Preface

This report is the result of my master´s thesis at the Norwegian University of Science and technology (NTNU), at the department of marine technology. The thesis is called *Life cycle model for economical evaluation of replacement/improved maintenance strategy for systems and equipment.* The problem definition was established between NTNU and Odfjell Drilling (OD).

I would like to thank professor Magnus Rasmussen (NTNU), my thesis instructor Hege Mjaatvedt Bjørge (OD), and Arve Olav Nordskag (OD), for valuable feedback during the work with my thesis.

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Summary

Systems that deteriorate over time can result in increased operational costs. Reduced efficiency, increased fuel consumption, increased failure rate that induces increased downtime costs, are some of the consequences due to deterioration.

Analysis of systems and equipment that deteriorate over time is an important aspect of ageing management. In this thesis, the available literature from maintenance and life cycle theory has been mapped. The goal was to develop a model for Odfjell Drilling, which could be used to estimate the life cycle costs for optimal repair intervals for systems and equipment.

Two models were derived. The first model was based on reliability theory, using Barlow & Hunter´s fixed age interval. Several parameters have been identified as necessary input values. The idea was to collect the input parameters from the operational database that Odfjell Drilling posses, and use these for optimizing optimal repair intervals, by means of the common Reliability Centered Maintenance (RCM) methodology. When the optimal intervals are found, the reduction of costs can be calculated for the remaining system life.

A major problem with the reliability model is that a probability density function (PDF) must be obtained. Obtaining this, in practice, is very difficult; systems are subject to maintenance, which prevents their history to become available to the analyst. Use of subjective expert opinions for how they *think* the system will behave, is one approach to obtain the PDF. However this is considered as inefficient, time-consuming and inaccurate. The model approach was hence rejected.

The second model is an availability-based model, which purpose is to identify systems that are main contributors to downtime. When these are found, diagnosis can be developed and evaluated in order to increase the system availability. Thus reducing the costs of downtime, which goes directly on the bottom-line of the budget.

Due to significant lack of data, the availability-based model could never be tested properly. The main idea was to test it on a racking arm on a platform that is in Odfjell Drillings portfolio. The few results that were obtained will be in a separate report as the data is sensitive.

Use of condition-based maintenance (CBM) is considered to be a strategy that offers more flexibility to the user, in terms of planning multiple actions. It is recognized that many systems, such as pumps and piping, could be subject to condition monitoring (CM) to a greater extent than they are today.

CBM will require the development of a database for storage of system history. Trend analysis can be evaluated and used as a tool for decision making in maintenance planning. As for Odfjell Drilling, it is recommended that they investigate the potential that CBM offers, and put a single model for optimizing equipment and systems at rest.

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List of acronyms

CBM – Condition Based Maintenance

C_c – Corrective costs

C_p – Preventive costs

CM – Condition Monitoring

FMECA – Failure Mode Effect Criticality Analysis

IAEA – International Atomic Energy Agency

LCC – Life Cycle Cost

MCDM – Mulitiple Criteria Decision Making

MDP – Markov Decision Process

MRL – Mean Residual Life

NPV – Net Present Value

OREDA – Offshore REliability DAta

RCM – Reliability-Centered Maintenance

TCI – Technical Condition Index

TTW – Time To Wear

UEC – Economic Unit Cost

Introduction

When systems and equipment deteriorate, their performance is reduced due to operational and environmental loads and stresses over time. An important aspect of *Ageing Management* is to monitor and optimize the process of maintaining the degrading equipment in a sustainable standard with respect to system availability, safety and costs. In maintenance terminology ageing can be separated into two categories:

1. Physical age, deterioration due to physical or other processes
2. Obsolescence: The system or equipment has poor performance compared to new and better technology; it has expired or needs to be replaced due to changes in the operational conditions or requirements.

This thesis, which will consist of six main sections, will focus on the first category. The main goal is to develop a *life cycle model for economical evaluation of replacement/improved strategy for systems and equipment*. The thesis is written for Odfjell Drilling as they seek to develop such a model both for internal use and for consultancy of field operators. Before deriving and describing the model, it will be necessary to introduce the reader to some basic principles in maintenance management and life cycle evaluation of systems. That will be done in the first section, which is a literature survey.

The second section will focus on Odfjell Drilling´s demands, needs and criterions for the model. In shortness they are after a model that can describe the technical condition of a system in economical terms and they emphasize the simplicity of such a model.

Based on the information from the first two sections there should be enough information to derive and develop the model in the following section. Boundary conditions and identification of variables and parameters will be part of defining the model.

The fourth section will be focusing on the problem with subjective information and how this can be made more objective, as some of the information in the model might depend on inputs from the personnel who are working offshore. Odfjell Drilling want a model that can describe the technical condition of a system and in addition a setup for calculating the residual life of systems and equipment.

Once in place, the model will be tested on a selected system or equipment in cooperation with Odfjell Drilling. The accuracy of the model will be evaluated based on the available information of the system.

The last section will be a discussion and review of the model, including the test results from the latter section. A proposal for further work and problems that has to be solved or evaluated will also be a part of this section.

1. Maintenance and life cycle management

The purpose of this chapter is to introduce the reader to the present life cycle maintenance models and the underlying theory behind the selected models and approaches found in the literature.

1.1 Maintenance definition

Maintenance is defined as *combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*[1].

There are several ways to model maintenance management. The different approaches depends on the system model and the selection of parameter optimization. Some systems needs high availability and reliability i.e. due to significant downtime costs and/or long repair time, while other systems might be easy accessible and cheap to repair without major consequences when being unavailable. Maintenance management is, according to EVS-EN 13306 [2], defined as:

All activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics.

In practice, the maintenance optimization is a basically a weighing of maintenance costs versus system reliability. This is substantiated by R. Dekker as he defines the maintenance optimizations models as "*those mathematical models whose aim is to find the optimum balance between the costs and benefits of maintenance, while taking all kinds of constraints into account*"[1].

Maintenance optimization can be described more accurately from the following quotation [1]:

> In general, maintenance optimization models cover four aspects: (i) a description of a technical system, its function and its importance, (ii) a modelling of the deterioration of the system in time and possible consequences for the system, (iii) a description of the available information about the system and the actions open to management and (iv) an objective function and an optimization technique which helps in finding the best balance.

When analysing a system, it is necessary to take the system characteristics and properties into account when selecting maintenance strategies. A complex system might require a set of different strategies depending on the failure rate on parts and the redundancy of the system. After the following section some common maintenance strategies will be introduced.

1.1.1 Basic principles in maintenance

Before establishing some of the different strategies that can be applied it is necessary to introduce some of the maintenance basics such as failure rate, failure rate functions, reliability and availability.

There are four common models for the failure rate function. These are the running-in failure, random failure , wear-out failure function and the weibull distribution.

The probability that a component or a system can function and operate through a given period of time without failure is called *reliability.* The probability of failure F(t) is the probability of failure in the interval [0,t]. When T is continuous with probability density function (PDF) f(t) the probability of failure becomes[3];

$$F(t) = P(T \leq t) = \int_{0}^{t} f(x)dx, for\ t\ \geq 0$$

For an exponential failure distribution, $f(t) = e^{-\lambda t}$, F(t) then becomes:

$$F(t) = \int_{0}^{t} \lambda e^{-\lambda x}dx = 1 - e^{-\lambda t}$$

The reliability function R(t) is the probability of survival on the interval (0,t) and that the given system functions at time = t.

$$R(t) = P(T > t) = \int_{t}^{\infty} f(x)\, dx\, , for\ t\ \geq 0$$

Because F(∞) = $\int_{t}^{\infty} f(t)dt = 1$the system has failed at t = ∞. When combining F(t) and R(t) the following relation can be established:

$$F(t) + R(t) = \int_{0}^{t} f(x)\, dx + \int_{t}^{\infty} f(x)\, dx = \int_{0}^{\infty} f(x)dx = 1$$

$$F(t) = 1 - R(t), or$$
$$R(t) = 1 - F(t)$$

For an exponential distribution, R(t) becomes: R(t) = 1- F(t) = 1 - (1+$e^{-\lambda t}$) = $e^{-\lambda t}$. The exponential distribution is used to describe components that are subject to random failures.

The *failure rate* or failure frequency is the number of failures occurring in a given operational time [3]:

$$\lambda = \frac{number\ of\ failures}{total\ operational\ time}$$

From λ the mean time to failure (MTTF) can be derived as $MTTF = \frac{1}{\lambda}$ which is the expected mean operational time until next failure occurs. MTTF reflects non-repairable systems, while the mean time between failure (MTBF) is used for repairable systems. Instead by letting T be a random variable with a continuous probability function the expected value of T is by definition [4]:

$$\lambda = E(T) = \int_{-\infty}^{\infty} tf(t)dt = MTTF\ (or\ MTBF)$$

The availability, A, of a system is the fraction of operational time divided by the sum of operational time plus the system downtime when a failure occurs [3]:

$$A = \frac{T_{operation}}{T_{operation} + T_{down}}$$

Calculations of the availability for systems in series can be estimated by the use of the product rule:

$$A_s = \prod_{i=1}^{n} A_i$$

The use of this formula is not 100% accurate and the error tends to increase when A_i is reduced. As most systems tend to have a high availability, the error is assumed to be negligible.

1.1.2 The Weibull distribution

The Weibull distribution is a semi-empirical model derived for analysis of steel strength, but the model is also applicable in maintenance management. In maintenance applications the load-factor, or stress, is substituted with time dependency. The development of the distribution is not relevant for this thesis, however the application of it is of importance.

Many mechanical and electrical components are subject to a “bathtub-shaped” failure distribution. When the component is new, there is a high failure-rate that decreases with respect to time. After a certain amount of time the failure-rate is low, and might be constant or slowly increasing as the component is being used. This part can be described as the “bottom of the bathtub”. At some point of time, the component will be subject to wear-out failure and the failure-rate increases more rapidly towards the end of the product-lifetime [17].

Figure 1 shows a set of Weibull, or "bathtub", curves with various shape factors. The first curve shows a rapid decrease of the failure-rate along the running time axis, from 0 to approximately 0,1. This is the running-in phase. From 0,1 to 0,6 the failure rate is at a constant low level, before entering the wear-out phase from 0,6 to 1,5.

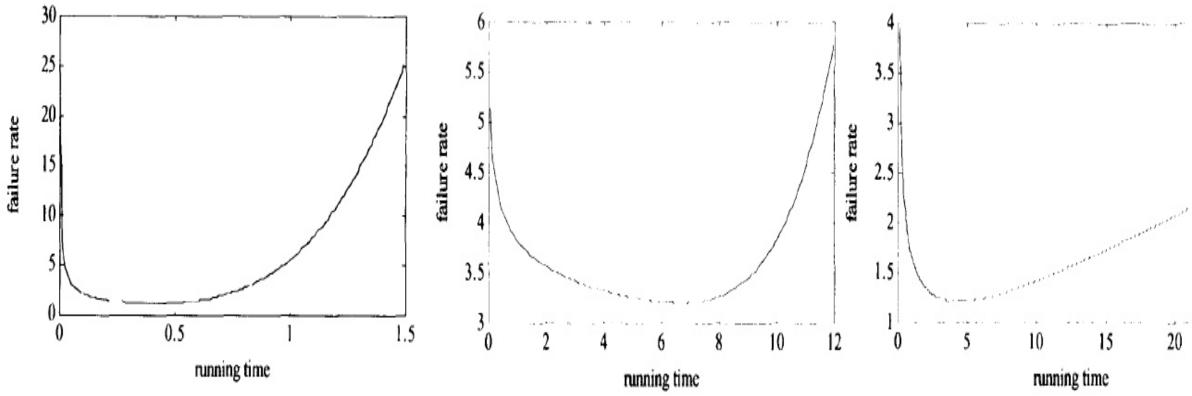

Figure 1 Weibull Curves

By Weibull distribution the following expressions yields for F(t), R(t), f(t) and z(t):

$$F(t) = \ 1 - e^{-\left(\frac{t-t_o}{\eta}\right)^{\beta}}$$

$$R(t) = \ e^{-(\frac{t-t_o}{\eta})^{\beta}}$$

$$f(t) = \frac{\beta(t-t_o)^{\beta-1}}{\eta^{\beta}} * e^{-\left(\frac{t-t_o}{\eta}\right)^{\beta}}$$

$$z(t) = \frac{\beta}{n^{\beta}}(t-t_0)^{\beta-1}$$

The letters used describes the following:

- Where β is the shape factor of the curve
- The minimum time to failure is $t_{0,}$, where F(t) = 0.
- When t-t_0 =η then R(t) = e^{-1} = 1, which means that η is a time interval from t_0 to the point where 63% of a component has failed (and 37% survived). η + t_0 is described as the characteristic mean time to failure.
- MTBF or MTTF is then :

$$MTBF = \int_0^{\infty} R(t)dt = t_o + \ \eta G\left(\frac{1}{\beta} + 1\right), G\ being\ the\ gamma\ function.$$

The gamma function will not be described any further at this point.

1.2 Maintenance Strategies

This section will focus on some common maintenance strategies, such as Reliabilit- Centered Maintenance (RCM), Condition-Based Maintenance (CBM), and technical condition (TC).

1.2.1 Reliability-Centered Maintenance

The Reliability-Centered Maintenance (RCM) method can be formally defined as *a process used to determine what must be done to ensure that any physical asset continues to do what its users wants it to do in its present operating context* [5].

The method, or concept, is a maintenance management tool that encompass failure-mode techniques, cause-and-effect, criticality and maintenance policy analysis. The objective is to establish a cost-effective maintenance program which includes optimal maintenance policies that satisfies external and company-internal requirements. Moubray, J, lists seven questions that are central in the RCM [5]:

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

From the listed questions it becomes evident that failure modes are vital points of focus in the RCM-context. Fault-tree analysis is therefore a useful tool in order to systemize and organize the failure mechanics. The top-event for a component or a system is typically a failure. Below the top-event there are causes and /or events that can lead to failure. If a system can have several failure-modes the fault-tree, if designed correctly, will list all the causes that might lead to a system or component failure. For a major system consisting of several sub-systems a fault tree can be designed for all the sub-systems. Based on the sub-system fault-trees it is possible to design the fault-tree for the system in its whole. Such a process is time consuming and generally only necessary on sub-systems with high criticality and a complex structure [6].

Another approach to failure analysis is the use of failure mode-effect-criticality-analysis (FMECA). The main purpose of this process is to *1) Identify a functional hierarchy for the proposed plant/system by a breakdown of functions and sub-functions, often via a system and sub-system level, to equipment level. 2) Identify functions and failure modes on the lowest possible level of the functional hierarchy.* The results of a FMECA analysis is a set of critical and non-critical system failures, where the critical failures will be subject to preventive maintenance in order to reduce the frequency of occurrence. The criticality, defined as consequence x frequency, can be measured in terms of safety, environment, availability and/or costs[6]

After establishing the critical components and failure modes a cost optimization of maintenance actions will be performed. This requires that the failure function of the different components are known. Components subject to random failure are not considered in preventive maintenance as these components are unpredictable. Stochastically an old component is as good as a new component, given that the component is subject to random failure. Another criterion for preventive maintenance is that the corrective maintenance cost is higher than the preventive maintenance cost. Maintenance policies and costs will be presented later. [6]

The last step in the RCM process is the operational aspect. A database is needed to collect key performance data such as operational hours between failure for the system, downtime, repair time, cost of spare parts, equipment or sub-system subject to failure etc. In order to be able to review and adjust the maintenance schedule the operational data will be used in a continuous feed-back loop. The RCM process can be simplified to the following sketch :

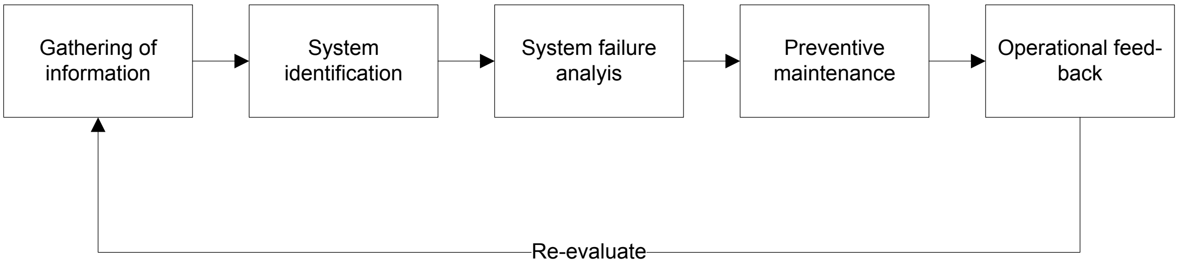

Figure 2 Simplified sketch of the RCM process

1.2.1.1 Preventive maintenance policies

There are several preventive maintenance policies, the first two being developed by the pioneers Barlow & Hunter in the 1960s. They focused their research on time based preventive maintenance. The first policy is the age-based preventive maintenance. An assumption for these models is that maintenance, both preventive and corrective, brings the system back to a "good as new"-condition. In other words, the maintenance is perfect. Before establishing the policy, some variables needs to be addressed:

- C_p = costs of a preventive maintenance action
- C_c = costs of a corrective maintenance action
- f(t) = probability density function, F(t) being the integral of the PDF
- R(T) = Survivability function = 1 - F(t)
- UEC(t_p) = expected cost per unit time = $\frac{Total\ expected\ cost\ per\ cycle}{Expected\ cycle\ length} = \frac{EC(t)}{EL(t)}$

The expected costs pr cycle can be defined as $EC(t) = c_pR(t) + c_cF(t)$, where R(t) is the probability of survival over the interval. Survival across the interval allows a preventive maintenance action to be performed. F(t) is the probability of failure before the time interval, t, has been reached. The latter leads to a corrective maintenance action. The expected cycle length, EL(t) can be proved to be $\int_0^{t_p} R(t)dt$. This gives the following expression for UEC(t) [10]:

$$UEC(t_p) = \frac{EC(t_p)}{EL(t_p)} = \frac{c_pR(t_p) + c_cF(t_p)}{\int_0^{t_p} R(t)dt}$$

The optimal interval t_p can be found by minimizing UEC(t_p).

The second policy established by Barlow & Hunter is the constant interval policy. The policy has the following expression for the UEC(t_p):

$$UEC(t_p) = \frac{C_p + C_c H_0(t_p)}{t_p}$$

In this model the c_p and c_c are preventive and corrective costs, while $H_0(t_p)$ is the expected number of corrective maintenance actions over the unit interval t_p. The expected number of corrective actions can be derived discretely or, often more difficult, by the Laplace inversion of H_0.

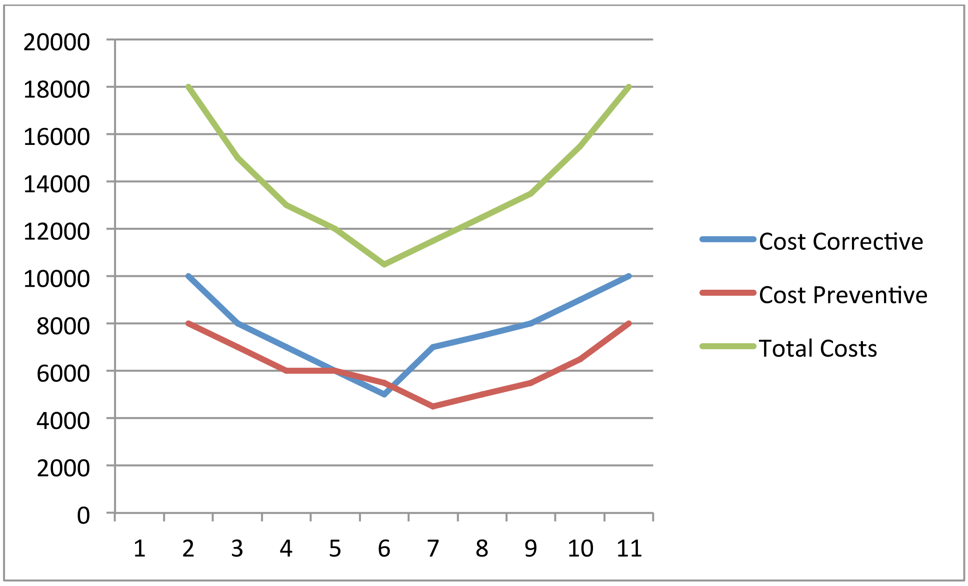

Figure 3 Total costs as a function of preventive and corrective maintenance costs

Figure 3 illustrates an example of how the corrective and preventive maintenance costs can vary along the time line (x-axis). The lowest total costs appear to be at a maintenance interval of 6 time-units. The illustration applies for both the age and time dependant maintenance policies.

1.2.2 Condition based maintenance

Another approach to maintenance of systems is condition based maintenance (CBM). According to Marseguerra, Zio and Podofillini [7] the approach is of interest in safe operation of offshore installations:

> *This policy shows great potential in systems such as nuclear power plants, offshore installations and aerospace components working under stressful conditions which damage their integrity and functionality and are typically continuously monitored because of the safety implications.*

Condition monitoring (CM) is useful on rotating and vibrating machinery and systems, where the condition of the system can be (continuously, if possible) monitored by measurements. Stand-by and safety systems can be tested and inspected. The strategy offers an advantage in terms of planning maintenance actions in addition to reducing efforts and resources spent on preventive maintenance. Preventive maintenance can be planned for and applied when necessary, thus increasing operational availability and reducing downtime costs.

The potential benefits from CM is discussed by Thorstensen[8] where the main points are

- *Reduced costs and repair time*
- *Avoided Revenue loss*
- *Maintenance cost savings*
- *Increased equipment lifetime*
- *Higher efficiency*
- *Sound basis for continuous improvement*
- *Improved safety assurance*

1.2.2.1 CBM - Reference Parameters

A common starting point when establishing reference parameters is to use the design criterions for the system of interest. This point is where the system has its maximum output or performance, hence the parameter is at 100% when the system is new. The condition parameter [9] is often expressed as the following:

$$Conditional\ Parameter = \frac{Reference\ (Design)\ Parameter - operational\ parameter}{Reference\ (Design)\ Parameter} * 100\%$$

As the system is operated and performance reduces due to deterioration, a maintenance action will be necessary at a certain point. If the maintenance action brings the system back to maximum level of performance the system is regarded "as good as new", and the conditional parameter reset to 100%. Whether the maintenance action can be recognized "as good as new" or not, can simply be decided by measuring the system performance after maintenance have been performed. This method allows the operators to know the system "health" at any time.

12.2.2 TCI - Technical Condition Index

A project called *Ageing Management* proposed the following definition of technical condition [11]:

> *The technical condition is defined as the degree of degradation relative to the design condition. It may take values between a maximum and minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation.*

In contrast to measuring components directly, which is done in CM, the TCI is obtained by the following methodology:

1. System description as a hierarchal structure of the objects which defines the system.

2. Criticality assessment by weight assignment of the potential outcome of failure for the different objects.

3. Describe the objects current health, or condition, by relevant input variables (if possible, at the bottom level of the hierarchy).

4. Aggregate TCI variables from bottom to top of the hierarchy, based on the available input data.

The necessary input can be extracted from the maintenance system or statistics, inspection data and conditional parameters. Once the measured values has been obtained they can be transferred to TCI by using transfer functions that describes the relationship between the measured value and the TCI [11].

The principles of the TCI can be described by the following figure 4:

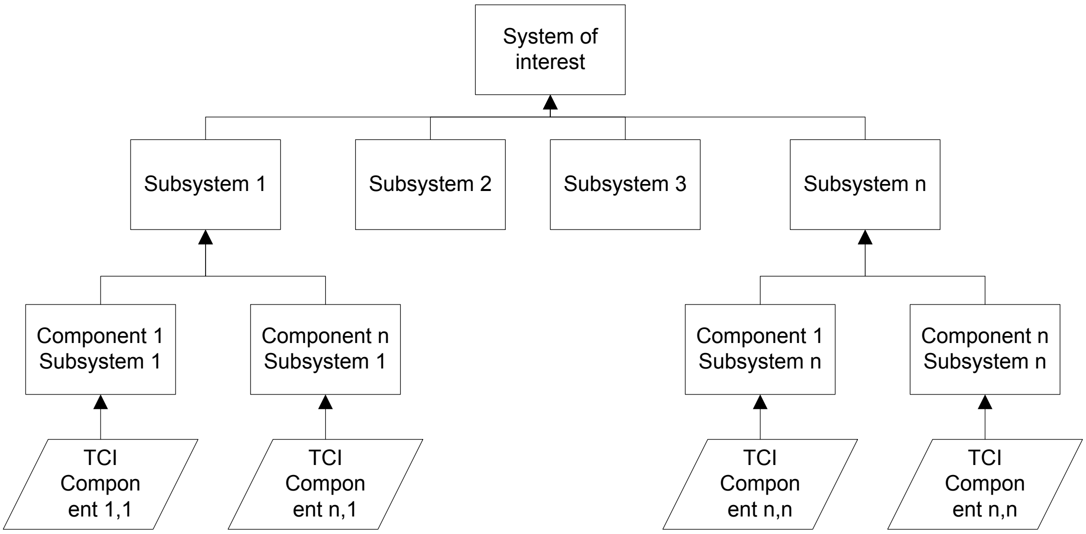

Figure 4 Basic principles of TCI for a given system

Figure 4 is an attempt to visualize the methodology for the TCI-concept. The "system of interest" can be any system that the analysts will describe by TCI. The system of interest consists of n subsystems, where each of the subsystems consists of n components. The technical condition of each subsystem can be derived by the condition of the components in the given subsystem. For instance, when the condition for all the components in subsystem 1 is known, and by weighing the criticality of failure for the different components, the TCI for subsystem 1 can be obtained. Then by deriving the TCI for all the subsystems, and weighing the criticality of failure for a subsystem, the TCI for the system of interest can be obtained.

1.2.2.3 Mean residual life

The residual life of a component is dependent of the load factor applied to the component. Linking this up with the TCI for a component, the operator will have information about the current state or condition of the component. Hence an operator may decrease or increase the residual life depending on the operational conditions for the component. A decrease in the load factor will increase the remaining life while increasing the load factor may reduce the remaining component life.

In reliability engineering, mean residual life is limited to the survivability function of the component given that the component have survived operations from $t = 0$ up to t_0= today. Rausand and Reinertsen [15] defined the mean residual life as:

$$MRL(t_o) = \int_0^\infty R(t|t_0)dt$$

When applying this in CBM there are some other sources of information available in order to provide more information about the technical condition. Andersen and Rasmussen [16] includes

- Historical information, MTTF and PDF
- Operational information from time 0 to t_0 (today), condition parameters and influence factors
- Current technical condition (TCI, diagnosis)
- Future operations and expected load factors

A new pdf can be established based on the quantitative and qualitative information, and hence applying it for an estimation of the future life expectancy. The new PDF, $f_{new}(t)$ can then be used in a simple definition of MRL, note that $t_o = 0$ at t_o:

$$MRL(t_0) = \int_0^\infty tf(t)dt$$

Knowing nothing more than the fact that the component survived up to t_0 gives the following:

$$f(t) = \frac{f_{old}(t+t_0)}{1-\int_0^{t_0} f(u)du} = \frac{1}{R(t_0)dt}\frac{d}{dt}\overline{R}(t+t_0)$$

The result for an exponential distribution for f(t) then gives

$$MRL\ (t_0) = \frac{1}{\lambda}$$

If f(t) follows a Weibull distribution gives the following expression, which has to be solved numerically [16]:

$$MRL(t_0) = \int_0^\infty t\alpha\lambda(t+t_0)^{\alpha-1}e^{-\left(\left(\lambda(t+t_0)\right)^{\alpha}-(\lambda t_0)\right)^{\alpha}}dt$$

1.3 Life cycle management

As the maintenance strategies were derived in the 1950s and with the introduction of reliability engineering, operators of plants and systems possessed a useful tool in order to predict and prevent system failure. Today, maintenance is included in system design and an important part of life cycle management. The International Atomic Energy Agency (IAEA) use the following definition on life cycle management:

> *Life cycle management is the integration of safety management, ageing management and business management decisions, together with economic considerations over the life of the nuclear power plant in order to:*
>
> *- Maintain an acceptable level of performance including safety.*
> *- Optimize the operation, maintenance and service life of structures, systems and components.*
> *- Maximize returns on investment over the operational life of the nuclear plant.*
> *- Take account of national strategies for life cycle funding (including decommissioning), fuel management and waste management (International Atomic Energy Agency, 2002, p 3).*

It should be mentioned that this thesis does not include all the focus points listed by the IAEA, but includes the safety, optimization and life cycle estimations, mainly covered by the first 3 points.

An important point in life cycle maintenance is the systematic methodology for maintenance strategy planning. According to Takata et.al [12] the efficiency of maintenance relies more on the appropriate strategy rather than maintenance task planning. When developing strategies there are two important factors that should be evaluated. By doing deterioration and a failure analysis the resulting failures and deterioration of the system is evaluated, while the other factor is the applicability of the different maintenance technologies. Both managerial and technological evaluations must be integrated in order to obtain an effective maintenance strategy.

The deterioration process of systems is of great interest in management of aging systems. Monitoring this process and being able to describe the condition of the system is therefore of major importance. Some common methods and techniques for monitoring the systems have already been introduced in the maintenance introduction chapter. A challenge with management of aging systems is the selection and scheduling of actions that might affect multiple goals. According to Thorstensen [8] the main objective in aging management is to provide the highest life cycle profit while satisfying safety and environmental demands.

A framework for life cycle maintenance have been suggested by Takata et al[12].

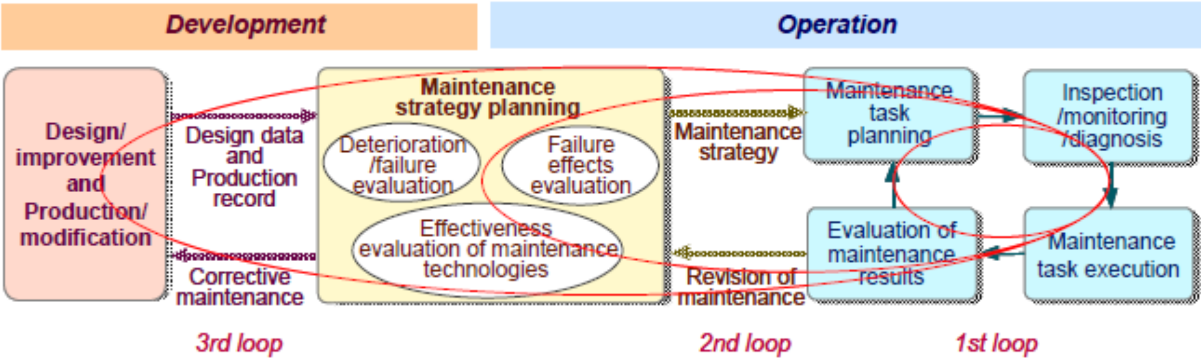

Figure 5 A framework for life cycle maintenance

The first loop in figure 5 is the general maintenance activities. The information from the first loop can be included in the second loop. Based on the information gained from operations the maintenance strategies can be re-evaluated and optimized, which is included in the 2nd loop. The 3rd loop includes the development phase, where improvements in new products or re-designed systems, can be made by utilizing information from the operational phase. For continuous improvement of a product the last cycle is essential [12]. However the main point of focus in this thesis is the first and the second loop.

1.3.1 Planning

Maintenance strategy planning is a key factor in life cycle maintenance management. Takata et.al(12) categorizes three sets of factors that plays an important role when planning and preparing strategies. These are

- *Criteria for providing treatment*
- *Opportunity of maintenance task executions*
- *Type of treatment*

Treatment is decided on a detection of breakdown, detection of symptoms and an analysis of the trend. Breakdown, symptoms and trend-analysis are all monitored over time. When the criterions for treatment are clear, maintenance tasks can be performed on the plant or the system of interest. In general there are three opportunities for performing maintenance; while under operation, when the plant or system is down, or the system is disassembled. Opportunity based maintenance policies can be used in order to calculate the costs, potential benefit, and risks of a preventive maintenance action.

Pintelon and Gelders (18) have suggested three types of maintenance planning phases: *Strategic Planning, Tactical planning* and *Operational planning*. *Strategic planning* focuses on ensuring the company´s ability of staying competitive by providing production resources. The maintenance manager does not decide replacement of equipment alone, as the maintenance costs and downtime costs play an important role in these decisions.

Tactical planning is referred to as resource management and optimization of the availability of the plant or system in terms of i.e. finding the most beneficial maintenance costs and policies. The point is to find the optimal balance between preventive and corrective maintenance. Focusing too much on preventive maintenance can in some cases lead to unnecessary high maintenance costs. However as the penalty cost for unavailability for an offshore drilling rig, or drill ship, may be in the region of 250.000-450.000[1] USD per day, high availability and reliable systems are of major importance.

Operational Planning focus on daily operational routines and scheduling decisions. On this level maintenance scheduling address sequences of task execution and by whom they will be performed.

1.3.2 Decision making

To be able to schedule and select the correct actions in aging management, more focus have been put in to decision-making. The massive amount of data collected from the operational phase is under evaluation in the maintenance strategy planning phase, handling these data in the correct manner is therefore important in order to obtain a continuous optimized policy.

Some decisions can be made upon statistical data, other decisions might affect more than one aspect in a system and the “correct” decision might not appear as obvious as the former. Tools for decision-making are available, all though not necessarily the most suitable for the problem at hand.

1.3.2.1 Multiple criterion decision making

Multiple criterion decision making (MCDA) is one aid to such situations. The process seeks to [13]

- Integrate objective measurement with value judgement;
- Make explicit and manage subjectivity

Belton and Stewart states that subjectivity is a natural part of all decision processes and particularly if there are several criterions to base the decision on. MCDA does not “solve” the problem; it rather “seeks to make the need for subjective judgement explicit and the process by which they are taken into account transparent”. Some problems where MCDA can be of an aid are [13]:

- The choice problematique: To make a simple choice from a set of alternatives
- The sorting problematique: To sort actions into classes or categories, such as “definitely acceptable”, “possibly acceptable but need more information”, and “defiantly unacceptable”
- The ranking problematique: To place actions in some form or preference ordering which might not necessarily be complete
- The descriptions problematique: To describe actions and their consequences in a formalized and a systematic manner, so that decision makers can evaluate these actions.
- The design problematique: To search for, identify or create new decision alternatives to meet the goals and aspirations revealed through the MCDA process
- The portfolio problematique: To choose a subset of alternatives from a larger set of possibilities, taking into account not only the characteristics of the individual alternatives, but also the manner in which they interact and of positive and negatives synergies.

As for aging management where a system degrades over time, the portfolio problematique is likely to be of use as a system interacts with subsystems and the plant as a whole.

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[1] http://www.rigzone.com/data/dayrates/ per 02.05.2011.

1.3.2.2 Markov Decision Processes

An interesting analytical tool, which can be applied to systems that are being monitored, is the Markov chain and foremost the Markov decision process (MDP).

> *Markov chains have the special property that probabilities involving how the process will evolve in future depend only on the present state of the process, and so are independent of events in the past.*

A stochastic process has the Markovian property if (19):

$$P\{X_{t+1} = J | X_0 = K_0, X_1 = k_1, .., X_{t-1} = k_{t-1}, X_i = i\} ,$$
$$for\ t = 0,1, \dots and\ every\ sequence\ i, j, k_o, k_1, \dots , k_{t-1}.$$

In order to find the optimal actions for the respective states when considering both immediate and subsequent costs the Markov decision process can be applied.

A model for the MDP can be summarized as follows [19]:

1. The state I of a discrete time Markov chain is observed after each transition (i = 0, 1,…M).
2. After each observation, a decision (action) *k* is chosen from a set of possible decisions (*k*=1,2,…K). (Some of the *K* decisions may not be relevant for some of the states.)
3. If decision d_i = *k* is made in state *I*, an immediate cost is incurred that has an expected value C*ik*.
4. If decision d_i = *k* in state *i* determines what the *transition probabilities* will be for the next transition from state *i*. Denote these transitions probabilities by $p_{ij(}(k)$, for j = 0, 1,…, M.
5. A specification of the decisions for the respective states ($d_0, d_1, \dots, d_M$) prescribes a policy for the Markov decision process.
6. The objective is to find an *optimal policy* according to some cost criterion which considers both immediate costs and subsequent costs that result from the future evolution of the process. One common criterion is to minimize the (long-run) *expected average cost per unit time*.

An example of the cost data and possible decisions based on the set of states a system can operate in can be as following (assuming states from 0-3, where state 0 is good as new, 1 is operable – minor deterioration, 2 is operable – major deterioration and 3 is inoperable which induces unavailability):

Decision	State	Maintenance costs	Cost of lost production	Total cost per week
1. Do nothing	0, 1, 2	0, 0, 0	0, 0, 0	0, 0, 0
2. Overhaul	2	15000	20000	35000
3. Replace	1,2,3	30000	20000	50000

Table 1 Markov Decision Process

By calculating the probabilities of the states the system can be in, based on i.e. weekly inspection or condition monitoring results, the costs can be optimized based on the set of possible decisions that can be made by running an optimization algorithm. This can be further investigated by optimising different maintenance policies, which introduces a more complex decision matrix.

Applying this to system consisting of a set of sub systems (referring to the TCI-section) will introduce a lot of possible decisions for the system as a whole and the sub-systems. This process is therefore likely to be solved by programming. Dynamic programing is an aid to such situations.

1.3.2.3 Dynamic programming

The dynamic programming process is an optimizing tool which can be used to find the optimal path from a set of variables, or in this case a set of possible decisions (linking it to the MDP) or a set of costs. From the MDP a solution matrix with a set of costs can be obtained based on the possible decisions that are identified. Knowing that the primary target is to minimize the costs, the solution of the dynamic programing is the minimal path, where the possible paths are cost variables.

The dynamic programming is a step-by-step process where a set of decisions have to be made from start (A) to end (B). If the criterion is to minimize the costs the idea is to work backwards from B to A via the set of possible decisions or paths. The relation is in general [10]:

$$f_n(I) = {}^{min}_{J}\{C_n(I,J) + f_{n-1}(J)\}$$

I is the starting point, J being the ending points.

$f_n(I)$ = the result of the best decision for stage n plus the best decision taken for the rest of the stages. The entry of the stage is I.

$C_n(I,J)$ = the result for stage n, when the entry is I and the exit is J.

$f_{n-1}(J)$ = the result of the best decision for the rest of the (n-1) stages when the entry for Stage (n-1) is J.

Running this algorithm will provide the optimal solution for the problem which is being optimized.

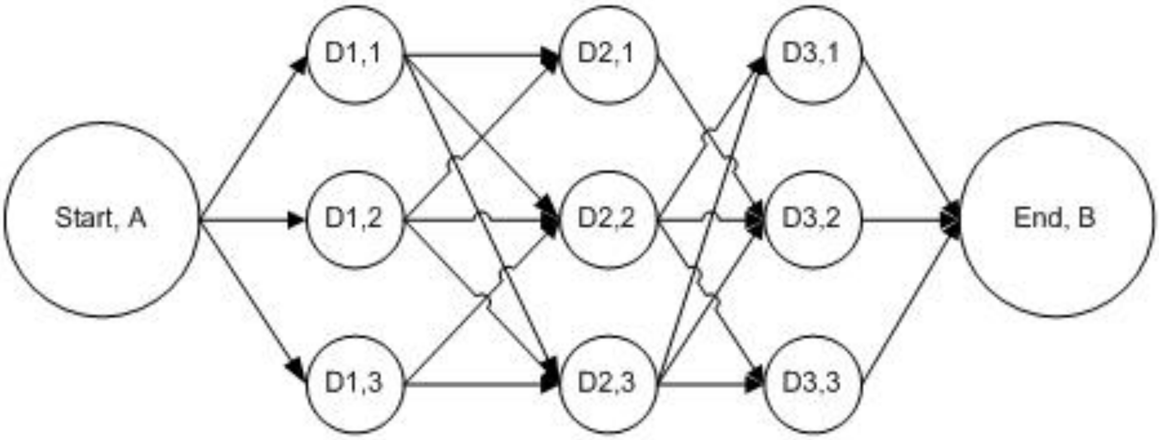

Figure 6 Illustrated example of dynamic programming

Figure 6 illustrates a simplified sketch for dynamic programming. Note that all the arrows are missing values, or variables, i.e. they could represent costs with different values depending on the direction of the path, or state the arrow leads to. $D_{2,1}$ does not include a path to $D_{3,1}$, this is done to visualize the fact that there might not exist, in this case, three paths to all the future decisions. The missing path will be assigned an infinite value, as this is a minimization example, which makes the program to exclude the possible path from $D_{2,1}$ to $D_{3,1}$. For maximizing problems, the value would be 0.

1.3.3 Life Cycle Costs

The Norwegian armed forces have developed a project handbook [14] which states that life cycle costs (LCC) shall be considered when executing new projects or buying new equipment. They demand that a material systems and logistic support systems must fulfil the operational demands and standards at the lowest possible life cycle cost. On a general basis the LCC has been defined as

- Development costs
- Procurement costs
- Operational costs
- End of life costs

The major cost driver for a plant, or a system, during its life cycle is in many situations the operational costs. Preparation for the operational phase should therefore begin at an early phase of a project when it is possible to affect the system design and construction without increasing the costs significantly. The phase usually includes system specifications and demands, cost calculations and verifying that the demands are being fulfilled.

In addition it is necessary with a logistics analysis, a process the army has named integrated logistics support (ILS). This process can include both the user and the suppliers, the main objective being to define a supply chain at the lowest possible costs. Other criteria are that the logistics system is user friendly and that it is reliable in operations.

Three maintenance and supply chain studies are mentioned for the project phase of the system:

The first of the studies is the system selection process. Analysing possible solutions and deriving a basis for decision-making, the best solution can be selected based on the selected criteria. The second study is an analysis of offers and recommendations of suppliers that can suit the ILS system derived in the project phase. The third phase focuses on operations. Material supply, maintenance strategy selection, necessary resources such as manpower, equipment and tools, documenting the need for spare-parts, technical documentation and procedures are some of the important points of focus in this phase.

An operational plan is also supposed to be derived in phase three, which include:

- Maintenance task for each of the maintenance levels
- Spares demand and articles of consumption and a plan for procuring these materials
- Necessary need of a storage room
- Plan for data collection when the system is being operated.

1.3.3.1 RCM IN A LIFE CYCLE PERSPECTIVE

In aviation the RCM process have been regarded as a valuable tool in a life cycle perspective and systems and routines are arranged to support this philosophy. It was developed late in the 1970s and recently been applied in areas such as nuclear power plants and the petroleum industry [12]. Also in an operational perspective the RCM is a useful tool used to revise the existing maintenance program. The results from the RCM process can be used directly in a LCC-analysis.

1.3.4 Basic tools for LCC calculations

The net present value (NPV) is the today's value of future value. P is the present value, F is the future sum, r is the annual discount rate and n is the number of annual periods. This gives us the following expressing for NPV (Eq 1.3.4.1):

$$P = F * \left[\frac{1}{(1+r)^n}\right]$$

For calculations of equal payments at the end of each year, for n years, the present worth can be calculated by the following equations (Eq 1.3.4.2) [10]:

$$P = A(e^{-r}) + A(e^{-r2}) + .. + A(e^{-rn})$$

$$= Ae^{-r}(1 + e^{-r} + e^{-2r} + \cdots + e^{-r(n-1)}$$

$$= Ae^{-r} * \sum_{j=0}^{n-1} \left(\frac{1}{e^r}\right)^j$$

$$P = A\left[\frac{1 - e^{-rn}}{e^r - 1}\right]$$

To be able to calculate the life cycle costs it is normal to develop a cost structure. From a maintenance point of view, the main factors are operational costs, preventive maintenance costs and corrective maintenance costs. The downtime costs can be calculated as a function of the repair time and included into the preventive and corrective maintenance costs. In addition, the residual value and minor operational maintenance costs can be added. The structure is shown in figure 7:

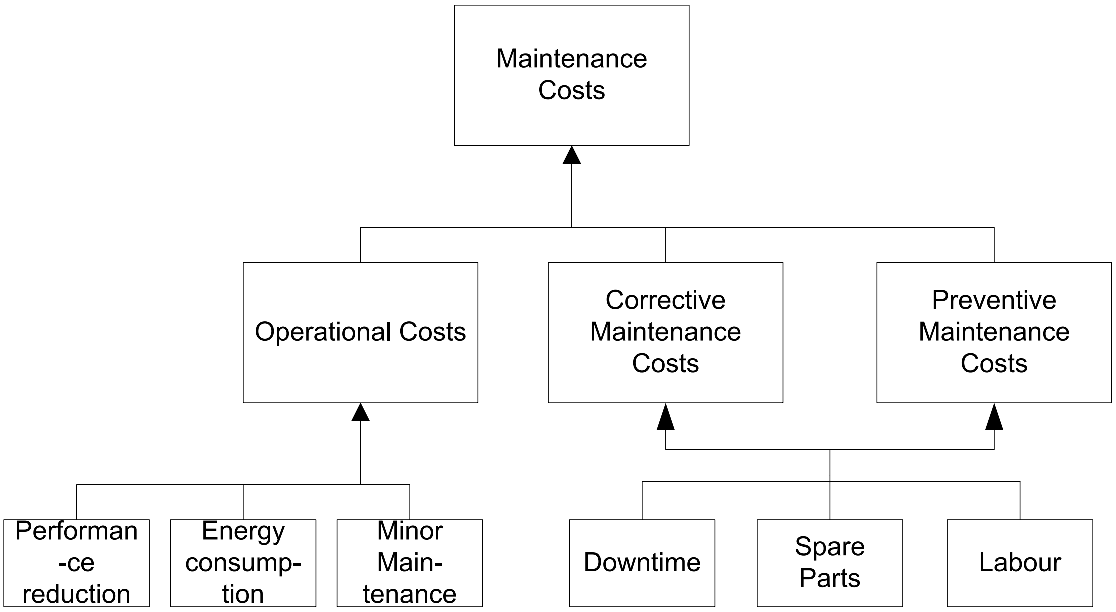

Figure 7 Breakdown of maintenance costs

The profit function or energy function, neglecting financial interest, can be written as:

$$E(T_{miss}) = \int_0^{T_{miss}} \big(B(t) - C(t)\big)dt$$

Where E is the net benefit of operating a plant, B(t) is the benefit and C is the total operating costs of the plant. This expression can be expanded as C(t) includes all the costs of operations. This means that C(t) = CO(t) + CC(t) + CP(t), where CO(t) is the operational costs, CC(t) is the cost of corrective maintenance and CP(t) is the cost of preventive maintenance. This gives :

$$E(t_{miss}) = B(t) - \big(CO(t) + CC(t) + CP(t)\big)$$

The expression for C(t) can be further used in a simple condition based repair model [16]:

$$C(t_r) = P(t_r) * \frac{\int_{t_0}^{t_t} f(t) * [CCD(t) + \ CCR(t) + \ \int_0^t co(u)du]dt}{\int_{t_0}^{t_t} f(t)dt}$$

$$+ R(t_r)[CPD(t_r) + \ CPR(t_r) + \int_{t_0}^{t_r} co(t)dt]$$

$P(t_r)$ is the probability for failure while $R(t_r)$ is the survival probability over the interval ($t_o..t_r$). CCD(t), CPD(t), CCR(t) and CPR(t) are corrective and planned downtime costs and repair costs. co is the cost of operation and minor maintenance costs.

The average number of spares necessary to perform corrective and preventive maintenance can be calculated for the constant age interval (10):

$$\bar{N}_{tp} = \frac{t}{MTBM} = \frac{t}{\int_0^{t_p} R(t)dt} = \ \lambda_T * t$$

By using a confidence level (1-α) the number of spares can be calculated as:

$$(1 - \alpha) = \sum_{i=0}^{s} (e^{-\bar{N}_{tp}}) \frac{\left(\bar{N}_{tp}\right)^i}{i!}$$

2. Model-preparations: Objectives and demands from Odfjell Drilling and authorities.

With the theory in place, the next step is to map the criteria and needs of the model in terms of limiting, and in terms of what information the company want the model to provide. The information is based on conversations with my thesis instructor in Odfjell Drilling and the company maintenance procedures.

The model is not supposed to be a textbook-model or solution. The emphasis should rather be the development of a methodology for doing a life cycle cost analysis based on data available to the company. It must also estimate technical condition of systems and equipment in economical terms. Other relevant questions are; how can cost-data and cost-models be used to define when to replace equipment or a system? What kind of input can the company provide to their customers investment portfolio, and how can they document their recommendations?

In an ideal situation the model should be applicable for all types of equipment being used in operations. Some relevant information is available from the Maisy, a database containing maintenance history, maintenance costs, hours spent on maintenance, and recorded downtime when systems become unavailable. There are no key numbers being tracked that can be used directly in the model. Methods for extracting quantitative data and how they can be used in an analysis is an interesting aspect in order to design the model.

System safety is an important aspect and reports concerning unwanted events are available from Maisy. Reports concerning damaged equipment or personnel injuries might be used as an indicator for evaluating the whether there is a need of replacing equipment or a system.

The final model should be kept as simple as possible and can be a presented in a spreadsheet format, preferably visualizing some graphed trend analysis and a technical condition of the equipment. A negative trend can indicate that replacement of the equipment investigated might be necessary. The users of the model should only need to retrieve necessary input data from Maisy and other relevant sources such as manufactures. By punching the relevant parameters needed into the model, the results should appear without calculations performed by the user.

Odfjell Drilling have developed procedures for maintenance management and system safety. As the procedures are meant for in-house use, they cant be referred to in this thesis without a clearance from the company. However, some of the maintenance procedures are based on the regulations related to conducting petroleum activities that are developed by the Petroleum Safety Authority Norway. The main regulations for maintenance are in section 45-51[2].

In short the section describes Maintenance (45), Classification (46), Maintenance Programme (47), Planning and Prioritisation (48), Maintenance Effectiveness (49), Special Requirements for Technical Condition Monitoring of Structures, Maritime Systems and Pipeline Systems (50) and Specific

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[2] http://www.ptil.no/activities/category399.html?lang=en_US

requirements for testing of blowout preventer and other pressure control equipment (51). From this the following necessary information have been extracted:

Maintenance: The responsible party shall ensure that facilities or parts thereof are maintained, so that they are capable of carrying out their intended functions in all phases of their lifetime.

Classification: Consequences of potential functional failures for the facilities systems and equipment shall be classified in regards to health, safety and environment. Failure modes that might cause serious consequences must be evaluated in terms of failure causes and failure modes, the responsible party must also estimate the failure probability of the individual fault mode. The classification shall be used as a basis when choosing maintenance activities and maintenance frequencies, and in prioritising between maintenance activities and spare-part demand.

Maintenance Programme: Maintenance programmes shall be used systematically to prevent fault modes that constitute health, safety or environmental risks. The programme shall include performance and technical monitoring to ensure correction of fault modes that have occurred or that are under development.

Planning and Prioritisation: An overall plan must be developed for executing of maintenance programme and corrective maintenance activities. Individual maintenance activities shall have criteria available for setting priorities with the associated deadlines.

Maintenance effectiveness: Shall be systematically evaluated based on registered performance and technical condition data for facilities or parts there of. Shall be used for continuous improvement of the maintenance programme.

Special requirements for technical condition monitoring of structures, maritime systems and pipeline systems: Technical monitoring of new structures and shall be carried out during their first year of service. For new types of load-bearing structures, data shall be collected during two winter seasons to compare them with the design calculations. When using facilities beyond their original design life, instrumentation of relevant structure sections shall be considered so as to measure any aging effects.

3. Model Development – a theoretical approach

This section will be a step-by-step walkthrough of the model development. The model will be developed in four stages, much like the “overall model for maintenance optimization” developed by Vatn, Hokstad and Bodsberg (20). Their model is carried out in four steps; *defining the problem*, *establishing the loss function and preferences*, *dependability modelling* and *result compilation*.

3.1 Problem definition and assumptions

The first focus point is to define the boundaries and overall goals for the model. The model shall:

- Estimate life cycle costs for optimal overhaul intervals for systems and equipment in economical terms
- Estimate Increased life time for systems and equipment when applying a new, or different, maintenance policy
- Indicate the Technical Condition of the system
- “Be as simple as possible in use”
- Include a method for converting subjective information to be more objective and evaluated by uniform guidelines

Like most maintenance models found in the literature, the model will be based on a set of assumptions. This will simplify and help defining the model to a certain extent of application. Ideally, the end-users will only need to derive and crunch the necessary parameters from their database and mainly use this as input as the model will provide the necessary output.

The model will be limited to systems and equipment that are subject to preventive maintenance. A general criterion for preventive maintenance is that *the preventive maintenance cost is lower than corrective maintenance costs*. If the latter were the lowest, the strategy would be simple: run the system until failure with no preventive maintenance actions. Consequences such as downtime and time to repair for preventive and corrective actions must be included.

Preventive actions are usually less time consuming, as they are prepared, and the corrective actions normally are unprepared. This can lead to a significant reduction in downtime costs for preventive maintenance costs compared to the corrective costs. The massive day rates for a drilling rig will affect the strategy selection and corrective breakdown might induce costs that are so high that the scenario must be avoided. In other words too much effort might be put into preventive maintenance. The challenge is to find the optimal interval for preventive maintenance so that it is not executed more than necessary.

When the system has been subject to major overhauls, either correctively or preventively, the system will be regarded as “good as new”. The technical condition of the system is hence at 100% after a major overhaul. The average costs of (major) preventive and corrective maintenance actions are assumed to be a good representation for C_p and C_c, Cost preventive and Cost corrective actions respectively.

The model will make use of the fixed age and fixed interval maintenance policies from section 1.2.1.1 Preventive maintenance policies. More advanced models are available although not necessarily applicable.

3.2 Establishment of parameters

There are several parameters that have been identified in order to perform the modelling. The parameter selection is based on a simple breakdown structure that can be applied to any system: Figure 8 shows a simplified sketch for the model development:

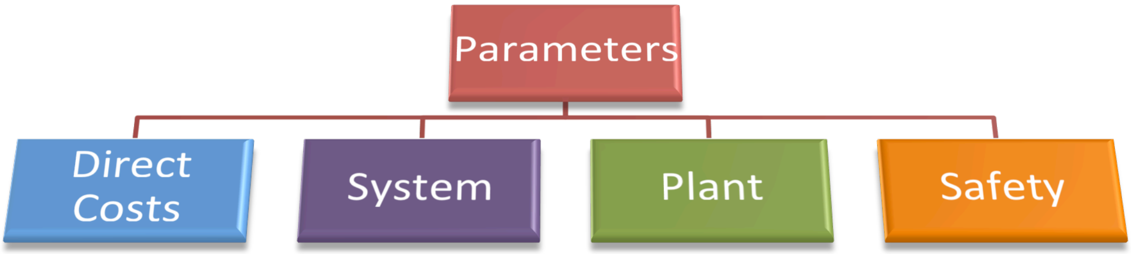

Figure 8 Parameter breakdown structure

3.2.1 Cost parameters

The cost parameters define the expenses related to downtime, preventive and corrective maintenance. The model is supposed to optimize with respect to economic evaluation and the following cost parameters (and some parameters that costs are derived from) has been identified:

Parameter	Index	Description	Formula	Unit
Day rate costs	C_D	Operator costs due to day rates paid to contractor	(-)	[NOK]
Downtime costs operator	C_{DTO}	Downtime costs for the operator	$C_{DTO} = C_D * T_r$	[NOK]
Downtime costs contractor	C_{DTC}	Downtime costs for the contractor	$C_{DTC} = (T_r - T_{free}) * C_D$	[NOK]
Shutdown costs	C_{SD}	Penalty cost due to shutdown	$C_{SD} = t_{SD} * C_{Lost\ Production}$	[NOK]
Cost Spare parts	C_{spare}	Unit cost of necessary spares, includes logistics	(-) Depends on demand	[NOK]
Personnel costs	C_{men}	Labour cost	(-) Assumed to be constant	[NOK]
Number of persons	n_{pers}	Number of persons involved in maintenance actions	(-)	[-]
Average preventive maintenance costs	C_p	Costs related to a preventive maintenance action.	Formula 3.1	[NOK]
Average corrective maintenance costs	C_c	Costs related to a corrective maintenance action	Formula 3.2	[NOK]
Fractional maintenance cost	ΔC_M	Mean difference between costs of corrective and preventive actions	$\Delta C_M = C_c - C_p$	[NOK]

Table 2 Cost Parameters

The *downtime costs* is defined in the contract between the operator and the contractor. In the model the downtime costs are referred to as the cost of downtime for the contractor. There can be specific circumstances that states when the actual downtime begins to run. Perhaps in some cases the contractor might have 15-30 min to repair the system before the downtime costs starts running. A simple assumption would be to neglect this, but this can have a huge influence on the accuracy of the real costs. Thirty minutes downtime on a rig with 400.000$ in day-rates would be approximately 50.000 NOK. Thus the "free downtime" is of great importance. In addition the downtime costs may be shared between the operator and contractor, this too might depend on the contract. The operator might pay 85% of the costs when the downtime costs are above a specific amount.

Shutdown costs are included but probably most applicable on production platforms. Maintenance activities that requires welding etc can in some cases require a production shutdown. The related costs are a contractual issue.

Cost of spares, number of personnel and personnel costs are self-explaining. These are needed to calculate the preventive and corrective maintenance costs. The spare part costs are assumed to include the logistics costs. Store keeping costs is assumed to be small, and hence neglected.

The *average preventive maintenance costs* are based on the downtime -, shutdown - , spare part - , number of persons and personnel costs. There might be differences between crews and their response time to a system failure. For instance can the time spent troubleshooting before detecting the failure vary which can increase or decrease the average total downtime. To take this into account the model will be based on the average "historical downtime", from breakdown to the system is repaired (which can be derived from the history in Maisy). This leads to the following equation (3.1):

$$C_p = \frac{\sum_0^{k_p}\left(C_{DT} * \left(t_{rp} - t_{free}\right) + \; C_{SD} * t_{SD} + C_{spares} * n_{spares} + C_{pers} * n_{pers} * t_{rp}\right)_i}{k_p}$$

Where t_{rp} is the preventive repair time, t_{SD} is total time where the production is shut down, i is preventive maintenance action from 0,1,2…k-1,k. Then by summing the preventive maintenance actions from 0 to K, and dividing by k number of actions the average cost for C_p is obtained.

The average costs for the corrective maintenance actions are very much like the preventive maintenance costs, however changing t_{rp} to t_{rc} to indicate a different repair time, as time to repair usually is longer for corrective actions. This gives the following equation (3.2):

$$C_c = \frac{\sum_0^{k_c}\left(C_{DT} * \left(t_{rc} - t_{free}\right) + \; C_{SD} * t_{SD} + C_{spares} * n_{spares} + C_{pers} * n_{pers} * t_{rc}\right)_i}{k_c}$$

The *fractional maintenance cost*, $\Delta C_M = C_c - C_p$, is included as a parameter to indicate the real cost difference between the corrective and preventive maintenance costs.

3.2.2 System parameters

This section focuses more on the technical aspect of general systems. The set of related parameters is listed in table 3:

Parameter	Index	Description	Formula	Unit
Probability density function	PDF	Necessary for calculating F(T) and R(T), failure and survivability functions respectively	Depends on the selected system. Exponential or Weibull distributions are common.	[Function]
MTBF	E(T)	Mean time to failure, depends on the PDF	$E(T) = \int_0^\infty tf(t)dt = \int_0^\infty R(t)dt$	[Hours]
MTTR	t_{rc}, t_{rp}	Mean time to repair, correctively and preventively	(-) Obtained from database	[Hours]
Technical condition substituted part	TC_{sub}	Technical condition of the defect part(s). Based on subjectivity or measured.	Evaluated to be in the region of 0-100%	[%]
Real operational hours	O_t	The real operational hours of the system, excluding standby and plant downtime. Real operation time of the system.	Formula 3.3	[-]
System availability	A_{sys}	Total availability of the system	$A_{sys} = \frac{T_{operations}}{T_{operations} + T_{down}}$	[-]
System Unavailability	U_{stys}	Unavailability due to system being down	$U_{sys} = 1 - A_{sys}$	[-]
Mean residual life	MRL	The average potential life of a system, given it has survived operations up to today	$MRL(t_0) = \int_0^\infty R(t\|t_0)dt$	[Hours]
Remaining system life	S_{RL}	Estimated remaining life of the system	$S_{RL} = P_{RL}$	[Years]
Future spares demand	D_{spares}	Estimates the future demand of spares with the current maintenance strategy	$D_{spares} = S_{RL} * E(T)$	[-]
Preventive maintenance interval	T_p	The current interval for preventive maintenance.	(-)	[Hours]
Total preventive maintenance actions	K_p	The number of preventive maintenance actions performed along the investigated timeline	Obtained from database	[-]
Total corrective maintenance actions	K_c	The number of corrective maintenance actions performed along the investigated timeline	Obtained from database	[-]

Table 3 System parameters

The *probability density function* is the basis for calculation of the failure probability and survivability, F(T) and R(T) respectively. The function can be subject to “running-in”, constant, and wear out failures. The Weibull distribution, described in 1.1.2, attempts to include all three types of failure for a system or a component. In practice it might be difficult to obtain this distribution.

The *expected mean time between failure* (MTBF), or E(T), is the integral of the survivability function, R(t). R(t) being based on the PDF means that also this variable is difficult to obtain.

The *mean time to repair* is the time it takes, on average, to repair a failed system. Normally the MTTR for preventive maintenance actions are shorter than the corrective actions, as the preventive actions have been a subject to planning and preparations, while the corrective actions are necessary due to breakdowns before reaching the preventive time interval.

Technical condition substituted part, is a subjective evaluation of the parts that are being replaced. This is mainly meant for parts substituted due to preventive maintenance. Based on inspection and /or experience from the operators, the parts can be given a technical condition value. These values can be used as an indicator of the potential residual life for the inspected parts.

The *real operational hours* (operating time), O_t, indicates the total time the system have been operating. This excludes standby-time and downtime due to failures of other systems. By doing this the following equation can be obtained (3.3):

$$O_t = S_{age} * T_{active} * A_{plant}$$

The equation can be easily explained by a simple example: Say the system age is 1 year, meaning that the last major preventive action was performed 12 months ago or approximately 9000 hours. Assuming an active system in 40% of the time while the plant is operation, this will give a 60% standby time. If the overall availability of the plant is included and set to 95% , this will by eq. 3.3 give O_t = 9000 *0,4*0,95 = 3420 hours. If the system or equipment that is investigated can be found in the OREDA and the average time to failure is listed, the estimation of the O_t might give an indication of the remaining life of the part or system.

System availability and unavailability is included and can be compared with the overall plant availability. If the system availability is lower than the average plant availability, the system might require more attention in terms of preventive maintenance.

The *mean residual life* is expressed in 1.2.2.3.

Remaining system life can be obtained from the design criteria for the plant and by subtracting the time up to today. Based on this information the future spares demand, with the current maintenance interval, can be estimated. Increasing the interval or changing the strategy based on the residual life estimations can indicate the potential cost savings in terms of a reduced spare parts demand.

3.2.3 Plant Parameters

In section 3.2.2 some of the parameters referred to plant parameters. The main parameters for the plant are the plant availability and corresponding unavailability, and the remaining life of the plant.

Parameter	Index	Description	Formula	Unit
Plant Availability	A_{plant}	Operational availability of the plant.	(-) KPI, measured	[%]
Plant Unavailability	U_{plant}	Unavailability of the plant.	$U_{plant} = 1 - A_{plant}$	[%]
Plant design life	T_{PD}	The design life of the plant, i.e. 30 years	(-) Constant	[Years]
Plant age	T_{PA}	The current age of the plant	$T_{pa} = T_{today} - T_{startup}$	[Years]
Remaining life of plant	P_{RL}	Based on the design criteria for the plant, the remaining life can be estimated.	$P_{RL} = T_{PD} - T_{PA}$	[Years]

Table 4 Plant parameters

The operational *plant availability* is continuously monitored and should be easily obtainable from the database. Once obtained the unavailability is easily calculated.

Plant design life and the current *plant age* are easily obtainable and can be calculated. When they are known the remaining life of the plant can be calculated. The remaining life of the plant is used for calculating the future spares demand. This thesis does not focus on obsolescence; hence it will be assumed that the system will remain in place through the remaining life of the plant.

3.2.4 Safety Parameters

The safety aspect of the system is not the main focus in this model as safety and risk management tends to require an active user. In order to keep the model as simple as possible and to avoid major risk-analysis the main safety parameters will be the following:

Parameter	Index	Description	Formula	Unit
Unwanted events related to the system	n_i	Total number of injuries or unwanted events related to the system at hand	(-) Obtained from RUH	[-]
Number of maintenance actions	K_a	Total corrective and preventive repair actions	$K_a = K_p + K_c$	[-]
Accident frequency	A_f	Describes personnel injuries due to system failure	$A_f = \frac{n_i}{K_a}$	$\left[\frac{injuries}{action}\right]$
Accident consequence	A_c	The consequence of the accident related to repair	(-) Subjective, may be a cost	[NOK]
Risk	R	Defined as probability of unwanted event times consequence	$R = A_f * A_c$	[NOK]

Table 5 Safety parameters

From the database the number of injuries of personnel, or damages on the system or surrounding systems, can be obtained from the unwanted event reports (RUH). The number of maintenance actions is the sum of the total major preventive and corrective actions, obtained from the system parameters.

By combination of the total actions performed and the number of injuries and damages of the system due to breakdown, the frequency of accidents can be calculated. The risk can then be calculated by consequence*frequency. The risk has to be evaluated subjectively by the end-user.

3.3 Dependability modelling: An idealized approach

The first maintenance program is based on design criteria for the system and most likely a RCM analysis before the system was put into operations. System data and history is, ideally, collected during operations and can be used for a re-optimizing of the maintenance program or interval, as described in chapter 1.3.

Given the set of parameters and assuming that all of them are available, it would be possible to establish the much-desired pdf for any system based on the historical data about the system. It would be a time consuming process, but in practice a program could be programmed for determining the shape of the pdf and integration of the survivability function R(t). Then by minimizing the unit economic cost function from section 1.2.1.1

$$UEC(t_p) = \frac{EC(t_p)}{EL(t_p)} = \frac{c_p R(t_p) + c_c F(t_p)}{\int_0^{t_p} R(t)dt}$$

the new ideal t_p can be determined. Where t_p now is determined on operational history rather than design criterions. Cp and C_c was derived in chapter 3.2.

Based on the new t_p, the future availability can be calculated. Based on this availability it is possible to determine the NPV of the new maintenance strategy. The increased availability will reduce the downtime costs, which will be a benefit and the, assumingly, increased amount of preventive maintenance cost will be a “penalty” cost. The net present value of the new strategy can then be simply calculated by:

$$P_{new\ strategy} = \left(\Delta A * Dayrate - C_{ipma}\right) * \left[\frac{1 - e^{-P_{rl} * n}}{e^r - 1}\right]$$

Where P is the present value of the new strategy, ΔA = A_{new} – A_{old} the increase in availability and C_{ipma} is the cost due to increased preventive maintenance actions. S_{RL} is the remaining life of the system, which is the same as the life of the plant and r is the annual discount.

The new spares cost can now be calculated by $t_{p,new}$ and the cost of a single spare. From 1.3.4 the new spares demand will be:

$$\bar{N}_{tp_{new}} = \frac{t}{MTBM} = \frac{t}{\int_0^{tp_{new}} R(t)dt} = \lambda_T * t_{p_{new}}$$

The new spares demand cost can now be calculated in a life cycle perspective:

$$TC_{spares_{new}} = \left(\lambda_T * t_{p_{new}} * C_{spare}\right) * \left[\frac{1 - e^{-P_{rl} * n}}{e^r - 1}\right]$$

Where TC is total cost of spares given a new interval. The net savings, given an increased maintenance interval will then be:

$$NSS = TC_{spares_{old}} - TC_{spares_{new}}$$

where NSS is the Net Saving Spares for the life cycle of the system. $TC_{spares,\ old}$ is obtained by the same procedure as the new spares demand cost, using the old maintenance interval.

The program could also include calculation of the mean residual life,

$$MRL(t_0) = \int_0^\infty R(t|t_0)dt$$

where it is given that we have survived up to t_0, t_0 could be substituted with O_t from section 3.2.2 and by doing so we would know exactly where on pdf the system is today – or in other words how much potential survivability "we have left". Based on this survival probability and the consequences of not surviving its possible to estimate whether it is best to perform an upcoming preventive maintenance task or if it is worth delaying it. It would be easy to estimate how well the system would survive another 100, 500 etc. hours of operation.

The establishment of a total solution for the model is not fully completed, and nor will it be. This is because the current approach is too idealized and hard to complete in practice. The model is based on the assumption that a probability density function can be obtained which is far from easy in practice. The approach described so far will hence be rejected as it deals with The Resnikoff Conundrum, or the ultimate contradiction.

In short the ultimate contradiction can be summarized as [5]: *Successful preventive maintenance entails preventing the collection of the historical data which we think we need in order to decide what preventive maintenance we ought to be doing.*

This applies directly to the obtaining of the much sought-after probability density function. The histories the pdf must be based upon simply don't exist. Hence a new approach will be established, and as most of the parameters still are valid they can be used. Result compilation for this approach will not be performed.

4. Model development: A practical approach

Basing the model on a pdf and deciding the optimal intervals by a theoretical approach was an assumption made in 3.1 which proves to be difficult in practice. The model still seeks to achieve the same goals as described in 3.1 but now it will exclude the pdf-based approach. Doing this, will lead to a more soft and subjective model.

The following further assumptions will now be made:

- The system of interest is part of the production line and when failed it will induce downtime.
- An extensive RCM analysis has been performed for the system before use in operation, and a preventive maintenance program is preventing the potential critical failures. The current maintenance intervals are known.
- Minor and medium system failures, which might have been neglected in the RCM analysis (due to low criticality), can in some cases lead to system breakdown that will cause downtime.
- The production line is in series and mainly consisting of; draw work, top drive, pipe handling arm, iron roughneck, pipe shuttle, gantry crane and mud system.

In the first modelling attempt, the focus was on major overhauls of the system. In this model the focus will be on the minor and medium errors, which have been allowed to occur and that are dealt with in the daily operations.

The operational plant availability is continuously monitored and can be used as a key performance indicator in this model. The system availability can be calculated relatively easy by investigation of the maintenance history of the system, of course given that the downtime, when repair is needed, is recorded.

4.1 Parameters

As mentioned, some of the parameters in the tables through chapter 3.2 can be of use in this model, and will be referred to with same indexes. This approach will attempt to investigate the costs due to unavailability, so some new parameters are necessary to define with respect to availability, along with some of the former availability parameters.

Parameter	Index	Description	Formula	Unit
Plant Availability	A_{plant}	Operational availability of the plant.	(-) KPI, measured $A_{plant} = A_{sys,1} *..A_{sys,n}$	%
Plant Unavailability	U_{plant}	Unavailability of the plant.	$U_{plant} = 1 - A_{plant}$	%
System availability	A_{sys}	Total availability of the system	$A_{sys} = \frac{T_{operations}}{T_{operations} + T_{down}}$	(-)
System Unavailability	U_{stys}	Unavailability due to system being down	$U_{sys} = 1 - A_{sys}$	(-)
Number of components in series	n_{comp}	The number of components in the production line	(-)	(-)
Average system availability	$\bar{A}_{sys}$	Average availability required for each system in the production serie	$\bar{A}_{sys} = \sqrt[n]{A_{plant}}$	%
New system availability	$A_{n,sys}$	New availability of system due to a new maintenance strategy	(-) Evaluate history of system after implementation of the new strategy	%
Minimum availability due to strategy expenses	$A_{sys,\ min}$	The minimum required new availability to cover expenses of implementing a new strategy		
Cost new strategy	C_{ns}	The estimated cost of a new strategy, preventive or inspection costs	(-) Estimate from operations manager and/or	

Table 6 Parameters for the practical approach

4.2 A simple availability-based life cycle cost model

Deriving the plant unavailability might be a time consuming process as it ideally should be unavailability due to system failures and hence exclude downtime due to other errors in operations. Given that this parameter is available it is possible to calculate the average loss due to plant unavailability per year:

$$L_u = U_{plant} * dayrate * 365$$

The unavailability loss can also be viewed as a potential benefit in terms of income by providing better maintenance routines. An operational availability of 0,95 and a dayrate of 300 000 USD would provide a loss approximately 5.5 millon USD. Or – it can be the potential income if it is possible to increase the availabilty.

A production line might consist of n number of systems, some in series and some might be in parallel. The assumption concerning the number of systems in this case is n=7, all assumed to be in series. For components in series the availability A can be calculated as:

$$A_{plant} \approx A_{sys1} * A_{sys\,2} * \dots * A_{sys\,n}$$

The average system availability can then be calculated to be:

$$\bar{A}_{sys} = \sqrt[n]{A_{plant}}$$

Where n is the number of components in the series. By obtaining the availability of the individual components in the series, and comparing it with the average system availability, it is possible to identify which of the systems that are the main contributors to downtime:

$$\bar{A}_{sys}\begin{cases} > A_{sys,i}, the\ system\ contributes\ to\ downtime \\ < A_{sys,i}, system\ not\ a\ main\ contributor\ to\ downtime \end{cases}$$

These systems can then be re-evaluated in terms of maintenance scheduling to prevent the corresponding failure modes.

The corresponding failure modes (minor and medium) can be categorized and if there are one or more types of failures that tend to occur more frequently a preventive maintenance interval or inspection interval can be established. If there is possible to identify any trends of the frequency of these failures, this can be taken into account when establishing a new strategy.

The cost of this strategy will depend on the cost of new equipment, inspection time and whether inspection requires a stop in the production line (operations) or not, substitution of spares more frequently etc. The operations technicians and the operations manager are probably the best source for providing estimations of cost of tools and equipment, along with their subjective view regarding how the new strategy can implemented in an effective manner.

Once the cost for new strategy, preventive or inspection, are estimated, the increased annual costs due to more maintenance actions can be calculated as:

$$C_{ans} = C_{ns} * n_{ya}$$

Where C_{ans} is the annual cost of the new strategy, C_{ns} is the cost of the new strategy, and n_{ya} is the number of yearly actions. When the costs are known it is possible to calculate the necessary new availability of the system to cover the extra costs it is provided. The same applies for the return on this "investment". It is possible to calculate the necessary availability i.e. 100% return on the "investment" per year. Once these yearly values are known, the present value for any of the variables can be calculated by the use of equation 1.3.4.2.

On the other hand, if a system can be excluded as a contributor to reduced plant availability, it will still be difficult to determine whether the system is being over-maintained or not. The model does not provide any information about the current time interval and the accuracy of this interval; it merely provides some indications about which of the systems that should be subject to more maintenance.

4.2.1 Example

Lets assume a fifteen-year-old drilling rig, designed for 30 years of operation, which has a daily rate of 2.000.000 NOK and an average operational availability of 0,95. The Iron rough neck is suspected to be a contributor to downtime and will be investigated. The number of components on the topside of the production line are 6; a gantry crane, a pipeshuttle, pipe handling tool, the draw-work, the top-drive and the iron roughneck. The annual interest rate is 5%. The availability of the roughneck was investigated and found to be 0,99. The rig manager and the maintenance supervisors decides to investigate a potential strategy, estimated to cost 300.000 NOK per action. This action is performed quarterly.

By use of the model, calculations of the availability of the iron roughneck, and calculations by an EXCEL spread sheet, the following results are obtained in table 7:

Parameter	Index	Result	Unit
Average system availabilty	$A_{sys,avg}$	0,992699168	[-]
Estimated unavailabilty	U_{sys}	0,01	[-]
Average unavailabilty in hours	$U_{sys,h}$	87,6	[Hours/year]
Loss due to unavailabilty	L_u	7300000	[NOK/year]
Annual cost new strategy	C_{ans}	1200000	[NOK/year]
Minimum Availabilty to cover costs of new strategy	$A_{min,ns}$	0,991643836	[-]
Required availabilty for 100% return on investment	$A_{100\%}$	0,993287671	[-]
Allowed unavailabilty for 100% return on investment	U_{all}	58,8	[Hours/year]
Increase uptime, hours pr year	T_i	28,8	[Hours/year]
Percent reduced unavailability	$T_{i,\%}$	32,87671233	%
Life cycle cost estimations			
Remaining life of plant	T_{rl}	15	[years]
Life cycle loss due to unavailability	$L_{lc\text{-}loss}$	75,1246694	[mNOK]
Life cycle cost new strategy	$C_{lc\text{-}ns}$	12,34926072	[mNOK]
Life cycle profit|100% return on new strategy	$P_{lc\text{-}ns}$	12,34926072	[mNOK]
Life cycle loss|100% return on new strategy	$L_{lc\text{-}\mid 100\%}$	62,77540868	[mNOK]
Life cycle loss unavailability|100% return new strategy	$L_{u\text{-}lc\text{-}\mid 100\%}$	50,42614795	[mNOK]

Table 7 Life cycle cost calculations for an illustrated example

The example shows that the availability must be reduced with approximately 33% in order to obtain a 100% return on the new strategy. In hours this means that instead of 88 hours downtime per year, the system can now only be down approximately 59 hours per year. The rig manager and the maintenance supervisor should evaluate whether a 29 hours per year reduction of the unavailability is likely. They are the ones that know the systems best and in the end are to make the decision.

The challenge is how we can know if the strategy provides a reduction in unavailability. Most likely it will take a few years, probably around 3-5, before the system can be re-evaluated and ideally show signs of better availability.

4.3 A subjective approach to obtaining the mean residual life

The problem with mean residual life is that also this is calculated based on the probability density function for the system or the equipment subject to investigation. A subjective approach for obtaining the MRL will be presented in this section. It should be mentioned that this procedure is merely a suggested approach and the potential pitfalls will be discussed later.

The reason why the MRL is important for systems and components in an operational aspect is, given that the necessary information needed is available, that it gives the operator a choice when it comes to delaying an upcoming preventive maintenance action for the system at hand. Situations where the system needs overhaul while being in middle of an operation might occur. By deciding the MRL of the systems and the potential consequences for system breakdown while in operations, it is possible in theory to calculate our odds for success and base the decision on this. This is easier to visualize by a very simple example:

Lets say there is about 100 hours of operation before a well is completed and there is an upcoming preventive maintenance action for one of the systems which is needed in order to be able to complete the well. Once the well is completed the operator has a day to prepare for the next upcoming operation. The action should ideally be performed within 50 hours and takes 10 hours to perform. The question to answer is whether the operator should stop the operation, prepare and perform the maintenance action and accept 10 hours of downtime, or postpone the PM-action to after well completion and execute a downtime-free maintenance action.

By calculation of MRL the operator´s odds for success (given that he or she choose to postpone the action) is calculated and weighed against the potential risk, or cost, if the system breaks down unexpectedly during the last phase of operations.

In practice the operator is unlikely to possess the probability density function for the system or the component that is subject to an upcoming maintenance action so an alternative approach is needed.

4.3.1 Assumptions related to MRL

The following assumptions will be made for the approach:

- The system or component subject to investigation has been running for a certain amount of time, so the running-in errors will not occur or they are very unlikely, and hence negligible.
- The probability density function is unknown, but it is assumed that the components are subject to wear out. Hence it might be possible to describe the pdf for the component by a Weibull distribution.
- Preventive maintenance actions are performed at certain intervals, the length of this interval is known.
- The preventive maintenance actions are performed before the system or component enters the wear out phase, but how much time left before entering the wear-out phase is unknown. In other words, the tail of the pdf is unknown but the system is still in the approximately “constant-failure” region.
- System or component history is available from database, where the TCI of old substituted parts (due to preventive maintenance) has been stored along with how many corrective replacements (if any) that have been performed.

4.3.2 Parameters

Parameter	Index	Description	Formula	Unit
Number preventive component substitutions	n_{sc}	The total number of components that have been substituted due to preventive maintenance	(-)	[-]
Number of corrective actions	n_{cc}	The total number of corrective maintenance actions due to component failure before reaching PM interval	(-)	[-]
Preventive maintenance interval	T_{PMI}	Length of the preventive maintenance interval	(-)	[Hours]
Technical condition of substituted parts	TCI_{old}	The subjective evaluation of the technical condition of a component substituted due to PM	(-)	%
Average technical condition	TCI_{avg}	The average TCI of components substituted due to PM	$TCI_{avg} = \frac{\sum_0^{n_{sc}} TCI_{old,i}}{n_{sc}}$	%
Corrective and preventive time to repair	$T_{RC,}$ T_{RP}	The average time to repair/replace a component. Corrective and preventive	(-)	[Hours]
Real operational hours	O_t	The real operational hours of the system, excluding standby and plant downtime. Real operation time of the system.	Formula 3.3	[Hours]
Subjective evaluation of wear out phase	T_{WR}	Experts subjective view of the component behaviour when entering wear-out	(-)	[Hours]
Remaining operational time	T_{RO}	The time until the operations are estimated to be finished	(-)	[Hours]
Consequence of postponing PM action	C_{PA}	Assumed to be a cost	(-)	[NOK]

Table 8 Parameters for obtaining Mean Residual Life

Most of the parameters listed are considered to be self-explained or sufficiently described in the table above. However the subjective evaluation of the wear out phase need some extra explaining. This is performed in the first part of 4.3.3

4.3.3 Dependability modelling, a subjective approach for obtaining MRL

In theory the wear out phase can be described by a pdf, but in practice a different approach might be more suitable for deciding this phase. The suggestion is to map a subjective evaluation of the component in order to decide how long it might have left. This evaluation is supposed to be carried out by the personnel that have most expertise and experience about the system and the component that is subject to substitution.

4.3.3.1 Subjective determination of the wear out phase

The maintenance supervisor and the rig mechanics are probably the best source for information about technical condition of components. They could decide what they *think* is a likely for a wear out phase for the component. For instance the wear out phase could be divided into six wear out phases with different intervals:

Wear out phase	Length of interval
Very short	0 < wear out < 10 [Hours]
Short	10 < wear out < 50 [Hours]
Medium short	50 < wear out < 150 [Hours]
Medium	150 < wear out < 300 [Hours]
Medium long	300 < wear out < 500 [Hours]
Long	500 < [Hours]

Table 9 Subjective evaluation of wear out phases

A general, or simplified way to calculate the expected subjective wear out value [Hours] can be done by the following equation [21]:

$$E(T) = \frac{ya + 4zb + xc}{y + 4z + x}, i.e\ for\ y = 1, z = 1\ and\ x = 1\ \ we\ get\ E(T) = \frac{a + 4b + c}{6}$$

where a is the pessimistic value, c is the optimistic value and b is the most likely value. X, y and z is the number of times a, b and c occurs. The variance can be calculated as:

$$Var(T) = \frac{(c - a)^2}{(y + 4z + x)^2}$$

By doing this approach it is possible to obtain a subjective expected value for the wear out phase based on the expert opinions. Note that this is not an estimation of how long the component is assumed to live, it is the wear-out phase only. The next step is to estimate at what TCI% the wear-out phase begins.

4.3.3.2 Subjective determination of time left to wear out

Assume the average historical technical condition of component is 70 % when they are being substituted. The question now is how long time in hours, or at what % technical condition, can we assume that the wear out phase will begin? This can be better visualized by figure 9:

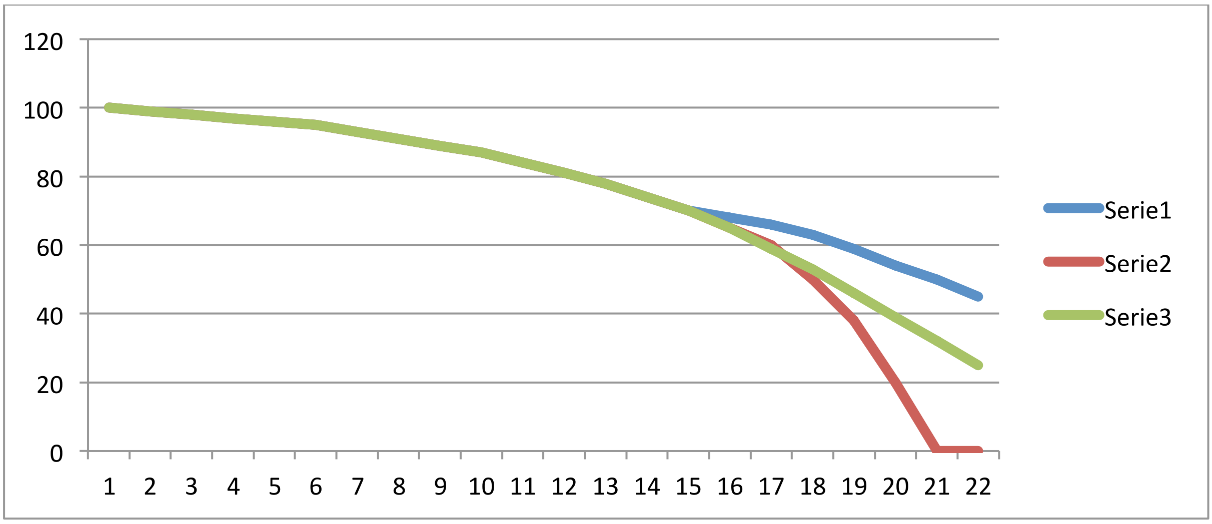

Figure 9 Various wear out function

The figure visualizes how the technical condition index (Y-axis) can vary for three different wear out series along the mythical time units (X-axis). For x= 14 the TCI = 70%. This is when components usually are being substituted, which means the preventive maintenance interval has been reached. In this scenario we are to exploit the preventive maintenance interval as a result of an opportunity to perform the maintenance action without inducing downtime, when the current operation is finished. The 1st and 3rd series does never reach the wear out phase in this figure. As for the 2nd series the wear-out phase is seen to begin when the component TCI is roughly below 40. Prediction of the last phase that the component will be about to enter will be performed by the aid of the experts.

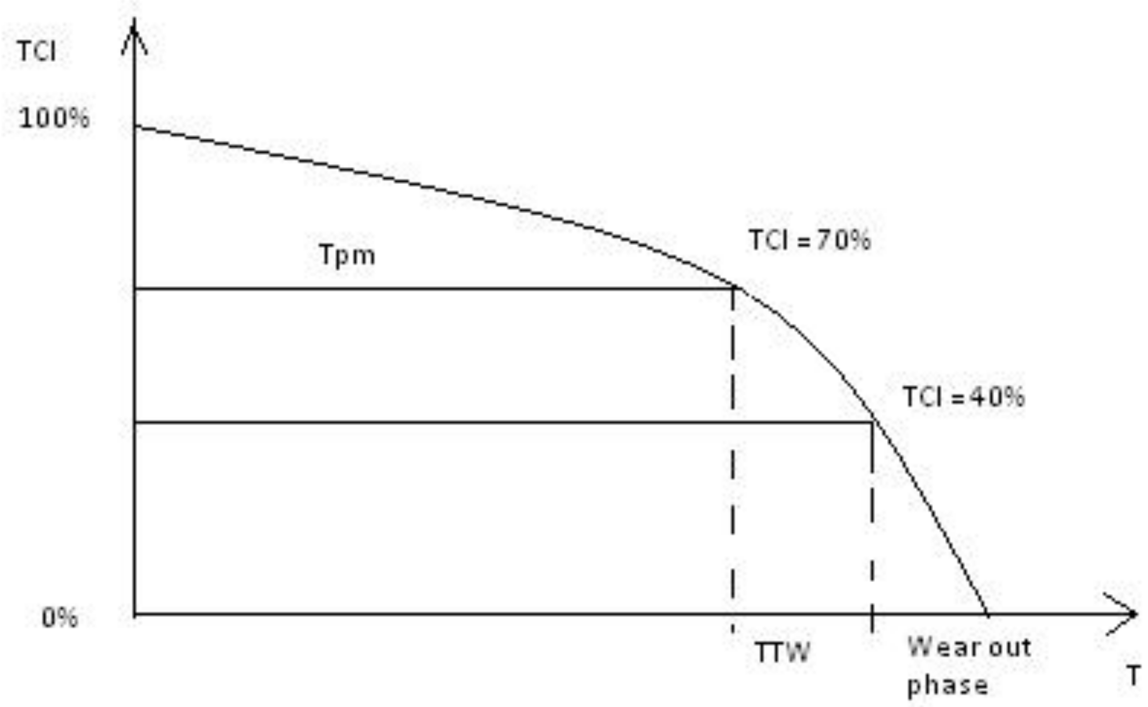

Figure 10 Determination of Time To Wear

In figure 10 the average TCI for substituted components are 70% when T_{pm} is reached. Time to wear-out phase (TTW) is the time it takes for the component to degrade to (in this illustrated example) 40%, where the actual wear-out phase begins. The latter has been identified in 4.3.3.1.

The challenge is to decide how long the component can run before it reaches the wear-out point, an unknown % TC, where the wear-out phase will begin. Again the need of the expert opinions are necessary, in order to make an estimate for when the wear out phase will begin.

When T_{pm} is known, the length of the wear out phase, and where the where out phase is assumed to begin is known, the last unknown is the TTW. This value can be found by regression analysis or by a subjective evaluation performed by the experts. In general the TTW should be shorter than T_{pm} and most likely longer than the wear out phase.

The MRL can then be established as:

$$MRL = TTW + T_{wop}$$

A general criterion is that the time of the remaining operation (T_{RO}) must be shorter than the MRL. It is very difficult to define the chance for success in terms of % by this approach. Other values should be taken into account, such as the load factor of the component during the last phase of the operation. Another interesting relationship is the T_{RO}/TTW. This ratio can give an indication of how close the operation is to reach the point where the wear-out phase is assumed to begin.

5. Discussion

This chapter will be divided in several subtopics in attempt to keep the discussion more organized and to maintain a better overview for the various topics.

5.1 Theory

The theory section contains a brief overview about the basics of maintenance optimisation and was also an attempt to map the literature about life cycle costing /theory. This part was supposed to be a short overview of what was found.

It should be recognized that the literature survey was not performed as a project thesis (which is considered fairly common) before the work with the master thesis started. It was a time consuming process and something that reduced the time to bury oneself in the model development. As of this I would recommend others to continue to build on their project thesis. As for this thesis, it is recognized that the literature survey and the mapping of the demands/requirements from Odfjell Drilling could have been an appropriate work scope for a project thesis.

A major challenge when performing the literature survey was that it was so hard to find proper and relevant life cycle management theory. Finding comprehensive theoretical maintenance optimisation models in reliability-theory was, on the other hand, rather easy.

5.1.1 Reliability based models

Among some of the theoretical reliability based models that were found was Borgonovo, Marseguerra and Zio (1999), who published *Monte Carlo methodological approach to model plant availability with maintenance, aging and obsolescence* [22]. Tsai, Liu and Lio (2011) published an article named *optimal maintenance time for imperfect maintenance actions on repairable product* [23]. Other extensive models have also been found, but there is a problem with the applicability of all of these models in practice.

The way I see it, these articles might be an integral part of some Ph.D thesis and might be difficult to implement in todays way of performing maintenance management. They are brilliant in theory and provide useful information there, but in practice they face several limitations.

First of all they are (all) built on a probability density function as a foundation for the analysis. A common approach is to use the Weibull distribution and evaluate the input variables based on this curve. Describing a system with a Weibull distribution and then assuming that this describes all the potential failure modes is a serious simplification, at least for a system that consists of several components. On a component level this might be an ok assumption but in my opinion it should be used with care. A system consists of several components, where all of them have a different, unique, PDF. They should ideally be evaluated on a component-level, but this would be very time consuming in practice.

Secondly it is difficult to obtain the PDF in practice. In theory the PDF is “obtained” and based on historical data and the PDF is adapted to these data. However, in practice, these histories are prevented to become visible by the fact that preventive maintenance is performed. When the history become available it means that the maintenance program has failed. In addition, the history must be prevented to become available due to the fact that a major breakdown might cause consequences that are unacceptable for the safety of the personnel and other systems. Reliability engineering deals with *the ultimate contradiction, The Resnikoff Conundrum (1978)* [5]:

> *"The acquisition of the information thought to be most needed by maintenance policy designers – information about critical failures – is in principle unacceptable and is evidence of the failure of the maintenance program. This is because critical failures entail potential (in some cases, certain) loss of life,* ***but there is no rate of loss of life which is acceptable to (any) organization as the price of failure information to be used for redesigning a maintenance policy****. Thus the maintenance policy designers is faced with the problem of creating a maintenance system for which the expected loss of life will be less than one over the planned operational lifetime of the asset. This means that, both in practice and in principle, the policy must be designed without using experiential data which will arise from the failures which the policy is meant to avoid."*

Nowlan and Heap makes further comments on the topic [5]:

> *"The development of an age-reliability relationship, as expressed by a curve representing the conditional probability of failure, requires a considerable amount of data. When the failure is one which has serious consequences, this body of data will not exist, since preventive measures must of necessity be taken after the first failure. Thus actuarial analysis cannot be used to establish the age limits of greatest concern – those necessary to protect operating safety."*

The ultimate contradiction is stated by Moubray [5]:

> *"that successful preventive maintenance entails preventing the collection of the historical data which we think we need in order to decide what preventive maintenance we ought to be doing."*

Even if the PDFs was obtained for several systems and were accurate, the approach with reliability theory is cumbersome. From my personal understanding, some companies - even those of significant size, do not necessarily have enough competent personnel to handle these models in terms of applying them into the daily operations. Especially if they are to identify PDFs, and perform analysis of every system and components.

The reason is, that the models are very theoretical and will provide difficult to use in practice, especially if the user do not have experience with obtaining probability functions, programing or program simulations. As for end users, who work with maintenance in practice rather than in theory, they might not have the program they would need in order to run the simulations. Obtaining the program and installing it is of course a quick fix, having the end users to understand and analyze the results is, however, not something that should be expected.

It might be possible to derive a program where the end user provide the necessary input data and the program could in theory be based upon heavy theory and be programmed to perform integration, minimization and plots of the results. However, the reliability models require that a PDF is obtained and used as an input. Obtaining the PDF for systems and for equipment is a time consuming process, and will be a necessity for running the simulation. This is recognized as a weakness with the models, because of the difficulty to obtain the PDF from a practical point of view. However once the PDFs are obtained the simulations are fairly straight forward, once the program code is in place.

In the model development chapter it was suggested to obtain the PDF based on experts opinions. Noortwijk, Dekker, Cooke, Mazzuchi, (1992)[23] published *Expert Judgment in Maintenance Optimization*, where they propose several methods for obtaining a PDF based on the experts opinions. Some of their methods could be combined with the article by Ma, Fan and Huang (1998) [24] who published *A subjective and objective integrated approach to determine attribute weights.* However most of the subjective methods for obtaining the PDFs are considered as complex, time consuming and also requires a computer tool in order to obtain the curves they are after. The point is that much of the theory is in place, the pitfall is the applicability in practice. Approaches that attempt to avoid the use of PDFs are available for use in maintenance programs and will be discussed later.

Another challenge with subjectivity as a tool for obtaining the PDF is that the Experts are located offshore, while the maintenance analysts are located onshore. This is not ideal when many PDFs must be established for a major system analysis. Tools for IT-communication are available as an aid to communication. However, the performance and efficiency is assumed to be higher if everyone was located in the same area, when a major optimization project is ongoing.

5.1.2 Life cycle management

The theory concerning maintenance life cycle management seems to be limited and was experienced as difficult to obtain. The models in the thesis suggest the use of data available from the database in the same procedure as suggested by Takata et.al [12], where old design parameters are substituted with new data from the operational phase – in an RCM manner. The first loop in figure 5 has a box, which includes inspection/monitoring and diagnosis. This is more applicable for condition based maintenance rather than reliability-based maintenance.

The reason why life cycle cost theory is regarded as limited is assumed to be due to the simplicity of the life cycle cost calculation. Once the yearly costs are obtained, the life cycle costing analysis is simple. From a maintenance point of view, the problem is to estimate the costs and not the calculation on how much that is saved or lost if a strategy is changed. The cost, however, are difficult to estimate due to the lack of data that are needed to optimize new intervals for maintenance task execution.

Another difficulty is to find out whether as system is subject to too much maintenance, if a system fails fairly often the evidence will be available from the database and it will be possible to develop a diagnosis for the system. However, if a system that is subject to preventive maintenance “never fails” the failure patterns are unavailable and hence it is very difficult to know how much longer the interval should be. If this interval can not be found, the reduction in costs can not be estimated as they are dependent on this interval.

5.1.3 Technical Condition Index

This index, or key performance indicator, is considered to be a valuable tool. It is put to its best use when used in a condition based maintenance strategy. Items that are substituted and given a subjective value on TCI can give an indication of how correct the maintenance interval is – given that the component is substituted at a fixed age or time. If the components that are substituted are "always" regarded as, or close to, being as good as new, then the interval at which they are substituted is probably too short. Re-evaluation of the interval can be performed by considering the operational load factor and comparing this with the max load factor. The latter is assumed to be the factor that was used to decide the first interval in the first place.

Subjective evaluation and inspection should be used with care. An example is that a crack development, in some cases, can be difficult to see unless the inspector knows exactly what he or she is looking for, and where to look. The use of technical condition indexes will be further discussed in the condition based maintenance section.

5.1.4 Mean Residual Life

The mean residual life is in theory based on the equation

$$MRL(t_0) = \int_{0}^{\infty} tf(t)dt$$

where f(t) is the probability density function. The difficulties with obtaining this have already been discussed. As a result of this, the same difficulty then must apply to MRL, as it depends on the PDF. If the MRL is needed because an upcoming maintenance action ideally should be postponed in order to reduce the costs, the experts need to evaluate the component. Inspection and checking the maintenance history of the component is recommended. If the component has a relative high average TCI when substituted, and the remaining time is fairly short compared to the normal running time of the component, then this probably indicate that it might be safe to continue operation and postpone the PM-action.

The potential benefits must be estimated as exactly as possible. The related consequences of failure must be evaluated closely and weighed against the benefit(s). Expert opinions are of major value. They might be able to answer questions like:

- Is the well put at risk?
- Are there components in the system that will be subject to secondary damage?
- Will failure induce longer repair time because the component might get stuck, or difficult to remove?

If there are no major consequences and the potential savings are high, postponement of the PM is probably justified. However this decision must be based on the expert opinions. As a precaution it will be suggested to prepare for a potential corrective action while in operation if the component should fail. This will reduce both the corrective repair time and downtime costs.

5.2 Odfjell Drilling´s demands and expectations

Odfjell Drilling are looking for a simple model that can estimate the technical condition in economical terms. They also want to model life cycle costing of optimal repair intervals when the maintenance strategy is changed. In addition they want the model to estimate the chance of success given that a component must survive over a given future operational interval.

Based on the information from OD and the description of their model it was assumed that the model was supposed to be derived and based upon reliability based theory. From this theory it is possible to optimize the maintenance interval based on operational data – where as these data was assumed to be available from the maintenance database. Once the necessary inputs had been identified it was assumed that it would be possible to derive a new ideal maintenance interval and hence change the strategy as OD expected.

The author will have to take critics for failing to realize that changing the strategy also could imply using another totally different approach, such as condition-based maintenance. The reason was that this was, considered, as an action that would lead to a drastic change on how today's maintenance actions are performed. This will however be discussed further later.

The importance of attempting to adjust maintenance strategies, or switch to a new and better approach, is considered as a professional decision by the company. It implies that they realize that they might have to adjust their approach in order to optimize and streamline their maintenance policies in an attempt to reduce the costs.

I do not believe that it is realistic to expect a single model to be able to tell us what to do in order to reduce the costs. This is because every system is considered to be unique and need to be evaluated individually. Every system will have its unique model. Input parameters can vary among different systems and if we were to describe all systems with one model, the model will be comprehensive and complex. Not simple and small, as expected. It is, however, worth to give this sort of research attention; models are not developed for future use unless they are being considered.

In this case I would put the approach of a simple model at rest.

5.3 Model Development

Two attempts have been made in order to obtain the model Odfjell Drilling expects. The first attempt was the theoretical approach based on Barlow & Hunters fixed age interval. That attempt was later rejected due to the significant struggle to obtain the necessary PDF. The main emphasis with the theoretical model was to include some of the advanced theories and models that are available from theory, in order to provide a more accurate repair interval. Given that the PDF is obtained, subjectively or theoretically, this model can be used to re-evaluate the repair interval.

Due to the fact that the failure history is prevented to become available as a result of preventive maintenance, the operational input parameters are hidden. This is a huge drawback with this model when put to use in practice. In some ways, the faith the author has had to the reliability theory has fallen into ruins as a result of the work with this thesis. Another approach to maintenance of systems is regarded as a necessity, preferably an approach independent of the reliability of the system. CBM arises as the best candidate to fill the void made by the reliability based approach.

The parameters will not be given much attention in this section as they are described through chapters 3-4. Most of the parameters that both models are based upon should be fairly easy to obtain from the maintenance database. They will mainly be subject to a review in section 5.4.

The safety parameters are the only parameters that prove difficult to analyse. The reason they are included is because the operator want to know how many injuries or unwanted events that has occurred when the system has been used, or been a subject to maintenance. They are difficult to evaluate because of the subjective estimation of the costs of injuries to personnel. If a system has a long history with accidents or “close calls”, it is recommended to evaluate the frequency of this and the cost related to the events. Comparing these values with an estimated cost of a redesigned or modified system can give an indication of whether it should be replaced or not.

The second model is an availability-based approach. This model does not provide the output that was expected from Odfjell Drilling, in terms of an ideal maintenance interval. The model is designed for analysis of single systems and is considered to be easier to apply in practice than the theoretical model.

The model aims to maintain a system overview by analysing the total production line. It is based on the assumption that all the major systems are placed in series and that all these systems has an individual availability. This assumption is however a major simplification and might prove to be incorrect in practice. When the average plant availability is known, the necessary average system availability can be calculated.

By performing an analysis of the individual systems in the production line where the main goal is to obtain the individual system availabilities, the results can be compared to the necessary average system availability. When this is done, the individual systems that appears to be the main contributors to downtime can be identified.

The next step is now to focus the attention on the systems that appears to be the weakest link(s) in the production line. It was assumed that an RCM analysis for these systems had been done, and that less critical failures was excluded in that analysis. Thus these failures have been “allowed” to occur and should ideally be available from the database in order to perform an investigation. By gathering information about the failures that occur and establishing the frequency (for the failures that appears more often) a diagnosis, or treatment, can be designed and evaluated.

The diagnosis must be established by the experts i.e. rig mechanics and maintenance supervisors. In addition to establishing the costs of the diagnosis the experts must also estimate the potential benefits of this diagnosis. By using the model it is possible to calculate the necessary increase in the system availability i.e. to maintain a 50%, 100% return on the invested effort to increase the system availability.

The model is limited to provide information about systems that are subject to an insufficient amount of maintenance. The strength with the approach is that it enables the users and operators to put their effort and focus into systems that are main contributors to downtime. The main idea is to make sure that the availability becomes as high as possible. When, or if, this is achieved, the next step should be to evaluate the systems that are suspected to be over-maintained.

Optimizing the systems that are over-maintained in terms of reducing the amount of maintenance will always be difficult because the preventive maintenance performed on the systems will not reveal the information needed to optimize them. The key to success is the expert opinions along with the historical TCI of the parts that are substituted due to maintenance. The use of subjective evaluation will induce a risk, because in this case we know for a fact that the system “delivers” in terms of availability.

Whether the system will continue its high availability or not, after extension of the preventive maintenance interval, will not be available for evaluation before the system has been running for a certain amount of time. The experts might be wrong, which might lead to applying an interval that is too long and the failure rate will increase, which will lead to a reduction in availability. Because of the time taken before a new analysis can be performed, there will always be the risk of increased costs due to an increase in downtime as a result of an overestimated interval length.

The model is meant to only serve as a tool, and does not provide accurate information alone on which a decision should be made upon. It should be used as an indicator , at best, and with care.

5.4 Condition based maintenance

Equipment and systems that deteriorate over time is most likely managed best by the use of a CBM strategy. This has not been investigated in the models through the thesis, but it has become more evident (to the author) that this strategy can offer more flexibility than the reliability-based approach. Implementation of a CBM-strategy does not mean that preventive and corrective maintenance actions are to be rejected. The best approach is a combination of the two.

Dialogs with maintenance engineers at Odfjell Drilling has revealed that the common approach to maintenance is the use of fixed intervals or fixed age. Rotating systems like turbines are likely to be subject to CBM already, but CBM can be implemented and used on smaller systems like pumps, pipes, bearings etc. Including a CBM-strategy to a greater extent is recommended. With the present technology the CBM offers various approaches to monitoring of systems and equipment. Jardine, Lin and Banjevic (2006) suggest the following categories for data monitoring [25]:

- *Value type*: Single value such as: Oil analysis data, temperature, pressure and humidity.
- *Waveform type*: Vibration and acoustic data.
- *Multidimensional type*: Image data from thermographs, X-ray Images, visual images.

A CBM-strategy will provide massive amounts of data over time. In order to be able to handle the data in a best possible manner it is recommended to establish a database where the data is stored. The use of technical condition index is valid and put to a better use in a CBM-environment. Use of continuous monitoring and trend analysis can reveal the behaviour of a component to a greater extent. Provided that the information is available it might be possible to use reliability theory to optimize the preventive intervals.

Thorstensen [8] includes the use of TCI in his Ph.D-thesis. He suggests a rather complex model based on trend analysis, Markov Decision Analysis and dynamic programing in order to obtain an ideal cost-efficient maintenance program. These analyses are based on the assumption that a database with massive amounts of data is available. Developing such a database and a program for trend analysis is costly, but the potential benefits and savings in the long run can make this a worthy investment. Once a program is developed it can be implemented on all of the rigs that are in Odfjell Drilling´s portfolio.

The users can´t base their decisions merely on the outputs from the program but it has the potential to be a helpful contributor to decision-making if implemented correctly. In addition, the users will know the current health of any monitored system and components. That will provide valuable information when it comes to opportunity-based maintenance. If an upcoming preventive maintenance action will induce downtime, the users can search the database for components that will be subject to replacement in near future. This offers flexibility in terms of planning and reduction of downtime costs, as more maintenance actions can be performed simultaneously when the plant is down.

Another major advantage that real-time CM can offer is the chance to shutdown systems before a component breaks down. If an old component drops below a pre-determined critical TCI-value an alarm can be activated. Ideally, this can give the operator a chance to shutdown the system and inspect it. The component that is about to fail can then be replaced before it reaches physical wear-out. This has the potential of saving other parts from breaking down in the system, if a chain-reaction was about to start. This can provide a reduction of both costs and use of spare parts.

The drawback with CBM is that some of the tools for measurements are costly. In addition, it is not possible to measure everything, so human inspection might be needed in some cases. This can induce some extra risk, as the human senses are not very accurate. Systems and equipment that cant´ be measured directly must be subject to a preventive maintenance plan.

For Odfjell Drilling´s case their current maintenance system does not support CBM in an effective manner. If they decide to implement an increased amount of CBM, they should also consider investing in an overhaul of their current database.

5.5 Test of the availability-based model

The model was supposed to be tested on a racking arm on a platform that is in Odfjell Drilling´s portfolio. As the model was supposed to be easier to use in practice, it was expected that the input parameters would be easy to obtain. However this was not the case; downtime-specific data is considered as sensitive information, and hence not obtainable. Other input parameters, such as system availability, is in practice impossible to obtain based on the data from the Maisy.

Dialogs with a person from Odfjell Drilling, revealed that a common approach is to assume 30% downtime for planned corrective actions and 100% downtime from unplanned corrective actions. The dataset available for this analysis does not have accurate information regarding the repair-time. The only available data was the number of man-hours and without the number of persons included in the actions it is difficult to estimate the downtime. Assuming that only one person was working alone would be a very weak assumption, and would only lead to the maximal downtime costs, not the real one.

Due to significant lack of data, there are no real results to discuss. A cost structure has been developed for the system, however as this is sensitive information this will be in a separate report.

As there are no real result compilations, it is impossible to accept, or reject, this model.

6. Conclusion

The objective in this thesis was to develop a life cycle cost model for Odfjell Drilling. The model was based on reliability theory, in order to estimate optimal intervals for overhaul, based on operational parameters. In practice, the reliability-based approach is considered to be cumbersome and time consuming. The theory is based on probability curves, which are difficult to obtain and predict in practice. This is a major disadvantage with the approach, and the reliability-theory itself. Further development of the reliability model was hence rejected.

An attempt to design a model that is more applicable in practice was performed. This is the availability-based model, which seeks to identify systems that are main contributors to downtime. The idea is to put the main emphasis on developing diagnosis for these systems and thus reduce the downtime related costs. Based on expert opinions, and their predictions of the benefits of the diagnosis, an estimation of the life cycle profit for the new diagnosis can be calculated.

The input parameters needed, for both models, proved difficult to obtain. Maisy, a maintenance database used by Odfjell Drilling, is recognized as a bottleneck for such analysis. The system lacks basic relevant information for this case study. The parameters could thus be subject to critique, but they are a necessity in both of the models. If these can not be obtained, nor can tests of the availability-based model be performed. Discussions, with personnel within the organisation, have revealed that Maisy is a considered to be a bottleneck for analysis of greater extent.

The author will have to take critique for not investigating CBM more detailed through this thesis. The basis for the model development was reliability-based theory, with RCM as a means of optimizing operational parameters, and hence calculate optimal life cycle costs. The problem definition mentions optimisation by a change in maintenance strategy. A new interval for maintenance task execution was interpreted as a change in maintenance strategy. A total different strategy such as CBM was hence not investigated detailed.

CBM, however, is recognised as a better strategy for maintenance in practice. It gives more flexibility to the users in terms of planning simultaneous activities, which will reduce the total costs. CBM is not the solution to all problems, but it should be used to a greater extent on components that can be subject to CM. A combination of CBM and fixed interval maintenance is probably the best solution.

Applying CBM to components of less significant importance than i.e. turbines is possible. However, as this will provide massive amounts of collected data, a new database would be required. In Odfjell Drilling´s case it is recognized that they are in need of a new and better database, in order to perform maintenance optimization more effectively. A recommendation to Odfjell Drilling is to consider a new database. That database could support use of CBM and TCI, and also provide necessary parameters that maintenance engineers need in order perform more accurate optimisation analysis.

7. Further Work

The availability-based model is subject to a serious oversimplification by assuming that all of the systems are in series. It will be necessary to develop a model that can include redundancy due to parallel systems.

Contract-specific downtime ratios that are shared between operator and contractor can also be included. At present this information is unavailable as it is sensitive information and is hence excluded.

The total rig availability, which is a key-parameter for the model, is also unavailable due to sensitivity. This must be obtained in order to perform the analysis.

If it is a system in a production line that the experts are certain to be a contributor to downtime this system should be selected for further investigation. Mapping downtime and failures related to the system must be performed, in order to establish a diagnosis for the system. The cost and the benefits of the treatment must be estimated and used as an input in the model.

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9. Appendix

Appendix 1:	Problem definition
Appendix 2:	Availability model for calculations
Appendix 3:	Separate report, analysis of sensitive data.

Appendix 1

Masteroppgave
for
Stud.Tech. Anders Ilstad Lenning
Vår 2011

Livssyklusmodell med fokus på økonomisk vurdering av utskifting/endret vedlikeholdsstrategi for systemer og utstyr.

(Life cycle model for economical evaluation of replacement/improved maintenance strategy for systems and equipment.)

Systemer og utstyr degraderes i operasjon. Dette kan resultere i øket driftskostnad (vedlikeholdskostnad, energiforbruk, øket nedetid, redusert effektivitet, redusert sikkerhet, øket forurensingsrisiko, etc.).
Å ha oversikt og kontroll med denne degraderingen er en viktig del av "Ageing Management". Aldring i denne forbindelse kan deles i to kategorier:

1. Fysisk aldring: Aldring og degradering p.g.a fysiske eller andre prosesser.
2. Ikke fysisk aldring: Systemet eller utstyret er utdatert p.g.a. ny/forbedret teknologi eller endrede operasjonsforhold.

Denne masteroppgaven skal fokusere på den første kategorien, og modell for å kunne vurdere/beregne optimalt utskiftingstidspunkt samt estimere forlenget levetid (restlevetid) ved endret vedlikeholdsstrategi. Modellen skal bl.a. gi et estimat av teknisk tilstand av systemet/utstyret.
Odfjell Drilling ønsker å utvikle en slik modell for eget utstyr og for eventuell rådgiving til feltoperatører for deres utstyr. Modellen skal være så enkel som mulig innenfor akseptable nøyaktighetsgrenser, og i hovedsak bygge på informasjon fra Odfells personell på installasjonene og fra relevant informasjon fra operasjons- og vedlikeholdssystemene.
Masteroppgaven skal derfor inkludere følgende:

1. Litteraturstudie. Kartlegge livssyklusmodeller gitt i litteraturen for dette beskrevne formål. Beskrive kort hvilken teori og informasjon modellene bygger på.
2. Kartlegge Odfjell Drillings ønsker og mer detaljert målsetning med en livssyklusmodell for systemer og utstyr. Bl.a. påpeker rederiet at det er viktig at modellen estimerer teknisk tilstand i økonomiske termer, og er så enkel som mulig i bruk.
3. Med bakgrunn i pkt. 1 og 2 tilordne en modell for livssyklusberegninger for optimal utskiftningstidspunkt og også forlenget levetid ved endret vedlikeholdsstrategi. En viktig del av utviklingen av en slik modell er identifisering av tilgjengelige parametre og utvelgelse av hvilke kriterier som legges til grunn for modellen.

4. Ettersom modellen bl.a. skal baseres på delvis subjektiv informasjon fra personell på installasjonene, skal det foreslås et opplegg hvor denne informasjonen blir mer objektiv og vurdert ut fra enhetlige retningslinjer (bl.a. en gradering 0-100 av teknisk tilstand. En estimering av levetid for eksempel prosent sannsynlighet for å overleve 100 timer, 500 timer, etc.).
5. Synliggjøre/teste modellen for et system/utstyr valgt ut i samarbeid med Odfjell Drilling. I denne sammenheng skal nøyaktigheter vurderes basert på den tilgjengelige informasjon/datatilfang som foreligger. Denne testingen må anonymiseres slik at tall/navn ikke kan spores tilbake. Hvis dette ikke er mulig, skal dette punktet rapporteres i en egen fortrolig separat rapport som er vedlegg til hovedrapporten.

Oppgaven utføres i nært samarbeid med Odfjell Drilling med Hege Mjaatvedt Bjørge som kontaktperson..

Besvarelsen redigeres mest mulig som en forskningsrapport med resymé, konklusjon, litteraturliste, innholdsfortegnelse, etc. Alle kilder skal dokumenteres. For bøker og tidsskrifter skal forfatter, tittel, år, sidenr. og eventuelt figurnr. oppgis. Ved utarbeidelse av besvarelsen skal kandidaten legge vekt på å gjøre teksten oversiktelig og velskrevet. Med henblikk på lesing av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktelig måte, og diskuteres utførlig.

Arbeidet er som oftest ledd i en større undersøkelsesrekke ved instituttet, som forbeholder seg adgang til å benytte alle resultater i hovedoppgaven i forbindelse med eventuell undervisning, publikasjoner eller annen virksomhet.

Besvarelsen leveres i 3 eksemplarer. Et av eksemplarene leveres av kandidaten til Odjell Drilling. En fullstendig kopi av rapporten skal også leveres instituttet i form av en CD-ROM i Word-format.

Oppgaven utlevert: 17. januar 2011
Oppgaven innleveres: 14. juni 2011
Oppgaven innlevert:

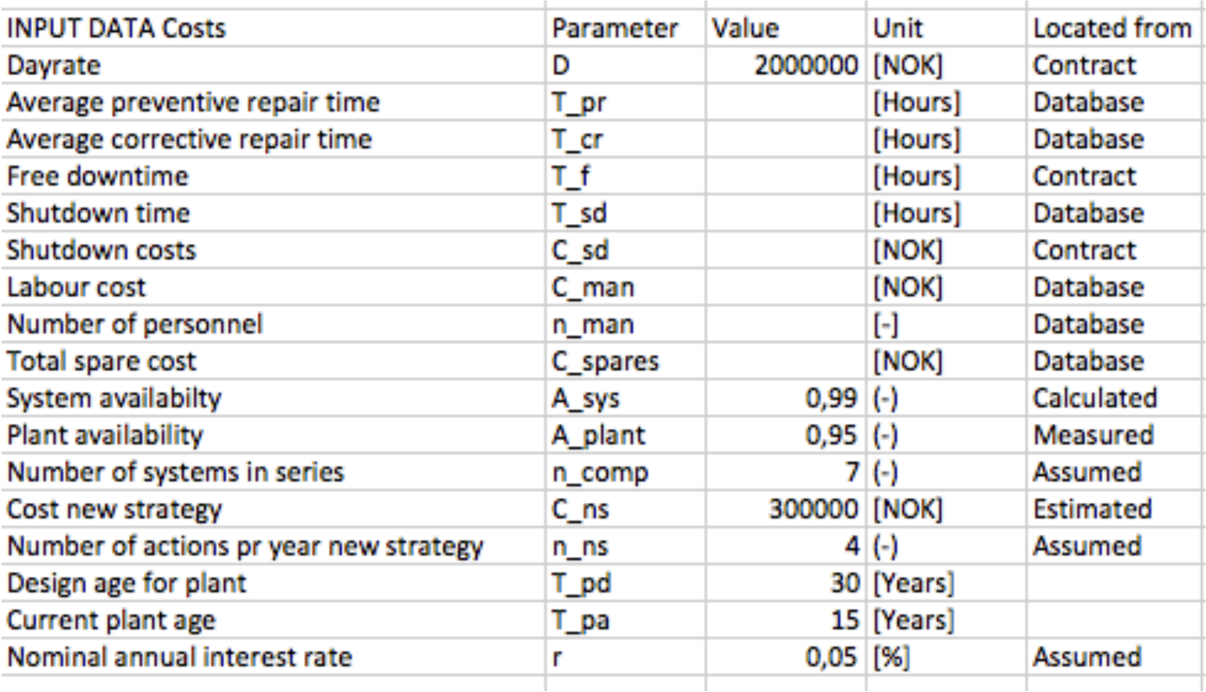
Trondheim 12.januar 2011

Magnus Rasmussen

Professor

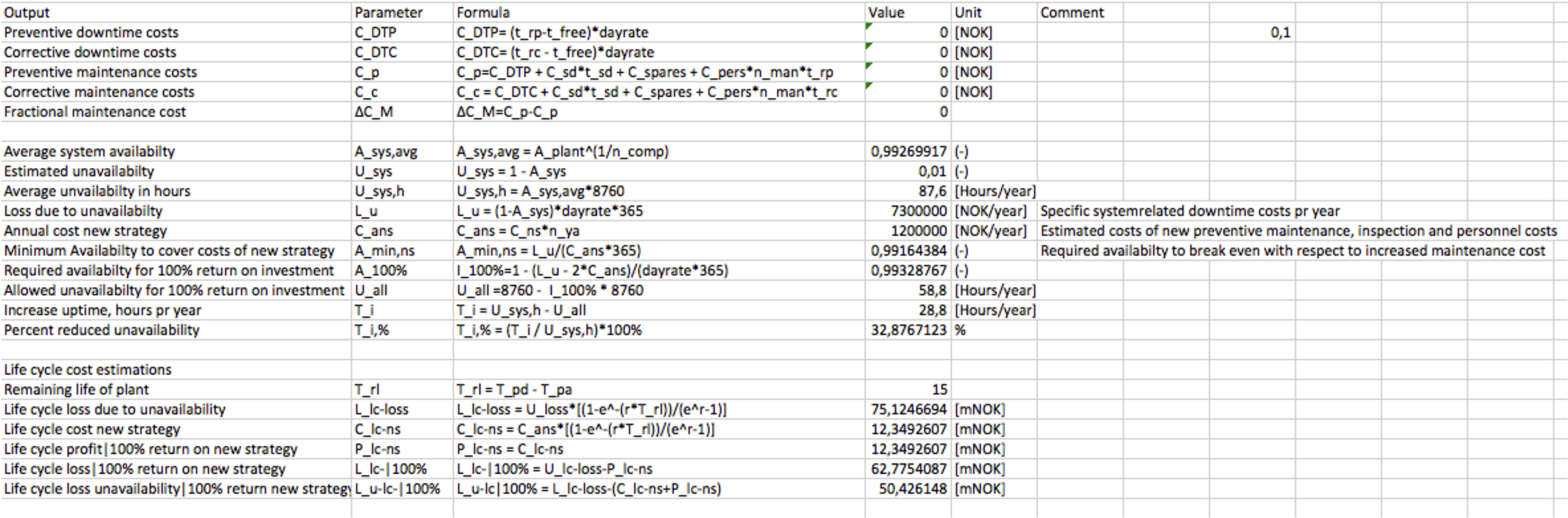
Appendix 2

Input:



INPUT DATA Costs	Parameter	Value	Unit	Located from
Dayrate	D	2000000	[NOK]	Contract
Average preventive repair time	T_pr		[Hours]	Database
Average corrective repair time	T_cr		[Hours]	Database
Free downtime	T_f		[Hours]	Contract
Shutdown time	T_sd		[Hours]	Database
Shutdown costs	C_sd		[NOK]	Contract
Labour cost	C_man		[NOK]	Database
Number of personnel	n_man		[-]	Database
Total spare cost	C_spares		[NOK]	Database
System availabilty	A_sys	0,99	(-)	Calculated
Plant availability	A_plant	0,95	(-)	Measured
Number of systems in series	n_comp	7	(-)	Assumed
Cost new strategy	C_ns	300000	[NOK]	Estimated
Number of actions pr year new strategy	n_ns	4	(-)	Assumed
Design age for plant	T_pd	30	[Years]	
Current plant age	T_pa	15	[Years]	
Nominal annual interest rate	r	0,05	[%]	Assumed

Output



Output	Parameter	Formula	Value	Unit	Comment		
Preventive downtime costs	C_DTP	C_DTP= (t_rp-t_free)*dayrate	0	[NOK]			0,1
Corrective downtime costs	C_DTC	C_DTC= (t_rc - t_free)*dayrate	0	[NOK]			
Preventive maintenance costs	C_p	C_p=C_DTP + C_sd*t_sd + C_spares + C_pers*n_man*t_rp	0	[NOK]			
Corrective maintenance costs	C_c	C_c = C_DTC + C_sd*t_sd + C_spares + C_pers*n_man*t_rc	0	[NOK]			
Fractional maintenance cost	ΔC_M	ΔC_M=C_p-C_p	0				
Average system availabilty	A_sys,avg	A_sys,avg = A_plant^(1/n_comp)	0,99269917	(-)			
Estimated unavailabilty	U_sys	U_sys = 1 - A_sys	0,01	(-)			
Average unvailabilty in hours	U_sys,h	U_sys,h = A_sys,avg*8760	87,6	[Hours/year]			
Loss due to unavailabilty	L_u	L_u = (1-A_sys)*dayrate*365	7300000	[NOK/year]	Specific systemrelated downtime costs pr year		
Annual cost new strategy	C_ans	C_ans = C_ns*n_ya	1200000	[NOK/year]	Estimated costs of new preventive maintenance, inspection and personnel costs		
Minimum Availabilty to cover costs of new strategy	A_min,ns	A_min,ns = L_u/(C_ans*365)	0,99164384	(-)	Required availabilty to break even with respect to increased maintenance cost		
Required availabilty for 100% return on investment	A_100%	I_100%=1 - (L_u - 2*C_ans)/(dayrate*365)	0,99328767	(-)			
Allowed unavailabilty for 100% return on investment	U_all	U_all =8760 - I_100% * 8760	58,8	[Hours/year]			
Increase uptime, hours pr year	T_i	T_i = U_sys,h - U_all	28,8	[Hours/year]			
Percent reduced unavailability	T_i,%	T_i,% = (T_i / U_sys,h)*100%	32,8767123	%			
Life cycle cost estimations							
Remaining life of plant	T_rl	T_rl = T_pd - T_pa	15				
Life cycle loss due to unavailability	L_lc-loss	L_lc-loss = U_loss*[(1-e^-(r*T_rl))/(e^r-1)]	75,1246694	[mNOK]			
Life cycle cost new strategy	C_lc-ns	C_lc-ns = C_ans*[(1-e^-(r*T_rl))/(e^r-1)]	12,3492607	[mNOK]			
Life cycle profit|100% return on new strategy	P_lc-ns	P_lc-ns = C_lc-ns	12,3492607	[mNOK]			
Life cycle loss|100% return on new strategy	L_lc-|100%	L_lc-|100% = U_lc-loss-P_lc-ns	62,7754087	[mNOK]			
Life cycle loss unavailability|100% return new strategy	L_u-lc-|100%	L_u-lc|100% = L_lc-loss-(C_lc-ns+P_lc-ns)	50,426148	[mNOK]			