Life Cycle Cost Model for Condition Monitoring of heat exchanger

Master Thesis, Faculty of Engineering Science and Technology

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PREFACE

This project is the M.Sc. Thesis of the author, which graduates from the Department of Marine Technology of the Faculty of Science and Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim. This thesis counts for 30 credits and the estimated work time is 800 hours. Professor Magnus Rasmussen has acted as teaching supervisor during the thesis.

The thesis is written in close collaboration with the Center for Integrated Operation in the Petroleum Industry (IO Center). The IO Center is a corporation between NTNU, Sintef/Marintek and Institute for Energy Technology (http://www.ntnu.no/iocenter). Torgeir Brurok has been the contact person from Marintek.

The work has been very exciting and challenging due to the focus from the IO Center on this special field. I am grateful for the opportunity to perform a study together with the IO Center and their participant. The thesis has been challenging since it is a field where there have been little research before.

I would use the opportunity to thank Professor Magnus Rasmussen and Torgeir Brurok for guidance through the project. I would also thank Harald Rødseth and John Cristian Brembo from Marintek for good input. At last I would like to thank the inspection crew from Aker Solutions, for relevant information from the field regarding inspection on a shell and tube heat exchanger.

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Date Daniel Melingen

SUMMARY

Shell and tube heat exchangers (H/X) are widely used in the industry. Offshore, the H/Xs are used as heaters or coolers. In this thesis it is assumed that the H/X function is to cool down gas or oil. A large number of different configuration of H/X exist today, single pass and u-bend is most used offshore. This thesis looks further into the most used H/X on an offshore platform single pass.

The thesis is dealing with formulas that indicate performance of an H/X. It is normal to have the ability to measure parameter as pressure, temperature and mass flow. With these parameters the efficiency of the heat exchanger can be calculated. In order to use the efficiency the reference efficiency, from when the H/X was new must be present. It is also possible to measure the performance over time. Calculations of efficiency give an indication of failure. However, it gives limited information what failure modes occurred.

There are present three different maintenance strategies, fixed time, fixed age and condition monitoring. Fixed time and fixed age is beneficial to use on critical items, and when condition monitoring (CM) has low probability to find failures or is impossible to use. If the failure is developing fast fixed time and fixed age could be beneficial to use. CM should give a good indication on the condition of the different items. This makes it easier to plan when a maintenance action should be carried out.

Six different CM methods are present in the thesis and used as a basis of the analysis. The different methods are Ultrasonic testing (UT), Eddy Current Testing (ECT), Visual inspection (VI), Magnetic Particle inspection (MPI) and HXAM-ST. These are methods which are widely used on H/Xs.

Failure modes and maintenance items used in the thesis are collected from source OREDA (1). The maintainable items are present in a block diagram. Fault tree analysis and Failure Mode and Effect (FMEA) analysis, shows that the most common failure cause is corrosion, erosion and external forces. The FMEA connects the failure modes with the CM methods.

Probability to detect failures with the different failure modes are based on assumption with values from 0-1. The methods have different characteristics and the probability to find failures are based on these characteristics. ECT is specially classified on finding failures in the tube bundle. VI is a more general method who is able to find failure over a wide range. MPI is a method used on shell while the H/X is in operation. HXAM-ST is a method on development stage and it monitors the H/X performance as pressure, temperature and mass flow.

The Life Cycle Cost (LCC) analysis is based on the report (2), and has been modified from a LCC for an item to a LCC regarding CM methods. To identify the different cost elements a cost break down structure is made. The CBS is decomposed into capital expenditure (CAPEX) and operation expenditure (OPEX). Pareto diagram is made to show the three largest costs regarding OPEX. On five of the methods personnel cost is the significant highest cost. On HXAM-ST that does not need personnel, documentation is the highest operational cost.

Benefits are calculated from less down time, less injuries and less death due to failure. In spite of this, factored benefits are taken into consideration. Factored benefit is based on issues as operation safety, personnel safety, technical fitness for purpose and operational issues.

A cost benefit model is made where both LCC and benefits from performing the CM method are taken into consideration. The model shows that UT is the most cost effective method, and MPI is the only method that has larger costs than benefits. HXAM-ST is a Non Intrusive method, and gives the ability to introduce Condition Based Maintenance (CBM).

Redundancy is the input parameter which has the largest impact on the model. The largest benefit with the methods is less downtime due to detection of the failure. If redundancy is present this benefit would disappear, since almost no downtime would appear. Changes in the operational condition like more sand or a more corrective environment would also have a large impact on the failure rate for the different failure modes.

The main outcome from sensitivity analysis is that method as: VI, HXAM-ST and HLT with low LCC cost scores when the benefits are decreasing and the more expensive methods as UT and ECT scores when the benefits is increasing, in spite of high probability to detect failures.

PROBLEM DESCRIPTION

A LCC (Life Cycle Cost) Model for Condition Monitoring of Heat Exchangers

(En LCC (Livssykluskostnad) model for tilstandskontroll av varmevekslere)

Non-Intrusive Inspection (NII) of heat exchangers, and in particular monitoring of their internals remains a challenge. The industry is asking for reliable NII methods with potential for on-line continuous monitoring, where equipment status easily can be presented to decision makers. Being able to accurately monitor the condition of heat exchangers and to efficiently present the information to decision makers will potentially decrease revenue losses through fewer and better prepared maintenance actions. Within the Center for Integrated Operations in the Petroleum Industry (IO Center) there is an interest towards increasing the implementation of Condition Monitoring (CM) methods for heat exchangers. However, the cost of this must be justified against benefits that can be achieved by implementing the methods.

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

1. CM methods:
    a. With a fault tree for heat exchangers as a basis, identify and describe the different methods applicable for CM of heat exchangers and arrange them according to the following categories: Thermodynamic-, material-, and flow medium-monitoring.
    b. Discuss probability of detection and sensitivity of the methods in relation to different failures and failure mechanisms.
2. Cost models:
    a. Do a literature survey and identify/describe model(s) for Life Cycle Cost (LCC) analysis.
    b. Describe input and output parameters that are used in the model(s)
3. Cost-benefit modelling:
    a. Develop a model for cost-benefit assessments of various CM methods for shell-and-tube heat exchangers.
    b. Discuss the various input parameters and the influence on the model with respect to operational conditions.
    c. Perform a sensitivity analysis of the model.

The work should be carried out in close cooperation with MARINTEK and the IOCenter 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

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Appendix 1: Fault Tree Analysis

Appendix 2: Failure Mode and Effects analysis

Appendix 3: The Model for Cost-Benefit analysis

ABBREVIATIONS:

CAPEX	Capital expenditure
ART	Acoustic Resonance Technology
CBA	Cost Benefit analysis
CBM	Condition Based Maintenance
CBS	Cost Breakdown Structure
CM	Condition monitoring
CMSP	Corrective maintenance spare parts
ECT	Eddy Current testing
FMEA	Failure Modes and Effects analysis
FTA	Fault Tree analysis
HLT	Helium leak testing
HXAM-ST	Heat Exchanger Asset Monitor –Shell and Tube

H/X	Heat Exchanger
MDT	Mean down time
MPI	Magnetic Particle inspection
MTBM	Mean Time between Maintenance
MTBR	Mean Time between Replacements
NDT	Non Destructive methods
NII	Non intrusive methods
NOK	Norwegian Krone
NPV	Net Present Value
OPEX	Capital expenditure
PM	Preventive Maintenance
PMSP	Preventive maintenance spare parts
R&D	Research and Develop cost
RBI	Risk Based Inspection
RCM	Reliability Centered Maintenance
REVLOSS	Revenue Loss
$SMSP$	Servicing maintenance spare parts
USD	United States Dollar
UT	Ultrasonic testing
VI	Visual inspection

Lowercase

c_{de}	[NOK/death]	Cost per death
c_f	[USD->NOK]	Conversion factor
c_i	[NOK/injury]	Cost per injury
c_p	[kJ/kg*K]	Constant pressure specific heat
k	[W/m^2K]	Heat transfer coefficient
i	[-]	Current year in the cycle
f	[-]	Inflation
n	[-]	The specific year in the life cycle costing period
m_{flow}	[kg/s]	Mass flow

p	[-]	Rent
p'	[-]	Rent adjusted with inflation

Uppercase

A	[m^2]	Area of tubes
B_i	[NOK]	Benefits for year i
B_{CM}	[NOK/y]	Benefits using CM-inspection per year
E	[-]	Equipment transportation (1 or 0)
C_{admin}	[NOK/h]	Cost administration onshore per hour
C_d	[NOK/h]	Cost per downtime hour
C_{de}	[NOK/y]	Cost of death per year
C_{dPL}	[NOK/y]	Cost downtime due to production loss per year
C_g	[USD/m^3]	Cost of gas
C_H	[NOK/trip]	Cost helicopter round trip
C_{HP}	[NOK/h]	Personnel cost per hour
C_i	[NOK/y]	Cost of injuries per year
$CMPS$	[-]	Average annual corrective maintenance spares consumption
C_o	[USD/barrel]	Cost of oil
C_p	[NOK/y]	Cost per year personnel
C_{PL}	[NOK]	Cost per year planning
C_{PR}	[NOK/m]	Cost per month practical education
C_T	[NOK/y]	Training cost per year
C_{TE}	[NOK/h]	Cost per hour theoretical education
C_{TR}	[NOK/y]	Transportation cost per year
D_C	[h]	Downtime due to critical failure
D_d	[h]	Downtime due to degraded failure
D_i	[h]	Downtime due to incipient failure
DS_{CM}	[h]	Downtime saved due to CM inspection
H_y	[h]	Hours per year downtime due to failure mode
F(i)	[-]	Probability for down time

F_{yc}	[Failure/y]	Failure per year critical failure
F_{yd}	[Failure/y]	Failure per year degraded failure
F_{yi}	[Failure/y]	Failure per year incipient failure
NH_{PL}	[h]	Number of hours planning onshore
NH_{PR}	[Month]	Number of month's practical education
NH_{TE}	[h]	Number of hour's theoretical education
NP_i	[P/insp]	Number of persons involved in the inspection
NP_E	[P]	Number of persons educated
NPV	[NOK]	Net present value
N_i	[-]	Number of inspection per year
NP_{TR}	[P]	Number of persons needed to be transported
P_{de}	[-]	Probability for death
P_{df}	[-]	Probability to detect failure
P_g	[m^3/day]	Production of gas
P_i	[-]	Probability for injuries
$PMSP$	[-]	Average annual preventive maintenance spare consumption
P_o	[Barrel/day]	Production of oil
PR(i)	[-]	oil price in year i
Q_{flow}	[W]	Heat transfer rate
V(i)	[-]	Volume not produced in year i
WH	[h]	Number of hours carrying out inspection
W_y	[h]	Number of hours in operation per year

Greek symbols:

ε_v	[-]	Efficiency of H/X
θ_i	[K]	Temperature into H/X
θ_o	[K]	Temperature out of H/X
$\Delta\theta_m$	[K]	Average temperature difference
λ_T	[-]	Failure rate

1 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

In the latest years, numbers of shutdowns has increased due to leakage from heat exchangers (H/Xs), causing changes in production, more sand in the process fluids, phase changes and extending of life for installations.

In spite of this, the industry is asking for more reliable Non Instrusive methods with potential for online monitoring, where data easily can be present for decision makers. Integrated Operation center (Marintek) has a project on these subjects now. The thesis can be seen as a start of this project. On the other hand, NII methods are not much used as Condition monitoring methods on H/Xs today. Furthermore, the analysis in the thesis would focus more on CM-methods used today.

The industry is interested in a cost-benefit analysis to make sure that investments are cost effective.

1.2 SCOPE OF WORK

The work has been carried out individually with counselling from supervisor Professor Magnus Rasmussen from NTNU and Torgeir Brurok from Marintek.

The work has been concentrate around CM methods used today. A Cost benefit analysis (CBA) is comparing six different CM methods. The methods are Ultrasonic testing (UT), Eddy Current testing (ECT), Visual inspection (VI), Magnetic Particle inspection (MPI), Helium leak test (HLT) and HXAM-ST.

A Bloc diagram, Fault Tree analysis (FTA) and Failure Mode and Effects analysis (FMEA) is made to connect failure modes with the condition monitoring types. A literature survey between different Life Cycle Cost analyzing (LCC) has been conducted. Most of LCC analysis is based on items. The author has adapted it to a LCC for CM methods.

“Cost Benefit Analysis Methods for Condition Monitoring” (3) is used as literature when the benefits from the methods should be consider up on different factors as operational safety, personnel safety technical fitness for purpose and operational issues.

The focus has been development of a model, not gathering cost information on different methods. As a result, it is difficult to achieve the information from the industry, yet the author hopes that the model can be used later with reliable data.

The software used on the thesis is Microsoft office Excel for the analysis and Failure Mode and Effect analysis (FMEA), and Cara for the Fault Tree analysis (FTA).

1.3 STRUCTURE OF THESIS

Chapter 2 is dealing with an explanation of a generally shell and tube heat exchanger.

Chapter 3 shows formulas used to describe the condition of the heat exchanger, it also describes material used on a heat exchanger and some design criteria for a heat exchanger.

Chapter 4 is dealing with different maintenance strategies. The strategies are fixed time principle, fixed age principle and condition monitoring.

Chapter 5 contains description of the CM-methods evaluated in the cost benefit model.

Chapter 6 involves approaches to attach failure modes with CM-methods. The methods used are block diagram, Failure Mode Effect and analysis (FMEA) and Fault Tree analysis (FTA):

Chapter 7 shows the theory behind the Life Cycle Cost analysis.

Chapter 8 develops an LCC analysis for the six different CM methods.

Chapter 9 is dealing with the theory behind the benefit analysis.

Chapter 10 is developing of the model, and shows the results from the cost benefit analysis. It also involves comments on input and output parameters and a sensitivity analysis.

2 SHELL AND TUBE HEAT EXCHANGER

A shell and tube heat exchanger (H/X) is, as the name indicates, an H/X with a shell where one of the fluids flows and a tube bundle where the other fluid flows. H/Xs can be used as heaters or coolers. It is used in a variety of applications that includes oil coolers in power plants and process heat exchangers in the petroleum-refining and chemical industries. A lot of different configurations are possible mainly in the detailed features of construction and provisions for differential thermal expansion between the tubes and shell. The flow can be either in parallel flow or counter flow as shown in figure 1. (4)

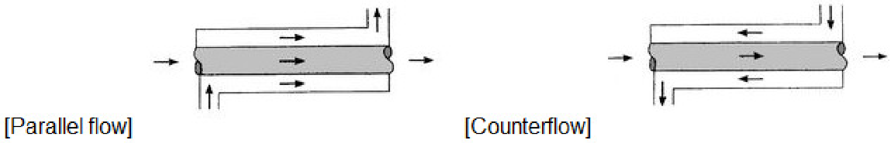


FIGURE 1: DIFFERENT TYPES OF SIMPLE HEAT EXCHANGERS (4)

Figure 2 shows a single pass heat exchanger. The mediums have one entry and one exit for both process and utility medium. This is the most used configuration offshore today. (5).

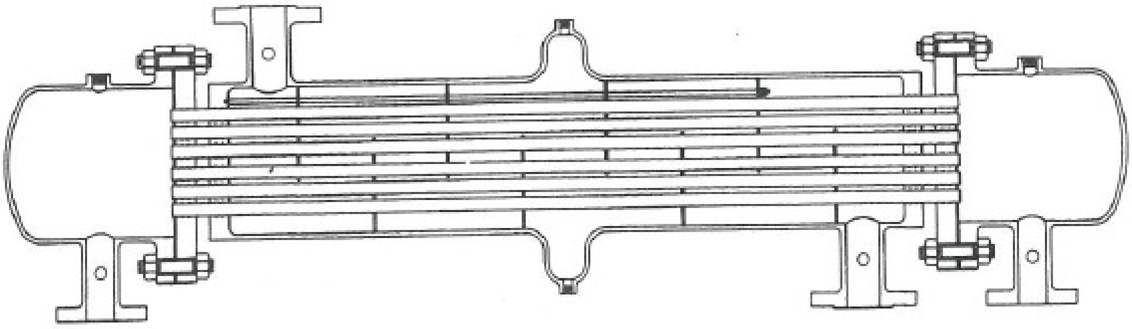


FIGURE 2: A SINGLE PASS SHELL AND TUBE HEAT EXCHANGER (4)

The second most used shell and tube H/X are with a U-bend (5), as shown in figure 3. The tube medium is flowing back and forth this to get better heat conduction. U-bend H/X is also shorter than the single pass H/X. This is beneficial offshore where the area is limited.

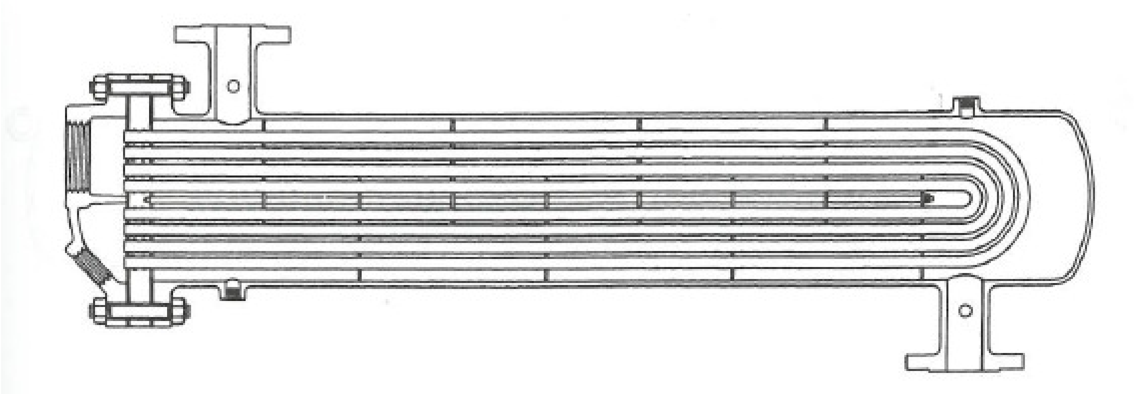


FIGURE 3: A U-BEND HEAT EXCHANGER (4)

In this thesis a single pass heat exchanger will be used since this is most widespread in the offshore sector today. In the analysis later on, the flow of process medium is in the tubes. The flow of utility medium is in the shell side and it is assumed that the utility medium is sea water (widely used and readily available offshore). Further on, the process medium is defined as oil or gas. The configuration of a shell and tube heat exchanger is shown in the figure below.

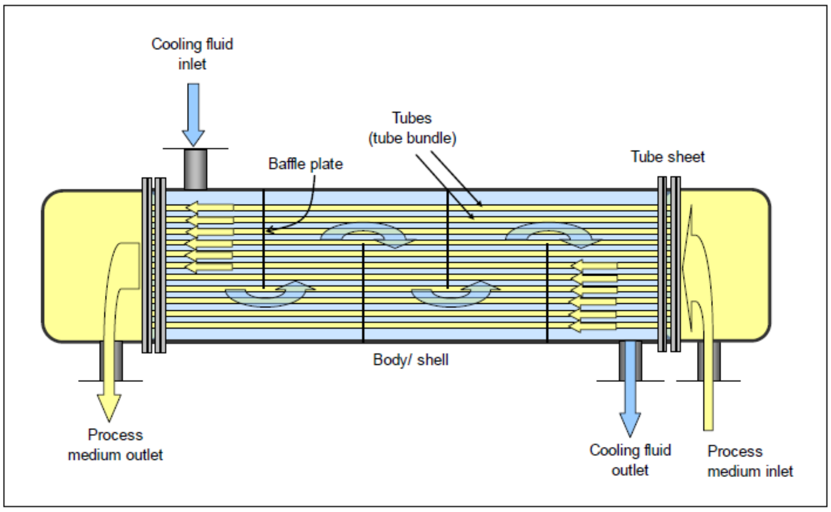


FIGURE 4: CONFIGURATION OF A SHELL AND TUBE HEAT EXCHANGER USED FURTHER IN ANALYSIS (6)

2.1 EXPLANATION OF THE DIFFERENT PARTS ON A HEAT EXCHANGER (7)

2.1.1 BODY/SHELL

The body has a rectangular or circular shape. The material needs to be solid to avoid leakage, since the cooling fluid flows inside the body. The most used material is galvanized steel. (8)

2.1.2 TUBES

The process medium flows through the tubes. It is important to choose material from given criteria. The material must be able to transfer heat well, because the cooling medium outside cools down the process medium inside. It must withstand stress corrosion over a certain amount of time. (8)

2.1.3 BAFFLE PLATES

The baffle plate has two features, one is to support the tubes and the other is to ensure an effective flow for the cooling medium. By forcing the cooling medium around the baffle plates, all of the tubes is equally cooled down. (8)

2.1.4 TUBE SHEET

The function of tube sheet is to support the tubes.

3 FORMULAS TO INDICATE PERFORMANCE OF A SHELL AND TUBE HEAT EXCHANGER

This chapter would consider some formulas used to determine the condition of the H/X. It would also give some general approach on design criteria as material, water speed and the most common failure modes.

The temperature difference between the warm and the cold medium are usually not constant along the tubes. Thus the heat flux will diversify along the tube. On behalf of this an effective average temperature difference must be discover. (9)

The material quality depends on the fluids corrosive characteristics. If sea water is used inside the pipe AL-Ms, Cu/Ni-connections are used. In new constructions where reliability is important, the expensive material titan is used. On the shell welded steel is used, on the end locks cast iron or in some cases brass and bronze alloy. (9)

3.1 CALCULATIONS OF AVERAGE TEMPERATURE DIFFERENCE AND HEAT STREAM (9)

The heat flow through a wall between two mediums can be written as (9):

$$\mathbf{Q_{flow} = k * A * (\theta_i - \theta_o)} \qquad \textbf{(3-1)}$$

Q_{flow}: Heat transfer rate
k: Heat transfer coefficient
θ_i: Temperature difference in
θ_o: Temperature difference out

If a flow take place alongside a pipe, both θ_i and $\theta_o$would vary. Because the heat flow, transfers from one medium to the other medium, that is why an expression for average temperature difference must be established. (9)

With the symbols described in the figure below, a derivation expression can be made for a little segment with area dA. (9)

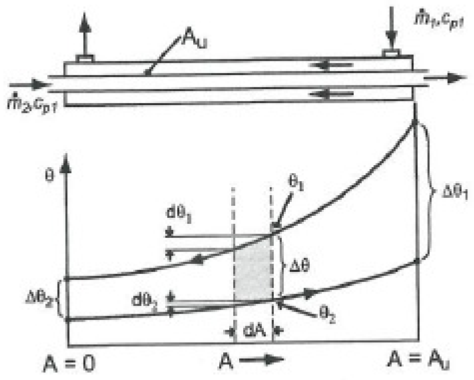


FIGURE 5: HEAT DIFFERENT ON MEDIUMS IN AN H/X (9)

The heat current that transfers can be described as (9):

$$\mathbf{dQ = k * dA * (\theta_1 - \theta_2) = k * dA * \Delta\theta} \qquad (3\text{-}2)$$

The energy balance between the two fluids gives:

$$\boldsymbol{dQ_{flow} = m_{1(flow)} * C_{p1} * d\theta_1 = m_{2(flow)} * C_{p2} * d\theta_2} \qquad (3\text{-}3)$$

$$\boldsymbol{dQ_{flow} = W_1 * d\theta_1 = W_2 * d\theta_2 \text{ where } W_1 = m_{1(flow)} * C_{p1} \;\; W_2 = m_{2(flow)} * C_{p2}} \qquad (3\text{-}4)$$

This gives:

$$\boldsymbol{d\theta_1 = \frac{dQ_{flow}}{W_1} \;\; d\theta_2 = \frac{dQ_{flow}}{W_2}} \qquad (3\text{-}5)$$

Further:

$$\boldsymbol{d(\Delta\theta) = d(\theta_1 - \theta_2) = d\theta_1 - d\theta_2} \qquad (3\text{-}6)$$

If you combined (3.2) and (3.6):

$$\boldsymbol{d(\Delta\theta) = \left(\frac{1}{W_1} - \frac{1}{W_2}\right) * \; dQ_{flow}} \qquad (3\text{-}7)$$

Integrated from the heat side’s inlet to outlet:

$$\boldsymbol{\left(\frac{1}{W_1} - \frac{1}{W_2}\right) * \; Q_{flow} = \Delta\theta_1 \; - \Delta\theta_2} \qquad (3\text{-}8)$$

If you combined (3.2) and (3.7):

$$\boldsymbol{d(\Delta\theta) = \left(\frac{1}{W_1} - \frac{1}{W_2}\right) * k * dA * \Delta\theta} \qquad (3\text{-}9)$$

$$\boldsymbol{\left(\frac{1}{W_1} - \frac{1}{W_2}\right) * k * dA = \frac{d(\Delta\theta)}{\Delta\theta}} \qquad (3\text{-}10)$$

Assume k=constant and integrate between the same limits as above:

$$\boldsymbol{\left(\frac{1}{W_1} - \frac{1}{W_2}\right) * k * A = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln{(\Delta\theta_1/\Delta\theta_2)}}} \qquad (3\text{-}11)$$

Divide (3.8) and (3.11):

$$\frac{Q_{flow}}{k*A} = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1/\Delta\theta_2)} \qquad (\ 3\text{-}12)$$

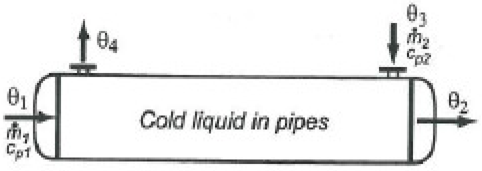
The right side is the same here as effective average temperature difference.

$$\Delta\theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1/\Delta\theta_2)} \qquad (\ 3\text{-}13)$$

In borderline case when $\Delta\theta_1 \rightarrow \Delta\theta_2$is $\Delta\theta_m = \Delta\theta_1$, thus constant temperature through the cooler. Generally when it is small difference between$\Delta\theta_1 and \Delta\theta_2$, a arithmetic average value between these can be used. (9)

3.2 THE HEAT EXCHANGERS HEAT BALANCE (9)

In an H/X measurement as temperature, pressure and mass flow are measured. In spite of this it is possible to calculate the total heat transfer. This is important when projecting an H/X. It is also useful in terms of CM. The heat balance for a heat exchanger can be described as: (9)



$$Q_{flow} = m_{flow\,2} * (h_{22} - h_{21}) = m_{flow\,2} * c_{p2} * (\theta_2 - \theta_1) \quad (3\text{-}14)$$

$$Q_{flow} = m_{flow\,1} * (h_{13} - h_{14}) = m_{flow\,1} * c_{p1} * (\theta_3 - \theta_4) \quad (3\text{-}15)$$

For heat transfer:

$$Q_{flow} = k * A * \frac{(\theta_3 - \theta_2) - (\theta_4 - \theta_2)}{\ln[(\theta_3 - \theta_2)/(\theta_4 - \theta_2)]} \qquad (3\text{-}16)$$

The logarithmic average temperature is useful regarding analyzes of an H/X when in and out temperature is known or easy to determine. The formula above can then be calculated and heat quantity, surface area or coefficient of thermal transmittance can be determined. (9)

3.3 THE HEAT EXCHANGERS EFFICIENCY (9)

The efficiency of a heat exchanger can be measured through the formula Efficiency=ε=(real conduction)/(maximum conduction). The real conduction can be calculated either with looking at the lost energy on the hot medium, or looking at the received energy in the cold medium. (9)

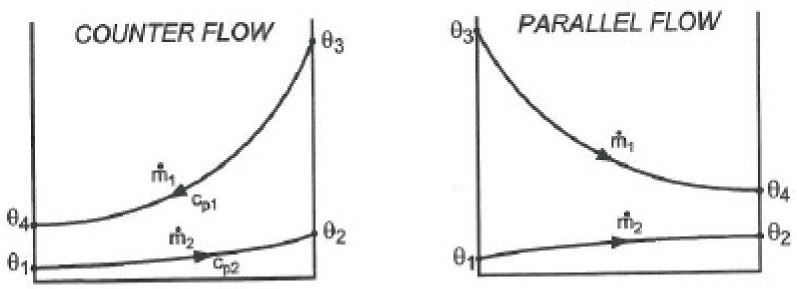


FIGURE 6: HEAT DIFFERENT IN AN H/X COUNTER FLOW AND PARALLEL FLOW (9)

The maximum conduction can only be achieved if one of the medium goes through a temperature difference equal to the maximum temperature difference in the H/X. This is the difference between the input temperatures for the different mediums. The medium that goes through the largest temperature difference is the medium with smallest $m_{(flow)} * C_p$ value. Since the energy balance necessitate that received energy from one medium is the same as delivered energy from the other medium. If the medium with the largest $m_{(flow)} * C_p$ value goes through the largest difference in temperature, the difference will exceed the maximum temperature difference. This is impossible, and the maximum temperature difference can be expressed as: (9)

$$\boldsymbol{Q_{flow} = (m_{flow} * c_p)_{min} * (\theta_3 - \theta_1)} \qquad (3\text{-}17)$$

Depending on what medium that has the lowest $m_{(flow)} * C_p$ value, the efficiency can be written as: (9)

$$\boldsymbol{\varepsilon_v = \frac{m_{flow\ 1} * c_{p1} * (\theta_3 - \theta_4)}{m_{flow\ 1} * c_{p1} * (\theta_1 - \theta_3)} = \frac{(\theta_3 - \theta_4)}{(\theta_1 - \theta_3)}} \qquad (3\text{-}18)$$

$$\boldsymbol{\varepsilon_v = \frac{m_{flow\ 2} * c_{p2} * (\theta_2 - \theta_1)}{m_{flow\ 2} * c_{p2} * (\theta_3 - \theta_1)} = \frac{(\theta_2 - \theta_1)}{(\theta_3 - \theta_1)}} \qquad (3\text{-}19)$$

3.4 MATERIAL USED IN HEAT EXCHANGERS OFFSHORE.

Different materials are used on an H/X offshore. In the latest years expensive materials as titan is used on tubes to prevent corrosion. However there are some problems with titan, the main problem is fretting. Fretting is caused of vibration or movements between tubes and baffle plates. The materials can be divided into three different categories: (10)

Non Ferritic is expensive but since it involves no corrosion it is used in H/Xs. Titan and stainless steel is often used. Although there are almost no problem regarding corrosion, fretting can occur and has been a large problem on thus material types. (10)

Midly Ferettic is, as the name indicates, something in the middle. Materials as Duplex and Sea cure are used. Duplex are corrosion resistant because it is alloyed with chrome. Sea cure are a patented alloy who secure against corrosion. (11) Consequently, pitting is a problem on this material, when the protective layer is wear down or if it is high temperature, corrosion can occur.

Ferritic steel is normal steel. This has all the failure modes normal for steel. Ferritic steel has a yearly corrosion rate and makes it easier to estimate remaining lifetime. (5)

3.5 WATER SPEED

Water speed below 0,8m/s is not desirable in seawater system, since it cause larger risk for marine organism to get stuck on the tube surface. This can lead to covering corrosion and results in less heat conduction. Larger water speed results in higher heat transmission coefficient. On the other hand, corrosion and erosion attack occurs when the water speed exceed an upper limit. For usual tube material in sea water system the following water speeds is recommended: (9)

Aluminium – brass	0,8-2,5 m/s
90/10 copper- nickel	0,8-3,0 m/s
70/30 copper- nickel	0,8-4,0m/s

The highest water speeds are too high and will cause fouling in an H/X. A recommended speed is about 0,5 m/s below the upper limits. (9)

3.6 FOULING

Fouling can be caused of organic components in the mediums which get stuck on the tube surface. Another possibility can be caused of bacteria or not organic particles that hang on or break on. It is today little or no data on these mechanisms. (9)

Common for most of the fouling types is that the layers are thin, and that the coefficient of thermal conductivity is low. That leads to high thermal conductance resistance, hence a reduction in the k-value. In addition, H/Xs are ordered with reserve surface. This means that the H/X is over dimension in the start, and has 100% heat exchanging after some fouling (9)

4 MAINTENANCE STRATEGIES:

There are different types of maintenance, planed and unforeseen. All maintenance should be planed, but you will always get some unforeseen maintenance. One example is when an item according to Mean Time Before Failure (MTBF) should not fail through the lifetime fails. (12)

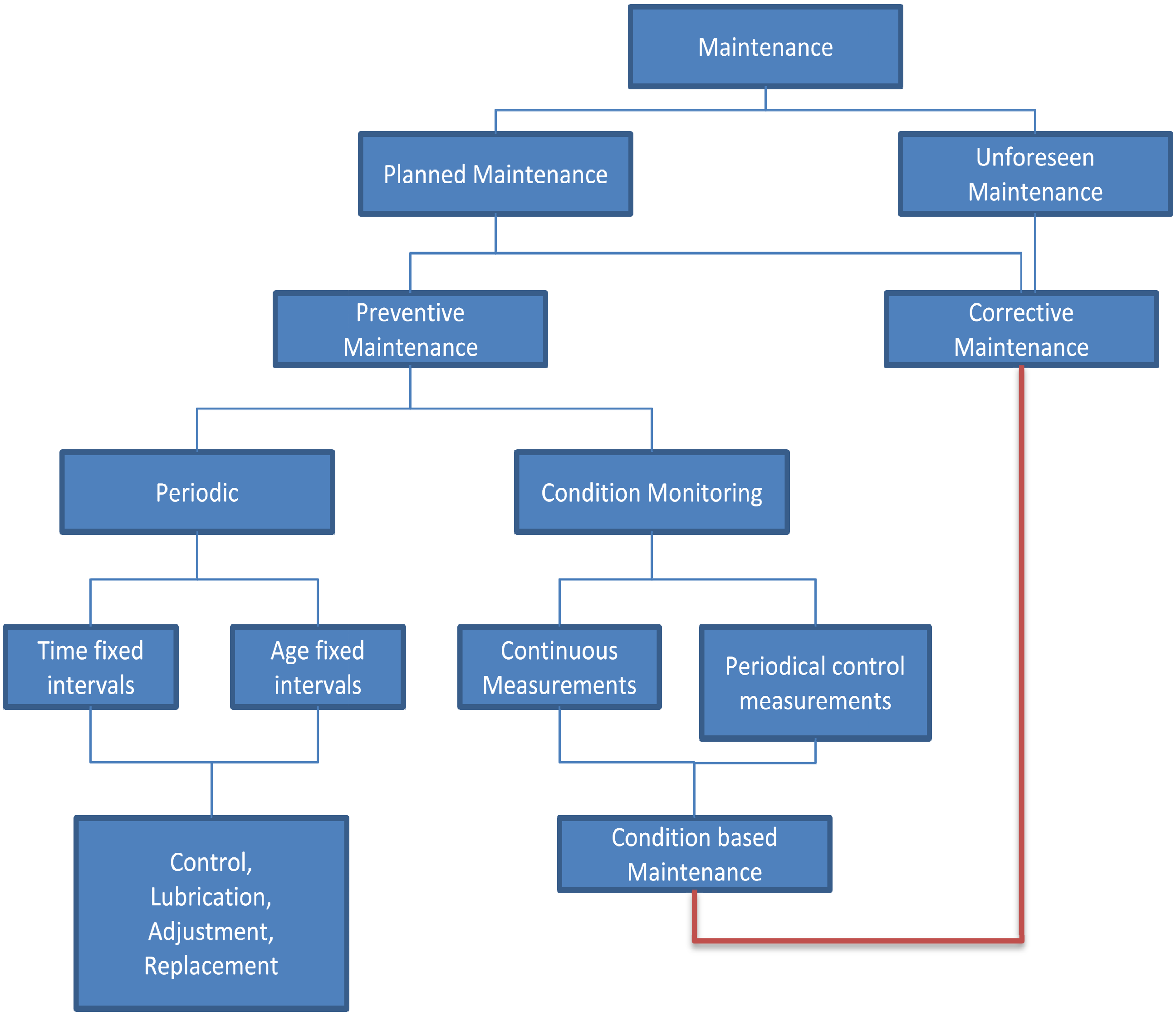


FIGURE 7: MAINTENANCE PLANNING (12)

Planned maintenance can further be decomposed into preventive- and corrective maintenance. Preventive maintenance is used to prevent damages or damage development. Corrective maintenance means that the part is going until it fails. This can be consistent when the part has no impact on safety, economy or the environment. This is characterized as planned maintenance because it is a chosen strategy, and it can be the most economic choice in some cases. (12)

The most common preventive maintenance is fixed time principle, fixed age principle or Condition Monitoring. (12)

4.1 FIXED TIME PRINCIPLES:

Maintenance would be performed after a given time. If there have been done some corrective maintenance in between, this will not be considered. This makes it easy to plan in advance, but it does mean that there are many actions during the life time of the component. The time between maintenance is based on experience data, often a combination between your own and the supplier experience. (12)

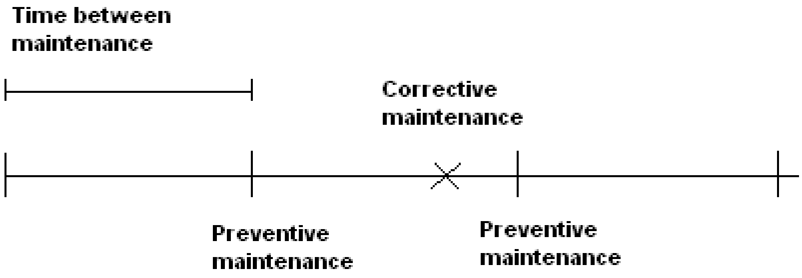


FIGURE 8: FIXED TIME PRINCIPLES (12)

4.2 FIXED AGE PRINCIPLES:

Is based on the same principles that Fixed time principles. But when a corrective action is performed the time to next preventive action is extended. (12)

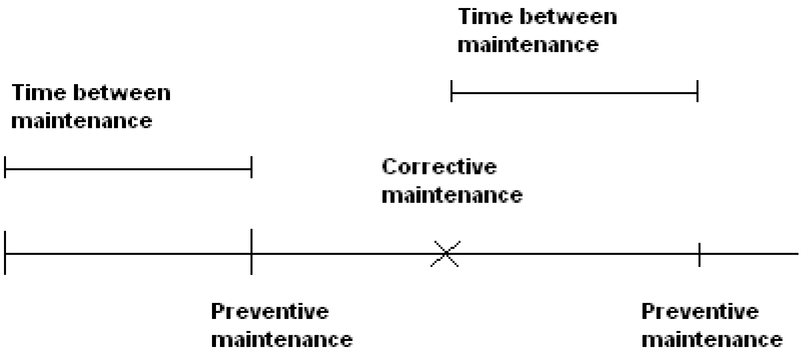


FIGURE 9: FIXED AGE PRINCIPLES (12)

4.3 CONDITION MONITORING

Condition monitoring is an alternative to fixed age and fixed time. In (13) Condition monitoring is defined as:

"Condition monitoring is a type of maintenance inspection where an operational asset is monitored and the data obtained analyzed to detect signs of degradation, diagnose cause of faults, and predict how long it can be safely or economically run." (13)

In source (12) the purpose with CM is defined as:

- CM can tell us something about failure conditions and process abnormality at an early stage.
- Decide maintenance scheduling, avoid unnecessary maintenance.
- Improve the evaluation of the result from a maintenance action
- Replace labour-intensive maintenance operation, with suitable technology on measuring and analysis, when establishing the state of different components.
- Reduce the use of spare parts.

The tree below shows the steps in a CM process.

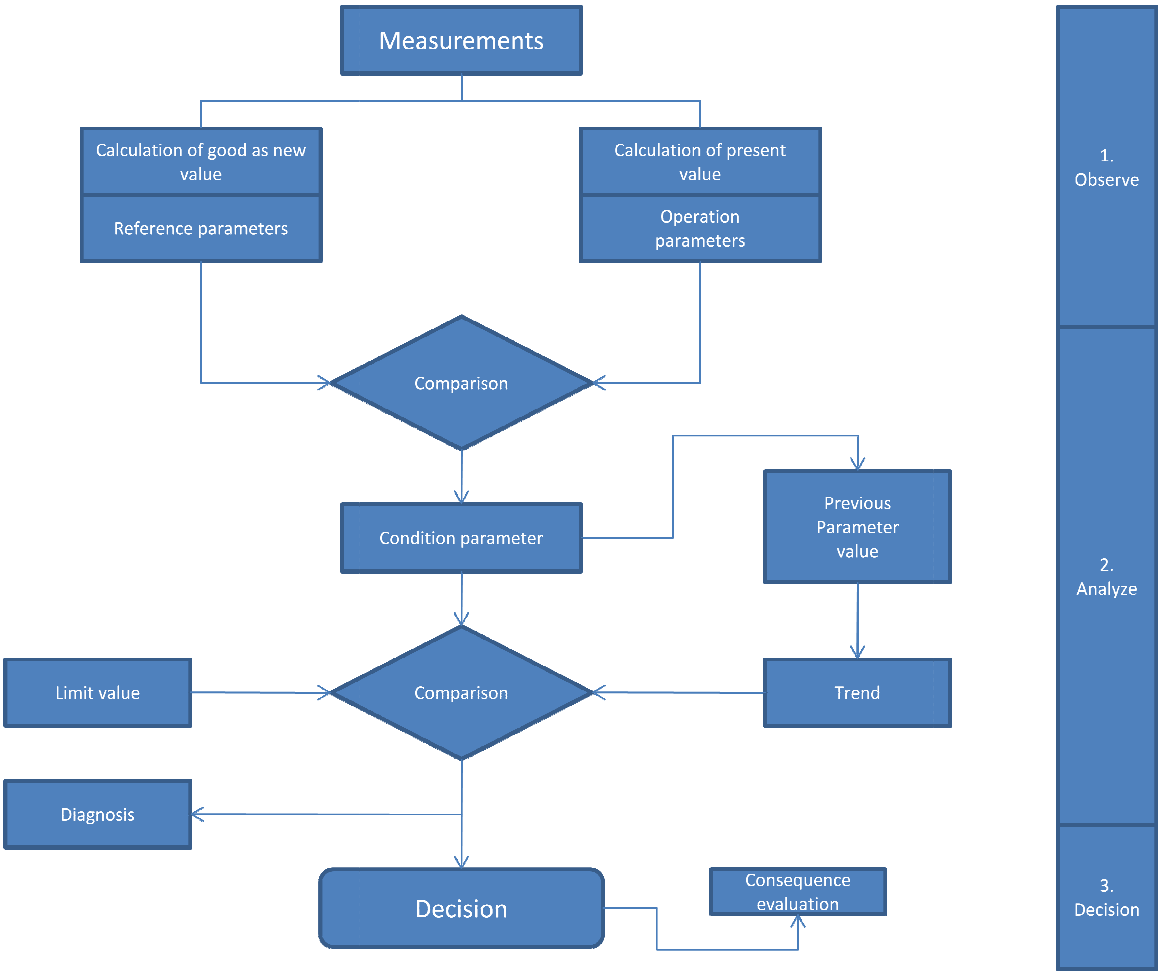


FIGURE 10: FLOW DIAGRAM FOR CONDITION MONITORING (12)

The first step is to observe and register signs that can tell us something about the condition of the component. The second step consists of comparing the results with the reference parameters, as shown in the formula below. From this trend it is easier to determine the optimal maintenance time for the component. A possible diagnose is determined, based on condition development. The third step is to make a decision, based on the analysis results. At last a consequence evaluation is made, to make sure that the decision is convenient. (12)

$$State\ paramete = \frac{Reference\ parameter - Operation\ parameter}{Referanse\ parameter} * 100(\%) \qquad 4\text{-}1$$

This is a general formula used to get an overview of the condition of the component. Reference parameter is often given from the manufacturer, but because of external condition and other differences it can vary. Then the reference parameter must be measured in working condition.

4.4 CONDITION METHODOLOGY

There are two criteria that must be fulfilled to use condition monitoring (12).

1. There has to be a sufficiently method which is accuracy to identify changes in the condition and it has to be convenient either in an economic- or safety aspect.
2. The problem has to develop so slowly that there is an opportunity to do maintenance before the failure occurs.

Measuring frequency depends of different parameters, failure rate, failure development time and time to prepare a maintenance action. The cost of the operation relies on procurement costs and advanced degree (12).

Failures that develop very quickly and has consequences for the economy and safety, is often covered by an observation system and an automatically “shut down” system. Important equipment is often combined with observation and periodical control. (12)

5 CM-METHODS APPLICABLE ON A HEAT EXCHANGER

The DNV-RP-G103 describes the procedure when applying Non-intrusive inspections (NII). The procedure is comprehensive and requires more work in both planning and performance. Questions about history of the vessel are important. "Has NII been performed before on the vessel, or a similar vessel?", "Is the vessel especially designed for NII inspections?" These are questions you must apply before deciding whether a NII procedure can be performed. (14)

In terms of H/X the amount of NII used is minimal. The reason for this is that there are few NII methods that are applicable on the tube bundle of an H/X.

Today there are developed several different types of methods used to inspect an H/X. This chapter would present six different methods used on an H/X today.

5.1.1 ULTRASONIC TESTING (UT):

Ultrasonic testing is based on high frequency sound energy to carry out examinations and measurements. The area of application is flaw detection/evaluation, dimensional measurements and material characterization. (14)

The picture below shows how sound wave discovers a crack.

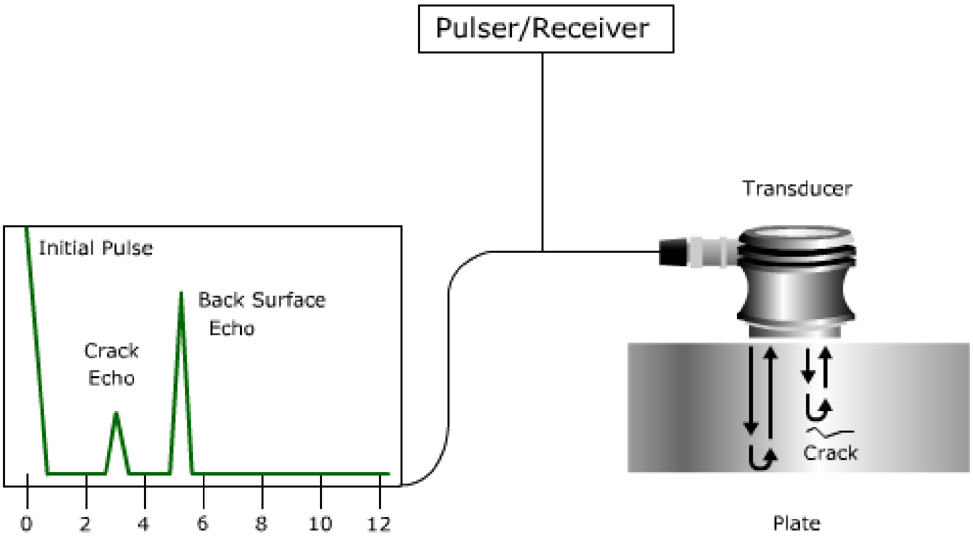


FIGURE 11: ULTRASONIC TESTING (15)

The equipment needed for a simple ultrasonic test is a transducer, receiver and a display. A receiver is an electronic device that produces high voltage electrical pulses. The transducer generates high frequency ultrasonic energy from the receiver. The sound energy is sent through the material and reflected back to the transducer. If the wave hits a crack, it would reflect some energy. The energy would be transformed to an electrical signal by the transducer, and be shown as an echo on the display. (15)

Benefits with ultrasonic testing are the sensitivity for both surface and subsurface discontinuities. The depth of penetration is considerable deeper than other NDT-methods. Ultrasonic testing can measure corrosion through thick walls. It can also detect and find the size of pits. [(14), (15)]

Poor surface finish, thick paint or high and low temperatures can cause problem with the reliability of the test. However there are developed transducers for different environment. This can be high temperature transducer. (14)Other disadvantages are expensive training of personnel since it is a rather complicated procedure. Some materials as cast iron are difficult to inspect. (15)

5.1.2 EDDY CURRENT TESTING (ECT):

ECT is a method based on electromagnetic induction. By inducing electrical currents in the material and observing the interaction between these currents and the material. The area of application is crack detection, material thickness measurements, coating thickness etc. [(14), (16)]

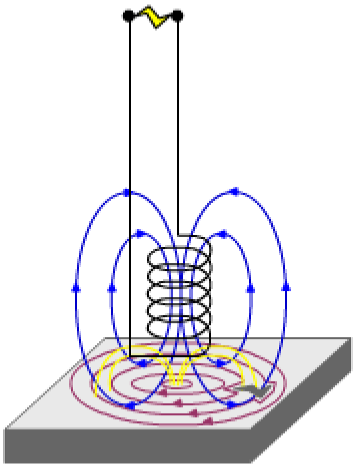


FIGURE 12: EDDY CURRENT TESTING (16)

The only equipment needed for a basic inspection is a portable instrument, with a probe and a display. The basic principle is as followed: When alternating current is applied to the conductor, such as copper wire, a magnetic field would develop in and around the conductor. The size of the magnetic field would rise while alternating current reaches its maximum and collapses when the alternating current is set as zero. (16)

The main advantages with ECT are that it discovers cracks through paint. It has immediate response, and is sensitive due to small cracks. The equipment is portable. (14). Although immediate response on the test, it is preferable for Aker Solutions to analyze the results onshore or in an office offshore, in spite of noise and other disturbing factors offshore. (5)

The main disadvantage is limited inspection depth. It has also problem with detecting small pits. [(16), (17)]

5.1.3 VISUAL INSPECTION (VI):

VI using equipment as boroscope, fibre optic boroscope and video scope can be useful tools which can give information on the condition of tubes, shell and baffle plates in an H/X. (14) VI represents also the eyes of the inspector; this is especially useful outside of the H/X.

A boroscope is a long pipe formed optical device that allows surface inspection in long narrow pipes and chambers. (14)

FIGURE 13: FLEXIBLE BOROSCOPE (18)

Rigid boroscopes are limited to applications with a straight line between the observer and the area to be observed. An orbital scan allows the user to view the surface in a 360 degree arc. The length is typically 0,15-30 meters and diameters from 0,9 – 70 mm. The magnification is typically 3-4 times although magnifications up to 50 times are available. (18)

FIGURE 14: RIGID BOROSCOPE (18)

Flexible boro-scopes are used where there is no straight passageway to the observation point. There are two types at the market flexible fibre-scopes and video scopes with a CCD image sensor at the end. Fibreoptic boro-scope carries visual information through fibre-optic cables each which makes up a picture of the final image. (14)

The advantages are the cost, and the fact that you do not need to disassembly the whole H/X to do an inspection. There are developed boro-scopes that can handle 1600 degrees Celsius. (14)

The video scopes give a black and white picture, and it has a larger operation area. On the other hand, it is more sensitive for temperatures. (14)

5.1.4 MAGNETIC PARTICLE INSPECTION (MPI)

MPI is a combination of visual- and flux leakage testing. It is used for detection of surface and near surface flaws in ferromagnetic. It is a relatively simple concept which gives immediately response. [(14), (19)].

A magnet with a South- and North Pole is applied to the material. The flux will flow from the South Pole to the North Pole. When you have magnetized the material, some iron particles are added creating a visible magnetic field. A flaw/crack in the field would create a local magnetic flux leakage. (19)

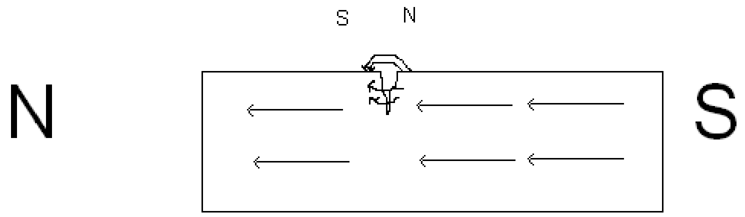


FIGURE 15: MAGNETIC PARTICLE INSPECTION

The main advantage is that the method is easy to apply and shows immediate visible results. The main limitation is that is only applicable to accessible component surface, only at the outside of the shell on an H/X. (14)

5.1.5 HELIUM LEAK TEST (HLT)

Helium is used to detect leaks. The helium is used as a tracer gas and its concentration is measured. If a leakage is detected a spectrometer would identify helium. The helium is used since it is one of the smallest gas molecules and is inert. (20)

According to source (20)the procedure for HLT is as follows:

First the test chamber is closed and evacuation in the vacuum chambers begins. If there is a pressure change inside the product, it is symptom on a “Gross leak”. If the test is ok, evacuating of the heat exchanger is started. Hopefully it will reach vacuum. When vacuum is reached in the chamber, the helium leak detector is being connected to the chamber and conducts a background check. The background check is performed, to make sure that there is no helium in the atmosphere surrounding. Secondly, a small amount of helium is injected and check for “Gross leakage”. Afterwards it fills up to specified pressure. A helium leak detector will detect a possible leakage. At last the test product will be evacuated to atmospheric pressure. (20)

FIGURE 16: HELIUM LEAK TEST (21)

The benefits using this technique are that you may discover smaller leaks. Other benefits are that the test is done with the same pressure that working condition. Leaks are detected and quantified, making it possible to monitor them over a period of time. The oxygen content is reduced, that will reduce the probability for explosive gas mixture. (20)

5.2 THERMODYNAMIC METHOD

5.2.1 HXAM-ST

HXAM-ST is currently a pilot project developed by ABB. However, it is possible to buy this system today. This program collects data for pressure, temperature and mass flow. In this matter the program can discover changes in operation parameters. The most common problem is fouling, and this can easily be controlled through HXAM-ST. The HXAM-ST looks at these process errors. (22)

- Temperature crossover
- Low shell side Flow
- Low heat transfer
- High/low tube velocity
- Low limiting Approach temperature.

The HXAM-ST needs almost no calibration, and for heat exchanger cooling oil is shown to be accurate. But with gas there have been some problems, in that matter ABB is working to make it accurate also for cooling of gas. The largest benefit with HXAM-ST is the potential for continuous monitoring of process data, this would help to have control over the process and not least potential of condition based maintenance (CBM). (22)

5.2.2 NON INTRUSIVE METHODS ON DEVELOP STAGE FOR CONDTION MONITORING

There are today some Non Intrusive methods on the market. HXAM-ST is discussed and would be analysed further in this thesis. Source (23) states that there are today no NII methods usable for the tube bundle. Tube bundle is the most important part on the H/X, and it is important that the method chosen after cost benefit analysis (CBA) has the ability to find failure in the tube bundle.

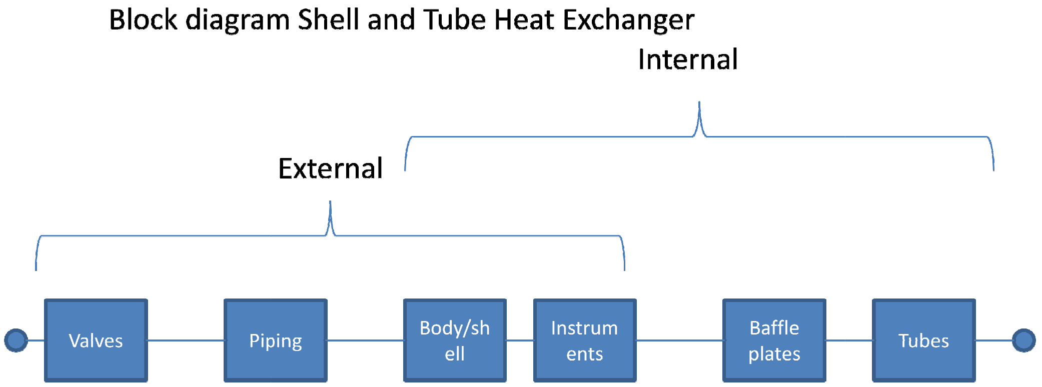
One method discussed on IO-meeting was Acoustic Resonance Technology (ART). This is a method using acoustic to measure the vibration in the tube bundle. However it is not verified to use on an H/X. (23)

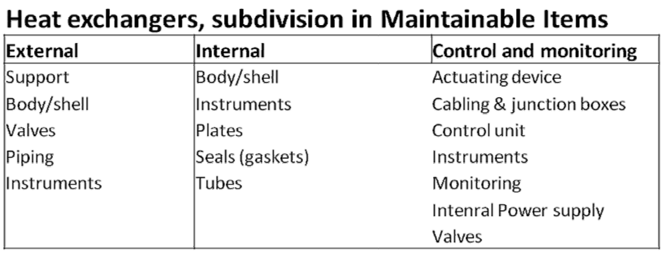
On the market today there are present tracers. The different tracers can discover corrosion particle, oil in water and PH value of the fluid. Roxar is dealing tracers and are helping companies by designing pipes to fit with tracers. (24) As far as the author knows this is not measured today in an H/X. Together with HXAM-ST this would give the decision makers more information on what failure modes that occur.

6 FAILURE MODES VS CONDITION MONITORING METHODS

6.1 BLOCK DIAGRAM

To identify failure modes a block diagram is made to get an overview of maintainable items at a heat exchanger. The maintainable items are the same as in source. (1)To make the Block diagram smaller maintainable parts as support and seals have been excluded, since it have been no problems with them after they started to use metal seals. The only problem has been if it is wrong moment on bolts (5).





Heat exchangers, subdivision in Maintainable Items

External	Internal	Control and monitoring
Support	Body/shell	Actuating device
Body/shell	Instruments	Cabling & junction boxes
Valves	Plates	Control unit
Piping	Seals (gaskets)	Instruments
Instruments	Tubes	Monitoring
		Intenral Power supply
		Valves

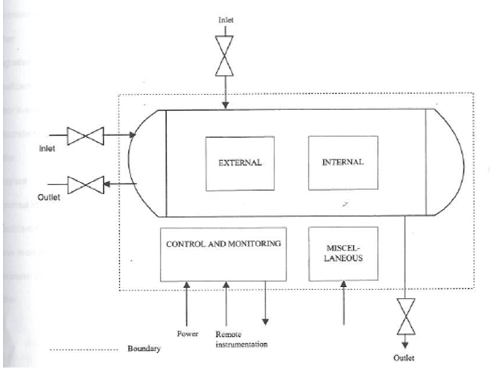


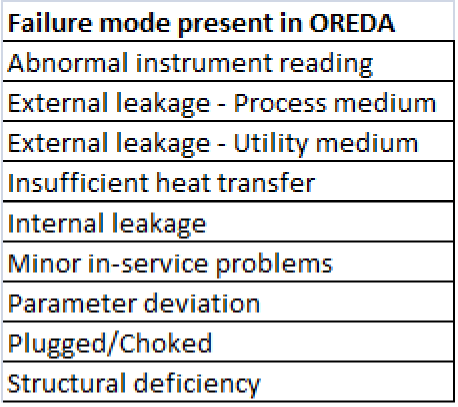
FIGURE 17: BLOCK DIAGRAM OF MAINTAINABLE ITEMS AT A HEAT EXCHANGER (1).

6.2 FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

The FMEA is an engineering approach which comes in different shapes. The purpose with FMEA is to identify potential problems in the design or process by examine the effects of lower level failures. (25)

The purpose with this FMEA is to connect failure modes with different CM methods. It also looks at cause and effect of failures, this to understand the influence of failure modes. The components included in the analysis are the same as the items from the block diagram figure 17.

The failure modes stated in source (1) is shown in the figure on next page:



Failure mode present in OREDA
Abnormal instrument reading
External leakage - Process medium
External leakage - Utility medium
Insufficient heat transfer
Internal leakage
Minor in-service problems
Parameter deviation
Plugged/Choked
Structural deficiency

FIGURE 18: FAILURE MODES ON AN H/X (1)

6.2.1 RESULTS FROM THE FMEA

The FMEA is presented in appendix 2.

6.2.1.1 VALVES

On an H/X there are inlet and outlet valves both for process and cooling medium. These are used to have control with the mass flow. The most critical failure modes are plugged/choked, external leakage of process medium (oil or gas) and internal leakage.

The reason for plugged/choked can be foreign object in the fluids or fouling. The valve can also be locked in closed position due to corrosion.

Leakage can occur due to corrosion of valves or erosion due to sand in the fluid. External forces as vibration can damage valves.

6.2.1.2 PIPING

External piping is the pipes that lead the mediums until the H/X. The failure modes are blocked/plugged and external leakage.

Blockage of pipe can occur due to either foreign object in fluid or fouling due to biological growth or corrosion.

External leakage can happen in spite of corrosion, erosion or external forces as for example vibration.

6.2.1.3 BODY/SHELL

Since the FMEA is based on cooling medium flowing outside the tube bundle. The main task of shell is containment of cooling medium.

External leakage of cooling medium is a failure mode that occurs if there is a crack through the wall. This can be caused of corrosion/pitting, erosion or external forces as vibration.

Corrosion can also lead to structural deficiency. If steel is used a yearly corrosion rate is expected, problems may occur if the lifetime of the H/X is extended, which is likely since the trend indicates extending of lifetime for offshore installations. However, if titan is used fretting and pitting can be a problem, this is difficult to detect and develops fast.

Fouling is also a problem regarding body/shell if there are organically materials in the fluids, corrosion or presence of microbes. This would reduce the heat exchanging and can as a worst case scenario lead to a shutdown of the system.

6.2.1.4 INSTRUMENT

The main task for instrument is monitoring the performance of the H/X. The failure modes are parameter deviation and abnormal instrument reading.

The failure modes are caused by wear and tear or oxidizing of cable to the sensors. Instruments measure pressure and temperature on both cooling and process medium, some is also measuring the mass flow. If there are failures on instruments the overview of the process would disappear.

6.2.1.5 BAFFLE PLATE

Baffle plates has two main tasks. One is to support the pipes inside the H/X. The other is to make sure that the cooling medium is flowing around the pipes. This to create an effectively flow pattern.

The failure mode for the baffle plate is structural deficiency. This is a wide concept and includes all from corrosion/pitting and small motion to buckling of baffle plate. The reason can be external forces as vibration, erosion or corrosion/pitting. Since one of the baffle plates task is to support the tubes, a destroyed baffle plate can cause crack in tubes, hence leakage of the process medium.

6.2.1.6 TUBE BUNDLE

The last maintainable item is the tube bundle. Since it is assumed that the process medium is flowing inside the tube bundle, the task is to transport the process medium inside the tubes. The tube bundle has three different failure modes structural deficiency, internal leakage and blocked/plugged.

The reason for Structural deficiency is corrosion/pitting, fretting or buckling of the tubes. Buckling of tubes is caused of wrong pressure either from shell side or tube side. (23)

Internal leakage can be caused of external forces, erosion and corrosion/pitting. As mention earlier a structural problem with the baffle plates can cause buckling of tubes, hence a leakage. This can be caused of vibration, and leads to shut down of the H/X.

Another problem regarding the tube bundle is plugged/choked. This is caused by both foreign object in the medium and fouling due to organically organisms in the mediums. The failure will lead to higher forces on remaining tubes.

6.2.2 CONDITION MONITORING METHODS APPLICABLE TO FIND FAILURE MODES

There are a lot of different CM-methods applicable for an H/X. In co-operation with advisors the thesis would deal with the CM-methods introduced in chapter 3. Since much of the failure modes are the same for the different maintainable items, the CM methods would be present in term of failure modes.

Blocked/plugged can be discover with tracers, HXAM-ST and VI. For the tube bundle also ECT and UT can be used to discover the failure.

External leakage process medium for valves and piping can be discovered with VI since a leakage would be shown outside the pipes. On gases without smell gas detectors must be used. With vibration measurements external leakage can be prevent, if it is possible to create less vibration.

Internal leakage in the tube bundle can be discovered with some of the CM methods. The most used is ECT (5) but also UT can be used. It is also possible to look after oil in the cooling medium (sea water). For gasses a HLT is possible to apply.

External leakage cooling medium at the shell can be found with VI. The cooling medium is assumed to be sea water hence no risk for injuries.

Structural deficiency is a problem on shell, tube bundle and baffle plates. It can be discovered with ECT, UT and VI on all maintainable items. On the shell MPI is applicable without closing down the operation.

Fouling can be found by VI and HXAM-ST. HXAM-ST would discover less temperature difference on the mediums. In many cases the reason is fouling. Fouling happens over time.

Instruments failure can be detected with fault finding.

6.2.3 FAULT TREE ANALYSIS

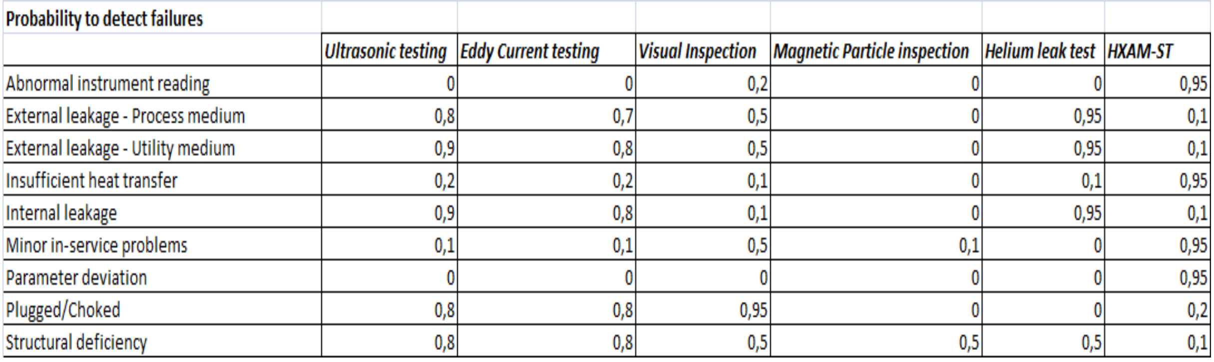
FTA was developed in 1962 by Bell Laboratories, in connection with the safety analysis of the Minuteman missile launch control system. In 1966 the civil aircraft design started to use FTA. In 1981 the Fault Tree handbook NUREG-0492 was published, since the FTA is used in different industries like the oil and gas industry. (26)

FTA is a top-down failure analysis. A top event can be breakdown or failure of the system. The lower level failures are what causing the top event either individual or in a combination. The top event is connected through logical gates, the two most used is and/or gates. (27)

Since a FMEA is made to connect the failure modes with the CM methods. The FTA is just to illustrate another way of finding the failure modes that leads to shutdown of the H/X. The FTA is going more in detail on what causing the top event then the FMEA. The FTA is shown in appendix 1.

6.3 PROBABILITY FOR DETECTION OF FAILURE MODES WITH DIFFERENT CONDITION MONITORING METHODS

It is difficult to set exact values on the probability to find failure modes. A value is proposed for the six different methods chosen to be investigated in this thesis. The methods are discovering different failure modes, and have differences concerning investments and execution. The scale is set from 0 to 1,0 where 1,0 is one hundred percent certain that the method would have the ability to discover the failure mode.



Probability to detect failures						
	Ultrasonic testing	*Eddy Current testing*	*Visual Inspection*	*Magnetic Particle inspection*	*Helium leak test*	*HXAM-ST*
Abnormal instrument reading	0	0	0,2	0	0	0,95
External leakage - Process medium	0,8	0,7	0,5	0	0,95	0,1
External leakage - Utility medium	0,9	0,8	0,5	0	0,95	0,1
Insufficient heat transfer	0,2	0,2	0,1	0	0,1	0,95
Internal leakage	0,9	0,8	0,1	0	0,95	0,1
Minor in-service problems	0,1	0,1	0,5	0,1	0	0,95
Parameter deviation	0	0	0	0	0	0,95
Plugged/Choked	0,8	0,8	0,95	0	0	0,2
Structural deficiency	0,8	0,8	0,5	0,5	0,5	0,1

FIGURE 19: DETECTION OF DIFFERENT FAILURE MODES

UT and ECT is most used for the tube bundle, hence the methods has high detection factor on leakage, plugged/choked and structural deficiency. Since area of application is more or less the same, the differences are in costs and inspection speed. The ECT method is a faster method than UT. But UT is more reliable.

VI is a cheap and comprehensive method both in execution and detection rate. The shown boroscopes in chapter 5.1 can only be used in production stops. But VI outside of the H/X on valves etc, can be carried out at any time. At the IO meeting it was discussed if it is beneficial to install an inspection hatch. This could raise the detection rate without shutting down the system. VI has very high detection rate on plugged/choked since a boroscope would easily discover blockage in the tube bundle, and the inspectors eyes would discover if a valve pipe is plugged. It is not so good on abnormal instrument reading and parameter deviation since it is difficult to observe this with VI.

Magnetic particle inspection is a method that can be used during operation. On the other hand, it is only usable on items with easy access, and therefore only applicable for structural deficiency. It is reliable on structural deficiency of the shell, the value is only set to 0,5 because it cannot discover structural deficiency inside the tube bundle. If the minor in service problems is corrosion on the shell, the MPI would discover it hence 0,1 on minor in service problems.

Helium leak test is the ultimate test to discover leakage, causing that almost all leakage would be discovered. On the other failure modes, for instance structural deficiency is only discover structural deficiency in terms of hole through the material.

HXAM-ST is the only system who discovers problems with process data as abnormal instrument reading and parameter deviation. But it would only indicate that something is wrong, not point out the exact failure mode as leakage corrosion and plugged/choked. Yet, it could establish condition based maintenance (CBM).

7 LIFE CYCLE COST MODEL

The literature in this chapter is based on the report "Life Cycle cost (LCC) analysis in the oil and chemical process industries" by Toshio Kawauch and Marvin Rausand.

LCC was developed in the late 60's early 70's. The minimization of LCC is taken from the process: Integrated Logistics Support (ILS). ILS us defined as *" a composite of elements necessary to assure the effective and economical support of a system or equipment at all levels of maintenance for its programmed life cycle."* (2)

The LCC's analysis started in the defence sector. However other sectors as Power industries and Oil & Chemical industries had benefits with using LCC analysis. The largest concern in the oil industries is unavailability of the system, due to downtime because of failure, maintenance etc. This since its difficult to take back lost production. (2)

It's generally stated that 80% of the LCC is allocated by decisions made within the first 20% of the life of the project. This means that with a LCC analysis is preferably to implement in the start of the project. However the uncertainty is large in the earliest phases, therefore a reassessment can be beneficial. It is therefore important to decide the best timing of LCC analysis for each program in consideration of the trade-off between the commitment curve and the uncertainty curve. (2)

It is stated in source (2) that a LCC analysis generally can be divided into 6 different processes.

1. Problems definition
2. Cost element definition
3. System modelling
4. Data collection
5. Cost profile development
6. Evaluation

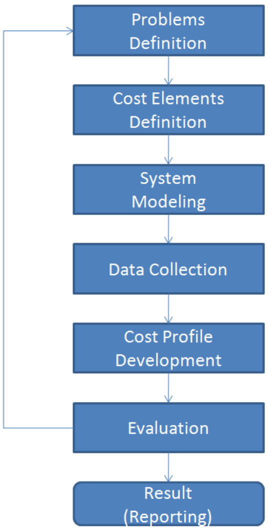


FIGURE 20: LCC PROCESSES

7.1 PROCESS 1: PROBLEM DEFINITION

The first step of a LCC analysis is the problem definition. It is important to define both problem and scope of work. The term scope means aspects, such as the scope of program phases to be modelled, the scope of equipment to be modelled, the scope of activities to be modelled. To get clear definitions of the cost element a clear definition of the scope is necessary. All assumptions need to be clarified as well. (2)

The evaluation criteria showed in figure 20 should also be defined in the first process. The criteria must take into account total cost, system performance and effectiveness, seen in the figure below (2).

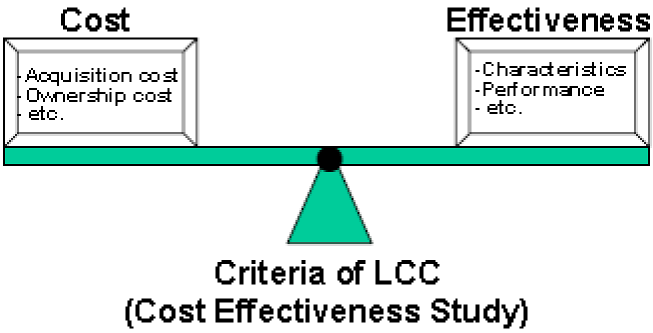


FIGURE 21: COST EFFECTIVENESS STUDIES IN LCC (2)

7.2 PROCESS 2: COST ELEMENT DEFINITION

It is important to identify all cost elements, which influence the total LCC of the system. It is convenient to define the cost elements in a systematic method to avoid ignoring significant cost elements. There are today present different standard for LCC (IEC 60300-3-3), this is based on a cost breakdown structure (CBS). Figure 22 shows this structure for an item (2).

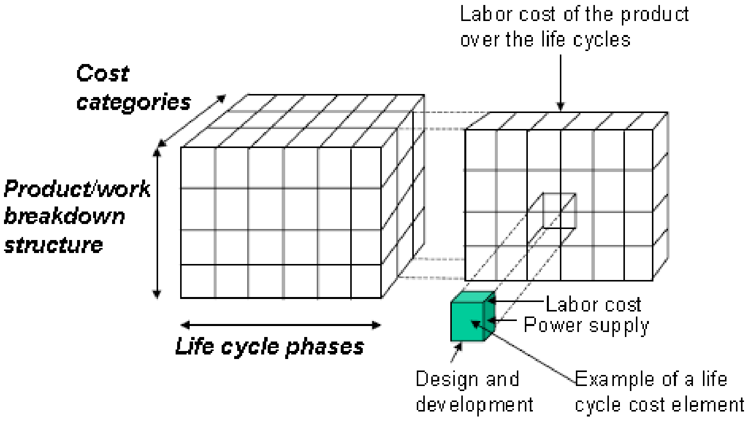
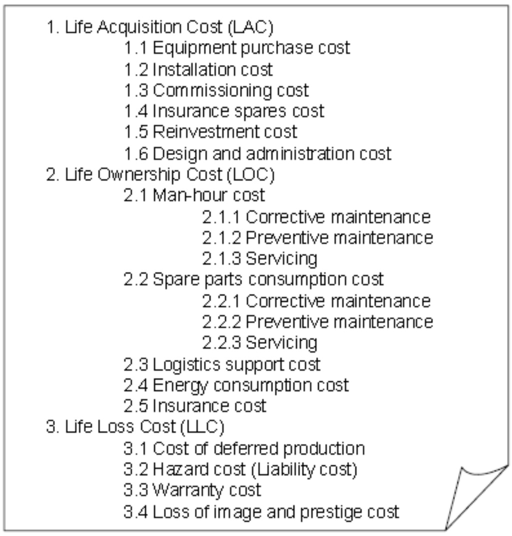


FIGURE 22: COST ELEMENT CONCEPT (2)

Since a LCC analysis can be applied for different systems it is difficult to find one standard to use. In this matter many different standards for LCC analysis is made. (2)

To have control on the different cost elements it is beneficial to grade the different costs as mention before. One example is shown below. (2)



1. Life Acquisition Cost (LAC)
    - 1.1 Equipment purchase cost
    - 1.2 Installation cost
    - 1.3 Commissioning cost
    - 1.4 Insurance spares cost
    - 1.5 Reinvestment cost
    - 1.6 Design and administration cost
2. Life Ownership Cost (LOC)
    - 2.1 Man-hour cost
        - 2.1.1 Corrective maintenance
        - 2.1.2 Preventive maintenance
        - 2.1.3 Servicing
    - 2.2 Spare parts consumption cost
        - 2.2.1 Corrective maintenance
        - 2.2.2 Preventive maintenance
        - 2.2.3 Servicing
    - 2.3 Logistics support cost
    - 2.4 Energy consumption cost
    - 2.5 Insurance cost
3. Life Loss Cost (LLC)
    - 3.1 Cost of deferred production
    - 3.2 Hazard cost (Liability cost)
    - 3.3 Warranty cost
    - 3.4 Loss of image and prestige cost

FIGURE 23: A SAMPLE OF A CBS IN LCC ANALYSIS (2)

7.3 PROCESS 3: SYSTEM MODELLING

To make a model you need to quantify the cost elements included in the LCC analysis. It is important to find the relations between input parameters and the cost elements. A system should be modelled from different viewpoint as availability, maintainability, logistics, risk and human error in the system. (2)

7.3.1 AVAILABILITY

Most of the cost related to availability is the out of order cost. If the outcome product has a high market value, the availability cost is significant high. In the oil producing industry this is especially important, since it can take years before a platform can recover the losses. (2) In the plateau period the capacity of production on the installation is at max and the oil would not be regained before after the plateau period. A plateau period is typically between 10 and 15 years for a field.

If a large spectre of data for the system is underlying. It is possible to calculate the availability by subtracting shutdown time plus the loss time of major stoppage from the calendar time of system operation, and dividing it by total calendar time. (2)

In prediction of availability, various measures can be used. The most used calculation is shown below.

$$Availability = \frac{MTTF}{MTTF + MTTR}$$

Where:

MTTF= Mean Time to failure

MTTR= Men Time to repair

This formula gives a good estimate of availability over a period of time.

To estimate availability for a completely system, different tools are used; reliability block diagram (RBD), Fault Tree analysis (FTA), Markov modelling, Petri Net etc. (2) In this thesis a FTA will be made, however the availability is based on failure rate from OREDA. (1)

7.3.2 MAINTENANCE AND INSPECTION MODELLING

The frequency between maintenance actions is based on availability, operating cost, man hour cost, spare part consumption etc. (28)

Maintainability may be measured through a combination of different factors as follows. (2)

1. Mean time between maintenance (MTBM), which includes both preventive and corrective maintenance requirements.
2. Mean time between replacements (MTBR) of an item due to a maintenance action.
3. Mean downtime (MDT), or total time during which the system (or product) is not in condition to perform its intended function, it includes mean time to repair (MTTR).
4. Turnaround time (TAT), or that element of maintenance time needed to service, repair, and/or check out an item for recommitment.
5. Maintenance labour hours per system/production operating hours.
6. Maintenance cost per system/production operating hours.

Since the quality of inspections can vary, methods like "Reliability-Centered Maintenance (RCM)", and "Risk-Based Inspection (RBI)" is been developed. RCM is a method to establish maintenance strategies for all units in a plant based on internal and external criteria related to, safety, environment, operation and economy. RCM looks at units in a system perspective based on function demand, malfunction, and prevention of those functions demand. (12)

Different approaches is made for RCM, one general twelve steps approach is proposed in source (29)

1. Study preparation
2. System selection and definition
3. Functional failure analysis
4. Critical item selection
5. Data collection and analysis
6. Failure mode, effects, and criticality analysis
7. Selection of maintenance actions
8. Determination of maintenance intervals
9. Preventive maintenance comparison analysis
10. Treatment of non-critical items
11. Implementation
12. In-service data collection and updating

RBI is based on a systematic inspection process to prioritize equipment inspection based on probability and consequence of failures. FMECA can be useful to establish the criticality. It can reduce the probability for critical failures and provides the ability to efficiently allocate limited budgets and inspections. (2)

7.3.3 RISK (HAZARD, WARRANTY) MODELLING

Risk development is useful information for decision making in system development. Risk is defined as frequency multiplied with consequence of a given failure. (2)

7.4 PROCESS 4: DATA COLLECTION

Reliable data is crucial to make a reliable LCC analysis. Therefore it is important to identify the requirements of input data. If actual data are available to quantify cost elements, it can be directly applied into the LCC analysis. If actual data not are available, the data may be estimated depending on expert judgments. (2)

7.4.1 ACTUAL DATA PREPARATION

A wide range of data is required in LCC analysis. This is data like maintainability data, operation data, and cost data etc. Reliability data is relatively simply to collect, through suppliers and experience data. However operation data and cost data is difficult to find. (2)

7.4.2 ESTIMATION OF DATA

When actual data not are available the value may be estimated. To estimate cost data some approaches have been proposed such as stochastic models, parametric techniques and analogous techniques. (2)

1. *Stochastic models take into account the random nature of events and rely on specialized statistical techniques.*
2. *Parametric techniques are based on statistical analysis of historic data bases. It usually results in a cost estimating or cost factor relationship.*
3. *Analogous techniques draw on relationships between current and similar previous data. Expert judgment is used to make adjustments to the previous data to reflect characteristics of the data under consideration.*

For estimation of reliability data, some methodologies have been reported. For instance a method based on Bayesian reliability theory, which derives posterior information from prior (known) information. (2)

7.5 PROCESS 5: COST PROFILE DEVELOPMENT

One of the main objectives of LCC analysis is an affordability analysis considering a long term financial planning. In the affordability analysis, a cost profile over the lifecycle is key information. This since it is important that financial judgement is compared in the same reference point. The graph shows that if an investment is done in the start the rest cost of the life cycle will be lower. (2)

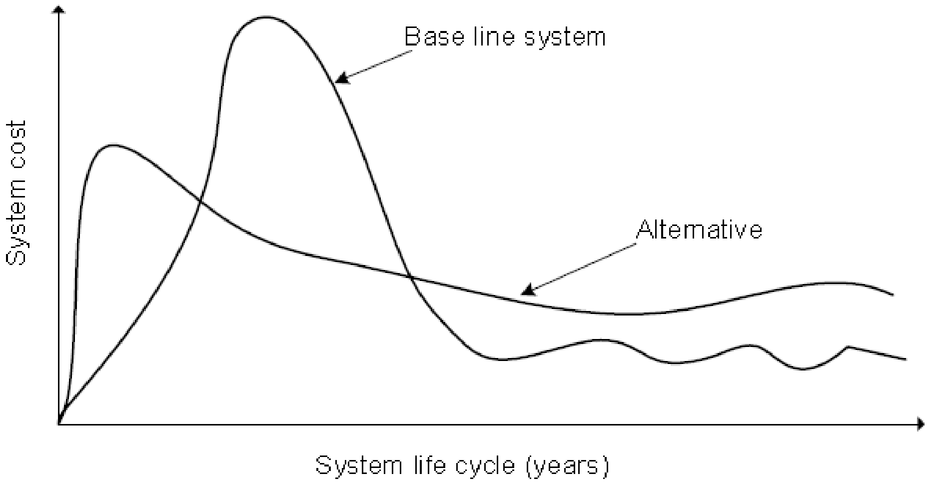


FIGURE 24: A SAMPLE OF COST PROFILE (2)

7.5.1 COST TREATMENT

For financial judgments, it is required to consider the effect of inflation, interest rates and exchange rates, taxation, etc. However, due to problems of predicting inflation and exchange rate, the cost profile may be prepared at "constant prices" basis. (2)

Since LCC analysis considers cost that will be incurred sometime in the future, it is necessary to discount all revenues and expenditures to a specific year with Net Present Value (NPV). (2)

7.6 PROCESS 6: EVALUATION

At last an evaluation must be implemented. The results must be compared to the criteria defined in the start of the LCC analysis. If a point not satisfied the criteria, the system should be modified as an alternative system, and hence the LCC for the alternative system should be estimated. During the evaluation process, the uncertainties of the input data should be considered. (2)

7.6.1 SENSITIVITY ANALYSIS

The purpose with a sensitivity analysis is to see what impact the different parameters has on the LCC analysis. In the offshore industry oil price is important. For instance would downtime cost be twice as much when the oil price is 150 USD per barrel vs 75 USD per barrel. In 2008 the oil price was 150 USD per barrel today it is around 70 USD per barrel. (30)

Today two methods are used to implement a sensitivity analysis. One is a deterministic approach, the other is stochastic approach. The deterministic approach computes the partial derivates of performance indices with respect to fluctuation of parameters. The performance indices may be RAM performance measures, the LCC measure etc. The deterministic approach can only be used at system with few parameters. The stochastic approach evaluates probabilistic properties of the performance indices against the possible statistical distribution of the parameters. The stochastic approach can be performed by Monte Carlo (stochastic) simulation. (2)

7.6.2 UNCERTAINTY ANALYSIS

Uncertainty analysis is an attempt to consider the ranges of the estimate and their effect on decisions. (2)

The different uncertainty can be categorized into the following main groups. (2)

1. Parameter uncertainties
2. Modelling uncertainties
3. Completeness uncertainties

7.6.3 COST DRIVERS IDENTIFICATION

One of the main goals for a LCC is to identify cost drivers, which may have a major impact on total LCC. It is beneficial to make a cause-and-effect relationship to identify causes of the high cost. (2)

7.6.4 OPTIMIZATION

The LCC is generally an approach to identify the best solution in terms of money. In a broad sense, identify important parameters to minimize the LCC of the total system. In a narrow sense, identify parameters to optimize for instance maintenance, design, spare parts etc.

8 LCC FOR CONDITION MONITORING FOR A SHELL AND TUBE HEAT EXCHANGER

The LCC is based on one inspection on each H/X per year. According to (5) the picture is more nuanced. The inspections are based on Risk Based Inspection (RBI). A lot of factors must be considered. If it is redundancy, it is cheaper to carry out an inspection. What other equipment must be shut down to carry out the inspection? The risks must also be taken into consideration as; production, environment, health etc.

8.1 PROBLEM DEFINITION

The system to be analyzed is different CM methods applied on a single pass H/X through the lifetime of the H/X. The lifetime of an H/X is set to 20 years. Net Present Value (NPV), back to year 0 will be used as a basis for the costs.

8.2 COST ELEMENT DEFINITION

To get an overview over the cost related to CM-methods a cost breakdown system (CBS), is created. The CBS for the different CM methods will be based on a procedure with two main costs categorize: Capital Expenditure (CAPEX) and Operational cost (OPEX). CAPEX is defined as procurement cost and research and develop cost. OPEX is the cost related to operation of the method. Downtime is not taken into the consideration, since this is cost for H/X and not for the different CM methods. (31)

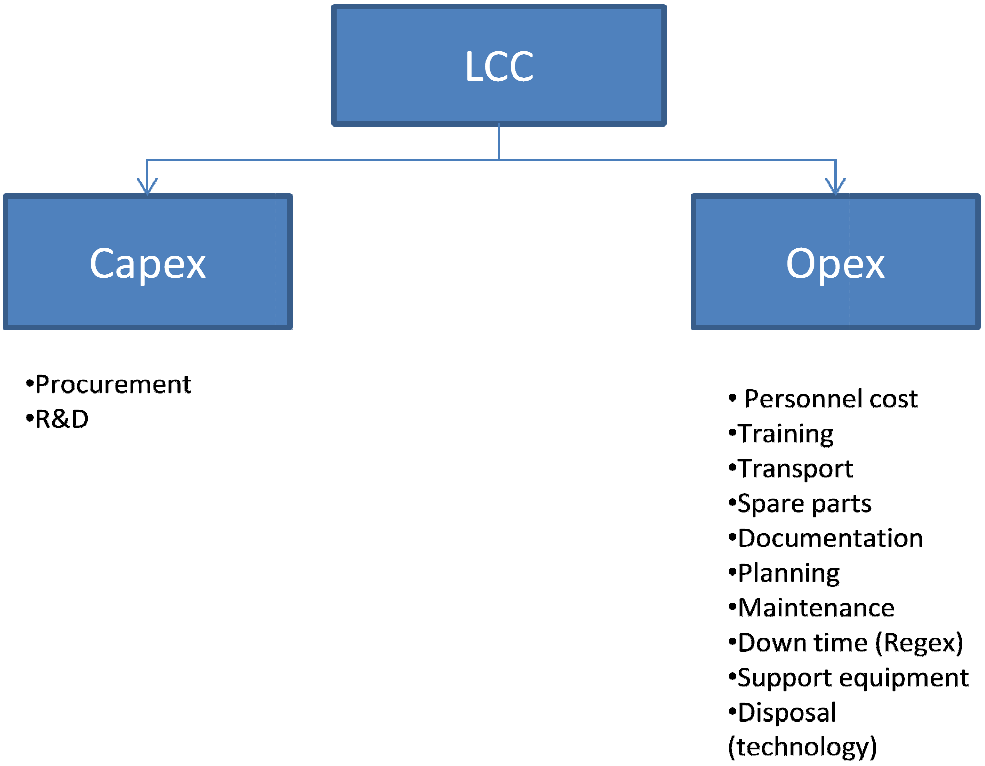
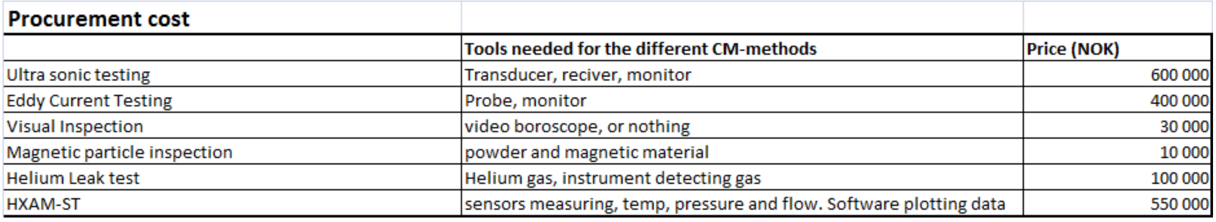


FIGURE 25: COST BREAK DOWN STRUCTURE

8.2.1 CAPEX

8.2.1.1 PROCUREMENT COST

The procurement cost is the price for the physical tools for the methods. The prices are based on assumptions.



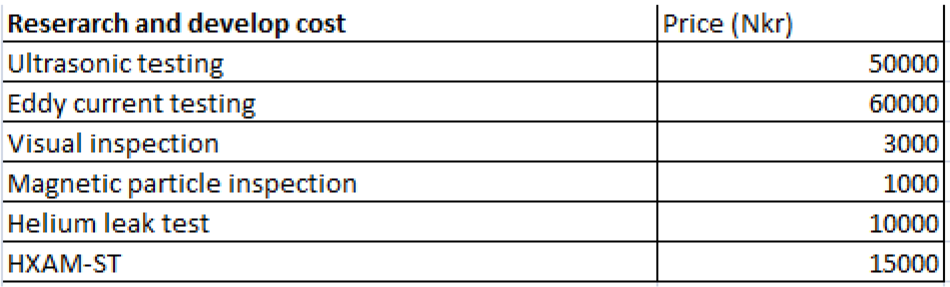
Procurement cost	**Tools needed for the different CM-methods**	**Price (NOK)**
Ultra sonic testing	Transducer, reciver, monitor	600 000
Eddy Current Testing	Probe, monitor	400 000
Visual Inspection	video boroscope, or nothing	30 000
Magnetic particle inspection	powder and magnetic material	10 000
Helium Leak test	Helium gas, instrument detecting gas	100 000
HXAM-ST	sensors measuring, temp, pressure and flow. Software plotting data	550 000

TABLE 1: PROCUREMENT LIST

8.2.1.2 RESEARCH AND DEVELOP COST (R&D COST):

This is cost considering everything in the develop stage of the method. The different methods are expensive to develop and have no value when a new and more reliable method is on the market.

R&D cost is difficult to estimate, but according to (5) the methods are well developed, and more complicated methods are too expensive and not appropriate to use. Despite of this, the research and develop cost is set to 10% of the procurement costs.



Reserarch and develop cost	Price (Nkr)
Ultrasonic testing	50000
Eddy current testing	60000
Visual inspection	3000
Magnetic particle inspection	1000
Helium leak test	10000
HXAM-ST	15000

TABLE 2: RESERARCH AND DEVELOP COST

R&D cost is assumed to take place every tenth year on well developed methods. MPI has R&D as a yearly cost. HXAM-ST is a new CM method and needs research and development, in spite of this it is assumed that R&D cost incurred yearly for the first five years.

8.2.2 OPEX

8.2.2.1 PERSONNEL COST:

In this thesis personnel cost is defined as the man hours regarding operation of the CM-method. This cost would vary between the different methods, since some methods needs a lot of personnel and others don’t. The methods which give direct answers, safes money compared to methods where the results need to be analysed.

The personnel cost on the different methods are based on assumptions from experience personnel (5) . It is shown in table 3. Hours on ECT is based on 2000 tubes and 500 tubes inspected per day. On UT it is assumed 350 tubes per day. Number of personnel is set to 3 persons, 2 offshore and 1 onshore. The price for hired personnel offshore is 3000NOK, and onshore is set to 1000 NOK.

VI is based on own personnel, which means that the cost per man hour would be 2000 NOK per hour. A complete inspection is assumed to take 20 hours; this includes use of video boroscope inside the tubes.

MPI is also performed by own personnel. The inspection is only on the outside of the H/X, because of preparation it takes 26 hours to perform MPI on one H/X.

HLT is done by hired personnel and it takes only 5 hours to perform the test.

HXAM-ST is assumed to have no personnel cost. The method only plots the H/X performance.

The formula used in appendix 3 is:

$$C_p = WH * C_{HP} * NP * Number\ of\ H/X \qquad 8\text{-}1$$

C_p: Personnel cost per year

WH: number of hours carrying out the inspection

C_{HP}: Cost per hour

NP_i: Number of persons involved in the inspection

Formula 8-1 gives personnel cost per year.

ECT/Ultrasonic testing	
Hours per heat exchanger ECT	48
Hours per heat exchanger Ultrasonic	69
Number of persons involved ECT/Ultrasonic	3

Visual Inspection	
Hours per heat exchanger Visual	20
Number of persons	1

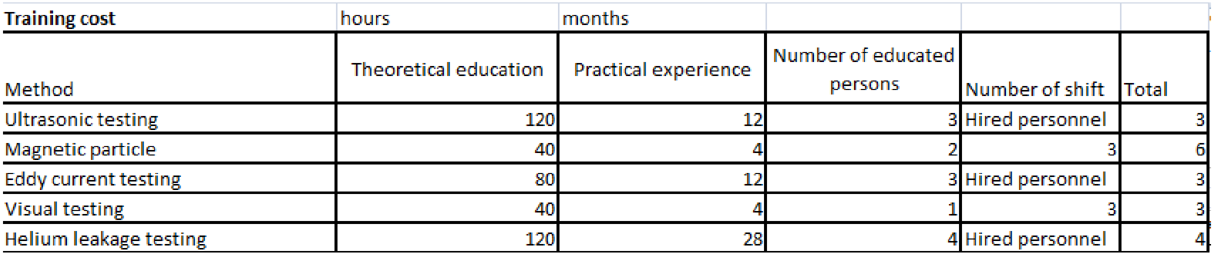
Magnetic particle inspection	
Hours per heat exchanger	26
Number of persons Magnetic particle inspection	2

Helium leak inspection	
Hours per heat exchanger Helium leak	5
Number of persons Helium Leakage test	4

TABLE 3: PERSONNEL COST FOR THE DIFFERENT METHODS

8.2.2.2 TRAINING COST:

The different methods require different range of training. Some methods need knowledge and experience to be carried out. HXAM-ST does not demand training, since it is only plotting of values in a program. Table 4 shows how many hours theoretical education and how many months practical experience needed to perform the different methods. (32)



Training cost	hours	months			
Method	Theoretical education	Practical experience	Number of educated persons	Number of shift	Total
Ultrasonic testing	120	12	3	Hired personnel	3
Magnetic particle	40	4	2	3	6
Eddy current testing	80	12	3	Hired personnel	3
Visual testing	40	4	1	3	3
Helium leakage testing	120	28	4	Hired personnel	4

TABLE 4: TRAINING HOURS ON DIFFERENT METHODS

$$\mathrm{C_T} = (C_{TE} * NH_{TE} + C_{PR} * NH_{PR}) * NP_i \qquad 8\text{-}2$$

$\mathrm{C_T}$: Training cost

$\mathrm{C_{TE}}$: Cost per hour theoretical education

$\mathrm{NH_{TE}}$: Number of hours theoretical education

$\mathrm{C_{PR}}$: Cost per month practical education

$\mathrm{NH_{PR}}$: Number of months practical education

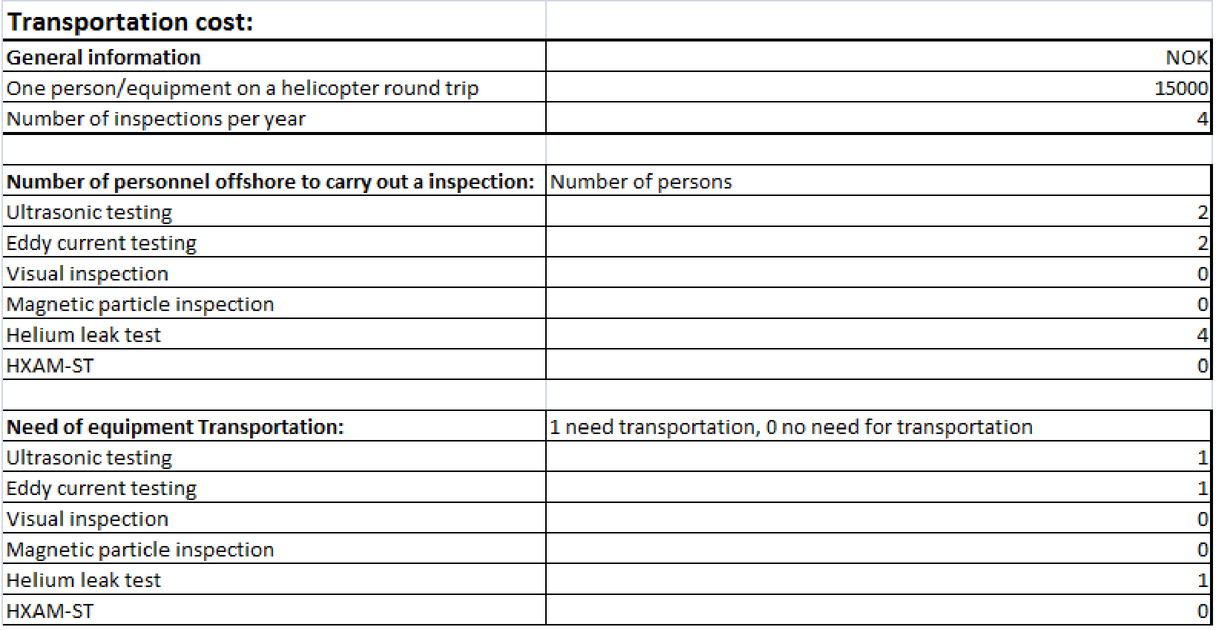
$\mathrm{NP_i}$: Number of persons educated

Number of persons educated depends if hired or own personnel are used. Three shifts need the education if own personnel is used. The price for education is assumed to be 10000 NOK per hour theoretical education, and 100 000 per month in practical experience.

The training cost occurs every fourth year, in spite of crew changes.

8.2.2.3 TRANSPORTATION COST:

Transport cost is both transport of personnel and tools. The transport cost depends if external personnel is used. The tools that are used are different in both size and weight. Some of the equipment can be brought out with helicopter and some needs to be brought out with a supply vessel. In this thesis it is assumed that the transportation cost is the same for helicopter and a supply vessel. The price is set to the same as a round trip for one person in a helicopter 15000 NOK.



Transportation cost:	
General information	NOK
One person/equipment on a helicopter round trip	15000
Number of inspections per year	4
Number of personnel offshore to carry out a inspection:	Number of persons
Ultrasonic testing	2
Eddy current testing	2
Visual inspection	0
Magnetic particle inspection	0
Helium leak test	4
HXAM-ST	0
Need of equipment Transportation:	1 need transportation, 0 no need for transportation
Ultrasonic testing	1
Eddy current testing	1
Visual inspection	0
Magnetic particle inspection	0
Helium leak test	1
HXAM-ST	0

TABLE 5: TRANSPORTATION COST

The formula used in appendix:

$$C_{TR} = ((NP_{TR} + E) * C_H) * N_i \qquad 8\text{-}3$$

C_{TR}: Transportation cost

NP_{TR}: Number of persons needed to be transported

E: Equipment transportation (1 or 0)

C_H: Cost helicopter round trip

N_i: Number of inspection per year

Table 5 shows both personnel and equipment transportation. The method without equipment or transportation cost is methods perform by own personnel on the installation. In these cases it is assumed that the CM equipment is stored offshore.

Formula 8-3 gives transport cost per year. It is assumed that a crew is capable to inspect 5 H/X through one period on the platform. This means that they would use 4 inspection rounds with 20 H/X.

Although the CM equipment is stored offshore and carried out by own personnel. Transportation cost would exceed in terms of spare parts, but this is not taken into consideration in this thesis.

8.2.2.4 SPARE PART COST:

It is important to always have available spare parts on wear parts. First it is expensive and time consuming to order new parts offshore. For example MPI needs powder and HLT needs helium for every inspection. The probes used for UT and ECT need to be change.

Spare part cost is set to 7% of the procurement cost.

Although the spare parts cost is assumed to be 7% in this thesis. The author will show how the calculation could be implemented in the excel sheet if the failure rate for the equipment for the different methods was known. The spare parts cost is a sum of spare parts used with corrective maintenance. Spare parts used with preventive maintenance and spare parts for servicing. (33) This would be taken into consideration if the LCC was made for an H/X and not CM methods.

Corrective maintenance (CM): (33)

$$CMSP = \lambda_T * 8760 * Average\ corrective\ spares \qquad 8\text{-}4$$

CMSP: Average annual corrective maintenace spares consumption

λ_T: Total failure rate as number of failures per hour.

8760: Number of hours in a hour

Preventive maintenance (PM): (33)

$$PMSP = \ Number\ of\ times\ per\ year * Average\ spare\ parts\ consumption\ per\ PM\ routine \qquad 8\text{-}5$$

PMSP: Average annual preventive maintenance spare consumption

Servicing:

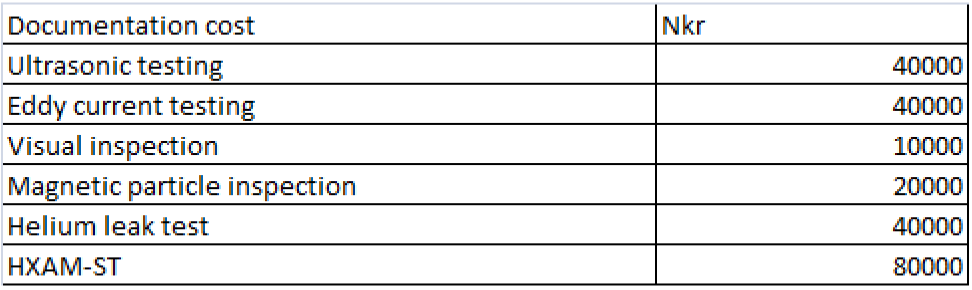
$$SMSP = \ Number\ of\ times\ per\ year * \ Average\ spare\ parts\ consumptions\ per\ servicing \qquad 8\text{-}6$$

The total spare parts consumption is then:

$$Yearly\ spare\ part\ consumption = CMSP + PMSP + SMSP \qquad 8\text{-}7$$

8.2.2.5 DOCUMENTATION COST

The rules for documentation are strict offshore. Everything needs to be certified. This means that documentation cost is a considerable high cost. Documentation before inspection includes technical information, procedures and follows up guidelines from the operator. After the inspection reports are made for the inspection and data is saved in a database. This way the data can be used for next inspection. It can also indicate findings on other similar H/Xs. (10)



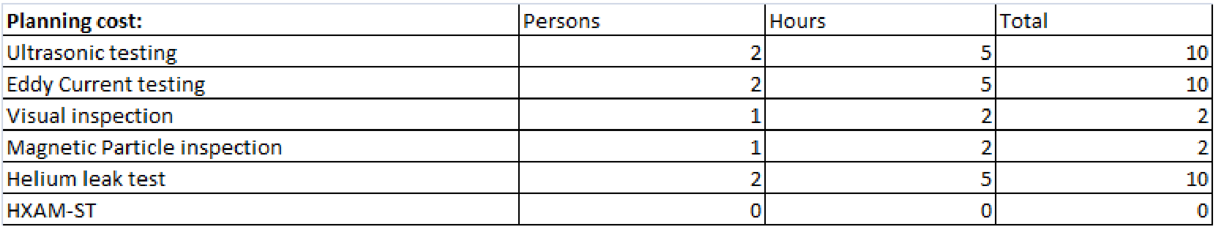
Documentation cost	Nkr
Ultrasonic testing	40000
Eddy current testing	40000
Visual inspection	10000
Magnetic particle inspection	20000
Helium leak test	40000
HXAM-ST	80000

TABLE 6: DOCUMENTATION COST

Documentation cost is assumed to be 40000 NOK for UT, ECT and HLT. VI is set to 10000NOK since this is only based on notes from the inspector. HXAM-ST is continuous monitoring and documentation cost is assumed to be 80000NOK. The documentation cost is a yearly cost.

8.2.2.6 PLANNING COST

Planning cost is all the cost related to planning of a CM inspection. This includes administration of time, personnel and tools.



Planning cost:	Persons	Hours	Total
Ultrasonic testing	2	5	10
Eddy Current testing	2	5	10
Visual inspection	1	2	2
Magnetic Particle inspection	1	2	2
Helium leak test	2	5	10
HXAM-ST	0	0	0

TABLE 7: PLANNING COST

Formula used in appendix 3

$$C_{PL} = NH_{PL} * C_{admin} \quad 8\text{-}8$$

C_{PL}: Planning cost

NH_{PL}: Hours used onshore on planning

C_{admin}: Cost administration onshore per hour.

The time used regarding planning for CM inspection, is based on the time used onshore to plan the inspection. Price per hour for planning onshore is set to 600NOK. UT testing, ECT testing and HLT is assumed to be five hours each for two persons. VI and MPI use two hours each to plan the inspection, since this is done offshore, and most of the planning time is done offshore. HXAM-ST is continuous monitoring of the performance of the heat exchanger, and do not need time for planning.

8.2.2.7 MAINTENANCE COST

Tools need frequently maintenance to work after given criteria. This cost accumulates for almost all methods. Probes for ECT needs to be calibrate once a year, to make sure that the method detect failures. (5). It is the cost for personnel carry out the maintenance on the equipment that should be calculated.

In the model the maintenance cost is set to 5% of procurement cost.

8.2.2.8 SUPPORT EQUIPMENT

Support equipment is equipment needed to carry out an inspection. This can be tools like screwdrivers, or data systems needed to analyze the results.

Support equipment is set to 3% of procurement cost.

8.2.2.9 DOWNTIME COST

Downtime is not included in the LCC analysis since it has the same amount on all methods. However, downtime cost is calculated to find less downtime by carrying out CM inspections.

Downtime cost is expensive offshore, because a platform is producing large values every day. In this thesis downtime would be based on number of failure occurs and assumed amount of downtime due to the failure. The formula for plateau period shows that if it is possible to collect some of the oil next year, the downtime cost would decrease. In this thesis it is assumed that nothing is collected next year, before the plateau period is completed. It is also assumed that in the five years after the plateau period, all loss of production is regained the same year. This means that the benefits regarding less downtime are zero for CM inspections after the plateau period.

8.2.2.9.1 PLATEAU PERIOD

If a reservoir is depleted without restriction the production rate over time would look like the stipple line in the figure below. (34)

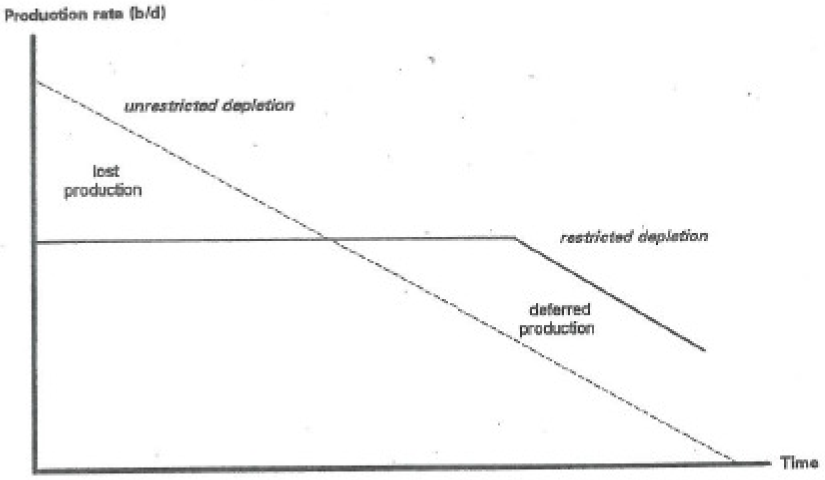


FIGURE 26: PRODUCTION PROFILE (34)

The production profile shows that over a period of time (plateau) the production is restricted. This means that it is not possible to recover the production loss before after the plateau period. After the plateau period it is possible to recover the losses the same year and hence no downtime cost due to lost production (34)

Consider a production over n years. With probability F (i), a volume V (i) not produced in year i. Further: (34)

- Let A(j),j=i+1,...n be the volume regained in the years following i. This volume is determined by the given production profile and may be zero when there is no make-up capacity in a year and will be zero from the years onwards, when the original lost volume has been made up completely.
- PR(i) is the oil price in year i
- R is the discount rate in %, rate which future income and cost values are discounted back to the current year.
- m is the number of plateau years of the production profile.

The expected revenue loss due to deferment of the volume V(i) is the difference between the expected financial value of V(i). (34)

$$F(i) * V(i) * PR(i) \qquad i = 1,2, \dots , n$$

And the expected value of oil regained in later years discounted back to year i. (34)

$$F(i)^{*} \sum_{j=i+1}^{n} \frac{a(j)^{*}PR(i)}{(1+r)^{j-1}} \qquad i = 1,2, \dots , n$$

Hence, the expected value of oil regained in later years discounted back to year i. (34)

$$F(i) * V(i) * PR(i) - F(i)F(i) * \sum_{j=i+1}^{n} \frac{a(j)^{*}PR(i)}{(1+r)^{j-1}} \qquad i = 1,2, \dots , n$$

The net NPV of this loss in terms of money in the current year (assume year 1, production start) is: (34)

$$\frac{F(i)*V(i)*PR(i)}{(1+r)^{i}} - \frac{F(i)}{(1+r)^{i}} * \sum_{j=i+1}^{n} \frac{a(j)^{*}PR(i)}{(1+r)^{j-1}} \qquad i = 1,2, \dots , n$$

Which also may be written as: (34)

$$\frac{F(i)*V(i)*PR(i)}{(1+r)^{i}} - F(i)^{*} \sum_{j=i+1}^{n} \frac{a(j)^{*}PR(i)}{(1+r)^{i}} \qquad i = 1,2, \dots , n$$

The expected revenue loss due to production deferment over all years then become: (34)

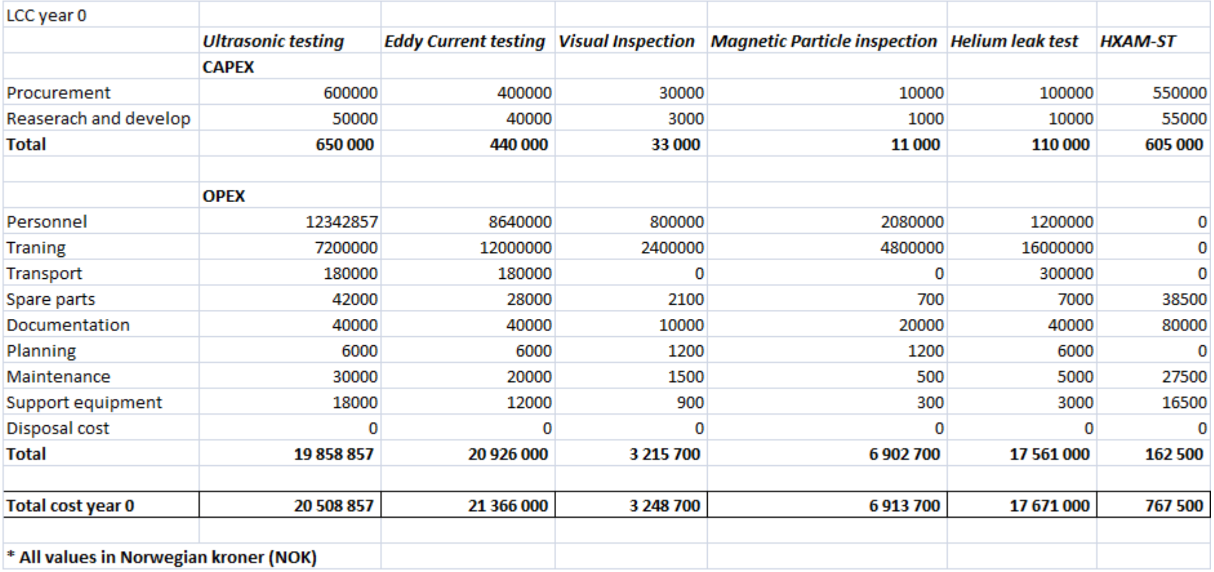
$$\text{Revloss} = \sum_{i=1}^{n} \frac{F(i)*V(i)*PR(i)}{(1+r)^{i}} - \sum_{i=1}^{n} F(i) * \sum_{j=i+1}^{n} \frac{a(j)^{*}PR(i)}{(1+r)^{i}}$$

8.2.2.10 DISPOSAL COST

Disposal cost of tools for the different methods is not taken into consideration. All the tools are small, and not harmful for the environment hence the disposal cost is set to zero.

8.2.2.11 TOTAL COST FOR YEAR 0

The table on the next page submit’s the total LCC cost for year 0. Downtime cost is, as mention before, not taken into consideration in the table. The costs for year 0, is not representative for the life cycle cost because most of the CAPEX costs are present here. Operational cost is more or less the same every year as seen in appendix 3, where yearly cost of the different methods is present.



LCC year 0						
	Ultrasonic testing	*Eddy Current testing*	*Visual Inspection*	*Magnetic Particle inspection*	*Helium leak test*	*HXAM-ST*
	CAPEX					
Procurement	600000	400000	30000	10000	100000	550000
Reaserach and develop	50000	40000	3000	1000	10000	55000
Total	**650 000**	**440 000**	**33 000**	**11 000**	**110 000**	**605 000**
	OPEX					
Personnel	12342857	8640000	800000	2080000	1200000	0
Traning	7200000	12000000	2400000	4800000	16000000	0
Transport	180000	180000	0	0	300000	0
Spare parts	42000	28000	2100	700	7000	38500
Documentation	40000	40000	10000	20000	40000	80000
Planning	6000	6000	1200	1200	6000	0
Maintenance	30000	20000	1500	500	5000	27500
Support equipment	18000	12000	900	300	3000	16500
Disposal cost	0	0	0	0	0	0
Total	**19 858 857**	**20 926 000**	**3 215 700**	**6 902 700**	**17 561 000**	**162 500**
Total cost year 0	**20 508 857**	**21 366 000**	**3 248 700**	**6 913 700**	**17 671 000**	**767 500**
*** All values in Norwegian kroner (NOK)**						

TABLE 8: OVERVIEW OF COSTS YEAR 0

The table shows that ECT is the most expensive method, tight followed up by UT and HLT. The cheapest method is HXAM-ST, since this is a monitoring system who only monitoring the H/Xs performance. HXAM-ST has also a significant lower operational costs than the other methods with only 162 500 NOK.

8.3 SYSTEM MODELLING

The analysis is based on an inspection method instead of an item. The different system modelling issues is discussed below.

Logistic risks are present due to bad weather, since some of the methods needs external crew. On the other hand, production stop on a platform due to maintenance is usually placed in the summer. In spite of this the logistics risk has not been taken into consideration regarding the model.

Human errors carrying out a CM inspection is close related to the operator's skills. Some of the methods are advanced and the findings can vary between an inspector with experience, and an unexpired inspector. This is taken into account in chapter 9.1.5 and partially in chapter 6.2. Inexperienced personnel can make dangerous situations when plugging the pipes, if it is not in accordance with regulations. Dangerous situations can also occur if personnel ignore dangerous failures. (5)

Maintenance is assumed to be carried out once a year on every H/X, when it is production stop on installation. If there is redundancy for H/X it is possible to carry out an inspection at almost any time. Methods as HXAM-ST and MPI can be carried out at any time, since they do not demand shut down of H/X.

Availability is calculated from failure data collected in the OREDA book. (1). A failure mode is assumed to have equal chance to occur at the beginning as the end of life for an H/X. In reality this is not correct since H/Xs are exposed to wear.

8.4 DATA COLLECTION

It is difficult to gather reliable information from both CAPEX and OPEX. Therefore the cost elements are based on assumptions and information from experienced personnel.

8.5 COST DRIVERS IDENTIFICATION

Pareto diagram are made to highlight the cost drivers and the vital few cost contributors. It is stated that 10%-20% of the cost element will identify 60% -80% of the total cost. In the figure below a Pareto diagram is made for operational costs for UT. (35)

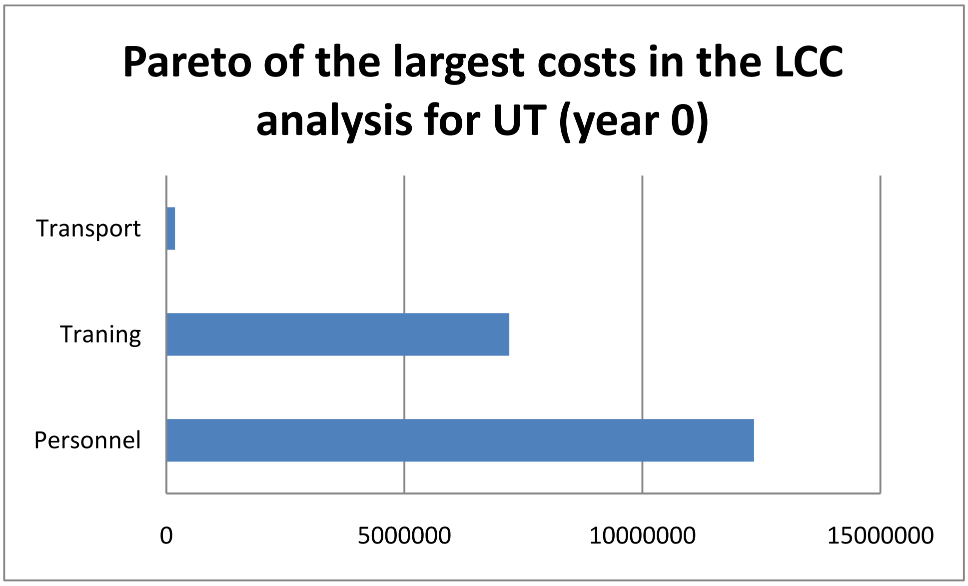


FIGURE 27: PARETO DIAGRAM FOR LIFE CYCLE COST ULTRASONIC

Figure 27 shows the three highest operation costs for UT. The other methods except HXAM-ST have more or less same distribution. The Pareto diagram shows that for operation matters, the personnel and training stands for the decidedly largest costs with 12 million NOK and 7 million NOK. The diagram represents cost from year zero.

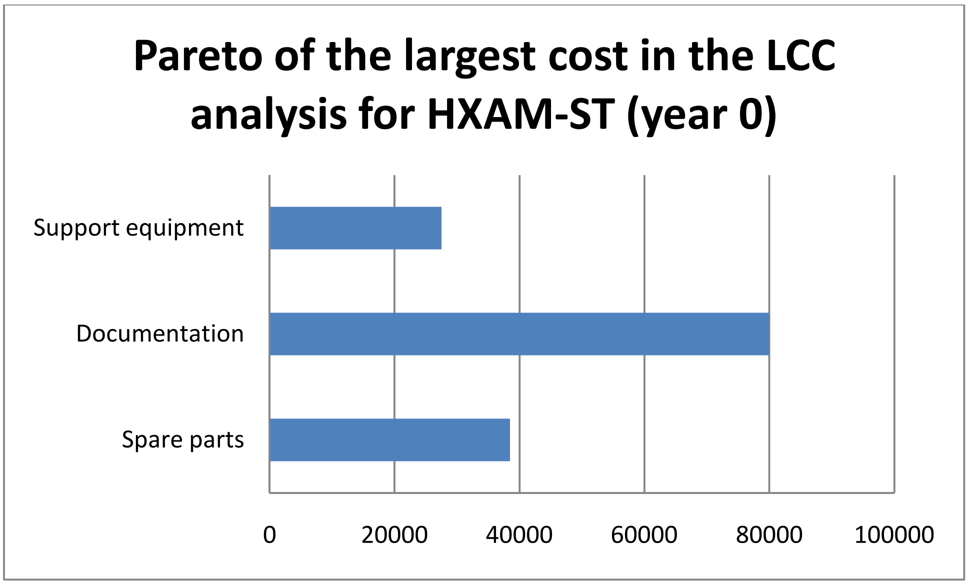


FIGURE 28: PARETO DIAGRAM FOR LIFE CYCLE COST HXAM-ST

Figure 28 shows the Pareto for operational costs for HXAM-ST. As you can see the cost are much smaller than for UT. Documentation is the highest cost with 80 000 NOK. This is because no personnel or training is needed to carry out the inspection.

8.6 EVALUATION OF LCC

The uncertainties in the LCC analysis is consider being high, since part of the costs is based on assumptions. In addition, some of the data is based on information from experienced personnel and some is found sources for. The LCC must be seen as values with uncertainties. It is stated in source (36) that the best results for uncertainties are based on subjective judgment, when the values already are uncertain.

Modelling uncertainties is considered to deal with number of inspections every year and down time cost. As mention before the downtime cost is based on that a failure of H/X would close the production on the installation. This is not probably since the H/Xs are on different production lines.

9 COST BENEFIT MODELL

The benefits of the different methods are difficult to find exact values on. A lot of different parameter needs to be taken into account. In the model benefits are calculated from less downtime, less injuries and less death.

9.1 BENEFIT MODEL

The benefit using CM is in source (3) defined as:

CM Initial Cost Benefit = Avoided costs - CM Investments Costs 9-1

Where;

Avoided Costs= Scheduled Maintenance reduction + In-service Repair reduction 9-2

And;

CM investments Costs = Equipment Capital and Installation + Operational Costs 9-3

The model generates initial cost benefit from inputs of investments costs, operational costs, scheduled maintenance costs and savings and in service repair costs. (3) Investments and operational cost is taken into consideration in the LCC analysis in chapter 8. Scheduled maintenance costs and in service repair cost is not taken into consideration.

In addition the model concerning benefits must take into account, the probability for the CM methods to detect failures, severity of different failure modes regarding safety and environment issues. (3) It is assumed in the thesis that the H/X would have no effect on the environment in spite of spill. The figure below illustrates the connection between the different benefits and cost for a CM method.

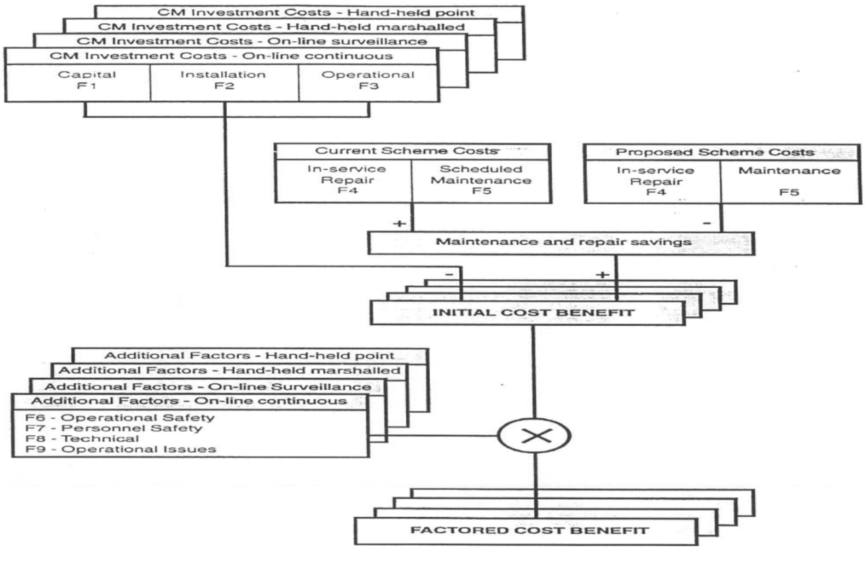


Figure 3: The Cost / Benefit Model

FIGURE 29: COST BENEFIT MODEL (3)

9.1.1 INITIAL BENEFIT

Initial cost benefit is the total possible cost saving in money by applying a CM method. It takes into account all the cost related to investments and operation of methods and all the money saved due to less downtime, less injuries and less death. (3)

9.1.2 FACTORED BENEFIT

The next stage is factored benefit. This would give a far more realistic estimate for benefits. The factors take into account safety, operational and technical issues. A general formula can be made: (3)

$$\text{Factored Benefit} = \text{Initial Benefit} * \text{Factors} \qquad 9\text{-}4$$

The factors are based on probability and informed judgements. The method is best illustrated with use of a technical aspect. (3)

In practise a number of different factors are present in the calculations. It could be organized in four different categories: (3)

- Operational safety (F6)
- Personnel Safety (F7)
- Technical Fitness for purpose (F8)
- Operational Issues (F9)

Operational safety is based on the safety around the operation, for example probability for leakage etc. (3)

Personnel safety is the opportunity for damage on personnel while carrying out the inspection. (3)

Technical Fitness for purpose is among others the probability to detect failures. (3)

Operational issues can be machine duty, similar machine proximity, and repair accessibility. (3)

The complete factored benefits can then be expressed as: (3)

$$\text{Factored Benefit} = \text{Initial Benefit} * F6 * F7 * F8 * F9 \qquad 9\text{-}5$$

For practical reasons a factor with no influence, or seen as not important, would be given factor 1. If one of the methods is seen as useless on one of the factor, the result would be almost 0. In that matter, source (3), suggest that the lowest possible factor is 0,1.

The safety consequence can cause server damages, in that matter the benefits for operational safety can be set between 2-0,1. Instead of 1-0,1 than the safety aspect would contribute a larger impact on benefits. (3) This is not taken into consideration since the methods is not that critical for safety.

In this thesis most emphasis would be put on the technical aspect. Since different CM methods would be compared.

9.1.3 OPERATIONAL SAFETY

Since most of the CM-methods are carried out while the H/X is shut down, there are not much damages like leakage etc. It is stated that almost 70 percent of the maintenance is made of maintenance action (5). This differs off course on what item maintenance is carried out on. But if the tube bundle is taken out of the shell and put on the offshore deck, damages could occur. This means that some maintenance action cause more maintenance.

Operational safety

Ultrasonic testing	0,95
Eddy Current testing	0,95
Visual inspection	0,85
MPI	1
Helium leak test	0,90
HXAM-ST	0,99

TABLE 9: OPERATIONAL SAFETY FACTORS

All of the operational safety factors are high. VI has most effect on the operational safety, since it involves a wide range of inspections, in some cases also dismantling of the H/X.

9.1.4 PERSONNEL SAFETY

The inspection involves in most cases no opportunity for injuries of personnel. Experience personnel have experience that plugs have been shot against them when the cover was open. In a gas cooler, there may be poison in the gas. However, there are strict rules offshore to make the operation safe. The different factors for operational safety are set to:

Personnel safety

Ultrasonic testing	0,8
Eddy Current testing	0,8
Visual inspection	0,8
MPI	1
Helium leak test	0,7
HXAM-ST	1

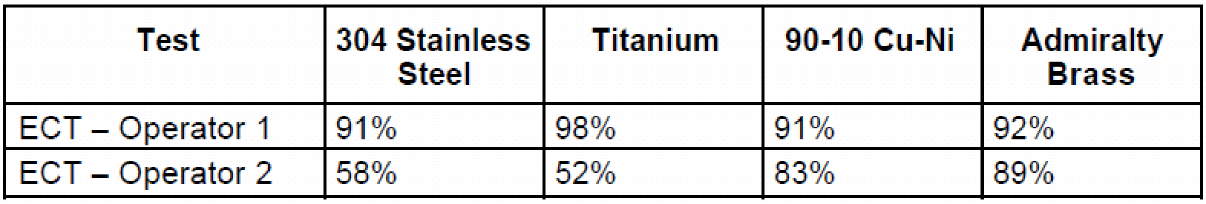
TABLE 10: PERSONNEL SAFETY FACTORS

UT, ECT and VI is set to 0,8 since they all need opening of the HX, HLT is set to 0,7 in spite that gas is used, and you need to open the HX.

HXAM-ST and MPI is categorized with no impact on the safety of the personnel carried out the inspection. Since HXAM-ST not involves personnel and MPI is assumed to be used from outside of the H/X.

9.1.5 TECHNICAL FITNESS OF PURPOSE

The probability to find failures for the different methods is present in chapter 6.3. The data is based on if the method has ability to detect the failure modes. Here the focus is put on reasons that make the method less suitable to find failure. The table below shows that personnel skills have impact on ECT.



Test	304 Stainless Steel	Titanium	90-10 Cu-Ni	Admiralty Brass
ECT – Operator 1	91%	98%	91%	92%
ECT – Operator 2	58%	52%	83%	89%

TABLE 11: FINDINGS FOR TWO OPERATORS ECT (10)

The same heat exchangers with different material are inspected with two different operators. The result shows difference on 31% for findings with ECT on stainless steel. This means that training is very important. The author has no data on the experience on the two operators, but the analysis show that the method is not 100 percent reliable.

The author has no information on personnel skills for the other methods. But is it assumed that there are differences in other methods as well. In spite of this a table is made for technical fitness of purpose.

Technical fitness for purpose

Ultrasonic testing	0,9
Eddy Current testing	0,85
Visual inspection	0,8
MPI	0,8
Helium leak test	0,95
HXAM-ST	0,5

TABLE 12: TECHNICAL FITNESS OF PURPOSE FACTORS

UT testing has got the factor 0,9 this since it is a comprehensive method, and gives reliable data on the inspection area. ECT is a faster inspection method but it requires more skill for analyzing the result in spite of this the factor is set to 0,85.

VI is a comprehensive method and the look for detail is important. On behalf of this the factor is set to 0,8.

MPI is a method with powder and a magnet. If the test is performed on the spot where the failure are, it would find the failure mode. It is important that the inspector has full concentration to discover the failure mode.

Helium leak test has the highest factor for technical purpose with 0,95 this since a leakage would be discover as long as the gas detector works.

HXAM-ST on the other hand has got a very low factor. HXAM-ST discovers easily that something is wrong, but has not the ability to show what is wrong. With good reference data it is possible to distinguish between leakage and fouling, based on parameter changes. If it is fouling the parameters would change slowly, for leakage the parameters would change rapidly.

9.1.6 OPERATIONAL ISSUE

There are a lot of H/Xs in the offshore industry and many are of similar type. This gives personnel the possibility to use experience data from other similar H/X from other installations. The repair accessibility is not good inside the tube bundle the only opportunity is to plug the tube. In spite of this the offshore company use fixed time (5), when they change the tube bundle. Other parts as shell and valves can be changed after needs.

Operational issues

Ultrasonic testing	0,9
Eddy Current testing	0,9
Visual inspection	0,9
MPI	1
Helium leak test	0,9
HXAM-ST	1

TABLE 13: OPERATIONAL ISSUES FACTORS

MPI and HXAM-ST is set to have no impact on operational issues since it is applied in operation, and not involves dissembling of the H/X. The other methods requires disassembling of the H/X, and the factors is set to 0,9.

10 THE MODEL

The model is based on a combination of the LCC analysis, present in chapter 8, and the benefit analysis present in chapter 9.

10.1 INPUT DATA

Input for the model is shown in table 14.

Lifetime for the installation	20	Years
Remaining plateau period	15	Years

Production of oil	100000	barrels/per day
Production of gas	300000	m^3 per day

Oil cost	50	USD/barrel
Gas cost	0,5	USD/m^3

Personnel cost	
Man hour cost onshore	1000
Man hour cost offshore	3000
Cost per hour Admin(onshore)	600

Injury cost		
Death cost	20 000 000	NOK
Injury cost	1500000	NOK
Spill cost	50000	NOK/m^3

Rent	12	%
Inflation	2,5	%

TABLE 14: INPUTA PARAMETERS FOR THE MODEL

The lifetime of the H/X is set to twenty years, while the remaining plateau period for the reservoir is set to 15 years. The production of oil and gas are based on assumptions discussed with supervisor. Personnel cost is set to respectively 1000NOK and 3000NOK for onshore and offshore man hours. Administration cost onshore is set to 600 NOK per hour.

It is stated in source (37) that the value of a human life in Norway is 18 million NOK in 1999, on behalf of this the cost for death is set to 20 000 000 NOK. Injury cost is set to 1 500 000 NOK per injury, because an injury would cause a lot of work regarding investigation.

Spill cost is set to 50 000 NOK/m^3. Yet, this is not taken into consideration since it is assumed that it is enough lines of defences to close down the H/X if spill occur. When it is assumed no spill also reputation loss is excluded.

Inflation is set to 2,5 percent and rent is set to 12%.

Price for oil and gas price is set to respectively 50 USD/barrel and 0,5 USD/m^3. They are calculated from USD to NOK.

Calculation of downtime cost

1USD	6	Nkr		
Production of oil	30000000	NOK/per day	**1 250 000**	NOK/per hour
Production of gas	900000	NOK/per day	**37 500**	NOK/per hour
		Total production	**1 287 500**	NOK/per hour

TABLE 15: CALCULATION OF DOWNTIME COST

The formula used is:

$$C_d = \frac{(P_O * C_O * c_{factor}) + (P_g * C_g * c_{factor})}{24} \qquad 10\text{-}1$$

C_d: *Downtime cost per hour*

P_o: Production of oil [barrel/day]

C_o: Cost of oil [USD/barrel]

c_{factor}: Conversion factor [USD → NOK]

P_g: Production of gas [m^3/day]

C_g: Cost of gas [USD/m^3]

24: Hours in a day and night

Formula 10-1 gives downtime cost per hour.

It is assumed that an H/X is running for 24 hours a day for the whole year except for 14 days maintenance.

Running hours per year

365	days
14	days maintenance
24	hours a day
8424	hours/year

TABLE 16: RUNNING HOURS PER YEAR

The second sheet in the model (appendix 3) is about LCC cost, the formulas are present in chapter 8.

10.2 CALCULATION OF DOWNTIME

The data for failure rate in the figure below is from OREDA 2002 (1), and is the failure per 10^6 hours for the different failure modes. The data is processed to failure per year on the installation. The formula for failure per year:

$$Failure\ per\ year = \left(\frac{f_{10\hat{}6}}{10\hat{}6}\right) * W_y \qquad 10\text{-}2$$

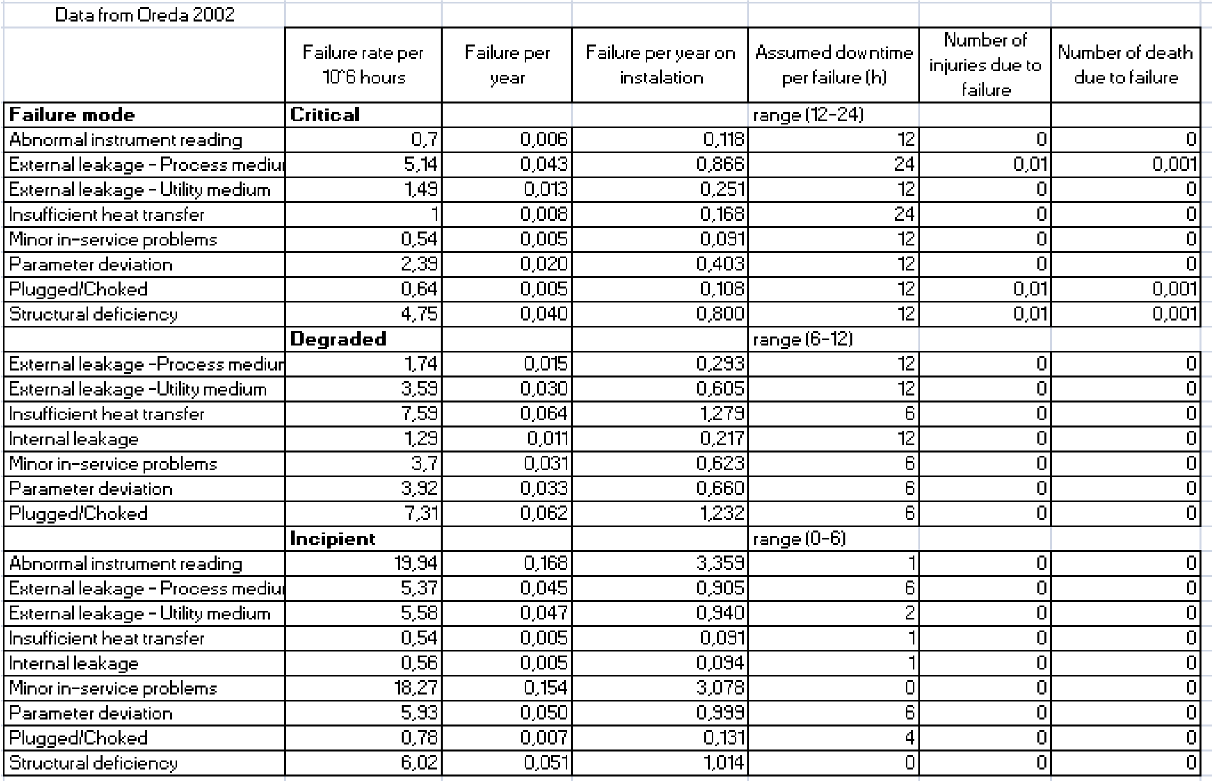
$f_{10\hat{}6} =$ failure per 10^6 hours

$$W_y = \text{number of hours in operation per year}$$

Further the failure per year on installation is calculated:

$$Failure\ per\ year\ on\ installation = Failure\ per\ year * number\ of\ heat\ exchangers \qquad 10\text{-}3$$

Afterwards, numbers of hour's downtime due to failures are assumed. The range is set between 12-24 hours for critical failures, 6-12 for degraded failures and 0-6 hours for incipient failures. Number of injuries and death due to failure modes are also assumed.



Data from Oreda 2002						
	Failure rate per 10^6 hours	Failure per year	Failure per year on instalation	Assumed downtime per failure (h)	Number of injuries due to failure	Number of death due to failure
Failure mode	**Critical**			range (12-24)		
Abnormal instrument reading	0,7	0,006	0,118	12	0	0
External leakage - Process mediu	5,14	0,043	0,866	24	0,01	0,001
External leakage - Utility medium	1,49	0,013	0,251	12	0	0
Insufficient heat transfer	1	0,008	0,168	24	0	0
Minor in-service problems	0,54	0,005	0,091	12	0	0
Parameter deviation	2,39	0,020	0,403	12	0	0
Plugged/Choked	0,64	0,005	0,108	12	0,01	0,001
Structural deficiency	4,75	0,040	0,800	12	0,01	0,001
	Degraded			range (6-12)		
External leakage -Process mediur	1,74	0,015	0,293	12	0	0
External leakage -Utility medium	3,59	0,030	0,605	12	0	0
Insufficient heat transfer	7,59	0,064	1,279	6	0	0
Internal leakage	1,29	0,011	0,217	12	0	0
Minor in-service problems	3,7	0,031	0,623	6	0	0
Parameter deviation	3,92	0,033	0,660	6	0	0
Plugged/Choked	7,31	0,062	1,232	6	0	0
	Incipient			range (0-6)		
Abnormal instrument reading	19,94	0,168	3,359	1	0	0
External leakage - Process mediu	5,37	0,045	0,905	6	0	0
External leakage - Utility medium	5,58	0,047	0,940	2	0	0
Insufficient heat transfer	0,54	0,005	0,091	1	0	0
Internal leakage	0,56	0,005	0,094	1	0	0
Minor in-service problems	18,27	0,154	3,078	0	0	0
Parameter deviation	5,93	0,050	0,999	6	0	0
Plugged/Choked	0,78	0,007	0,131	4	0	0
Structural deficiency	6,02	0,051	1,014	0	0	0

FIGURE 30: FAILURE MODES OREDA

External leakage process medium and insufficient heat transfer is set to have the largest downtime after critical failures. This is because critical insufficient heat transfer most likely leads to cleaning of the whole H/X. The process is time consuming. External leakage process medium leads to leakage of gas or oil, which is serious and would lead to immediate shut down. It must be properly fixed before H/X can be used again.

Injuries are only assumed to occur for external leakage process medium, plugged/choked and structural deficiency.

External leakage can cause burn injuries from both oil and gas. Plugged/choked can cause injuries if a pipe is not properly plugged, than the plug can be shoot out when opening the cover. Structural deficiency includes a wide range of failures and for example corrosion on support could lead to injury from breakdown of support. The number is set to 1 injury per 100 failures for these three failures. The probability for death is set to 1 injury per 1000 failures for the same failure modes as for injuries.

10.3 COST OF FAILURE

The failure rate from chapter 10.2 is processed to hours per year downtime due to failure mode. Formula used:

$$H_y = F_{yc} * D_c + F_{yd} * D_d + F_{yi} * D_i \qquad 10\text{-}4$$

H_y: Hours per year down time due to failure mode

F_{yc}: Failure per year critical failure

D_c: Downtime due to critical failure

F_{yd}: Failure per year degreaded failure

D_d: Downtime due to degraded failure

F_{yi}: Failure per year incipient failure

D_i: Downtime due to incipient failure

Formula (10-3) gives hour downtime on the different failure modes.

Formula for downtime cost per year:

$$C_{dPL} = H_y * C_d$$

C_{dPL}: Cost down time due to production loss

H_y: Hours per year down time due to failure mode

C_d: Cost per downtime hour

Cost of injuries is calculated as shown in formula (10-4)

$$C_i = c_i * P_i \qquad 10\text{-}5$$

C_i: Cost of injuries per year

c_i: Cost per injury

P_i: Probability for injuries

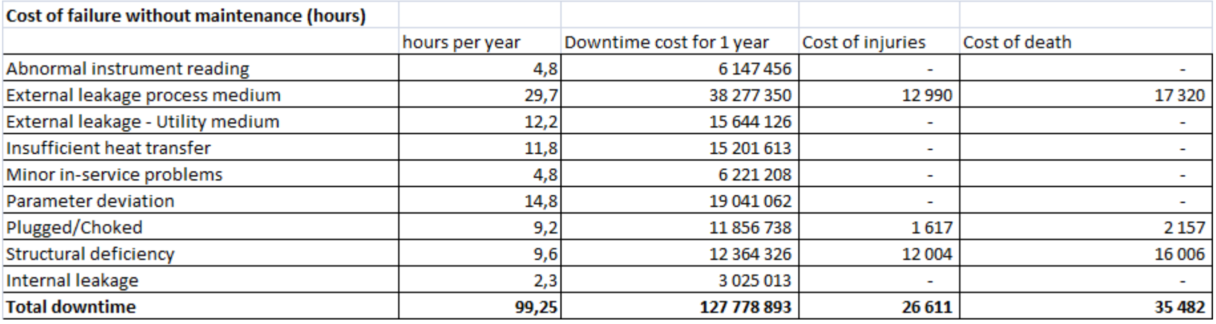
Cost of death is calculated as shown in formula (10-5).

$$C_{de} = c_{de} * P_{de} \qquad 10\text{-}6$$

C_{de}: Cost of death per year

c_{de}: Cost per death

P_{de}: Probability for death



Cost of failure without maintenance (hours)				
	hours per year	Downtime cost for 1 year	Cost of injuries	Cost of death
Abnormal instrument reading	4,8	6 147 456	-	-
External leakage process medium	29,7	38 277 350	12 990	17 320
External leakage - Utility medium	12,2	15 644 126	-	-
Insufficient heat transfer	11,8	15 201 613	-	-
Minor in-service problems	4,8	6 221 208	-	-
Parameter deviation	14,8	19 041 062	-	-
Plugged/Choked	9,2	11 856 738	1 617	2 157
Structural deficiency	9,6	12 364 326	12 004	16 006
Internal leakage	2,3	3 025 013	-	-
Total downtime	**99,25**	**127 778 893**	**26 611**	**35 482**

TABLE 17: COST OF FAILURE WITHOUT CM

The table above shows that loss of production is the decidedly largest cost. If no CM inspection or maintenance is carried out the yearly downtime cost would be almost 128 million NOK. External leakage process medium is the failure mode with decidedly largest cost, 38 million NOK. On the other hand, internal leakage only cost 3 million NOK per year.

The cost for injuries and death would be respectively 26 000 NOK and 35 000 NOK.

10.4 LESS DOWN TIME DUE TO CM

Less downtime due to CM inspection are calculated from the probability to detect failures presented in chapter 6.3. The formula used is:

$$DS_{CM} = H_y * Pd_f \qquad 10\text{-}7$$

DS_{CM}: Downtime saved due to CM inspection

H_y: Hours per year downtime due to failure mode

Pd_f: Probability to detect failures

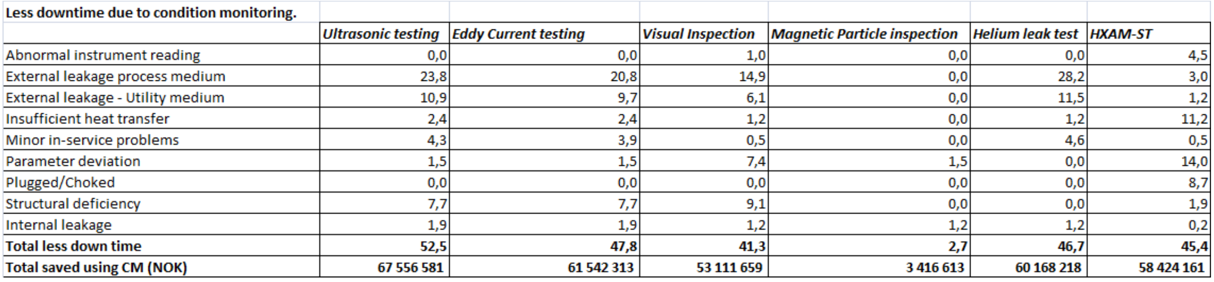
Less downtime due to CM is calculated as this:

$$B_{CM} = DS_{CM} * D_c$$

B_{CM}: Benefit using representative CM method

DS_{CM}: Downtime saved due to CM inspection

D_c: Downtime cost

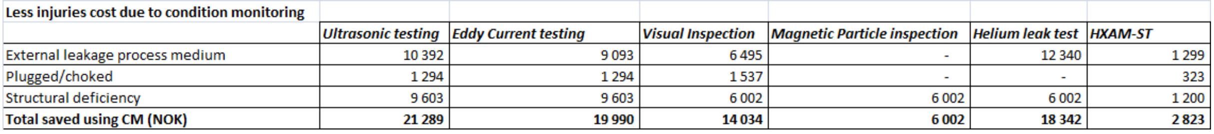


Less downtime due to condition monitoring.						
	Ultrasonic testing	***Eddy Current testing***	***Visual Inspection***	***Magnetic Particle inspection***	***Helium leak test***	***HXAM-ST***
Abnormal instrument reading	0,0	0,0	1,0	0,0	0,0	4,5
External leakage process medium	23,8	20,8	14,9	0,0	28,2	3,0
External leakage - Utility medium	10,9	9,7	6,1	0,0	11,5	1,2
Insufficient heat transfer	2,4	2,4	1,2	0,0	1,2	11,2
Minor in-service problems	4,3	3,9	0,5	0,0	4,6	0,5
Parameter deviation	1,5	1,5	7,4	1,5	0,0	14,0
Plugged/Choked	0,0	0,0	0,0	0,0	0,0	8,7
Structural deficiency	7,7	7,7	9,1	0,0	0,0	1,9
Internal leakage	1,9	1,9	1,2	1,2	1,2	0,2
Total less down time	**52,5**	**47,8**	**41,3**	**2,7**	**46,7**	**45,4**
Total saved using CM (NOK)	**67 556 581**	**61 542 313**	**53 111 659**	**3 416 613**	**60 168 218**	**58 424 161**

TABLE 18: LESS DOWNTIME DUE TO CONDITION MONITORING

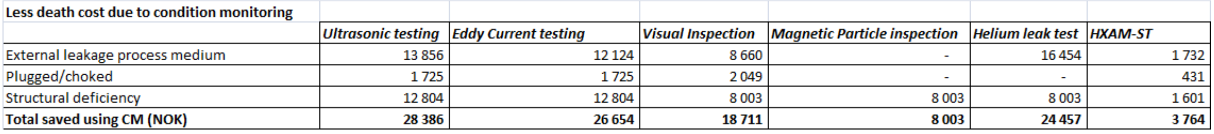
The table above shows that there is much money to save for using the different CM-methods every year. UT is the method who gives the best results with 67,5 million NOK per year, MPI is the method with less savings with 3,4 million NOK per year.

For injury and death the same procedure is followed, but only external leakage –process medium, plugged/choked and structural deficiency is taken into consideration. Since these are the three failure modes who can cause an injury or a death.



Less injuries cost due to condition monitoring						
	Ultrasonic testing	***Eddy Current testing***	***Visual Inspection***	***Magnetic Particle inspection***	***Helium leak test***	***HXAM-ST***
External leakage process medium	10 392	9 093	6 495	-	12 340	1 299
Plugged/choked	1 294	1 294	1 537	-	-	323
Structural deficiency	9 603	9 603	6 002	6 002	6 002	1 200
Total saved using CM (NOK)	**21 289**	**19 990**	**14 034**	**6 002**	**18 342**	**2 823**

TABLE 19: LESS INJURIES COST DUE TO CONDITION MONITORING



Less death cost due to condition monitoring						
	Ultrasonic testing	***Eddy Current testing***	***Visual Inspection***	***Magnetic Particle inspection***	***Helium leak test***	***HXAM-ST***
External leakage process medium	13 856	12 124	8 660	-	16 454	1 732
Plugged/choked	1 725	1 725	2 049	-	-	431
Structural deficiency	12 804	12 804	8 003	8 003	8 003	1 601
Total saved using CM (NOK)	**28 386**	**26 654**	**18 711**	**8 003**	**24 457**	**3 764**

TABLE 20: LESS DEATH COST DUE TO CONDITION MONITORING

Table 19 shows less injuries cost and table 20 shows less death cost due to CM. It is the same trend as for less downtime, UT saves most. HXAM-ST has low probability to detect the failure modes, which leads to injury and death. This leads to limited savings on injuries and death.

10.5 BENEFIT FOR THE DIFFERENT METHODS

Cost-benefit is shown in appendix 3. The cost and benefits are calculated with the simple formula.

$$Benefit = Avoided\ cost - CM\ investment\ cost \qquad 10\text{-}8$$

10.6 NET PRESENT VALUE (NPV) ADJUSTMENT

The rent is set to 12% and the inflation is set to 2,5%. The formula used to calculate NPV is from source (12)

$$NPV = \sum_{i=1}^{n} B_i * (1 + p')^{\wedge} - i \qquad 10\text{-}9$$

B: Benefits for year i

i: year in the life cycle

p’: rent adjusted with inflation

Further the formula for p’ is:

$$p' = \frac{1+p}{1+f} - 1 \qquad 10\text{-}10$$

p: Rent

f: inflation

Calculated for every year on each method, gives a total benefit over the period. This is present in appendix 3. Since it is assumed that the production can be regain after the plateau period, all of the methods would give negatively results in year fifteen to end of life in year nineteen.

10.7 RESULTS FROM THE MODEL

The results from the model would be present as initial benefit and factored benefit over the lifetime of H/Xs.

10.7.1 INITIAL BENEFIT

The result from the cost-benefit analysis is presented graphical in figure 31 (initial benefit) and figure 32 (factored benefit).

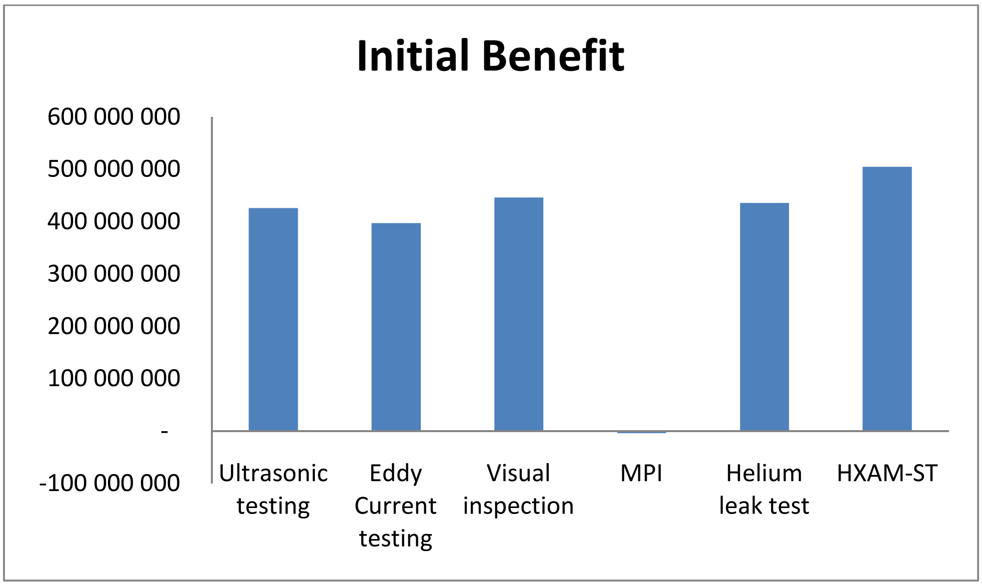


FIGURE 31: INITIAL BENEFIT

	Initial benefit over lifetime (NOK)
Ultrasonic testing	441 618 345
Eddy Current testing	412 843 323
Visual inspection	446 107 927
MPI	-4 187 915
Helium leak test	462 190 653
HXAM-ST	504 229 137

TABLE 21: INITIAL BENEFIT

Table 21 shows initial benefits over the life cycle before factored benefit is taken into consideration. HXAM-ST has the largest benefits with just over 504 million NOK. This is likely since HXAM-ST has no cost regarding personnel and training, who is by far the largest operational cost for the other methods. HXAM-ST has also good ability to detect failures.

HLT is the second best method regarding initial benefit. HLT has large expenditures with training the personnel, but the personnel cost is low since it is assumed that it only takes five hours to perform a HLT test. HLT detect almost all failure modes concerning leakage.

The benefit using VI and UT has benefits on respectively 446 million NOK and 441 million NOK VI has low cost regarding both capital expenditure and operational expenditure. A lot of the method is based on using the inspector eyes. VI has also the ability to find a wide range of failures. UT is the method with the second largest operational costs, but UT has a large detection rate since the response data is very exactly.

ECT is the last method with significant benefits. ECT has the highest operation cost and the total benefit is 412 million NOK.

MPI is the only method who gives a negatively result with 4 million NOK. MPI has a limited range of finding failures, hence the benefits due to less downtime is limited. In spite of this the MPI is not consider with factored benefit.

10.7.2 FACTORED BENEFIT

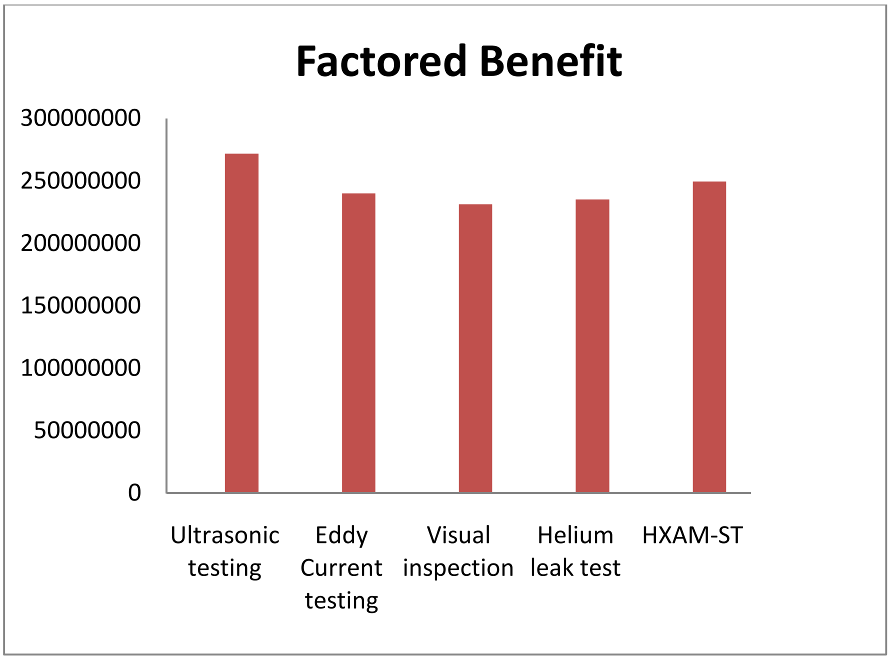
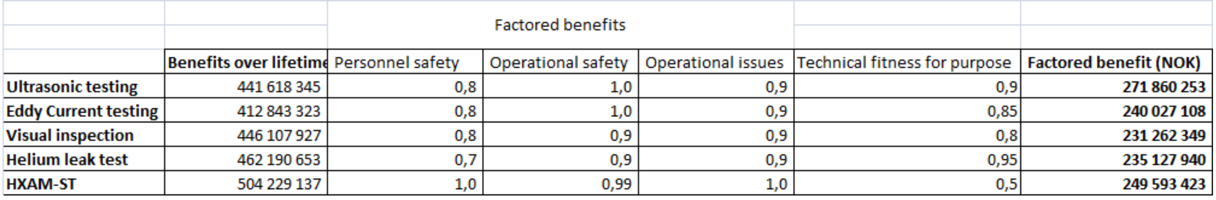


FIGURE 32: FACTORED BENEFIT



		Factored benefits				
	Benefits over lifetime	Personnel safety	Operational safety	Operational issues	Technical fitness for purpose	**Factored benefit (NOK)**
Ultrasonic testing	441 618 345	0,8	1,0	0,9	0,9	**271 860 253**
Eddy Current testing	412 843 323	0,8	1,0	0,9	0,85	**240 027 108**
Visual inspection	446 107 927	0,8	0,9	0,9	0,8	**231 262 349**
Helium leak test	462 190 653	0,7	0,9	0,9	0,95	**235 127 940**
HXAM-ST	504 229 137	1,0	0,99	1,0	0,5	**249 593 423**

TABLE 22: FACTORED BENEFIT

The distribution will look like the table and figure above when the factored benefit is taken into consideration.

UT is now the most cost effective method with a total benefit of 271 million NOK. This since UT has high factors on all of the four criteria.

HXAM-ST is now on second place with a total benefit of 249 million NOK, because HXAM-ST has problems with distinguish what failure that occurs.

ECT has a benefit around 240 million NOK. ECT has high factors on all of the four criteria.

HLT has felt from second best to fourth best method. The reason for this is that the factor 0,7 on personnel safety. The total profit over lifetime is 235 million NOK.

VI has a benefit on 231 million NOK, thus VI is based on experience personnel and skilled personnel, hence the factored are lower than the other without HXAM-ST on technical fitness for purpose.

It is important to notice that the last five years are expected no downtime due to all oil would be regained the same year after the plateau period. This means that all the methods would give negatively result the last five years. In spite of this the only benefits with CM methods are less death and injuries. This means that no CM inspection should be consider. As mention before, the thesis is based on same probability for fail over the life cycle for the H/X, in reality the failure rate would increase with the age of the H/X.

10.8 THE INFLUENCE OF INPUT PARAMETERS WITH RESPECT TO OPERATIONAL CONDITIONS

The input parameters in the model have some vulnerable moments regarding operational conditions.

The model is not taking change in H/Xs operation condition, for example can more corrosive surroundings increase the rate of failures. This is a known problem in the industry, and it would increase the failure rate for H/Xs.

If the concentrate of sand is increasing in the process fluid, the sand would wear down the protection layers in pipes and tubes connected to H/Xs. It would also increase the possibility the failure mode plugged/choked.

If the process fluid contains large amount of CO2 and H2S, this would demand more and more inspections. If number of inspections on each heat exchanger doubles, the cost per year would double since the operation costs are based on one inspection per year.

If velocity of flow is decreasing on water side problem with fouling would increases. This would lead to more cleaning of tubes before carrying out ECT and UT who demands clean tubes to be carried out in the tube bundle. The capacity of H/X would decrease and if the temperature on process fluid is increasing the H/X would need to be cleaned regularly, hence increased downtime.

The general environment condition around the platform could have an impact on the failure rate, in spite of rain storm and difficulty to carry out CM inspections. This could increase both transport and personnel cost due to more time on the platform for inspection crew and more expensive transport in spite of demanding weather conditions. In worst case set the person in charge in a dilemma, start without doing the inspection or have more than planned downtime to carry out the inspection.

The parameters mention above is considering operational conditions. The parameters mention below would also have a great influence on the model.

If redundancy is present, all the cost for decreased downtime due to CM inspection would disappear and the only benefits left is less death and injury cost.

Number of H/Xs is assumed to be 20 on the offshore platform. This can differs from installation to installation. When a failure mode occurs on one of the H/X is it assumed that it leads to a production stop on the installation. In reality this would not happen since the different H/Xs are connected to different production lines.

The cost of death and injuries could increase if the process medium gas or oil contains larger concentrations of health harmful gases, for example could present of H2S be dangerous for personnel with a leakage or under an inspection.

Availability in terms of possibility to carry out the maintenance action after the CM inspection has detected failure modes. In offshore platforms there are some production stops due to maintenance every year. In the model it is assumed that the findings from CM inspection would be repaired before it fails.

Accessibility is a keyword, the inspection crew on Aker Solutions told about inspection when the H/X was not ready for inspection. In spite of this, they used up to a week before starting with inspection. This increases the personnel cost.

Production rate and oil price has a large impact on the model, since the CM benefits is principally based upon downtime.

On the other hand the failure probability is taken out from OREDA 2002, this is an eight years old book. Better materials and design of H/X could introduce lower failure rates.

10.9 SENSITIVITY ANALYSIS

The data used in the model has a large uncertainty since most of the values are based on assumptions. A sensitivity analysis can highlight some of the large uncertainties. The sensitivity analysis will look at differences in production rate, changes in oil price, amount of failure modes leading to production stop, what oil price would make UT and HXAMST not beneficial and what are the benefits if there is redundancy on the installation. 50% reduction in probability to detect failure and only five H/Xs on an installation is also considered.

If the method has negatively initial benefit it would not be shown graphical, in the sensitivity analysis.

10.9.1 CHANGES IN PRODUCTION RATE

Since the cost benefit model is based on a given amount of production, it would be interesting to look at reduced and increased production. This is also important since reduced downtime is the dominant benefit element. The production would be decreased to 25 000 barrels of oil per day, and increased to 150 000 barrels of oil per day.

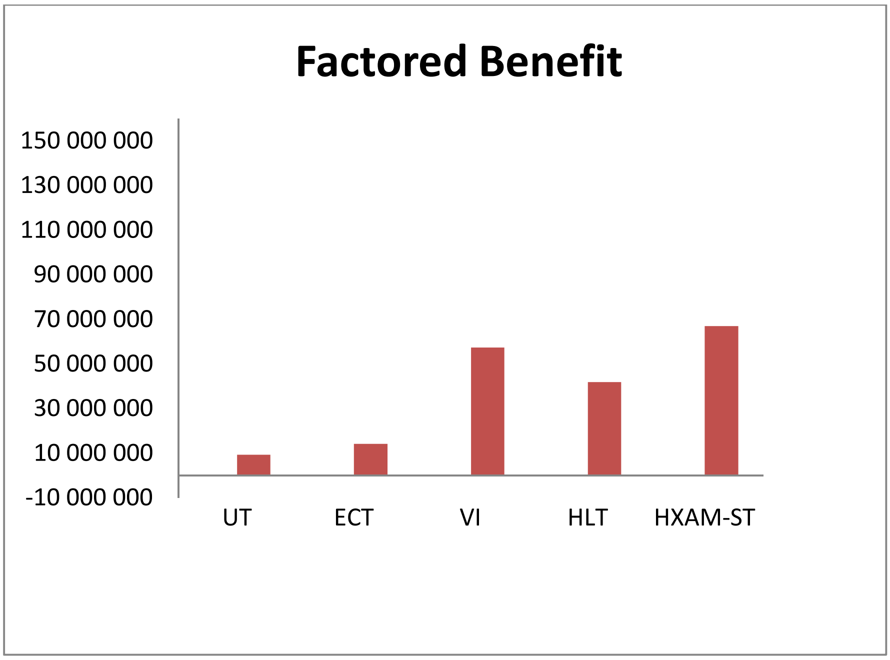


FIGURE 33: BENEFITS WITH PRODUCTION OF 25000 BARRELS/ DAY

As the figure shows the benefits is decreasing a lot if the production is 25 000 barrels/day instead of 100 000 barrels/day. VI and HXAM-ST is now the best and second best method. This since they have significant lower life cycle costs carrying out the inspection than methods like UT and ECT who have the highest LCC.

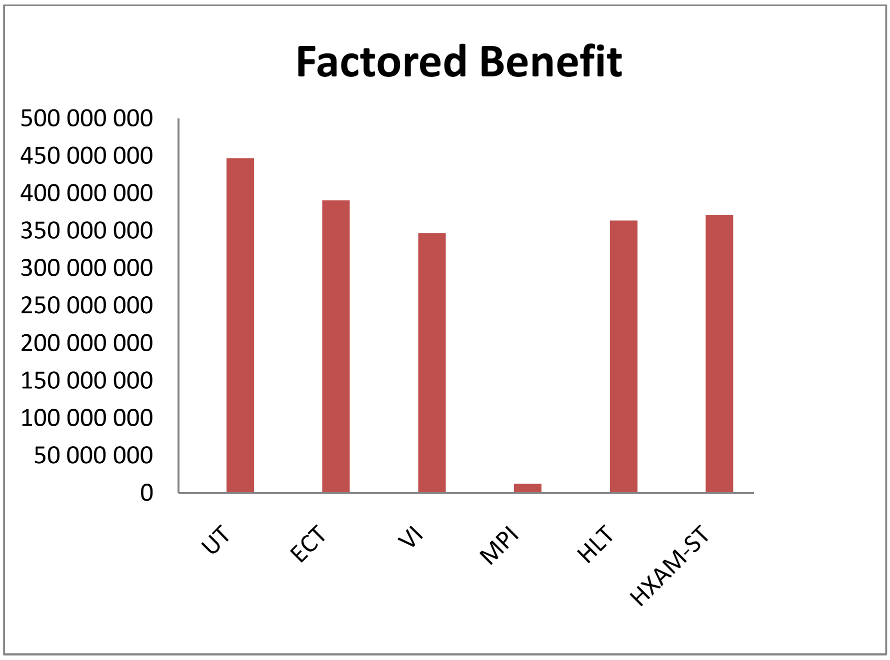


FIGURE 34: BENEFITS WITH PRODUCTION OF 150 000 BARRELS/DAY

If the production rate is 150 000 barrels/day five of the methods has benefits between 350-450 million NOK through the lifetime of the H/X. Although MPI would be beneficial to apply, the savings are small. And the method must be investigated further before being applied.

10.9.2 CHANGES IN OIL PRICE

The oil price calculated within the cost-benefit analysis is 50 USD/barrel. The graph below shows the change in crude oil from 1978. It could therefore be interested to look at what changes in the oil price would affect the cost benefit model. If a real and more environmentally friendly alternative to crude oil would be discovered. The price could fall to 10 USD/barrel. The most realistic is that the prices would increase. An average oil price of 80 USD/barrel would also be looked at.

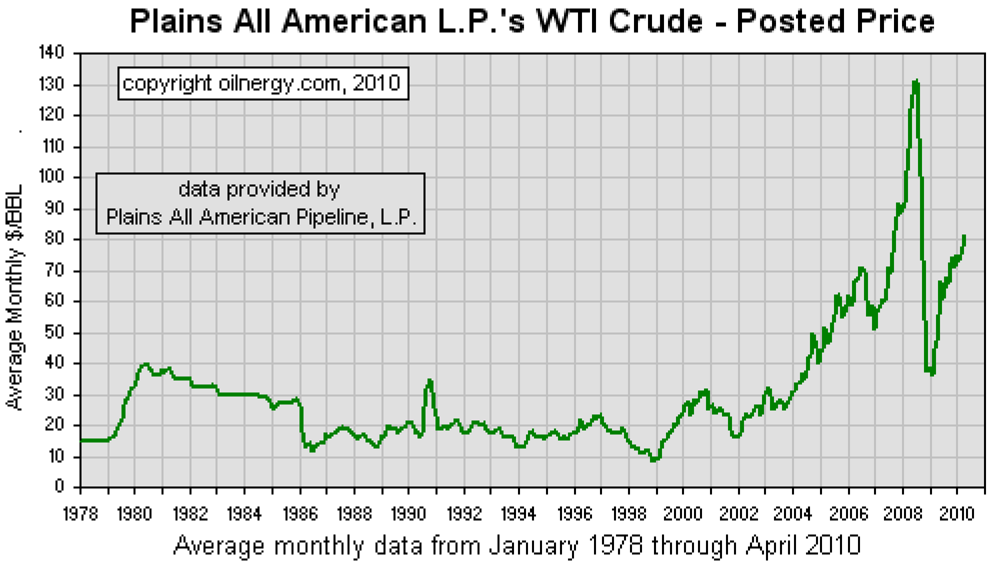


FIGURE 35: CHANGES IN CRUDE OIL PRICE SINCE 1978 (38)

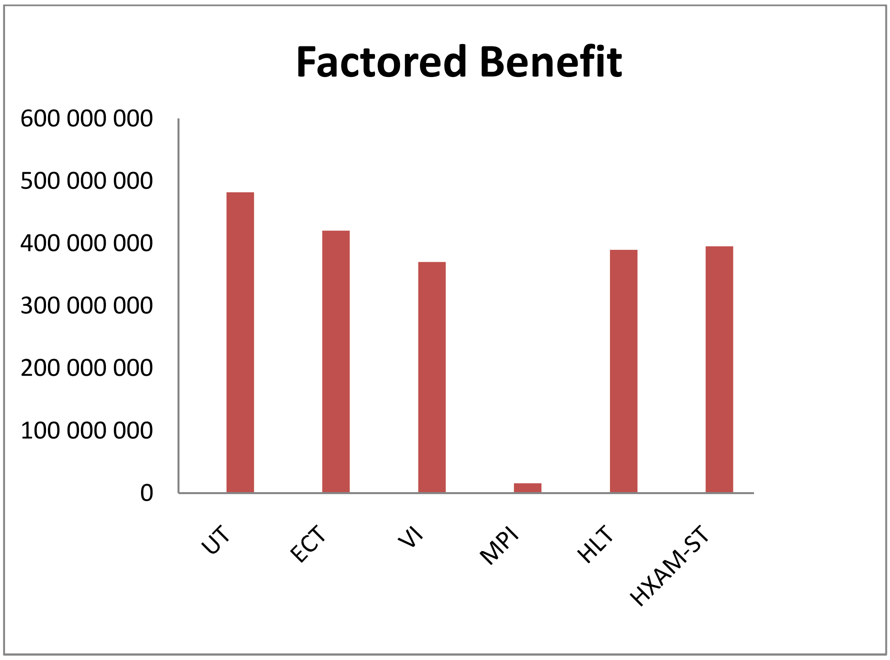


FIGURE 36: BENEFITS WITH OIL PRICE 80USD/BARREL

If the average oil price is 80 USD/barrel, all of the method would be beneficial. UT is almost turning 500 million NOK in benefit over 20 years. The benefit with MPI is still very moderate and an investment must be further investigated.

	Initial benefits over lifetime (NOK)
UT	-13 306 086
ECT	-1 581 166
VI	88 455 264
MPI	-27 195 305
HLT	57 019 284
HXAM-ST	110 802 210

TABLE 23: INITIAL BENEFITS WITH OIL PRICE 10USD/BARREL

The table above shows that UT, ECT and MPI have negative values. This means that they would not be taken into consideration for the factored benefit.

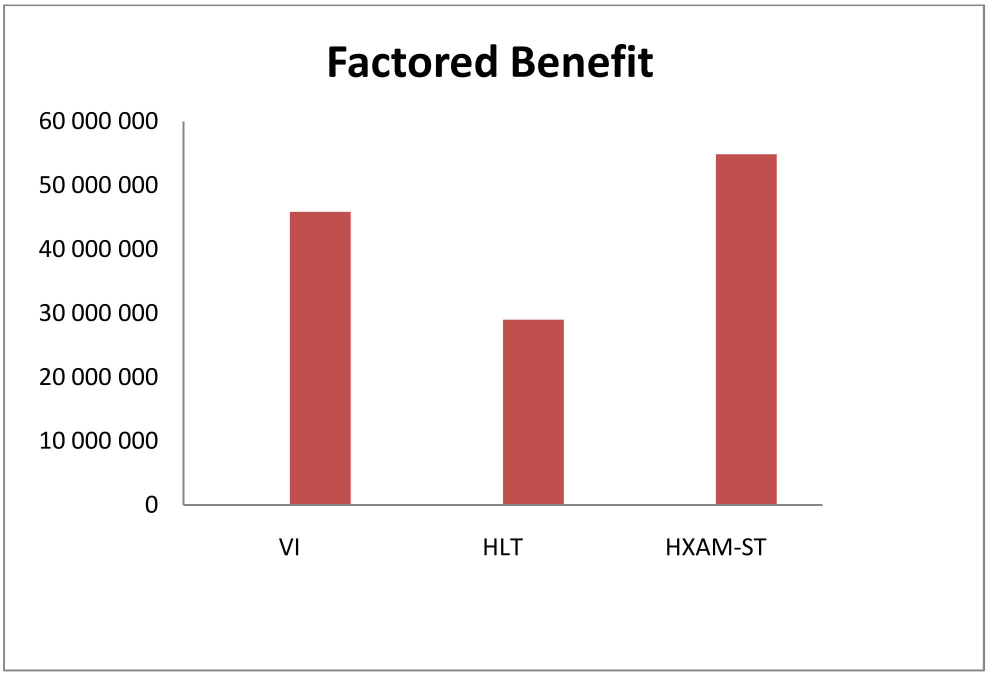


FIGURE 37: BENEFITS WITH OIL PRICE 10 USD/BARREL

Figure 37 shows that only VI, HLT and HXAM-ST is beneficial to apply if the average oil price is 10 USD/barrel through the life cycle, although the benefits are decreased to 60 million NOK for the most cost effective method HXAM-ST.

10.9.3 20% OF THE FAILURE LEADS TO PRODUCTION STOP

If a failure mode occurs on an H/X (one out of twenty), it is assumed that the production for the whole platform would be shut down, if it is assumed that only 20% of the failure leads to shut down of the production. The benefits of the different methods would look like this:

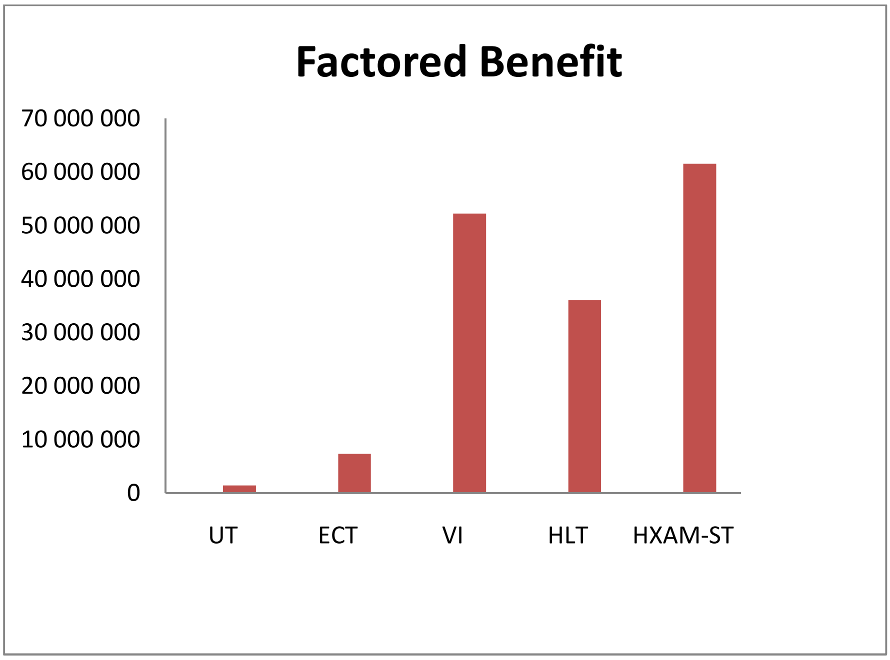


FIGURE 38: BENEFITS WHEN 20% OF THE FAILURE LEADS TO SHUTDOWN

The table above shows that VI, HLT and HXAM-ST are still beneficial when only 20% of the failure leads to a shutdown of the production. UT and ECT have now just a little benefit on respectively 1 million NOK and 7 million NOK. This means that these two methods must be investigated further before they can be carried out.

10.9.4 OIL PRICE WHEN HXAM-ST AND UT NOT IS BENEFICIAL ANYMORE

It is interesting to look at what oil price HXAM-ST not is beneficial anymore. In this case the gas production is set to zero. By manipulate the oil price in the model, the results is 0,2 USD/barrel to make HXAM-ST not beneficial anymore. This is unlikely and based on this it is beneficial to apply HXAM-ST regardless of the future oil price.

The same procedure is done with UT. UT is the most beneficial method from the starting point. If the oil price is set to 12,6 USD/barrel. UT would not be beneficial anymore. In the future the oil price would most likely be more than 12,6 USD/barrel in average. UT is the method with second most life cycle costs, in spite of this it is likely to also recommend UT.

10.9.5 REDUNDANCY ON H/XS

Redundancy is, as mention in chapter 10.8, a parameter that would have a large impact on the outcome from the analysis. In spite of that much of the downtime cost would disappear. If all the downtime cost disappear only benefits for less injuries and death is present.

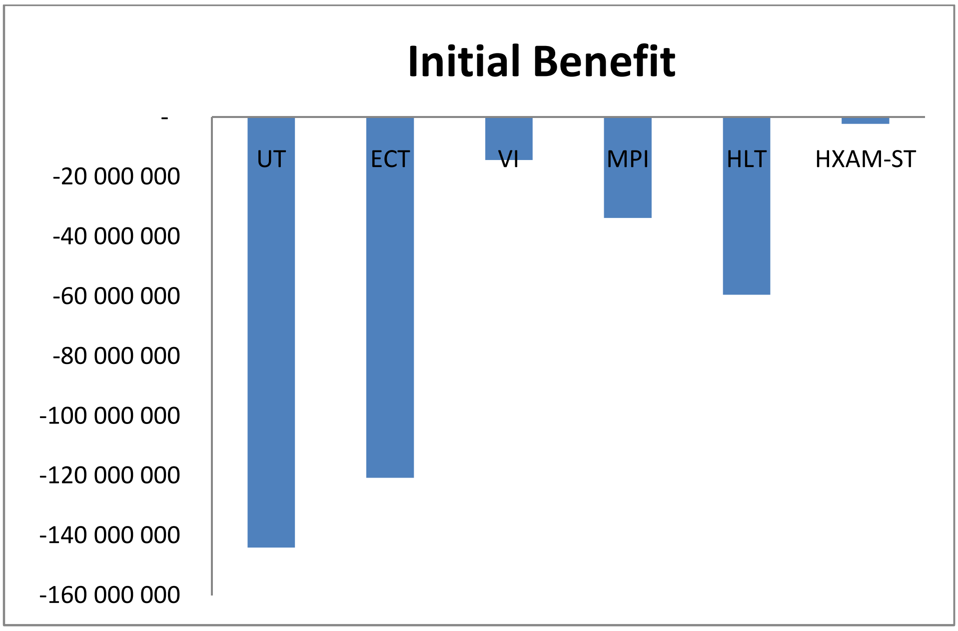


FIGURE 39: INITIAL BENEFIT WITHOUT DOWNTIME

The figure above shows that all of the methods have a negative benefit if downtime is excluded from the calculation. The limited area offshore would make redundancy on all H/Xs impossible. It gives a picture on how important downtime is on an offshore installation.

10.9.6 PROBABILITY TO DETECT FAILURE

The probability for detection of failure is based on assumptions. In addition, it could be useful to look at differences in probability to detect failures. The detection rate for failure is reduced with 50%.

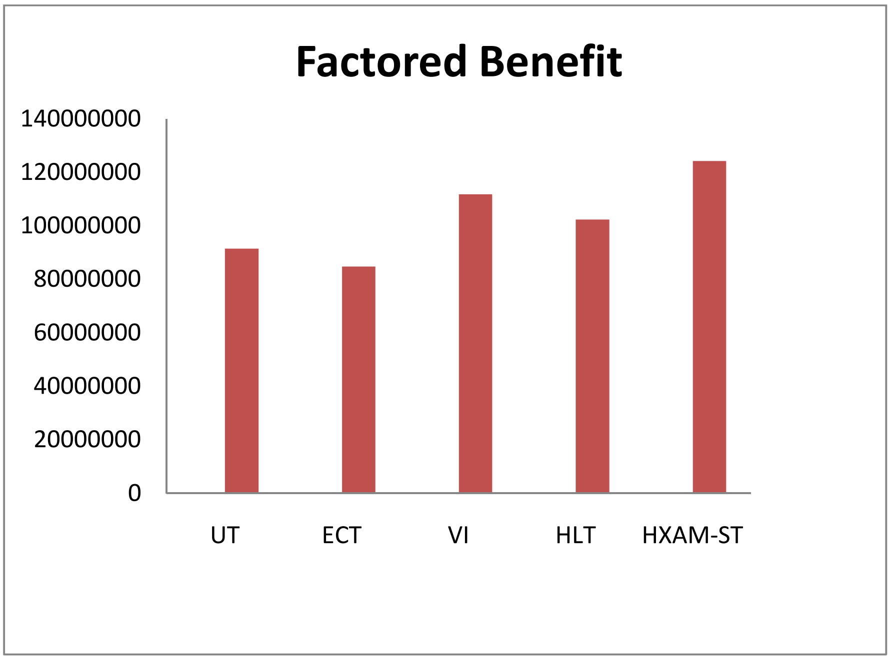


FIGURE 40: BENEFITS WITH 50% REDUCTION IN FAILURE DETECTION

The figure above shows that with a 50% reduction of detection rate. Five of the methods would have a benefit between 80 million NOK and 120 million NOK. This means that the method have much to go on regarding probability to detect failures.

10.9.7 5 H/XS ON THE INSTALLATION

The number of H/Xs on the installation is discussed in chapter 10.8. As a case the number of H/Xs is reduced from twenty to five.

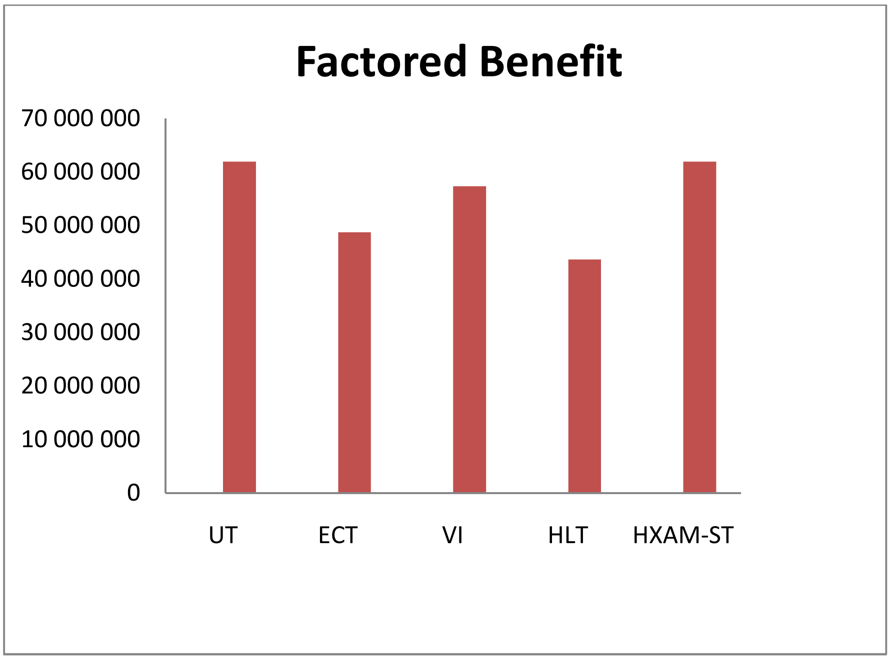


FIGURE 41: 5 H/XS ON THE INSTALLATION

Figure 41 shows that the benefit would vary between 60 and 40 million NOK, if it is assumed five H/Xs on the installation. With five H/Xs personnel and transport cost would decrease. This indicates that CM methods are preferably to apply on installation with fewer H/Xs as well.

11 CONCLUSION

H/X is decomposed into valves, piping, body/shell, instruments, baffle plates and tube bundle. This is used as maintainable items. Six different CM methods are present in the thesis. These are mainly based on finding material failures, however HXAM-ST is a method that monitors the performance and has the opportunity for Condition Based Maintenance.

The FMEA and FTA show the reasons for failure modes on these parts. Failure leading to shut down of H/X is on all items without instruments, corrosion, erosion and fouling. In addition also external forces can cause failure in forms of vibration. Material fatigue is a general failure mode for aging of H/X.

To sum up, the methods have differences regarding probability to find failures. UT and ECT is mainly used in the tube bundle, in spite of this the method has high probability to find failures as leakage and material based failure modes as plugged/choked and structural deficiency.VI has possibility for finding almost all failures in a smaller scale. VI has a large probability to find the failure mode plugged/choked. The rest is from 50 % to 10 % detection rate. MPI has only the probability to find structural deficiency. HLT has a large detection rate on leakage. HXAM-ST has a large detection rate on abnormal instrument reading, insufficient heat transfer, minor in service problems and parameter deviation. The problem with HXAM-ST is that it is difficult to find what is causing the problem.

The LCC analysis shows that UT and ECT have the largest life cycle costs, while VI and HXAM-ST has the lowest life cycle costs. Personnel and training cost is the dominant cost for all inspection methods except HXAM-ST.

The cost-benefit analysis shows that UT is the most cost effective method with total benefits of 270 million NOK followed up by HXAM-ST with total benefits on 250 million NOK. ECT, VI and HLT follow with total benefits from 240 million NOK to 231 million NOK. MPI stands out negatively with a loss on 4 million NOK.

The benefit from CM-methods is basically in form of less downtime. If the H/Xs on the installation has redundancy it would decrease this benefit to almost zero. This means that this is the factor that would have most impact on the model.

HXAM-ST and VI are standing out as the most cost effective methods, if benefits are decreasing. This is because of the low life cycle costs on these methods. If benefits are increasing UT and ECT is most cost effective since these two methods has largest detection rate.

Today there are no NII methods for the tube bundle. An inspection hatch in the heat exchanger could make it easier to see if something is wrong inside the heat exchanger. If the hatch also could open some of the inspection could be carried out without disassembling the H/X.

12 FURTHER WORK

The focus on Non-Intrusive methods must increase, because all the method except HXAM-ST and MPI only can be carried out while stop in production.

This thesis involves six CM-methods with more or less different effects area. There are a lot more CM-methods on the market today, and investigation of other types could be beneficial.

The thesis is based on one inspection per year on each heat exchanger. As Frode Haukanes stated, the time between inspections are based on Risk Based Inspection. This should be implemented. The age of the H/X should also been taking into consideration since failures would increase when H/Xs are aging.

The CBA analysis discovers the method that is most beneficial. However, as further work it could be beneficial to look at combination of the methods. If for example one decides to perform both UT and HXAM-ST, what would then be the total benefit?

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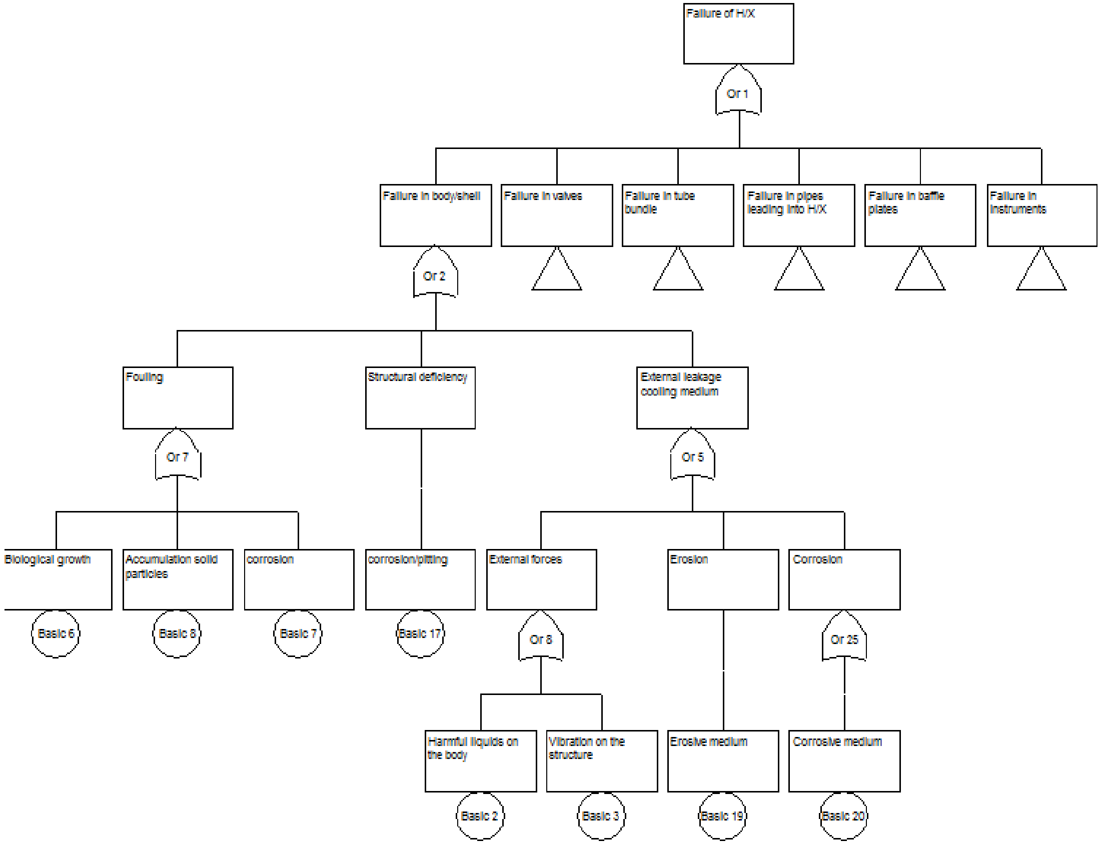
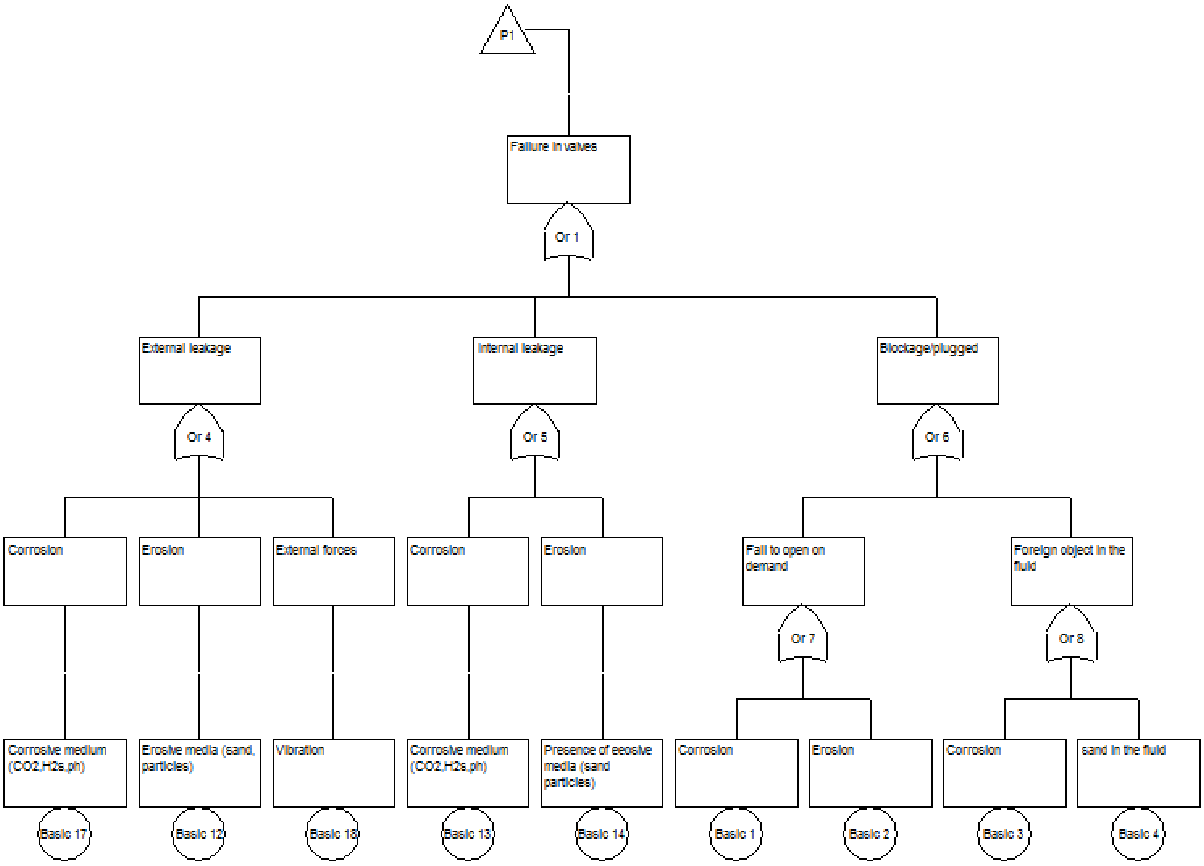
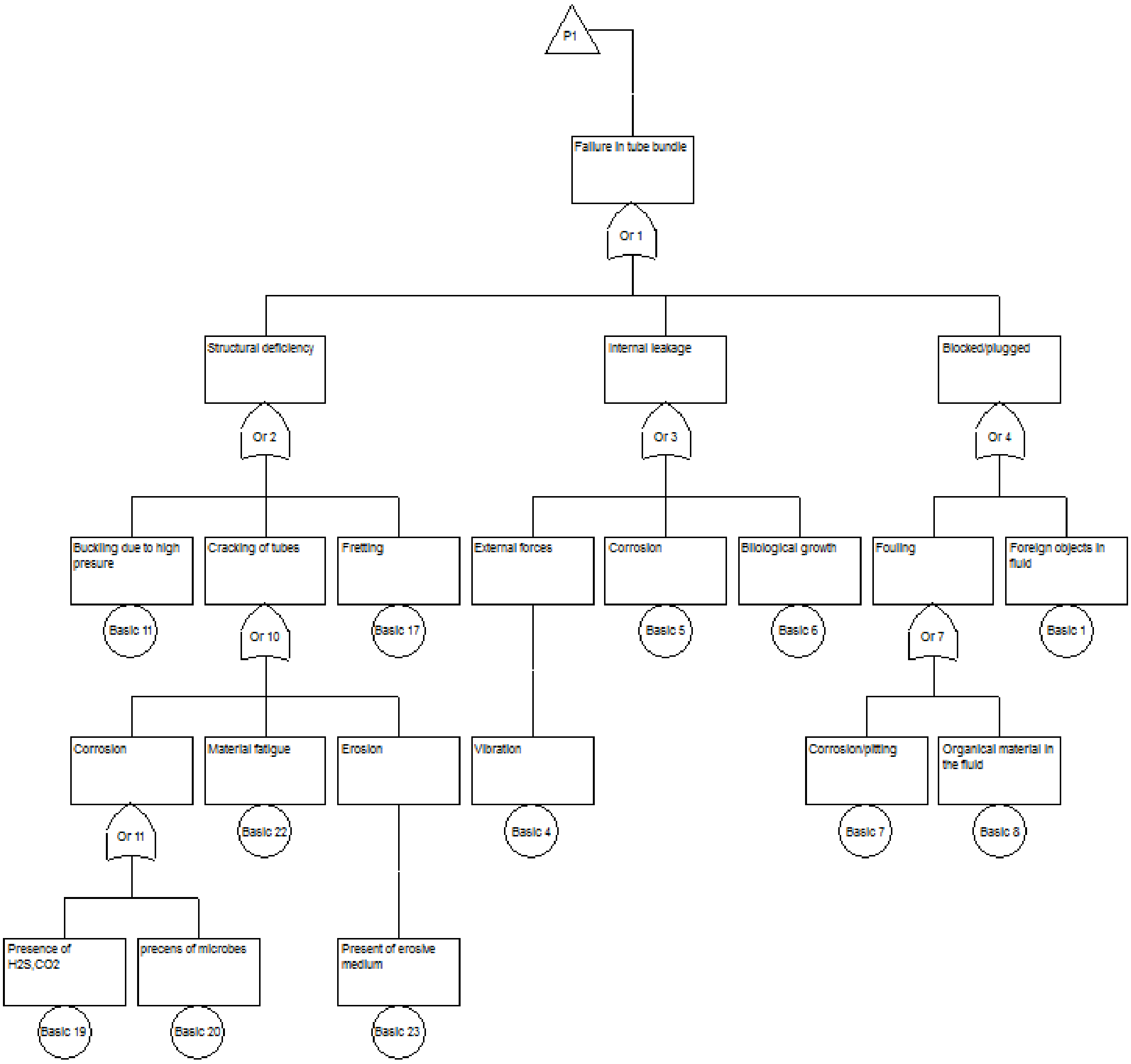
APPENDICES

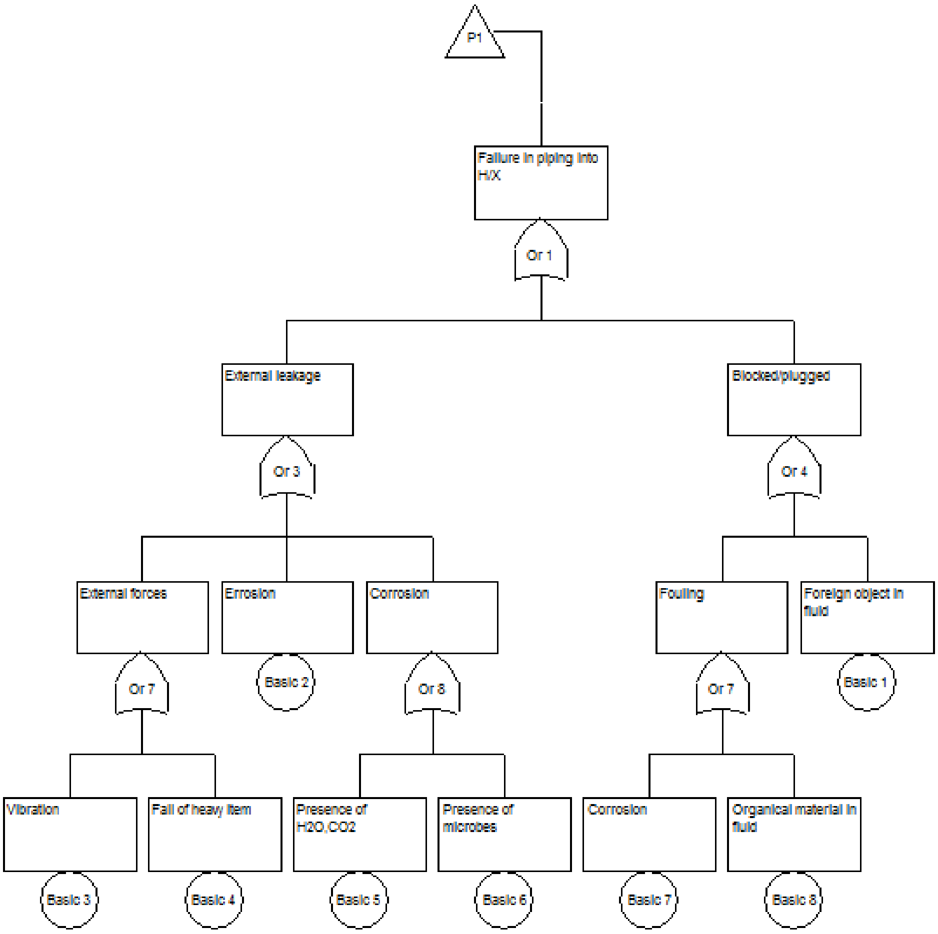
Fault Tree analysis
FMEA
Model in Excel

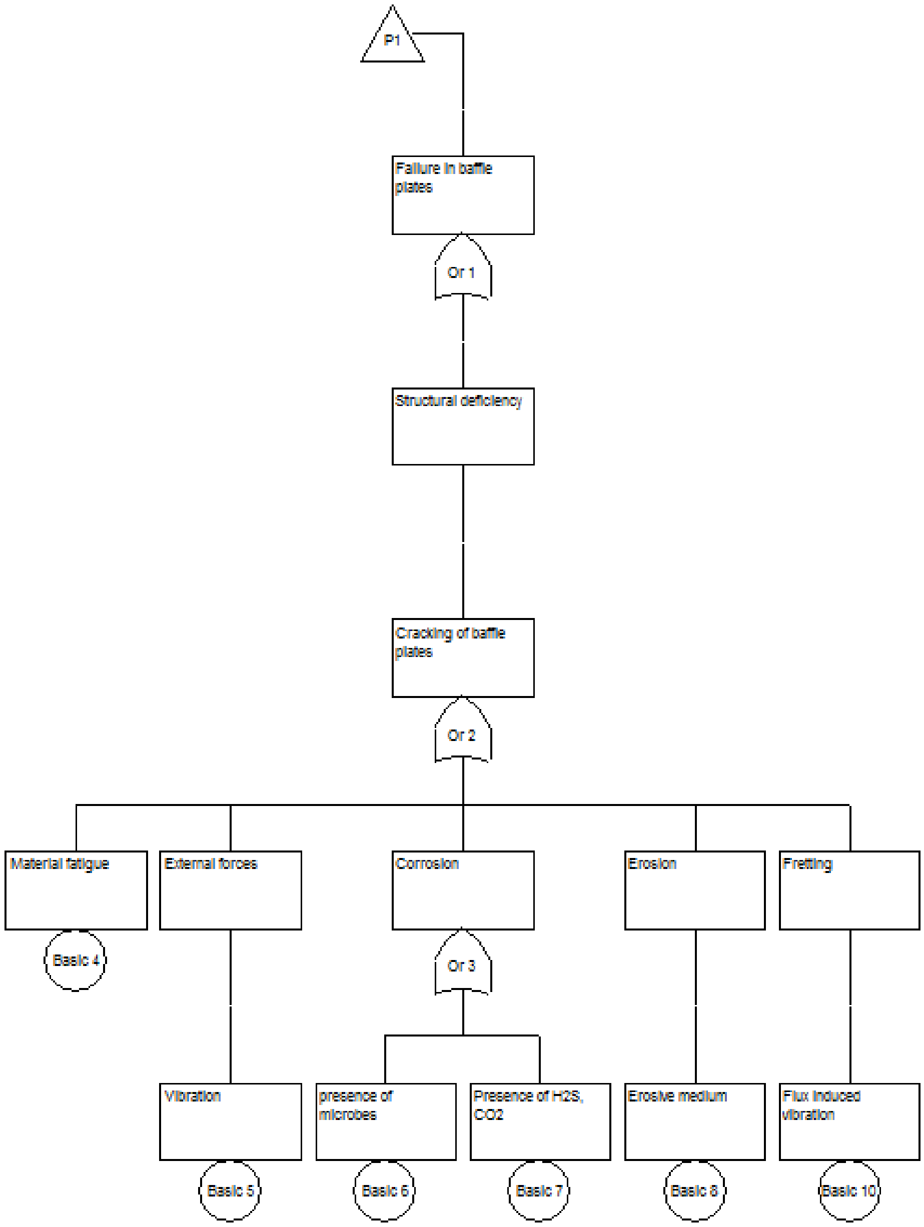
A.1 FAULT TREE ANALYSIS

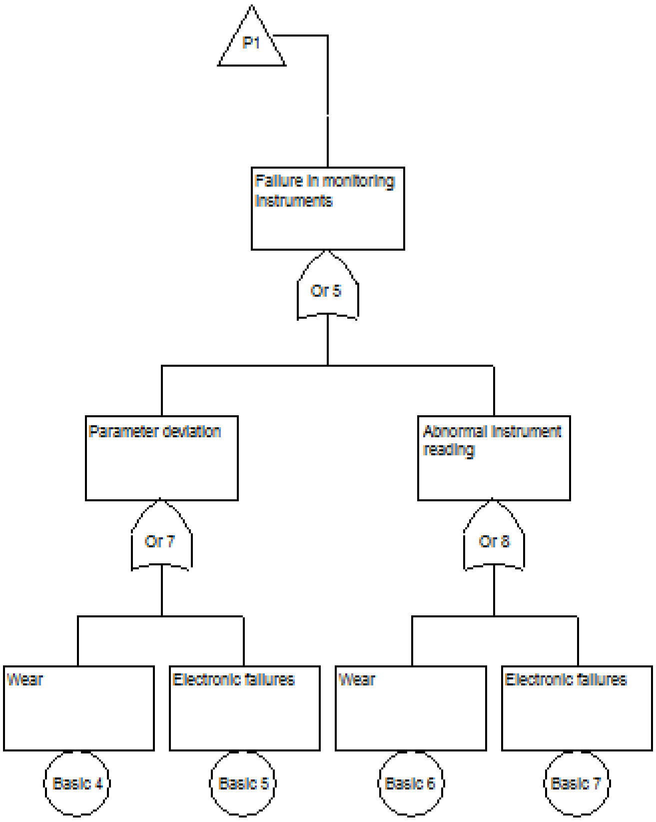



P1
Failure in valves
Or 1
External leakage
Internal leakage
Blockage/plugged
Or 4
Or 5
Or 6
Corrosion
Erosion
External forces
Corrosion
Erosion
Fail to open on demand
Foreign object in the fluid
Or 7
Or 8
Corrosive medium (CO2,H2s,ph)
Erosive media (sand, particles)
Vibration
Corrosive medium (CO2,H2s,ph)
Presence of eeosive media (sand particles)
Corrosion
Erosion
Corrosion
sand in the fluid
Basic 17
Basic 12
Basic 18
Basic 13
Basic 14
Basic 1
Basic 2
Basic 3
Basic 4


P1
Failure in tube bundle
Or 1
Structural deficiency
Internal leakage
Blocked/plugged
Or 2
Or 3
Or 4
Buckling due to high presure
Cracking of tubes
Fretting
External forces
Corrosion
Biliological growth
Fouling
Foreign objects in fluid
Basic 11
Or 10
Basic 17
Basic 5
Basic 6
Or 7
Basic 1
Corrosion
Material fatigue
Erosion
Vibration
Corrosion/pitting
Organical material in the fluid
Or 11
Basic 22
Basic 4
Basic 7
Basic 8
Presence of H2S,CO2
precens of microbes
Present of erosive medium
Basic 19
Basic 20
Basic 23


P1
Failure in piping into H/X
Or 1
External leakage
Blocked/plugged
Or 3
Or 4
External forces
Errosion
Corrosion
Fouling
Foreign object in fluid
Or 7
Basic 2
Or 8
Or 7
Basic 1
Vibration
Fall of heavy item
Presence of H2O,CO2
Presence of microbes
Corrosion
Organical material in fluid
Basic 3
Basic 4
Basic 5
Basic 6
Basic 7
Basic 8


P1
Failure in baffle plates
Or 1
Structural deficiency
Cracking of baffle plates
Or 2
Material fatigue
External forces
Corrosion
Erosion
Fretting
Basic 4
Or 3
Vibration
presence of microbes
Presence of H2S, CO2
Erosive medium
Flux induced vibration
Basic 5
Basic 6
Basic 7
Basic 8
Basic 10

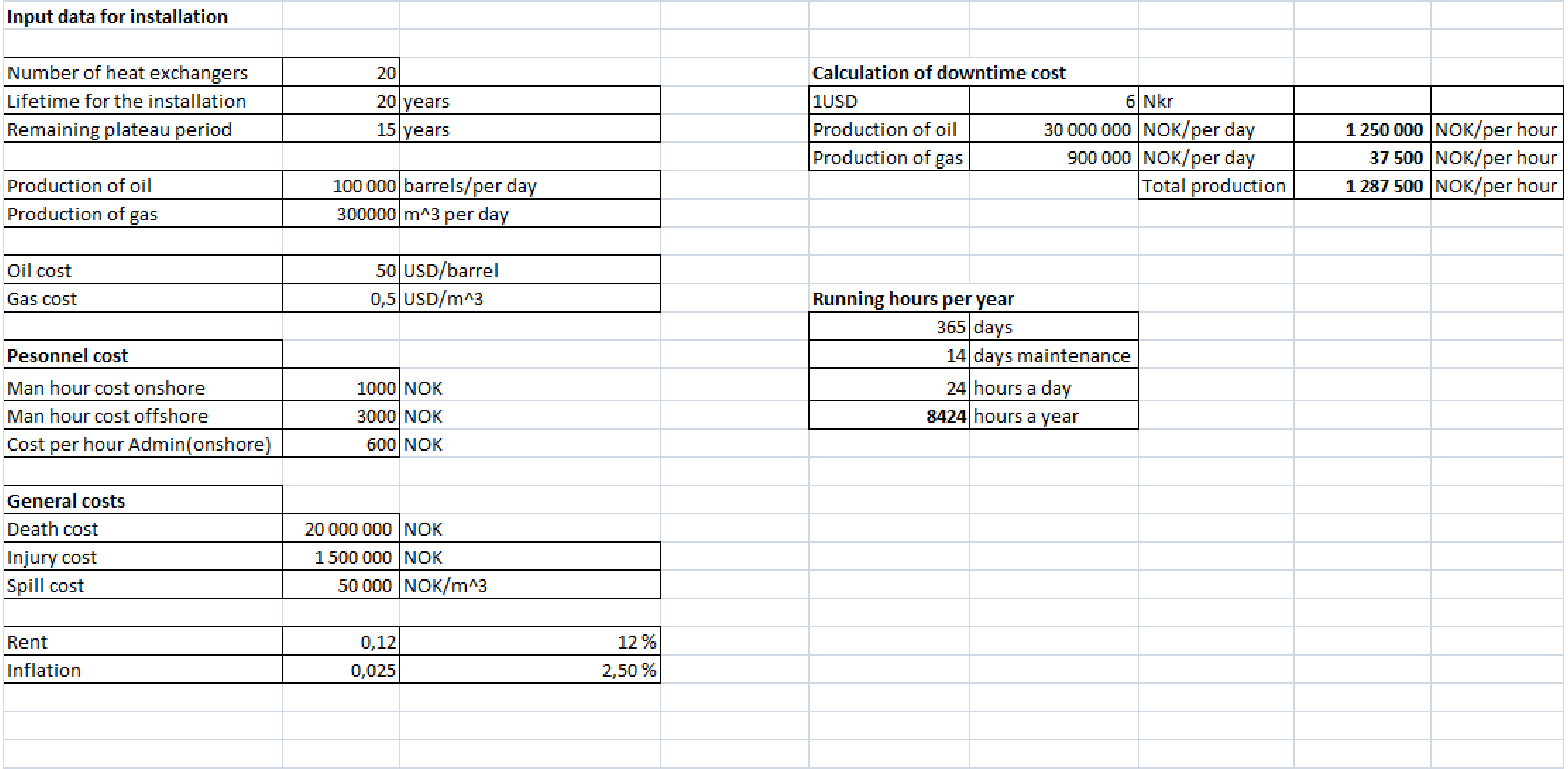

P1
Failure in monitoring instruments
Or 5
Parameter deviation
Abnormal instrument reading
Or 7
Or 8
Wear
Electronic failures
Wear
Electronic failures
Basic 4
Basic 5
Basic 6
Basic 7

A.2 FMEA

Description of unit			Description of failure			CM-methods
System	Component	Function	Failure mode	Failure cause or mechanism	Effect of failure	Detection method
1	Valves	Control of mass flow, both process and cooling medium	Blocked/plugged	Foreign object in the fluids	Lower flow rate (Shut down)	Tracers, HXAM-ST, VI
				Corrosion	Locked in one posistion (shut	
			External leakage process medium	Corrosion	oil/gas leak (shut down)	Visual inspection, vibration measurements,
				External forces	oil/gas leak (shut down)	
				Erosion	oil/gas leak (shut down)	
			Internal leakage	Corrosion	Open/close mechansism out of order	Visual inspection
				Erosion		
2	Piping	Transportation of fluid in and out of the heat exchanger	Blocked/plugged	Foreign object in the fluids	Lower flow rate (Shut down)	Tracers, VI ,HXAM-ST
				Fouling		
			External leakage process medium	Corrosion	oil/gas leak (shut down)	Visual inspection, vibration measurements,
				External forces	oil/gas leak (shut down)	
				Erosion	oil/gas leak (shut down)	
3	Body/shell	Make sure that the cooling medium is flowing around cooling tubes	External leakage cooling medium	Corrosion	Shut down	Visual inspection,
				External forces		
				Erosion		
			Structural deficiency	Corrosion/pitting	Shut down	Eddy Current Testing, Ultrasonic testing, Magnetic Particle Inspection, Visual inspection
			Fouling	Biological growth	Less heat exchanging	Visual inspection , HXAM-ST
				Corrosion		
				Foreign object in the fluids		

4	Instruments	Monitoring the performance	Abnormal instrument reading	Wear	No overview of the process (shut down)	Faultfinding, Visual inspection, HXAM-ST
				Oxidize		
			Parameter deviation	Oxidize		
				Wear		
5	Baffle plates	Structural for pipes and make sures that the cooling medium is flowing aroud the process pipes	Structural deficiency	Material fatigue	Leakage (shut down)	Eddy Current Testing, Ultrasonic testing, , Visual inspection
				Erosion		
				External forces as vibration		
				Corrosion/pitting		
6	Tube bundle	Transport process medium	Structural deficiency	Buckling due to high pressure	Shut down	Eddy Current Testing, Ultrasonic testing, Visual inspection
				Fretting		
				Cracking of tubes		
			Internal leakage - process medium	External forces	Shut down	Visual inspection (look after oil in water), Eddy Current testing, ultrasonic testing.
				Erosion		
				Corrosion/pitting		
			Blocked/plugged	Foreign object in the fluids	Higher forces on other tubes (shut down)	Tracers, Instrument reading, boroscope, Eddy current testing,
				Fouling		

A.3 THE COST BENEFIT MODEL



Input data for installation

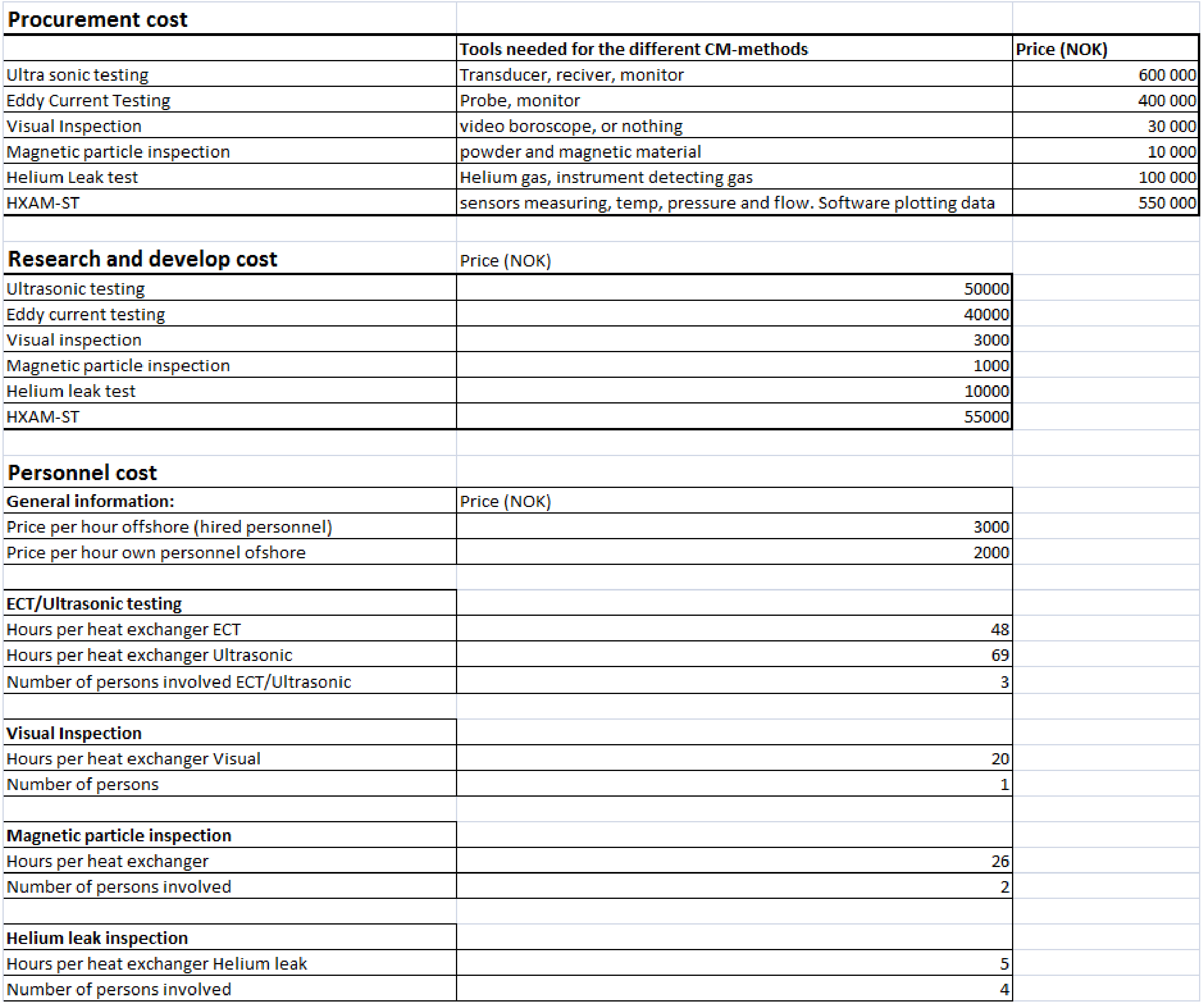
Number of heat exchangers	20	
Lifetime for the installation	20	years
Remaining plateau period	15	years
Production of oil	100 000	barrels/per day
Production of gas	300000	m^3 per day
Oil cost	50	USD/barrel
Gas cost	0,5	USD/m^3
Pesonnel cost		
Man hour cost onshore	1000	NOK
Man hour cost offshore	3000	NOK
Cost per hour Admin(onshore)	600	NOK
General costs		
Death cost	20 000 000	NOK
Injury cost	1 500 000	NOK
Spill cost	50 000	NOK/m^3
Rent	0,12	12 %
Inflation	0,025	2,50 %

Calculation of downtime cost

1USD	6	Nkr		
Production of oil	30 000 000	NOK/per day	**1 250 000**	NOK/per hour
Production of gas	900 000	NOK/per day	**37 500**	NOK/per hour
		Total production	**1 287 500**	NOK/per hour

Running hours per year

365	days
14	days maintenance
24	hours a day
8424	hours a year



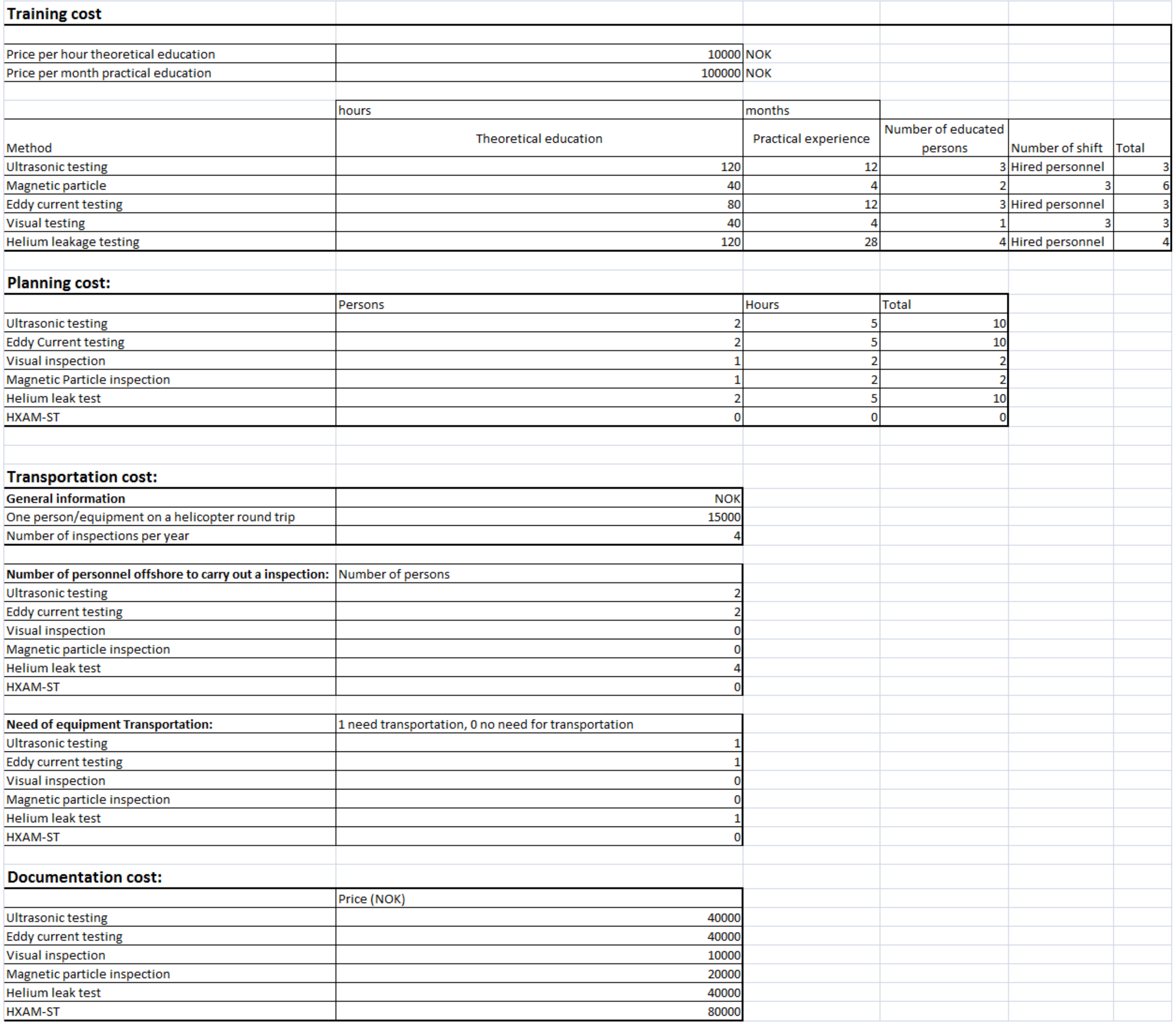
Procurement cost

	Tools needed for the different CM-methods	Price (NOK)
Ultra sonic testing	Transducer, reciver, monitor	600 000
Eddy Current Testing	Probe, monitor	400 000
Visual Inspection	video boroscope, or nothing	30 000
Magnetic particle inspection	powder and magnetic material	10 000
Helium Leak test	Helium gas, instrument detecting gas	100 000
HXAM-ST	sensors measuring, temp, pressure and flow. Software plotting data	550 000

Research and develop cost	Price (NOK)
Ultrasonic testing	50000
Eddy current testing	40000
Visual inspection	3000
Magnetic particle inspection	1000
Helium leak test	10000
HXAM-ST	55000

Personnel cost

General information:	Price (NOK)
Price per hour offshore (hired personnel)	3000
Price per hour own personnel ofshore	2000
ECT/Ultrasonic testing	
Hours per heat exchanger ECT	48
Hours per heat exchanger Ultrasonic	69
Number of persons involved ECT/Ultrasonic	3
Visual Inspection	
Hours per heat exchanger Visual	20
Number of persons	1
Magnetic particle inspection	
Hours per heat exchanger	26
Number of persons involved	2
Helium leak inspection	
Hours per heat exchanger Helium leak	5
Number of persons involved	4



Training cost

Price per hour theoretical education	10000	NOK			
Price per month practical education	100000	NOK			

	hours	months			
Method	Theoretical education	Practical experience	Number of educated persons	Number of shift	Total
Ultrasonic testing	120	12	3	Hired personnel	3
Magnetic particle	40	4	2	3	6
Eddy current testing	80	12	3	Hired personnel	3
Visual testing	40	4	1	3	3
Helium leakage testing	120	28	4	Hired personnel	4

Planning cost:

	Persons	Hours	Total
Ultrasonic testing	2	5	10
Eddy Current testing	2	5	10
Visual inspection	1	2	2
Magnetic Particle inspection	1	2	2
Helium leak test	2	5	10
HXAM-ST	0	0	0

Transportation cost:

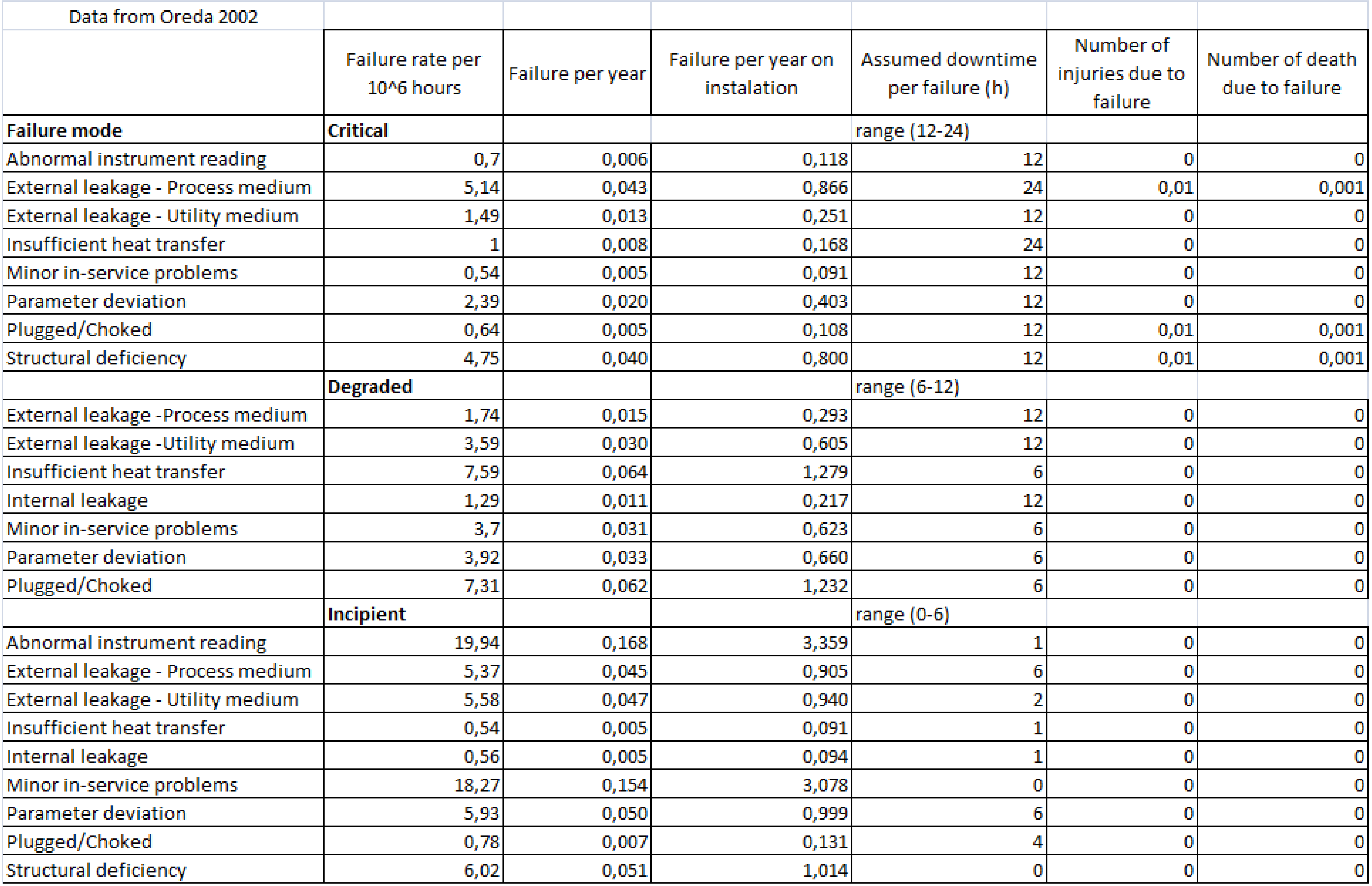
General information	NOK
One person/equipment on a helicopter round trip	15000
Number of inspections per year	4

Number of personnel offshore to carry out a inspection:	Number of persons
Ultrasonic testing	2
Eddy current testing	2
Visual inspection	0
Magnetic particle inspection	0
Helium leak test	4
HXAM-ST	0

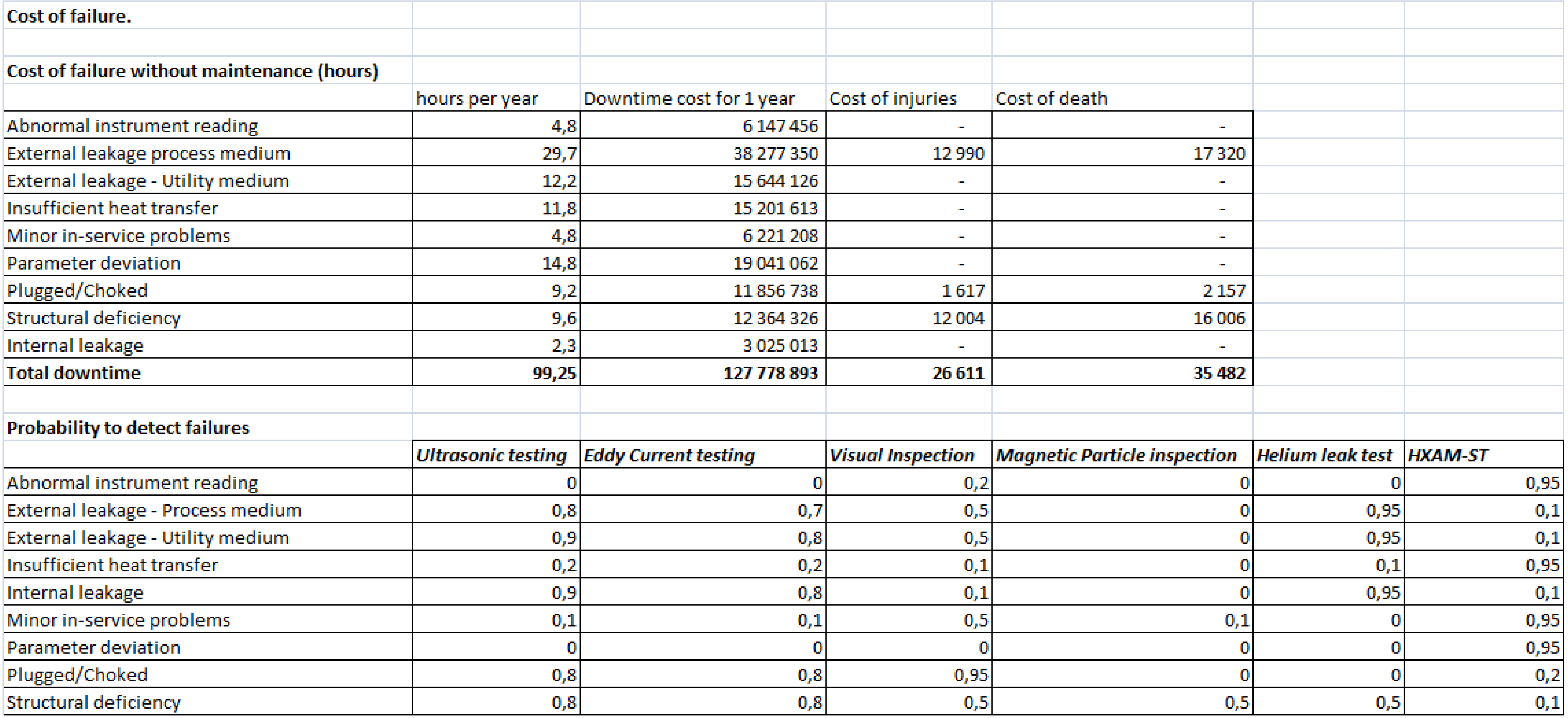
Need of equipment Transportation:	1 need transportation, 0 no need for transportation
Ultrasonic testing	1
Eddy current testing	1
Visual inspection	0
Magnetic particle inspection	0
Helium leak test	1
HXAM-ST	0

Documentation cost:

	Price (NOK)
Ultrasonic testing	40000
Eddy current testing	40000
Visual inspection	10000
Magnetic particle inspection	20000
Helium leak test	40000
HXAM-ST	80000



Data from Oreda 2002						
	Failure rate per 10^6 hours	Failure per year	Failure per year on instalation	Assumed downtime per failure (h)	Number of injuries due to failure	Number of death due to failure
Failure mode	**Critical**			range (12-24)		
Abnormal instrument reading	0,7	0,006	0,118	12	0	0
External leakage - Process medium	5,14	0,043	0,866	24	0,01	0,001
External leakage - Utility medium	1,49	0,013	0,251	12	0	0
Insufficient heat transfer	1	0,008	0,168	24	0	0
Minor in-service problems	0,54	0,005	0,091	12	0	0
Parameter deviation	2,39	0,020	0,403	12	0	0
Plugged/Choked	0,64	0,005	0,108	12	0,01	0,001
Structural deficiency	4,75	0,040	0,800	12	0,01	0,001
	Degraded			range (6-12)		
External leakage -Process medium	1,74	0,015	0,293	12	0	0
External leakage -Utility medium	3,59	0,030	0,605	12	0	0
Insufficient heat transfer	7,59	0,064	1,279	6	0	0
Internal leakage	1,29	0,011	0,217	12	0	0
Minor in-service problems	3,7	0,031	0,623	6	0	0
Parameter deviation	3,92	0,033	0,660	6	0	0
Plugged/Choked	7,31	0,062	1,232	6	0	0
	Incipient			range (0-6)		
Abnormal instrument reading	19,94	0,168	3,359	1	0	0
External leakage - Process medium	5,37	0,045	0,905	6	0	0
External leakage - Utility medium	5,58	0,047	0,940	2	0	0
Insufficient heat transfer	0,54	0,005	0,091	1	0	0
Internal leakage	0,56	0,005	0,094	1	0	0
Minor in-service problems	18,27	0,154	3,078	0	0	0
Parameter deviation	5,93	0,050	0,999	6	0	0
Plugged/Choked	0,78	0,007	0,131	4	0	0
Structural deficiency	6,02	0,051	1,014	0	0	0



Cost of failure.

Cost of failure without maintenance (hours)

	hours per year	Downtime cost for 1 year	Cost of injuries	Cost of death
Abnormal instrument reading	4,8	6 147 456	-	-
External leakage process medium	29,7	38 277 350	12 990	17 320
External leakage - Utility medium	12,2	15 644 126	-	-
Insufficient heat transfer	11,8	15 201 613	-	-
Minor in-service problems	4,8	6 221 208	-	-
Parameter deviation	14,8	19 041 062	-	-
Plugged/Choked	9,2	11 856 738	1 617	2 157
Structural deficiency	9,6	12 364 326	12 004	16 006
Internal leakage	2,3	3 025 013	-	-
Total downtime	**99,25**	**127 778 893**	**26 611**	**35 482**

Probability to detect failures

	Ultrasonic testing	***Eddy Current testing***	***Visual Inspection***	***Magnetic Particle inspection***	***Helium leak test***	***HXAM-ST***
Abnormal instrument reading	0	0	0,2	0	0	0,95
External leakage - Process medium	0,8	0,7	0,5	0	0,95	0,1
External leakage - Utility medium	0,9	0,8	0,5	0	0,95	0,1
Insufficient heat transfer	0,2	0,2	0,1	0	0,1	0,95
Internal leakage	0,9	0,8	0,1	0	0,95	0,1
Minor in-service problems	0,1	0,1	0,5	0,1	0	0,95
Parameter deviation	0	0	0	0	0	0,95
Plugged/Choked	0,8	0,8	0,95	0	0	0,2
Structural deficiency	0,8	0,8	0,5	0,5	0,5	0,1

Less downtime due to condition monitoring.

	Ultrasonic testing	*Eddy Current testing*	*Visual Inspection*	*Magnetic Particle inspection*	*Helium leak test*	*HXAM-ST*
Abnormal instrument reading	0,0	0,0	1,0	0,0	0,0	4,5
External leakage process medium	23,8	20,8	14,9	0,0	28,2	3,0
External leakage - Utility medium	10,9	9,7	6,1	0,0	11,5	1,2
Insufficient heat transfer	2,4	2,4	1,2	0,0	1,2	11,2
Minor in-service problems	4,3	3,9	0,5	0,0	4,6	0,5
Parameter deviation	1,5	1,5	7,4	1,5	0,0	14,0
Plugged/Choked	0,0	0,0	0,0	0,0	0,0	8,7
Structural deficiency	7,7	7,7	9,1	0,0	0,0	1,9
Internal leakage	1,9	1,9	1,2	1,2	1,2	0,2
Total less down time	**52,5**	**47,8**	**41,3**	**2,7**	**46,7**	**45,4**
Total saved using CM (NOK)	**67 556 581**	**61 542 313**	**53 111 659**	**3 416 613**	**60 168 218**	**58 424 161**

Less injuries cost due to condition monitoring

	Ultrasonic testing	*Eddy Current testing*	*Visual Inspection*	*Magnetic Particle inspection*	*Helium leak test*	*HXAM-ST*
External leakage process medium	10 392	9 093	6 495	-	12 340	1 299
Plugged/choked	1 294	1 294	1 537	-	-	323
Structural deficiency	9 603	9 603	6 002	6 002	6 002	1 200
Total saved using CM (NOK)	**21 289**	**19 990**	**14 034**	**6 002**	**18 342**	**2 823**

Less death cost due to condition monitoring

	Ultrasonic testing	*Eddy Current testing*	*Visual Inspection*	*Magnetic Particle inspection*	*Helium leak test*	*HXAM-ST*
External leakage process medium	13 856	12 124	8 660	-	16 454	1 732
Plugged/choked	1 725	1 725	2 049	-	-	431
Structural deficiency	12 804	12 804	8 003	8 003	8 003	1 601
Total saved using CM (NOK)	**28 386**	**26 654**	**18 711**	**8 003**	**24 457**	**3 764**

Ultrasonic testing

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	600 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	50 000	-	-	-	-	-	-	-	-	-	50 000	-	-	-	-	-	-	-	-	-
Total	**650 000**	-	-	-	-	-	-	-	-	-	**50 000**	-	-	-	-	-	-	-	-	-
Opex																				
Personnel	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857	12 342 857
Traning	7 200 000	-	-	-	7 200 000	-	-	-	7 200 000	-	-	-	7 200 000	-	-	-	7 200 000	-	-	-
Transport	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000
Spare parts	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000	42 000
Documentation	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000
Planning	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
Maintenance	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000	30 000
Support equipment	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000	18 000
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**
Capex +Opex	**20 508 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 708 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**	**19 858 857**	**12 658 857**	**12 658 857**	**12 658 857**
Benefits																				
Less downtime	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	67 556 581	-	-	-	-	-
Less injuries	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289	21 289
Less death	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386	28 386
Total benefits	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**67 606 256**	**49 675**	**49 675**	**49 675**	**49 675**	**49 675**
Benefits- cost	***47 097 399***	***54 947 399***	***54 947 399***	***54 947 399***	***47 747 399***	***54 947 399***	***54 947 399***	***54 947 399***	***47 747 399***	***54 947 399***	***54 897 399***	***54 947 399***	***47 747 399***	***54 947 399***	***54 947 399***	***-12 609 182***	***-19 809 182***	***-12 609 182***	-12 609 182	-12 609 182

*** All values in Norwegian kroner (NOK)**

Eddy Current testing

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	400 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	40 000	-	-	-	-	-	-	-	-	-	40 000	-	-	-	-	-	-	-	-	-
Total	**440 000**	-	-	-	-	-	-	-	-	-	**40 000**	-	-	-	-	-	-	-	-	-
Opex																				
Personnel	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000	8 640 000
Traning	12 000 000	-	-	-	12 000 000	-	-	-	12 000 000	-	-	-	12 000 000	-	-	-	12 000 000	-	-	-
Transport	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000	180 000
Spare parts	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000
Documentation	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000
Planning	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
Maintenance	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000
Support equipment	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000	12 000
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**20 926 000**	**8 926 000**	**8 926 000**	**8 926 000**	**20 926 000**	**8 926 000**	**8 926 000**	**8 926 000**	**20 926 000**	**8 926 000**	**8 926 000**	**8 926 000**	**20 926 000**	**8 926 000**	**8 926 000**	**8 926 000**	**20 926 000**	**8 926 000**	**8 926 000**	**8 926 000**
Total costs (Capec+opex)	***21 366 000***	***8 926 000***	***8 926 000***	***8 926 000***	***20 926 000***	***8 926 000***	***8 926 000***	***8 926 000***	***20 926 000***	***8 926 000***	***8 966 000***	***8 926 000***	***20 926 000***	***8 926 000***	***8 926 000***	***8 926 000***	***20 926 000***	***8 926 000***	***8 926 000***	***8 926 000***
Benefits																				
Less downtime	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	61 542 313	-	-	-	-	-
Less injuries	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990	19 990
Less death	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654	26 654
Total benefits	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**61 588 957**	**46 644**	**46 644**	**46 644**	**46 644**	**46 644**
Benefits- cost	***40 222 957***	***52 662 957***	***52 662 957***	***52 662 957***	***40 662 957***	***52 662 957***	***52 662 957***	***52 662 957***	***40 662 957***	***52 662 957***	***52 622 957***	***52 662 957***	***40 662 957***	***52 662 957***	***52 662 957***	***-8 879 356***	***-20 879 356***	***-8 879 356***	-8 879 356	-8 879 356

*** All values in Norwegian kroner (NOK)**

Visual Inspection

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	30 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	3 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**33 000**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Opex																				
Personnel	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000	800 000
Traning	2 400 000	-	-	-	2 400 000	-	-	-	2 400 000	-	-	-	2 400 000	-	-	-	2 400 000	-	-	-
Transport	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Spare parts	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100	2 100
Documentation	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000
Planning	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200
Maintenance	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500	1 500
Support equipment	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**
Total Capex+Opex	**3 248 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**	**3 215 700**	**815 700**	**815 700**	**815 700**
Benefits																				
Less downtime	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	53 111 659	-	-	-	-	-
Less injuries	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034	14 034
Less death	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711	18 711
Total benefits	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**53 144 404**	**32 745**	**32 745**	**32 745**	**32 745**	**32 745**
Benefits- cost	***49 895 704***	***52 328 704***	***52 328 704***	***52 328 704***	***49 928 704***	***52 328 704***	***52 328 704***	***52 328 704***	***49 928 704***	***52 328 704***	***52 328 704***	***52 328 704***	***49 928 704***	***52 328 704***	***52 328 704***	***-782 955***	***-3 182 955***	***-782 955***	***-782 955***	***-782 955***

*** All values in Norwegian kroner (NOK)**

Magnetic Particle inspection

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	10 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000
Total	**11 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**	**1 000**
Opex																				
Personnel	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000	2 080 000
Traning	4 800 000	-	-	-	4 800 000	-	-	-	4 800 000	-	-	-	4 800 000	-	-	-	4 800 000	-	-	-
Transport	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Spare parts	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700
Documentation	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000	20 000
Planning	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200
Maintenance	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Support equipment	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**6 902 700**	**2 102 700**	**2 102 700**	**2 102 700**	**6 902 700**	**2 102 700**	**2 102 700**	**2 102 700**	**6 902 700**	**2 102 700**	**2 102 700**	**2 102 700**	**6 902 700**	**2 102 700**	**2 102 700**	**2 102 700**	**6 902 700**	**2 102 700**	**2 102 700**	**2 102 700**
Total Capex+opex	**6 913 700**	**2 103 700**	**2 103 700**	**2 103 700**	**6 903 700**	**2 103 700**	**2 103 700**	**2 103 700**	**6 903 700**	**2 103 700**	**2 103 700**	**2 103 700**	**6 903 700**	**2 103 700**	**2 103 700**	**2 103 700**	**6 903 700**	**2 103 700**	**2 103 700**	**2 103 700**
Benefits																				
Less downtime	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	3 416 613	-	-	-	-	-
Less injuries	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002	6 002
Less death	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003	8 003
Total benefits	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**3 430 618**	**14 005**	**14 005**	**14 005**	**14 005**	**14 005**
Benefits- cost	***-3 483 082***	***1 326 918***	***1 326 918***	***1 326 918***	***-3 473 082***	***1 326 918***	***1 326 918***	***1 326 918***	***-3 473 082***	***1 326 918***	***1 326 918***	***1 326 918***	***-3 473 082***	***1 326 918***	***1 326 918***	***-2 089 695***	***-6 889 695***	***-2 089 695***	***-2 089 695***	***-2 089 695***

*** All values in Norwegian kroner (NOK)**

Helium leak test

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	100 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	10 000	-	-	-	-	-	-	-	-	-	10 000	-	-	-	-	-	-	-	-	-
Total	**110 000**	-	-	-	-	-	-	-	-	-	**10 000**	-	-	-	-	-	-	-	-	-
Opex																				
Personnel	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000	1 200 000
Traning	16 000 000	-	-	-	16 000 000	-	-	-	16 000 000	-	-	-	16 000 000	-	-	-	16 000 000	-	-	-
Transport	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000	300 000
Spare parts	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000
Documentation	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000
Planning	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000
Maintenance	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000	5 000
Support equipment	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000	3 000
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**
Total Capex+Opex	**17 671 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 571 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**	**17 561 000**	**1 561 000**	**1 561 000**	**1 561 000**
Benefits																				
Less downtime	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	60 168 218	-	-	-	-	-
Less injuries	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342	18 342
Less death	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457	24 457
Total benefits	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**60 211 017**	**42 799**	**42 799**	**42 799**	**42 799**	**42 799**
Benefits- cost	***42 540 017***	***58 650 017***	***58 650 017***	***58 650 017***	***42 650 017***	***58 650 017***	***58 650 017***	***58 650 017***	***42 650 017***	***58 650 017***	***58 640 017***	***58 650 017***	***42 650 017***	***58 650 017***	***58 650 017***	***-1 518 201***	***-17 518 201***	***-1 518 201***	***-1 518 201***	***-1 518 201***

*** All values in Norwegian kroner (NOK)**

HXAM-ST

Capex	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19
Procurement	550 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Reaserach and develop	55 000	55 000	55 000	55 000	55 000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**605 000**	**55 000**	**55 000**	**55 000**	**55 000**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Opex																				
Personnel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Traning	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Transport	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Spare parts	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500	38 500
Documentation	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000	80 000
Planning	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Maintenance	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500	27 500
Support equipment	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500	16 500
Disposal cost	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**
Total Capex+Opex	**767 500**	**217 500**	**217 500**	**217 500**	**217 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**	**162 500**
Benefits																				
Less downtime	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	58 424 161	-	-	-	-	-
Less injuries	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823	2 823
Less death	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764	3 764
Total benefits	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**58 430 748**	**6 587**	**6 587**	**6 587**	**6 587**	**6 587**
Benefits- cost	***57 663 248***	***58 213 248***	***58 213 248***	***58 213 248***	***58 213 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***58 268 248***	***-155 913***	***-155 913***	***-155 913***	***-155 913***	***-155 913***

*** All values in Norwegian kroner (NOK)**

	Ultrasonic testing		Eddy Current testing		Visual Inspection		Magnetic Particle Inspection		Helium Leak test		HXAM-ST	
Year	Total	**NPV**	Total	**NPV**	Total	**NPV adjusted**	Total	**NPV adjusted**	Total	**NPV adjusted**	Total	**NPV adjusted**
0	47 097 399	**47 097 399**	40 222 957	**40 222 957**	49 895 704	**49 895 704**	-3 483 082	**-3 483 082**	42 540 017	**42 540 017**	57 663 248	**57 663 248**
1	54 947 399	**50 286 682**	52 662 957	**48 196 009**	52 328 704	**47 890 108**	1 326 918	**1 214 367**	58 650 017	**53 675 239**	58 213 248	**53 275 517**
2	54 947 399	**46 021 294**	52 662 957	**44 107 955**	52 328 704	**43 828 001**	1 326 918	**1 111 362**	58 650 017	**49 122 429**	58 213 248	**48 756 611**
3	54 947 399	**42 117 702**	52 662 957	**40 366 655**	52 328 704	**40 110 447**	1 326 918	**1 017 095**	58 650 017	**44 955 794**	58 213 248	**44 621 006**
4	47 747 399	**33 494 468**	40 662 957	**28 524 781**	49 928 704	**35 024 639**	-3 473 082	**-2 436 343**	42 650 017	**29 918 691**	58 213 248	**40 836 189**
5	54 947 399	**35 275 758**	52 662 957	**33 809 166**	52 328 704	**33 594 578**	1 326 918	**851 870**	58 650 017	**37 652 807**	58 268 248	**37 407 714**
6	54 947 399	**32 283 618**	52 662 957	**30 941 424**	52 328 704	**30 745 038**	1 326 918	**779 613**	58 650 017	**34 459 042**	58 268 248	**34 234 738**
7	54 947 399	**29 545 275**	52 662 957	**28 316 928**	52 328 704	**28 137 200**	1 326 918	**713 485**	58 650 017	**31 536 177**	58 268 248	**31 330 899**
8	47 747 399	**23 496 137**	40 662 957	**20 009 936**	49 928 704	**24 569 540**	-3 473 082	**-1 709 078**	42 650 017	**20 987 753**	58 268 248	**28 673 367**
9	54 947 399	**24 745 699**	52 662 957	**23 716 895**	52 328 704	**23 566 363**	1 326 918	**597 581**	58 650 017	**26 413 182**	58 268 248	**26 241 251**
10	54 897 399	**22 626 126**	52 622 957	**21 688 708**	52 328 704	**21 567 430**	1 326 918	**546 893**	58 640 017	**24 168 657**	58 268 248	**24 015 431**
11	54 947 399	**20 725 805**	52 662 957	**19 864 128**	52 328 704	**19 738 050**	1 326 918	**500 505**	58 650 017	**22 122 409**	58 268 248	**21 978 408**
12	47 747 399	**16 482 377**	40 662 957	**14 036 831**	49 928 704	**17 235 362**	-3 473 082	**-1 198 906**	42 650 017	**14 722 763**	58 268 248	**20 114 168**
13	54 947 399	**17 358 936**	52 662 957	**16 637 237**	52 328 704	**16 531 640**	1 326 918	**419 199**	58 650 017	**18 528 664**	58 268 248	**18 408 055**
14	54 947 399	**15 886 526**	52 662 957	**15 226 042**	52 328 704	**15 129 402**	1 326 918	**383 642**	58 650 017	**16 957 036**	58 268 248	**16 846 658**
15	-12 609 182	**-3 336 373**	-8 879 356	**-2 349 466**	-782 955	**-207 169**	-2 089 695	**-552 931**	-1 518 201	**-401 714**	-155 913	**-41 254**
16	-19 809 182	**-4 796 893**	-20 879 356	**-5 056 041**	-3 182 955	**-770 769**	-6 889 695	**-1 668 374**	-17 518 201	**-4 242 120**	-155 913	**-37 755**
17	-12 609 182	**-2 794 385**	-8 879 356	**-1 967 799**	-782 955	**-173 515**	-2 089 695	**-463 108**	-1 518 201	**-336 456**	-155 913	**-34 553**
18	-12 609 182	**-2 557 361**	-8 879 356	**-1 800 888**	-782 955	**-158 797**	-2 089 695	**-423 826**	-1 518 201	**-307 918**	-155 913	**-31 622**
19	-12 609 182	**-2 340 442**	-8 879 356	**-1 648 134**	-782 955	**-145 328**	-2 089 695	**-387 877**	-1 518 201	**-281 800**	-155 913	**-28 940**
	Total Benefits(NOK)	**441 618 345**	Total Benefits(NOK)	**412 843 323**	Total Benefits(NOK)	**446 107 927**	Total Benefits(NOK)	**-4 187 915**	Total Benefits(NOK)	**462 190 653**	Total Benefits(NOK)	**504 229 137**

		Factored benefits				
	Benefits over lifetim	Personnel safety	Operational safety	Operational issues	Technical fitness for purpose	**Factored benefit (NOK)**
Ultrasonic testing	441 618 345	0,8	1,0	0,9	0,9	**271 860 253**
Eddy Current testing	412 843 323	0,8	1,0	0,9	0,85	**240 027 108**
Visual inspection	446 107 927	0,8	0,9	0,9	0,8	**231 262 349**
MPI	-4 187 915	1,0	1,0	1,0	0,8	**-5 025 498**
Helium leak test	462 190 653	0,7	0,9	0,9	0,95	**235 127 940**
HXAM-ST	504 229 137	1,0	0,99	1,0	0,5	**249 593 423**