NOK
Procurement				
Logistics	500000	NOK		
Software	300000	NOK		
Hardware	2000000	NOK		
sum	2800000	NOK		
Installation				
Offshore manhours	150	hrs	300000	NOK
Signal /power cables			600000	NOK
other (brackets etc)			1000000	NOK
installation sum			1900000	NOK
Initial training				
Initial training onshore	150	hrs	75000	NOK
initial training offshore	50	hrs	100000	NOK
		sum	175000	NOK
Operation				
Hardware	200000	NOK/year		
Software	75000	NOK/year		
Oper personell onshore	50	hrs	25000	NOK/year
Oper personell offshore	20	hrs	40000	NOK/year
		sum	65000	NOK/year
Operator training	35000	NOK/year		
End of life				
Decommisioning			20000	NOK
Scrapping			30000	NOK
Documentation	4000	hrs	2000000	NOK
		sum	2050000	NOK