University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore technology - Industrial Asset Management	Spring semester, 20.17.. Open / ~~Restricted access~~
Writer: Fredrik Westeng Olsen	Fredrik W. Olsen .... (Writer's signature)
Faculty supervisor: Prof. Jayantha Prasanna Liyanage External supervisor(s): D.Eng. Jawad Raza	
Thesis title: Assessment method for review of existing maintenance strategies based on reliability, availability, risk, and cost parameters.	
Credits (ECTS): 30	
Key words: Asset management Maintenance strategy Maintenance analysis Cost-Risk-Benefit analysis Maintenance management Continuous improvement	Pages: ......69......... + enclosure: .....9..... Stavanger, ..14/06/2017..... Date/year

Abstract

Maintaining assets is a fundamental part of any industrial facility. Oil and gas operators are often using advanced maintenance strategies, but the strategies are usually built pre-operation and not systematically updated later in-operation. Still, the operators often record the necessary maintenance data that would allow them to optimize these strategies. The lack of this experience has been challenging in the recent years were operators have had to cut back on maintenance without truly knowing the consequence of these cuts. Another issue is the silo thinking between the different disciplines, operator personnel, and service providers. They are often working towards their own solutions, without sharing information and experience that would allow for a more optimal solution. A full overview of economical, technical, and risk figures are of great benefit for the decision maker and subsequently the end result.

Apply Sørco recognized these problems and proposed this as a master thesis. The objective of the thesis was to develop a cost-risk-benefit method to assess existing maintenance strategies and support maintenance optimization (benefit in terms of reliability and availability).

The assessment method contains reliability engineering, costing, and risk analysis techniques to present an overview of both performance and possible improvements. In addition, the method suggests considerations of internal and external elements under continuous change that affects feasibility and performance of the maintenance. The output of the assessment method works as a foundation for optimizing maintenance strategies, and as a justification method through the comparison of the existing and the optimized strategy.

The method is able to show performance and possible trends, which combined with changing internal and external elements should enable optimization of maintenance strategies and asset performance. The performance is not able to tell what's wrong, but shows if there is something wrong. Trends may show the problem, but the root cause could stem from internal or external factors. The assessment method is therefore a great tool for managing and controlling performance, due to considering all aspects.

The assessment method was tested on a real case supplied by Apply Sørco. The assessment method showed promising results and made up a good overview of the existing maintenance strategy. It allowed the analyst to assess and review the existing maintenance strategy from a real case, based on the performance and the failure trends. The results from the assessment method showed that the test case would benefit from an update. The updated strategy was expected to perform better in all analyzed aspects and was therefore recommended.

While there exist several management methods that include an analysis and improvement part, they seldom explain how to perform this part or what to include in the process. This method proposes techniques, prerequisites and guidelines for performing the assessment, and makes for a more defined method.

Acknowledgements

This thesis is submitted as a partial fulfillment of the master program (MSc) Offshore technology - Industrial Asset Management at the University of Stavanger.

This work has been carried out during the spring of 2017 under the supervision of academic professor Jayantha Prasanna Liyanage and industrial professional D.Eng. Jawad Raza. I have been privileged with the trust of this thesis and their valuable time.

I would like to express my thankfulness for their contribution and invaluable guidance throughout this whole project. Their patience and support has been highly appreciated. I would also like to thank Kahraman Veysel Dogan, Koorosh Sabetian Ivali, and the rest of the employees at Apply Sørco for their helpfulness and friendly reception.

Finally, I would like to thank my family for their support and faith in me.

Table of Contents

Table of figures

List of abbreviations

AIS	Asset Integrity Strategy
ALARP	As Low As Reasonably Possible
CBA	Cost-Benefit Analysis
CBM	Condition-Based Maintenance
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
FMECA	Failure Mode, Effects and Criticality Analysis
GMC	Generic Maintenance Concept
HSE	Health, Safety and Environment
ISO	International Organization for Standardization
LCC	Life Cycle Costing
MHr	Man-hour
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTM	Mean time to maintain
MTTR	Mean Time To Repair
NCS	Norwegian Continental Shelf
NS	Norwegian Standard
O&G	Oil and Gas
OREDA	Offshore and Onshore Reliability Data
PDO	Plan for Development and Operation
PM	Preventive Maintenance
R&A	Reliability and Availability
RAR	Reliability, Availability, and Risk
RBI	Risk Based Inspection
RBM	Risk Based Maintenance
RCM	Reliability Centered Maintenance
RTF	Run To Failure
WO	Work Order

Chapter 1 – Introduction

Background

The oil and gas industry witnessed a recent collapse in the oil price that in turn have led to enormous changes and challenges for the industry. Maintenance strategies that have been developed during design and commissioning (pre-operation phase) have a tendency to be exaggerated due to the wish for a safe start and a good run-in phase (Raza, 2017). This philosophy might be a good choice in the early start of operation due to the typical burn-in failures. Burn-in failures make it hard to predict the optimal maintenance strategy, but when the assets mature this makes for a good opportunity to improve the maintenance strategy as more failure and maintenance data becomes available. A lot of the assets at the Norwegian Continental Shelf are mature in regards of asset age (PSA, 2016). NCS consists of several assets that are close to or past their expected lifetime, but still in operation because they are able to fulfill the intended function without compromising integrity. These assets need careful considerations in regards to maintenance because uncertainty emerges when they are close to or past the age they are designed for. They can no longer be treated as new or matured assets, and technical, organizational, economical, and market conditions are no longer the same as when they where installed. Because the oil price has been at such a high level, there has been less motivation among operators to spend their limited time improving maintenance strategies (according to industry experts Raza and Hansen). The asset integrity service providers also encounter challenges in their work: the collaboration is insufficient, meaning information and experience is not shared; their experience is shifted towards asset integrity at new installations; operation in harsh and unpredictable environments needs field-specific considerations; and having to work with various company-specific regulation documents that are non-standardized (Dogan, 2014). Experts, such as Herring and George (2016), predict a lag in maintenance work due to the cost savings done and the issue that frightens the stakeholders is the potential disasters that might appear because of this lag. The Norwegian Petroleum Safety Authority (PSA) expresses their concern on the trends in the industry, and has initiated a project called "Reversing the trend" because of their findings. Their report, RNNP 2015 (Risk level in the Norwegian petroleum industry), shows a decrease in performed maintenance (Figure 2) and a higher frequency of serious injuries (Figure 1) from 2014 to 2015, which are just two of the negatively shifting trends.

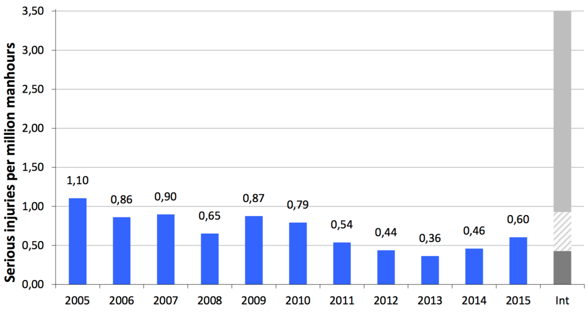


Figure 1 – Serious injuries per million man-hours (PSA, 2015)

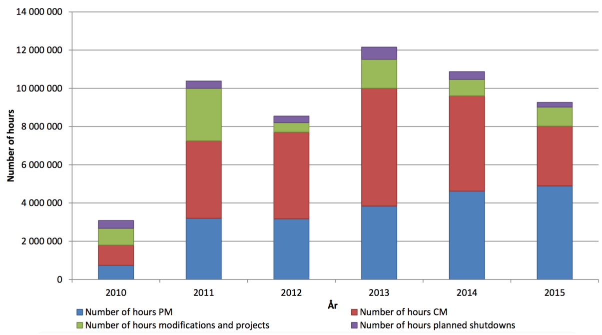


Figure 2 – Hours of performed maintenance (PSA, 2015)

Now, the industry is looking for ways to reduce costs, and the need for methods to improve maintenance strategies while still maintaining proper safety are required. A solid understanding of which maintenance activities that can be reduced, changed or removed are necessary to maintain the safety that is required by authorities, workers, and other stakeholders.

Scope and Objectives

The balance of cost and risk has always challenged maintenance management. An approach that analyzes cost, risk, and benefits (in terms of reliability and availability) is therefor required to justify the maintenance strategies.

The thesis seeks to find a method to assess the reliability, availability, cost, and risk of the maintenance strategy at system and equipment level. The assessment should work as a foundation for optimization based on the latest status. The best strategy will not be the same through the asset life, and therefore, the strategy needs to be updated periodically to handle the current life phase. Rather than finding the most advanced method, a simple, relevant and user-friendly method is sought for.

Objectives for the thesis is to learn about maintenance in practice, identify a suitable assessment method for optimizing maintenance strategies at system and equipment level, and test the method on a real case provided by Apply Sørco.

Research approach

The research process started by studying industrial practices, relevant standards, and maintenance literature. The work was a comprehensive and demanding process as there exist a variety of academic theories, industrial practices, and different standards and regulations. The result of this process is presented in chapter 2, as the theoretic foundation for chapter 3 and 4. Based of the theoretic foundation, techniques were adapted and used as inspiration for creating the assessment method presented in chapter 3.

For running all the calculations, the spreadsheet software MS Excel was used to develop a spreadsheet application to perform the assessment of the real case in a more automated fashion.

As a timeline for the project, a Gantt chart was used to keep track of progress. The chart was updated continuously as new tasks emerged and when tasks where finished. The Gantt chart provides a good overview of all the activities and when they are due.

Structure of the report

The report consists of six chapters, a bibliography, and an appendix. After this chapter, the introductory chapter, the structure goes as following:

Chapter 2 of the thesis presents general theories and concepts that are relevant to, or used directly or indirectly to solve this thesis. This chapter is the theoretical foundation for the next chapters.

Chapter 3 is the result of the investigation, evaluation, and adaption of techniques and methods relevant for reaching the objectives. The chapter presents an assessment method for reliability, availability, cost, and risk parameters as well as suggesting considerations of affecting factors.

Chapter 4 presents the case study using the presented assessment method on Apply Sørco's real case.

Chapter 5 discusses the case study and the assessment method.

Chapter 6 presents future studies that could be implemented in the presented method, or is closely related to this subject.

Chapter 7 presents the concluding remarks of the thesis.

Limitations

This thesis aims at presenting an assessment method for optimizing maintenance strategies at system and equipment level. The real case is not an in-house case at Apply Sørco as they are a service provider. Therefore, a lot of the information necessary to perform the full assessment was lacking. To be able to perform the case study, the missing data was assumed. These assumptions were made by a student with no maintenance experience and should not be used in a real optimization process.

Chapter 2 – General concepts and theory

This chapter aims to present and introduce the main concepts and theories used in this thesis.

Asset Management

Asset is defined according to ISO 55000 as "*an item, thing or entity that has potential or actual value to an organization.*" Further, "*the value will vary between different organizations and their stakeholders, and can be tangible and intangible, financial or non-financial*" (ISO, 2014a)(P.13)

Asset management includes the processes, decisions, plans, and activities to operate, control, and optimize assets in the best way relative to the expectations and objectives of the involved stakeholders (ISO, 2014a). Figure 3 shows the scope of each element, where asset management is a sub-part of managing the organization. ISO 55000 defines asset management as the "*coordinated activity of an organization to realize value from assets*", asset management system is the "*interrelated or interacting elements to establish asset management policy, asset management objectives and processes to achieve those objectives*" and the asset portfolio are the available assets that are part of the asset management system (ISO, 2014a)(P.14-15).

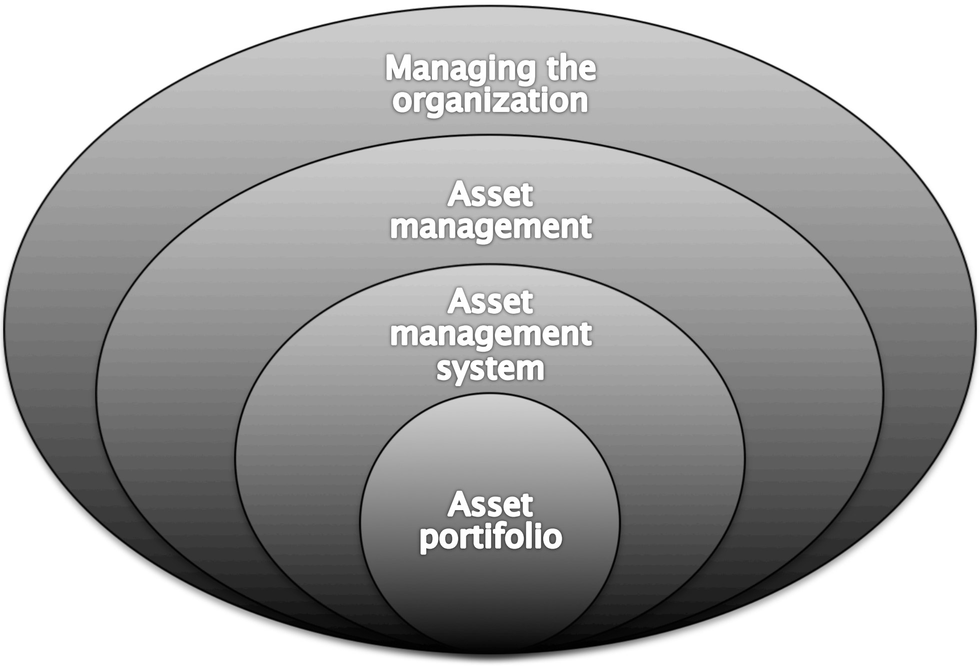


Figure 3 – Relationship in asset management (ISO, 2014a)(P.4)

Optimized asset management needs to be built on some key principles and should integrate:

- A holistic multidisciplinary value focus
- A systematic and structured management system
- A systemic view of the assets

- A risk-based approach to all decision making
- Optimal compromises of cost, risk, and performance
- Sustainable operation

(iAM, 2008)

Asset Integrity

Considered as a multi-disciplinary approach, asset integrity combines disciplines such as design, construction, operation and maintenance to prevent unwanted accidents and events. Every asset needs proper attention such that it remains safe, reliable and efficient to perform as intended. Another important aspect is that integrated management of asset integrity contributes to an environment people feel safe to work in.

Asset integrity management is the work of ensuring business processes, tools, systems, resources, and competence are up to the task of delivering integrity throughout the asset life. Asset integrity can be subdivided in to design integrity, operational integrity, and technical integrity. In the context of maintenance, technical and partly operational integrity covers the subject of maintenance management. (DNV GL, 2017)

The asset integrity strategy is the high-level plan of how to keep the asset integrity performance at the required level, and to meet the asset objectives. The maintenance strategy is a sub-part of the asset integrity strategy and will be presented in the following sections.

Maintenance today

In the past 40 years, maintenance has seen key changes in the management of technology, people, and assets. As resources are limited, the three key areas aim to utilize every advantage such as profit and service of these expensive resources (Starr et al., 2010). Maintenance has changed from being an expensive necessity, where actions were reactive, to a profit center with advanced management and proactive and predictive tasks (Piltelton et al., 1997). This advanced management is capable of optimizing performance in a sophisticated way. The realization of the availability and reliability factors is responsible for lifting the concept of maintenance from a cost center to a profit center. Maintenance and system providers are adopting new technologies continuously for further exceeding the performance. Traditionally exploiting new technology required some economy of scale, but new business models have made remote high quality services at a low entry cost possible. Among other things, the greater integration of collected equipment-data will help decision makers to perform more informed and justified decisions. (Starr et al., 2010)

While maintenance management today has become highly advanced, there is still room for improvements. Kartfjord (2017) states that the company Xafe, a Norwegian risk consultant company, have never performed or heard of any studies on the risk effect of doing less or more maintenance at offshore facilities. What seems to be the practice today is that there is a common understanding of the need for cost efficient maintenance programs, but the foundation for updating the maintenance strategy is inconsistent. A holistic framework for optimizing maintenance strategies, covering risk, cost, benefits, and internal and external changes could be the next step for improved maintenance management.

Maintenance Management

According to ISO 14224, maintenance is defined as a "*combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state in which it can perform a required function*" (ISO, 2006)(P.5).

Maintenance management includes all technical, financial, and administrative tasks for planning and assessing maintenance actions. To reach the most sustainable maintenance program with regards to the organization's goals and the available resources is the task for a maintenance manager. Then again, to be truly effective, the management methods need to be integrated in the organization such that the common goal of all workers is in line with the maintenance strategy.

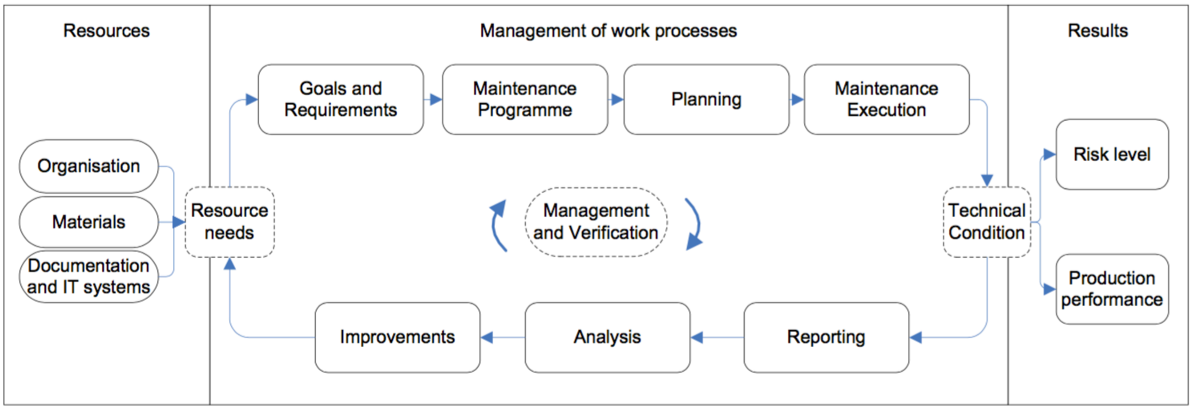


Figure 4 – Maintenance management process (NORSOK, 2011)(P.14)

Figure 4 presents the suggested maintenance management process by NORSOK Z-008. Briefly, the steps represent:

- Goals and requirements: goals that commit the organization to the required risk, production, cost, etc. performance.
- Maintenance programme: the interval of maintenance and procedures for maintaining, testing, and preparing the components.
- Planning: the work of budgeting, prioritizing, everyday planning, and long term planning.
- Execution: every step from preparation and getting work permits to performing and reporting the work.
- Reporting: presentation of collected and quality assured maintenance data to the maintenance department.
- Analysis: The work of analyzing the historical failure and maintenance data
- Improvements: The evaluation of the analysis and the further actions for improvement.

For further reading, see NORSOK (2011).

Risk and reliability based methods

In the literature there exist several methods for developing maintenance strategies. Three of the modern, and more recognized methods are Risk Based Maintenance (RBM), Risk Based Inspections (RBI), and Reliability-Centered Maintenance (RCM). These methods are capable of implementing business, safety, environmental, and reliability considerations in to the decision-making. This provides the decision-maker with a more comprehensive view on how they spend their limited resources (R-Tech, N.D.).

Risk is a common word, and often used inconsistently and imprecise. In the context of maintenance engineering, the definition according to Aven (1992)(P.6) is used: "*risk is the danger that undesirable events represents to human beings, the environment and economic values*". The more quantitative way of defining risk is according to NORSOK Z-008 as "*the combination of the probability of an event and the consequence of the event*" (NORSOK, 2011)(P.10).

According to ISO 14224, reliability is defined as the "*ability of an item to perform a required function under given conditions for a given time interval*" (ISO, 2006)(P.7). The reliability may also be interpreted as the probability R(t). R(t) is the reliability as a function of time, which is the probability of surviving the time t without any failures. Failure is here defined by ISO 14224 as the "*termination of the ability of an item to perform a required function*" (ISO, 2006)(P.4).

Risk based maintenance

Risk based maintenance is a management method that relies on the principles and techniques found in risk management. The aim of the method is to manage risk in a balanced way. While the term is inconsistently used, the common consensus is that dynamic equipment is covered by RBM.

The principles from risk management that this method builds on are:

Figure 5 - Risk methodology process (Tirabosco, 2001)(P.2)

These are the very same principles that ISO 31000 describes as the process in risk management. Asset integrity is managed and controlled based on these principles, combined with the suited maintenance activities. Tirabosco (2001) suggests a nine-step RBM approach which starts with defining the assets functional requirements; then breaking down the asset by system functionality; breaking each system down to manageable components; do a FMEA analysis for each component; assess the criticality of each component; identify the maintenance options; do a cost-benefit analysis of each maintenance option; reduce risk according to ALARP principles; and finally create a maintenance reference plan for all maintenance activities on the asset. While there exist several approaches, the essence is still the same for the RBM method (e.g. NORSOK Z-008, maintenance management process).

Risk based inspections

Building on the same risk principles as RBM, RBI is typically used for static pressure containing equipment. Tirabosco (2001) presents a seven-step approach, based on the American Petroleum Institute Recommended Practice 580, for performing an RBI. The steps goes as following:

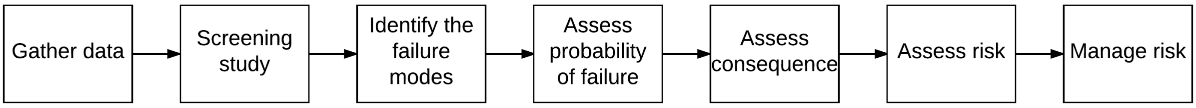


Figure 6 – The process of an RBI approach

1. Whether a qualitative or quantitative approach is used, typical required data is: type of equipment, volume of contained flow, flammability and toxicity of contained flow, temperature and pressure, degradation mechanisms, and effectiveness of inspection.

2. The screening study is used to determine the criticality of the equipment.

3. The failure modes should be identified as either complete or partial. Complete failure modes are loss of function, such as loss of containment. Partial failure modes are the type of damage that is observable and used to predict the loss of function.

4. With the failure modes as the basis, the probability of having each failure mode should be assessed.

5. Subsequently, the corresponding consequence of each failure or failure mode should be determined and assessed in regards of severity for HSE and operation.

6. Risk should then be assessed. The risk value derives from the probability of failure and the consequence of the failure combined.

7. Finally, the risk should be managed. Actions that mitigate or reduce unacceptable risk should be defined, and which of the factors that drives the risk should be identified.

Reliability-centered maintenance

Reliability-centered maintenance is a method used to determine a system's maintenance requirements in a systematic way. RCM assumes an inherent reliability for a system, and builds the maintenance requirements upon this baseline in combination with required safety. RCM is defined as "*a process used to determine the maintenance requirements of any physical asset in its operating context*" (Moubrey, 1997)(P.28) and characterized as a process to establish a minimalistic but safe maintenance strategy. RCM is therefore a cost-effective maintenance management method, based on maintaining the dominant causes for equipment failure. This enables the maintenance program to be optimized to handle the most frequent failure causes, and not everything else. Standard SAE JA1011 proposes a "seven-step" evaluation process as the minimum criteria for calling a maintenance evaluation RCM. The seven steps are:

1. Define the asset functions and performance standards in the operating context.
2. Define how the function could be lost.
3. Define the causes of functional failure.
4. Define the consequences of failure.
5. Define how each failure matter.
6. Define actions to predict or prevent each failure.
7. Define actions for when proactive tasks cannot be found.

(Moubrey, 1997)

These steps serve the purpose of enabling the owner to understand, monitor, and predict their assets and are the initial part of the RCM evaluation. Once the operating context is defined and FMECA performed, the "RCM logic" may be applied to determine the maintenance tasks for the dominating failure causes. For successful integration, the organization needs to "do maintenance by the numbers", and use the FMECA as a maintenance-driver. Finally, the maintenance tasks should be updated through the asset-life as more data and experience is gained. If the performance of excellent maintenance programs is below expected, the inherent reliability is misjudged and the physical assets may need to be refined or changed.

The RCM method requires a disciplined staff that are motivated and driven by excellence in: safety, operability, minimizing maintenance time, maximizing availability, and minimizing possibility of failure (Barringer, 2013).

Generic Maintenance Concept

Generic maintenance concept (GMC) is a term used in several industries, which describes the maintenance strategies, activities, and details that can be used for defined equipment under certain conditions to provide a cost efficient maintenance procedure. The oil and gas industry often base the GMC on regulations, standards, and experience. The maintenance routines describe information such as resources needed, tools, relevant documentation, man-hours to perform routine, required competence and reporting procedures. Cost is usually left out, as cost evaluations are performed separately (Kayrbekova, 2011).

Maintenance strategies

The maintenance strategy is defined by NORSOK Z-008 as a "*management method used in order to achieve the maintenance objectives*" (NORSOK, 2011)(P.10). The maintenance strategy may contain several different management methods, depending on the different sub-objectives of the different sub-systems. The strategy should aim to reach the objectives of the organization; otherwise the strategy should be adjusted.

There are several different maintenance strategies that are being applied in the industry, and often they are applied in combination to be as efficient as possible. The objective of a maintenance strategy is to balance the tradeoff between costs and benefits. Which strategy to choose is dependent on the objectives and resources in the organization. Some systems require high reliability, while others may run to failure if that is the optimal solution. Maintenance costs can be major part of the operations cost, often somewhere in the range of 15% to 70% (Bevilacqua and Braglia, 2000). Therefore the choice of maintenance strategy should be justified by costs, risks, and benefits. For the justification to be truly comprehensive, intangible value such as reputation, safety, environment, etc. could be implemented and assessed as well. A method such as the consequence classification, a quantitative analysis of events and failures, may help assessing the consequences of these.

Figure 7 shows an overview of the commonly known maintenance strategies. First step in defining maintenance strategy is to choose either a planned maintenance strategy, unplanned maintenance strategy, or to design-out maintenance. If an unplanned strategy is chosen, the only option is to do corrective maintenance (CM). Planned maintenance has several options and is usually based upon a preventive maintenance (PM) strategy where corrective maintenance is used if a failure appears before the planned maintenance. Preventive maintenance strategies may be done periodically based on calendar scheduling or run-time scheduling, or the preventive maintenance may be based on condition monitoring. Predictive maintenance and Condition based maintenance (CBM) is done by continuous monitoring or periodic inspections.

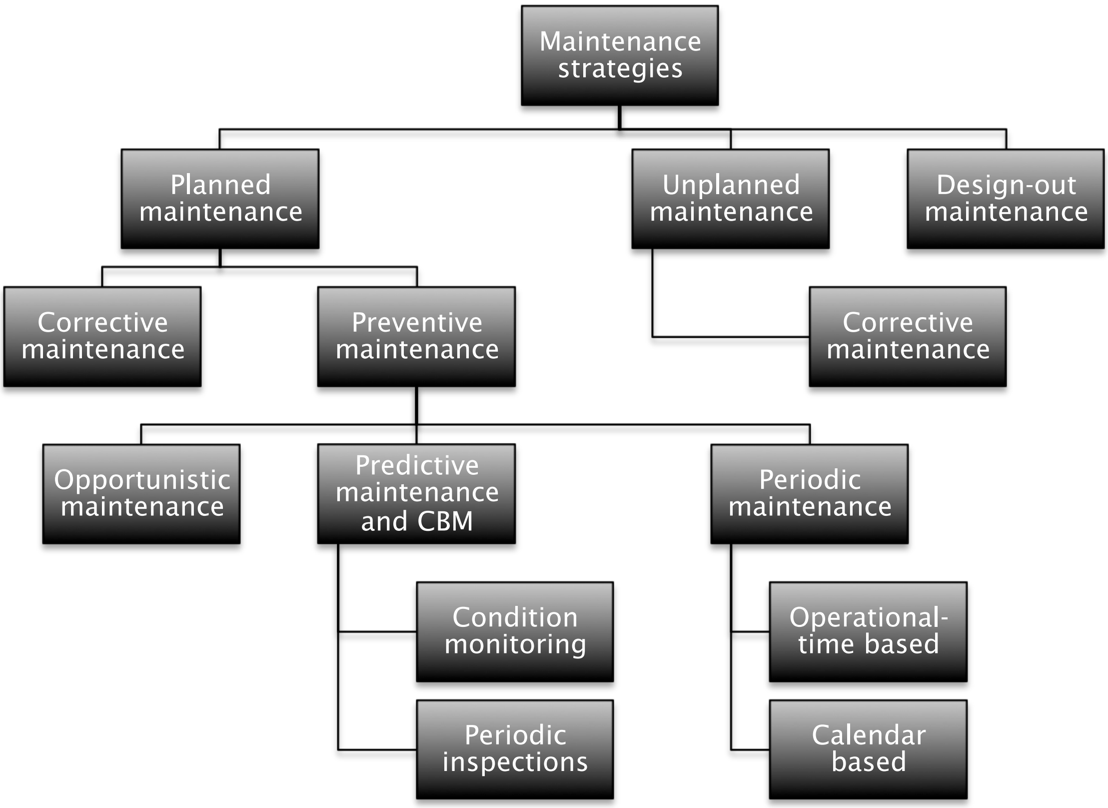


Figure 7 – Maintenance strategies (Olofsson, N.D.)

Corrective maintenance

Corrective maintenance is usually always a part of the maintenance regime as failures may happen even if you follow a planned preventive maintenance strategy. If the strategy is to do planned corrective maintenance, it is often called a Run To Failure (RTF) strategy. In the RTF strategy you install the equipment and run it until it fails. Upon failure the equipment is either repaired or replaced, and other than that it does not need much management attention. The burden of RTF strategies is that spare parts are needed in very short notice. Less critical equipment may wait for corrective actions to be done, but equipment that is critical to production or safety may require immediate action in the form of repair, replacement, or redundancy equipment. Unplanned corrective maintenance, also known as reactive maintenance, is often a result of unexpected breakdowns. This might be because of under-maintenance or lack of attention. Compared to preventive maintenance, the corrective maintenance activities are mostly repairs. Repairs are known to usually be more expensive than preventive activities (e.g. periodically lubricating an engine is often cheaper than repairing a seized engine).

Preventive maintenance

Preventive maintenance is activities that aim to prevent failure by doing maintenance before a failure happens. The objective is usually to maximize the availability of the function the equipment provides. Typical benefits of doing preventive maintenance activities are less machine breakdowns, less expensive repairs, higher output from the production, and increased safety levels.

Periodic maintenance

The maintenance interval in preventive maintenance may be given as a pre-determined length of time or by the condition of the equipment. When preventive maintenance intervals are given as calendar time or operational-time it is called periodic maintenance. Operational-time could mean the number of hours in operation, number of units or volume produced, or number of start-ups. Periodic maintenance intervals are usually based on OEM recommendations, MTTF statistics, experience, or a combination of these.

There is usually a change in length of the intervals due to the typical bathtub characteristics (Figure 8) of the failure rates. Another factor is that the operator learns more about the equipment and its needs during operation.

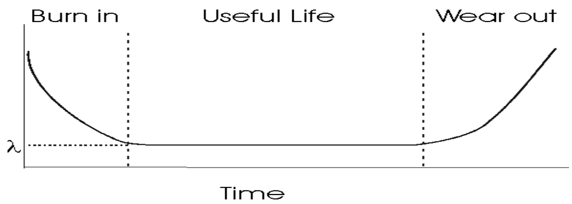


Figure 8 – Bathtub curve (Pan, 1999)

Predictive maintenance and Condition Based Maintenance

Predictive maintenance and Condition Based Maintenance (CBM) are done by inspecting or monitoring the condition of the equipment. The techniques are very similar, except in predictive maintenance the condition readings are being analyzed to predict when the next maintenance needs to be performed. One of the typical terms for a prediction analysis is trending. Trending makes it possible to plan the maintenance in advance and procure the right spares when needed instead of having them stored, at least to a certain degree. In CBM, action is taken upon findings, certain values, or parameters that are pre-determined. This reduces the time to plan and procure spares, which is essential for spares that have some lead-time. The maintenance activities and routines are usually similar to the periodic activities and routines because you usually perform preventive work, not unexpected repairs. Essentially it is preventive maintenance with a dynamic interval. The activities and routines are often called preventive maintenance activities and routines. The benefit of condition monitoring comes with a cost of sophisticated sensors and devices, and maybe even some modification of the equipment itself.

Opportunistic maintenance

Opportunity based maintenance is considered as a preventive form of maintenance. It is performed when equipment conveniently can be maintained or replaced upon another planned or unplanned system shutdown, given that resources are directly available. The benefits are the reduced production losses and number of shutdowns, which often are the most expensive costs due to maintenance. Opportunistic maintenance require a solid overview of which components that soon are up for maintenance, otherwise the cost advantage may turn in to costly over-maintenance.

According to Borges (2015), opportunistic maintenance is considered very effective for oil and gas assets because of the complex dependencies at offshore platforms. Borges (2015) states that failures in one system are likely to shut down other systems, which may be even more critical in regards to production or safety. Opportunistic maintenance then provides a great opportunity to save a substantial amount of money, compared to following a strict regular schedule.

Reliability

In reliability engineering, there exist several distribution models used for modeling reliability and lifetimes. The dominating model is the exponential distribution model followed by the Weibull distribution model. While the exponential distribution is simpler, the Weibull distribution allows for more complex lifetime modeling, especially in the burn-in and wear-out phases. Both models are presented in further detail in the following sections.

Exponential distribution

The exponential distribution is a memory less distribution, which means the failure rate is constant and not dependent on unit-age. The proof of the memory less property is given by:

$$\begin{aligned} P(T > u + v | T > u) &= \frac{P(T > u + v \cap T > u)}{P(T > u)} \\ &= \frac{P(T > u + v)}{P(T > u)} \\ &= \frac{e^{-\lambda(u+v)}}{e^{-\lambda u}} \\ &= e^{-\lambda v} = P(T > v) \end{aligned}$$

Ref: Aven (1992) page 267.

The proof shows that the probability of surviving the additional time v is not dependent of the age u. This is the only distribution with the memory less property, which also simplifies the mathematical modeling. This property might seem unrealistic for most components; however, as we only are interested in the lifetime in a limited period of time, the exponential distribution will give a good description of the lifetime. The exponential distribution has shown to be well suited for modeling the lifetime of electrical and electronic units, as well as some complex mechanical components that are in their useful-life phase. For such units and components in the useful-life phase, the failures are best described as random failures.

The exponential probability density function (PDF) f(t) and cumulative distribution function (CDF) F(t) are on the form:

$$f(t) = \lambda e^{-\lambda t}, \qquad t \geq 0$$

$$F(t) = 1 - e^{-\lambda t}$$

The reliability function is expressed by:

$$R(t) = e^{-\lambda t}$$

And MTTF:

$$MTTF = \frac{1}{\lambda}, where\ \lambda\ is\ the\ failure\ rate$$

Ref: Aven (1992) page 268.

A commonly used practical estimate for the failure rate is:

$$\hat{\lambda} = \frac{n}{\tau}$$

Where n is the number of failures, and τ is the aggregated time in service (SINTEF and NTNU, 2015).

For further reading, see Aven (1992) section B.1.2, Walpole et al. (2007) section 6.6 and 6.7 and OREDA (SINTEF and NTNU, 2015).

Weibull distribution

The Weibull distribution is a distribution model after the Swedish mathematician Waloddi Weibull. In reliability engineering, the Weibull distribution will adequately fit 85% to 95% of the reliability data (Barringer, 2013). This probability distribution is deemed suitable for lifetime modeling for equipment with an increasing (β>1) or decreasing (β<1) failure rate. The parameters of the two-parameter Weibull distribution are called scale parameter α and shape parameter β. If the equipment has a constant failure rate (shape parameter β=1), it corresponds to a special case of the Weibull distribution also known as the exponential distribution.

As shown in the Figure 9, the curve changes shape for the different β values, while the α is kept constant. The Weibull PDF and CDF are on the form:

$$f(t) = \alpha^{\beta} \beta t^{\beta-1} e^{-(\alpha t)^{\beta}}, \qquad t \geq 0$$

$$F(t) = 1 - e^{-(\alpha t)^{\beta}}$$

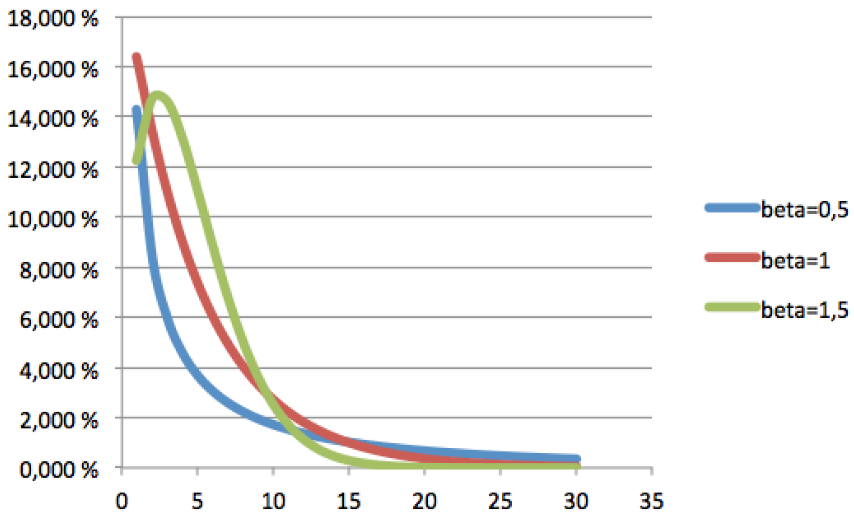


Figure 9 – Weibull PDF plot for different β's

The Weibull distribution is well suited for modeling the burn-in phase (β<1) and the wear-put phase (β>1). During the mature phase of the bathtub curve, the failure rate is approximately constant resulting in β≈1, which suggests using the exponential distribution.

Figure 10 shows a PDF plot with a constant β=1,5 and a changing α. A higher value of α results in wider spread of the density function.

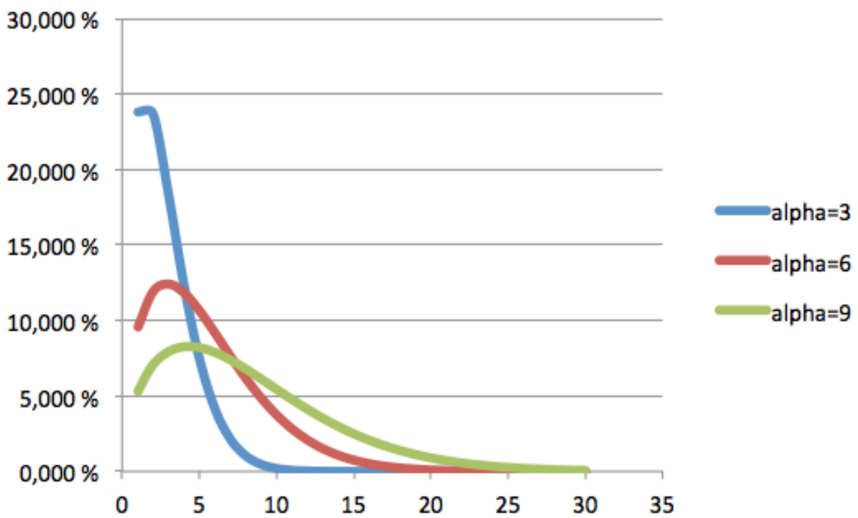


Figure 10 – Weibull PDF plot for different α's

The reliability function is expressed as:

$$R(t) = e^{-(\alpha t)^{\beta}}$$

And MTTF:

$$MTTF = \alpha\, \Gamma\left(1 + \frac{1}{\beta}\right)$$

Ref: Aven (1992) page 268.

For further reading, see Aven (1992) section B.1.2 and Walpole et al. (2007) section 6.10.

Probability and hazard plots

Probability and hazard plotting are methods that help identify the underlying distribution of equipment lifetimes. By the probability and hazard plots, there exist several techniques to estimate the parameters necessary in the probability models. For further reading on probability and hazard plots, see Aven (1992) page 277, Reliawiki.org (N.D.) and Minitab (2016).

Nelson plotting

One of the graphical hazard plotting methods for identifying lifetime distributions is called Nelson plotting. Nelson plotting is based on the Nelson estimator $\hat{Z}(t)$, which is a estimate of the cumulative hazard function Z(t). The Nelson estimator is based on the formula:

$$\hat{Z}(t) = \sum_{j:\delta_j=1,T_j\leq t} \frac{1}{n-j+1}$$

Figure 11 presents an example of the input to a Nelson plot, where j is the cumulative number of failures at the corresponding time T and n is the total number of failures encountered during the period.

j	T [days]	n-J+1	Z(t)
1	21	22	0,045454545
2	35	21	0,093073593
3	57	20	0,143073593

Figure 11 – Input to a Nelson plot

Figure 12 shows a Nelson plot with an increasing failure rate (IFR). The $\hat{Z}(t)$ is plotted against time at the X-axis.

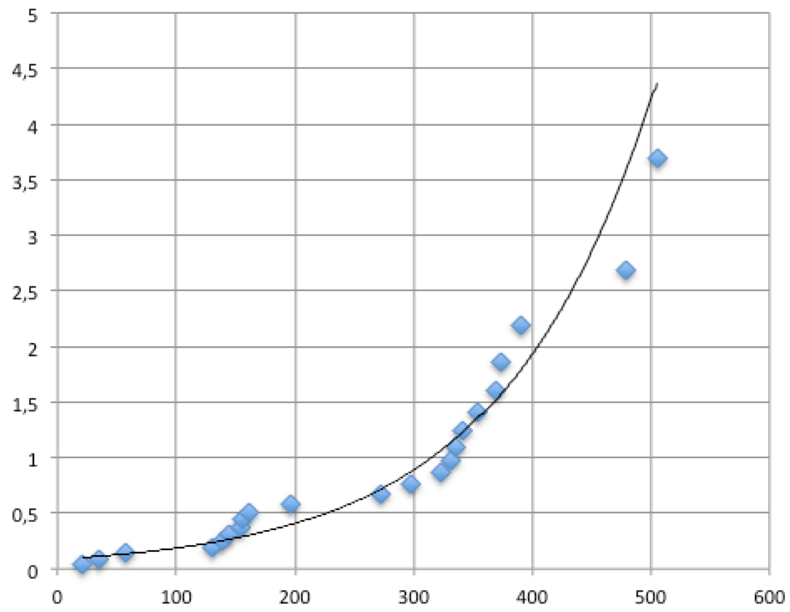


Figure 12 – Nelson plot

When the Nelson plot shows an IFR, the exponential distribution is not suited because that would require a constant failure rate (a straight line through the plot). When the Nelson plot shows an increasing failure rate or decreasing failure rate, a logarithmic Nelson plot can show if the Weibull distribution is suited for lifetime modeling. The logarithmic Nelson plot is based on the natural logarithm of $\hat{Z}(t)$ and T, and if the plot shows a near straight line the Weibull distribution is suited for the dataset. Further, the β value is estimated as the slope of the logarithmic Nelson plot, and the α value is calculated by re-arranging the formula:

$$LN\left(\hat{Z}(t)\right) = \beta LN(t) - \beta LN(\alpha)\ , at\ point\ \hat{Z}(t) = 1\ and\ corresponding\ t\ (time)$$

Ref: Aven (1992)

Benard's Approximation

Benard's approximation is a rank regression method to approximate the median ranks. Since the unreliability of each failure seldom is available before doing the probability plot, the median rank can be used as an estimate. When the unreliability of each failure shall be estimated, the median rank method is used. The median rank equals the true unreliability $Q(T_j)$ at the j^{th} failure, in a sample of N failures at a 50% confidence interval. For any unreliability greater than zero and less than one, the rank can be found as a percentage point. (Reliawiki.org, N.D.)

"Today the median ranks plotting position is generally accepted as best practice for reducing errors and bias with tailed distributions" (Barringer, 2004). Barringer (2004) also states that Benard's approximation is validated trough Monte Carlo simulations and considered superior to the other rank methods. The median ranks are suitable for estimating the Weibull distribution parameters.

Benard's approximation is on the form:

$$MR = \frac{j - 0{,}3}{N + 0{,}4}$$

Ref: Reliawiki.org (N.D.)

J is the rank number when the failure times are sorted in ascending order, and N is the total number of failures. Then calculating:

$$LN\left(LN\left(\frac{1}{1 - MR}\right)\right)$$

And:

$$LN(t)$$

If the plot of these makes an approximately straight line the Weibull distribution is suited for the dataset. Given that the plot makes up a straight line, it can be described by the equation:

$$LN\left(LN\left(\frac{1}{1 - MR}\right)\right) = \beta LN(t) - \beta LN(\alpha)$$

This equation can be proved to be on the form:

$$y = mx + b$$

Ref: Dorner (1999)

At this form, the β equals the slope (m) of the line, x equals LN(t), and b equals (-βLN(α)) as the point of interception. β and b may be found graphically or by doing a regression analysis. α is found by rearranging:

$$b = -\beta LN(\alpha)$$

To:

$$\alpha = e^{(-\frac{b}{\beta})}$$

Availability

According to ISO 14224, availability is defined as the "*ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided*" (ISO, 2006)(P.2).

The availability is often given as a percentage, and calculated by one of the following equations:

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

Where:

$$MTTF = MTBF - MTTR$$

Or the exact availability:

$$Availability = \frac{uptime}{uptime + downtime}$$

As shown in Figure 13, the difference between MTTF and MTBF is that MTTF does not account for MTTR. MTTF is mostly used for non-repairable systems, while MTBF is used for repairable systems. For activities that are not repairs, the term MTTM should be used. The "Mean Times" are the time predicted between certain events (failures, repairs, maintenance, etc.) for an asset in operation. See list of abbreviation for meaning. "Mean Time" terms are commonly used in plant maintenance contexts.

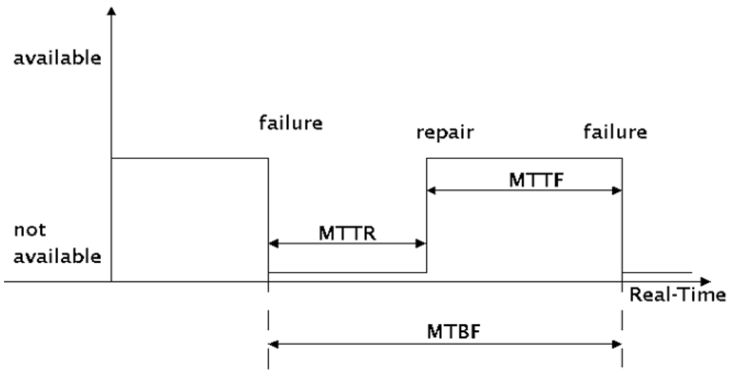


Figure 13 – Explanation of mean time terms (Foskett, n.d.)

Risk

Equipment and component failures may lead to such undesired events, and the result could be injuries, loss of lives, economic losses, and/or environmental damage. While a numerical and similar unit would be preferred for the consequences, the conversion is in practice demanding and often avoided because of the ethical difficulties (Aven, 1992). There is no harm in presenting the consequences in different categories, but it should always be thoroughly understood.

If the losses for each consequence are determined, the expected loss could be used as a measure of risk. This is a statistical expected loss, and should be treated with care. There is a saying, “one should never expect, the expected value” and the reason is because the expected value is the long run average. The benefit of using the expected value is the easily comparable risks, but the evaluation should also include the consequence spectrum. Only if the spectrum is very small, the expected value could be used alone.

Using an event tree analysis (Figure 14) and conditional probability calculus, the probabilities of each event can be estimated.

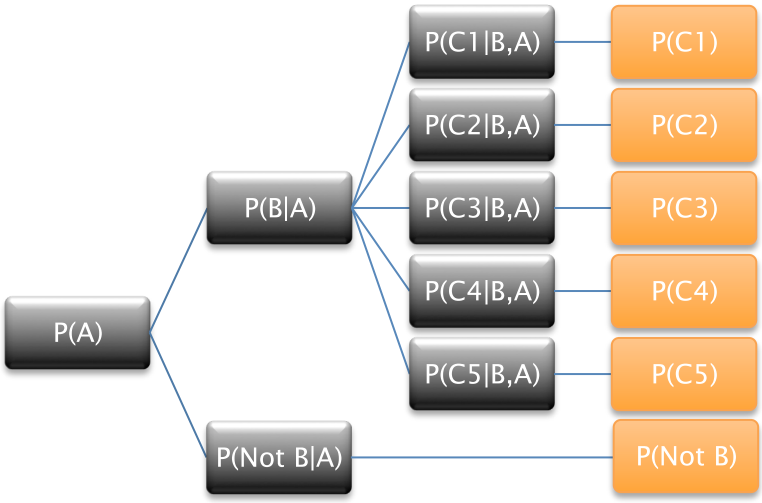


Figure 14 – Event tree analysis with probability of consequence

The probabilities in the orange nodes are on the form $P(A \cap B \cap C)$ which can be solved using Bayes theorem for conditional probability.

It can be shown that:

$$P(A \cap B \cap C) = P(C|A, B) \cdot P(B|A) \cdot P(A)$$

For proof and further reading, see Hakim (2009).

To show an example,

$$P(C1) = P(C1|B, A) * P(B \mid A) * P(A)$$

The calculation starts at the black node farthest to the right, and by multiplying the nodes as you move left in the “tree” will yield the consequence probability. The sum of all the orange nodes will equal P(A).

For calculating the risk, the consequence probability is multiplied with the connected consequence. By the same example as above, the risk would be:

$$Risk = P(C1) * Consequence(C1)$$

The risk spectrum is made up of the risk for each orange node, and the sum of all risks is the expected loss.

Cost Benefit Analysis

A cost benefit analysis (CBA) is a decision-making tool where several alternatives are assessed and selected upon given strategic preferences to make the best investment/decision. A CBA is often used to assess business decisions and can be as simple as benefits minus cost. A CBA may also be much more complicated and require qualitative justifications. It might even implement the third factor, risk, and a cost-risk-benefit analysis requires great knowledge about the alternatives.

The process in its simplest form goes as following:

1. Present the alternatives
2. Present the stakeholders (if relevant)
3. Choose performance criteria's and measure the alternatives
4. Estimate costs and benefits
5. Convert costs and benefits to a common unit (if possible)
6. Apply discount rate (If applicable)
7. Calculate NPV for each alternative
8. Check the sensitivity of the outcome
9. Choose according to your analysis.

Life cycle costing

Life-cycle costing is a CBA method used as a decision support tool for finding the cost of ownership. Rather than just comparing investment costs of two or more alternatives, life-cycle costing enables the decision maker to assess the full cost of the assets through all of the life-phases. The life phases includes procurement, installation, operation, maintenance, and disposal (from cradle to grave). Already in the LCC, constraints are set for the maintenance of the asset, the asset performance, and the expected life. ISO 15663 defines life-cycle costing as "*the process of evaluating the difference between the life-cycle costs of two or more alternative options*" where life-cycle cost is "*the discounted cumulative total of all costs incurred by a specific function or item of equipment over its life cycle*". A life-cycle is defined as "*all the development stages of an item of equipment or function, from when the study commences up to and including disposal*" and the typical discounting method is the Net Present Value (NPV) method that is defined as "*the sum of the total discounted costs and revenues*". (ISO, 2000)(P.3)

Chapter 3 – Assessment method and optimization

The assessment method is used for periodic evaluation of existing maintenance strategies in the operation phase. The assessment and optimization is a two-step process, where the assessment method aims at being a decision support tool that presents a review of the maintenance strategy at system or equipment level. Further, the review is used as foundation for changes and updates to the maintenance strategy. The assessment process should also be able to reveal if the strategy is properly defined. Asset is hereafter used for physical asset at system or equipment level.

Prerequisites for the assessment

The following sections introduce the prerequisites for the assessment. The purpose is to make the maintenance strategy measurable, and present the important elements that are required for the assessment process.

Asset-owners want their maintenance strategies to be as cost efficient as possible, but to achieve that the maintenance strategy needs to be properly developed. To be able to develop such maintenance strategies, the asset needs to be thoroughly understood, objectives and targets clearly defined, and performance factors identified. If poor or wrong maintenance activities are performed, it not only costs time and resources, it may also decrease availability and induce new failures.

Inspired by Mills (2008) "Maintenance management" method, the RCM method, the RBM method and NORSOK Z-008 the following steps was developed (Figure 15).

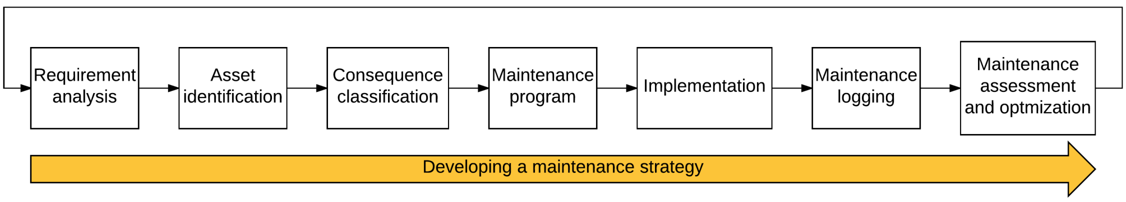


Figure 15 – Process of developing a maintenance strategy

The steps are brief and do not aim to replace other well-recognized methods, but rather highlight some of the important and additional considerations in the process of developing maintenance strategies.

Requirement analysis

Step one considers the technical and functional requirements of the asset, where Figure 16 presents the input. The requirements should be based on industry best practice, relevant standards, applicable regulations, economic evaluations, and facility requirements. The facility requirements are usually decided in the development phase, and make up a picture of what a specific field and facility will generate in regards of production volume or such.

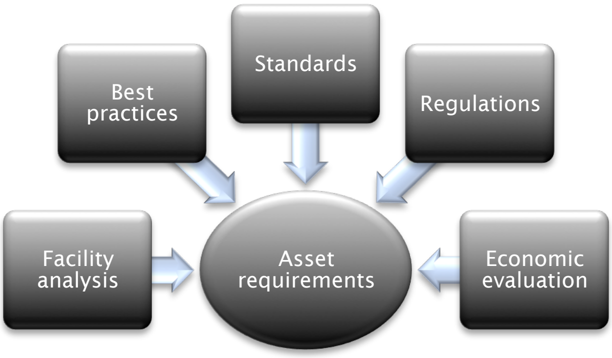


Figure 16 – Input to an Asset requirement analysis

Important requirements in a maintenance setting will include availability, reliability, expected life, and maintenance budget for the asset. These factors will be a minimum of information to perform a proper assessment and should be defined during planning and installation. Whether the operator itself or a service provider performs the requirement analysis, the requirements should always align with the facility requirements to achieve the intended purpose.

Often the result is a compromise between the different inputs. For instance, if the required reliability demands monthly maintenance and the maintenance budget only allows for annual maintenance, a justified trade-off is necessary to find the acceptable balance.

Asset identification

Step two concerns the understanding and identification of the asset. In the work of understanding the asset, vendor recommendations and the OEM manual should be studied and discussed with operational personnel to get a comprehensive understanding of the system. Identification of the system and sub-equipment is important to minimize project execution time, ensure common coding for all disciplines, ensure efficient and reliable communication, and to enable functional facility-breakdowns. The asset and its sub-parts should receive tag codes and all relevant documentation should be tied to the asset through documentation codes. This coding process should be performed according to coding standards and company-specific numbering documents, all clearly stating how each element shall be defined. On the NCS, NORSOK Z-002 is the leading standard for asset coding. Examples of tag construction are presented in Appendix A2. Once the asset is properly identified by code, the equipment-tag database should be updated. This step should start as soon as the asset is installed, and updated continuously through operation.

Consequence classification

Step three is a quantitative analysis of events and failures, which involves defining the potential consequences the asset may have on the facility, the workers and the environment. The function of the equipment, and how the function could be lost shall be defined and tied to all the failure mechanisms, modes, and causes of significance. This shall be identified in order to determine the connected risks for the system locally and globally. FMECA, fault tree analysis, event tree analysis, and/or other risk analysis methods should be applied in this process together with prior history, OREDA data, and similar databases as the foundation. The RCM, RBI and RBM methods are commonly used and may be considered the best practice for processes like this.

Maintenance program

Step four goes in to the maintenance program, and which maintenance activities that shall be a part of the maintenance strategy. A maintenance program contains the activities, resources, and procedures required to perform the maintenance. The program should define both preventive maintenance tasks and the tasks for undesired events that preventive tasks can't handle. Creating a maintenance program is a collaborative work. Deciding which parts that need condition monitoring, preventive maintenance, corrective maintenance, or inspections will be based on the asset requirements and consequence classification as well as expert input, operational input, applicable standards, relevant regulations, warranty programs, and service agreements. Maintenance activities shall be defined such that a maintenance program is ready when or shortly after the asset is installed, even for a run-to-failure strategy.

Implementation

Step five concerns the implementation of maintenance strategies in the organization. This involves processes of creating work descriptions, control documents, work allocation, and estimate resources. This is usually the content of a job card, a common term for this part of the implementation process. Scheduling of the maintenance and work order planning is also a major part of the implementation process, because of the complex relations and dependencies that often are present in modern facilities.

Maintenance logging

Step six regards the maintenance logging, an important part of making the maintenance strategy measurable. To enable assessment of the strategy, the maintenance history needs to be recorded such that a review can be performed and further action can be justified. The log should collect data such as "type of maintenance", "main tags" and "object tags", "failure mode", and other data that is of value. Only the relevant data should be recorded, and maybe even with predefined values or descriptions to make the data as consistent as possible. For instance, if "type of maintenance" is considered to be relevant for the maintenance log, one could predefine "Preventive maintenance" and "Corrective maintenance" as the input options. This ensures consistency in the maintenance data instead of having several different descriptions (e.g. instead of "preventive maintenance", the user might type PM, proactive maintenance, preventive activity, etc.). This will particularly be of importance for data that will be used for safety and cost related calculations. The British standard BS 5760-11 even suggests using only a yes/no format for the reporting to generate unambiguous data with minimal bias.

Data in the maintenance log could be used for more than one purpose, and that can lead to a very cost efficient data collection. Maintenance data may also be recorded for other purposes than maintenance evaluations, for instance for economic evaluations.

Maintenance assessment and optimization

The final step is to choose how often the maintenance strategy should be optimized. Optimization should be performed periodically throughout the asset life. This decision should reflect the complexity of the maintenance strategy, and the size of the system. For a large system, a full assessment and optimization may require a lot of resources. A better alternative might be to break down the system in smaller pieces and update these pieces in a more continuous fashion. For instance, if a system could be broken down to three main components, each component could be optimized every 6 months meaning the system is fully updated after 18 months.

Figure 17 shows the generic idea of optimization throughout the asset life. The asset is likely to need different attention in the early burn-in phase, compared to the late life stage. If a burn-in strategy is brought in to the mature phase of the asset life, asset-owner is likely to over-maintain the asset. For instance, oil samples from an engine will show a certain amount of metal particles during burn-in, but when the engine are entering the late burn-in/mature phase the oil should stay clean for longer intervals. Likewise, if a maintenance strategy from the mature phase is brought in to the burn-out phase, the asset might not get the correct attention.

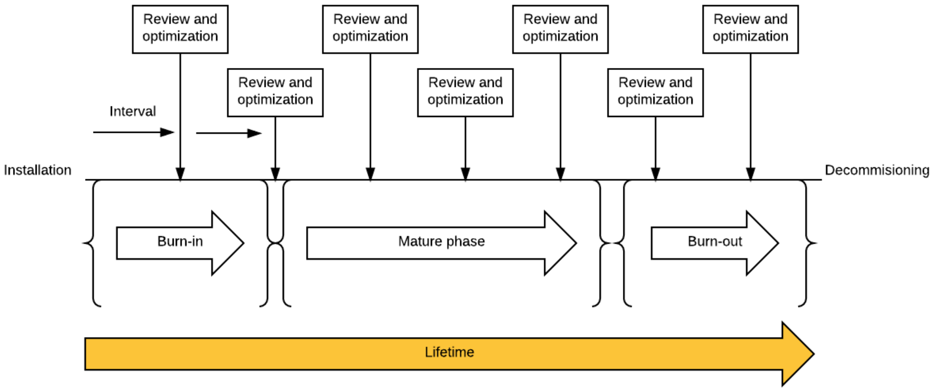


Figure 17 – Periodic optimization of the maintenance strategy

The performance gaps and change in external and internal elements should be analyzed to update the asset requirements and the maintenance strategy. As requirements, performance, and other elements change, the development steps have to be redone periodically to improve the maintenance strategy.

As aforementioned, many systems are running on the maintenance strategy created prior to operation. These strategies can be optimized to cover the necessary maintenance, and remove the parts that don't contribute to the performance.

Under the same reliability and risk, the start-up strategy may consume unnecessary resources that are better spent elsewhere (Figure 18). This can be the result of over-estimated wear, "better safe than sorry" thinking, or different use than planned for.

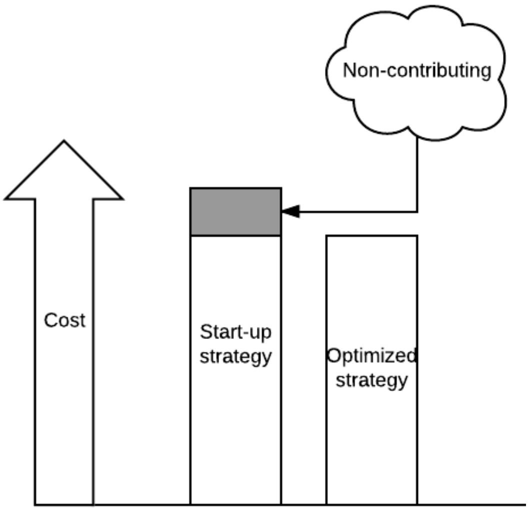


Figure 18 – Non-contributing cost

In the same manner, this applies to the maintenance hours spent. If a system consumes valuable maintenance hours without really contributing, they reduce availability and locks up maintenance personnel from maintaining systems that would benefit from the hours.

Assessment method and optimization

The assessment (Figure 19) is a four-step learning and review process starting with a description of the current strategy. The asset requirements and maintenance strategies are presented to give an overview of status quo. The next steps are driven by the historical maintenance and failure data that are obtained during the period in operation. Step two is to extract the relevant maintenance data from the maintenance log. Step three is to perform the reliability, availability, risk, and cost calculations based of the maintenance data. Step four is to review all the input and output from the previous steps. The review measures the actual performance and compare it to the equipment requirements. The results then functions as the foundation of the optimization process.

The optimization is a three-step method of testing and verification. This starts with building a new maintenance strategy/program based on the review and the new internal and external elements. This part is driven by expertise and experience. For instance, if actual availability shows that you underperform, it is a justification to do changes that will increase availability. Once the new strategy is in place, next step is to predict the new in reliability, availability, risk, and cost. The new RAR and cost will be based on certain assumptions, such as more preventive maintenance lead to less corrective maintenance or similar. Based on the review the assumptions should be able to hold proper accuracy. The new estimates and output should be compared to the existing strategy such that a justified decision of how to proceed could be made.

As mentioned, the assessment and optimization consists of two phases, and Figure 19 show the process of the phases step-by-step. The steps will be described in further detail.

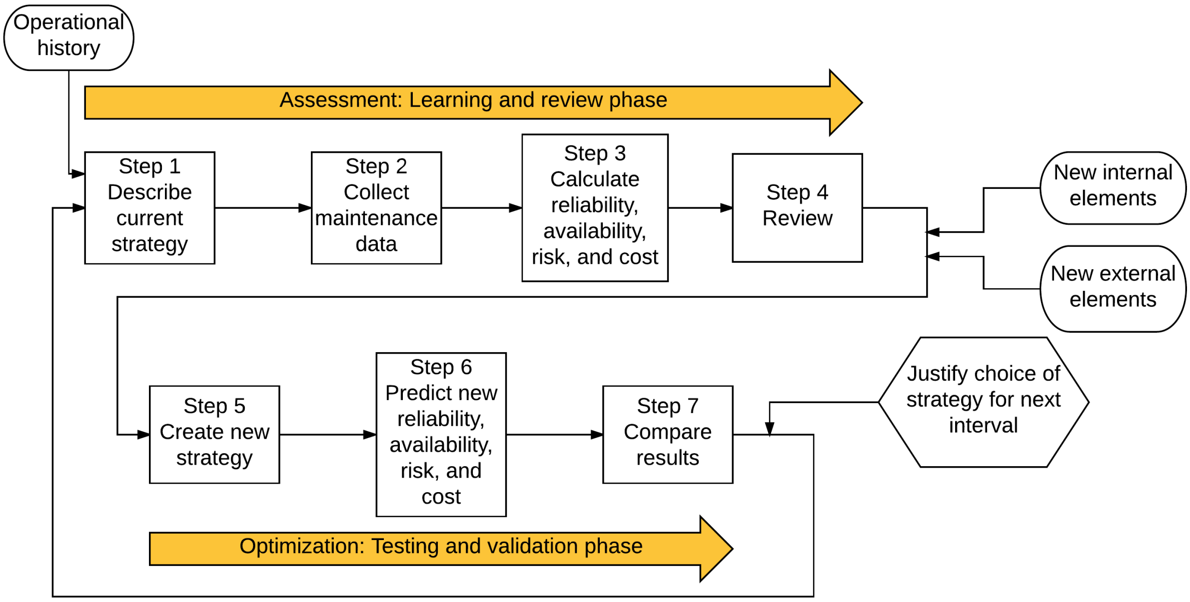


Figure 19 – Assessment and optimization framework

Step 1 - Describe current maintenance strategy

A description of the current maintenance strategy should be the foundation of the assessment. The input to this step is the outcome of step one to four in the prerequisites. The essential information is the asset requirements, the maintenance strategy and program, and their intervals. This information is necessary for both calculating the performance gaps, and for knowing what to optimize.

Step 2 - Collect maintenance data

To be able to assess the current strategy, failure and maintenance data needs to be collected such that the status quo can be analyzed. As described in the prerequisites, step six; a proper logging tool has to be designed to capture the relevant data. The data needs to be selected carefully to capture what's relevant for the system and facility. A common tip is to ask why the data is needed. If there is no good reason, maintenance personnel should not be overloaded with unnecessary work.

The pure minimum of data to record for performing this analysis is:

- Start date
- Failed object
- Main tag the object is connected to
- Type of maintenance (preventive or corrective work)
- Shutdown description
- Maintenance description
- Failure mode (only for corrective work)
- System downtime
- Equipment downtime
- Maintenance/Repair time
- Number of workers repairing or maintaining

"Start date" is used to pinpoint when the maintenance and failure found place, and to estimate machine life (time since installation). "Main tag" and "failed object" is used to identify where and which component that failed. The reason for recording both is to see if there is a specific main component that fails more than the others, and if there is a specific object in that component that is the troublemaker.

"Type of maintenance" is relevant to record to see the ratio of preventive and corrective work, and if either one of them dominates in reducing availability. "Shutdown description" is recorded using pre-defined descriptions which are: System operating, no shutdown, equipment shutdown, and system shutdown. System operating means the system has to be in operation when the maintenance is performed. No shutdown means the system can remain as is, whether running or not, while the maintenance is performed. Equipment shutdown means the equipment that will receive maintenance needs to be shut down, but the system may still operate. System shutdown means the full system needs to be shut down during the maintenance.

"Maintenance description" is a short description of what maintenance/repair that is performed. This could be a 6-months routine on compressor A, or fixed valve-leak in air dryer B. Failure mode is used to record the effect of failure, and to show the dominating effect of failure for the system.

"System downtime" is the time in hours the system is out of function, and used for calculating the availability of the system. "System downtime" should not be mistaken with "equipment downtime", because many systems have redundancies that allow a system to stay in operation even though a component fail. "Equipment downtime" is the time in hours the equipment is out of function. "Maintenance/Repair time" is the time in hours the whole maintenance crew uses to maintain and repair to a good-as-new state. "Number of workers", in combination with repair time, will yield the man-hours the maintenance crew used.

Step 3 - Reliability, availability, risk, and cost calculation

Depending on the asset under consideration there are different ways of doing the reliability calculations. If a system or equipment is up for review there is at least two ways of assessing it. First, is assessing the asset as a whole, where the asset function or not. All failures are reviewed at asset level, and the asset is assigned a suitable probability distribution. Second, is breaking the asset down to equipment/component level and assessing each part separately, and then rebuilding the asset. Each single part could have a different probability distribution. For this approach, the Reliability-Block Diagram method is suitable to break down the asset.

Identify lifetime distribution model

The calculations start by finding the best suited lifetime distribution model. The exponential and Weibull distribution are the most common models. Other distributions such as the Gamma distribution, the Normal distribution, or the Log-normal distribution could be used. According to Barringer (2013), the Weibull distribution and the Log-normal distribution are the best suited models for most failure data.

A method to identify the underlying lifetime distribution is by using probability plots. The probability plot will let you graphically evaluate the fit of your dataset and distribution. A similar method is hazard plotting, which is performed by plotting the cumulative hazard rate and graphically identifying the fit of the lifetime distribution. Otherwise, goodness-of-fit models could be used for a more mathematical approach. Some common goodness-of-fit models are:

- Anderson-Darling test
- Kolmogorov-Smirnov test
- Cramér-von Mises criterion
- Shapiro-Wilk test
- Akaike information criterion
- Hosmer-Lemeshow test
- Regression analysis
- Chi-squared test

Upon finding the best suited distribution model, the corresponding distribution parameters are defined either graphically or mathematically depending on the method of distribution identification.

Reliability and Availability

Calculating the reliability could be performed for a given maintenance interval or an interval spectrum. It may be beneficial to calculate both to see the reliability and the distribution characteristic for the spectrum.

The measures MTTF and MTBF derive from the corresponding distribution model's expected time to failure. Every distribution model has their unique formula for calculating the expected time to failure. MTTM and MTTR derive from the maintenance data, where MTTM are the common term for preventive maintenance and MTTR for corrective maintenance. The availability can be estimated by dividing MTTF by MTBF. The true availability could be calculated if the maintenance data contains the time the system have been out of operation. If the system contains redundancy, the estimated availability might deviate from the true availability.

Consequence probabilities

The consequence probabilities are based on the probability of a failure during the maintenance interval, which is equal to the cumulative distribution function at time t (assuming only one failure can happen before the asset is repaired).

$$P(failure) = F(t) = 1 - R(t)$$

The consequence probability is on the form:

$$P(consequence\ A) = \\ P(consequence\ A|\ case, failure) \ * \ P(case\ |\ failure) \ * \ P(Failure)$$

A "case" is hereafter used for the type of failures that have a consequence of significance (i.e. more than just a repair). P(case|failure) and P(consequence A|case, failure) could either be assumed qualitatively or be based on failure data. P(case|failure) is used to describe how many failures, out of all the failures, that lead to some sort of consequence other than just a repair. This factor may be removed. For instance, if there exists data on how many failures that led to a consequence A, the probability of consequence A is reduced to:

$$P(consequence\ A) = P(consequence\ A|failure) * P(failure)$$

Redundancy needs to be accounted for, because a system may have equipment failures without loosing its function. Therefore, it should be defined how the asset might cause consequences.

Risk calculation

The risk is calculated as the consequence probability multiplied with the cost of the corresponding consequence. Risk could also be used for non-monetary units such as human lives. Due to the way of calculating consequence probabilities, the risk is per interval. The expected loss is the sum of all the risks, and equals the average loss per interval in the long run. As aforementioned, "one should never expect the expected value". An investment, or maintenance measure, is deemed beneficial if the cost is lower or equal to reduction in expected loss. This means you can spend an amount up the expected loss to prevent failures from leading to consequences. If an amount equal the expected loss where spent, the probability of having a consequence should be 0%.

Cost calculation

Cost calculation is based on the maintenance data. Cost of the current strategy shall be calculated, as it is an essential part when justifying a strategy. In the setting of maintenance, common cost drivers are:

Preventive maintenance cost drivers

- Personnel cost (employed staff)
  - Salary
  - Personnel training
- Planning and reporting
  - MHr (onshore & offshore)
  - CMMS tool cost
  - Accounting
- Execution cost
  - Special tools
- Material cost
  - Spares
  - Consumables
  - Storage
  - Transport
  - Handling
- Cost of deferred production

Corrective maintenance cost drivers

- Call out personnel (Experts)
  - MHr cost
  - Transport cost
  - Boarding and lodging cost
- Personnel cost (employed staff)
  - Salary
  - Personnel training
- Planning and reporting
  - MHr cost
  - Accounting
- Execution cost
  - Special tools
  - Overhaul (onshore, incl. transport)
- Material cost
  - Spares
  - Consumables
  - Lead time
  - Storage
  - Transport
  - Handling
- Cost of deferred production

Condition monitoring cost drivers

- Equipment cost
  - Online based eq. (Sensors, etc.)
  - Offline based eq. (thermal camera, oil analysis, etc.)
  - Operations cost (server, database, etc.)
  - Equipment maintenance (calibration, etc.)
- Monitoring cost
  - MHr online
    - Internal MHRs
    - External MHr cost
  - MHRs offline (offshore inspections, etc.)
    - Internal MHr cost
    - External MHr cost
- Lab analysis cost
  - Oil analysis
- Planning and reporting
  - MHr cost
  - Accounting

Cost calculations may be performed in three steps: first the man-hour cost, second the spare part consumption, and third the logistic and support cost. If an element has connected overhead cost, it can be added to that element (e.g. 2% overhead on each man-hour for personnel training). The total man-hour cost is calculated by the sum of:

$$PM\ MHr\ cost = Number\ of\ PMs\ performed * MHr's * MHr\ rate$$

$$CM\ MHr\ cost = Number\ of\ CMs\ performed * MHr's * MHr\ rate$$

And

$$Condition\ monitoring\ MHr\ cost = MHr's * MHr\ rate$$

Similarly, the spare part consumption cost is calculated separately for both preventive and corrective maintenance. If the condition monitoring equipment detects deviation, it is assumed handled by preventive maintenance. There are events that will be performed as corrective maintenance as well. The total spare part consumption cost is calculated by the sum of:

$$PM\ spare\ part\ consumption\ cost = Number\ of\ PM * Avg.\ PM\ spare\ part\ cost$$

And

$$CM\ spare\ part\ consumption\ cost = Number\ of\ CM * Avg.\ CM\ spare\ part\ cost$$

Spare parts carry an overhead cost deriving from the transport, storage, and handling. Usually, overhead makes up an substantial amount, and de Decker (1998) suggest somewhere in the range of 16% to 42%. The total material overhead is calculated by the sum of:

$$PM\ material\ overhead\ cost = PM\ spare\ part\ consumption\ cost * PM\ overhead\ percentage$$

And

$$CM\ material\ overhead\ cost = CM\ spare\ part\ consumption\ cost * CM\ overhead\ percentage$$

Each work order, preventive or corrective, drives an overhead cost of planning and reporting of the maintenance work. If there are indirect costs of planning and reporting, it could be added to the element it is driven from (i.e. either per work order or per man-hour). The total planning and reporting cost is calculated by the sum of:

$$PM\ planning\ and\ reporting\ cost = Number\ of\ PM * MHr's\ per\ WO * MHr\ rate$$

And

$$CM\ planning\ and\ reporting\ cost = Number\ of\ CM * MHr's\ per\ WO * MHr\ rate$$

One of the basic ways of calculating deferred production is:

$$Cost\ of\ def.production = Number\ of\ WO * MTTM/R * cost\ of\ one\ def.production\ hour$$

The cost of deferred production requires consideration as many systems have redundancy, which means they might stay in operation during maintenance and repair.

Step 4 - Review the current strategy

The review should present the main figures/results from step 3 for a total overview. That is: machine life, system downtime, current maintenance interval, MTTF/MTBF, MTTR/M, availability, reliability, maintenance cost, expected loss, and risk spectrum. These figures could also be presented as curves in a plot for an interval spectrum to see their characteristics.

Performance should be checked against the asset requirements to reveal potential performance gaps. Performance gaps could be a variety of measures and are not limited to MTTF/MTBF, reliability, availability and budget. The actual performance should be compared to the expected performance for this part of the asset life, as expected performance might be different than the asset requirements. The ratio of preventive and corrective work should be determined to see if either one of them significantly reduces availability.

Failure mode plot, main tag plot and object tag plot should be used to reveal failure trends.

- Number of failures per failure mode
- Number of failures per main tag
- Number of failures per object tag

They are useful because they are able to show trends of failure causes, faulty components, and/or incorrect maintenance. If certain failure modes are dominating, this might be a result of an inappropriate maintenance strategy. Similarly, if a main component or object fails frequently this might stem from the lack of attention, or simply that it is a faulty part.

If the plots show a trend or returning problem, action should be taken to handle these. The result of the current strategy acts as the basis for the new strategy where measures/activities are added or removed.

Step 5 - Create new maintenance strategy

There does not exist a single "best strategy" throughout the lifetime. The needs and circumstances will change several times in the asset life, and the strategy should therefore be updated accordingly. An integrated maintenance strategy shall align with the business and asset objectives.

To have proper quality in the optimization process, maintenance experts and operators should be included. Another reason to include them, are to make for acceptance of changes and continuous improvement.

Based on the assessment process, the review of the current strategy should give an indication of the most beneficial modifications. Actions could be new risk barriers, better suited maintenance activities, better spare part management, condition monitoring equipment, or other maintenance regimes that are deemed more suitable.

First question should be: Does the maintenance regime cover the typical failures? If not, does it cover anything else? Upon very few failures, with no clear trend the failures could be deemed as random, but the strategy might still benefit from an update. For instance, if the asset is over-maintained, an update might lead to cost savings without sacrificing performance or safety.

Second question is: Are there any new internal or external factors affecting the maintenance strategy?

Change management has become a field of it's own because organizational dynamics have become so demanding. By change there also emerges challenges such as forecasting and predicting technical development, market conditions, company resources, and capabilities.

Management is also seeing changes, both at business and technical level. Independent of the level the change happens, the organization will have to be flexible and agile to maintain performance. Value-creation is no longer only a financial aspect. Stakeholders require value to be created in financial, environmental and social (triple bottom line) direction. Maintenance, and the ability to maintain asset integrity will be a major factor contributing to building value through production performance and HSE. Companies, and subsequently the organization within, have to work towards objectives that are able to bring performance towards the triple bottom line. Decision-making is no longer based on the financial figures, but rather a compromise of cost, risks, and benefits.

Because changes happen continuously, improvements also have to happen continuously. Recording maintenance and failure data and recognizing internal and external change enable continuous improvement.

Figure 20 shows issues that are likely to change during the asset life. The internal and external elements need to be aligned with the asset objectives, since these factors influence the feasibility and performance of the maintenance strategy.

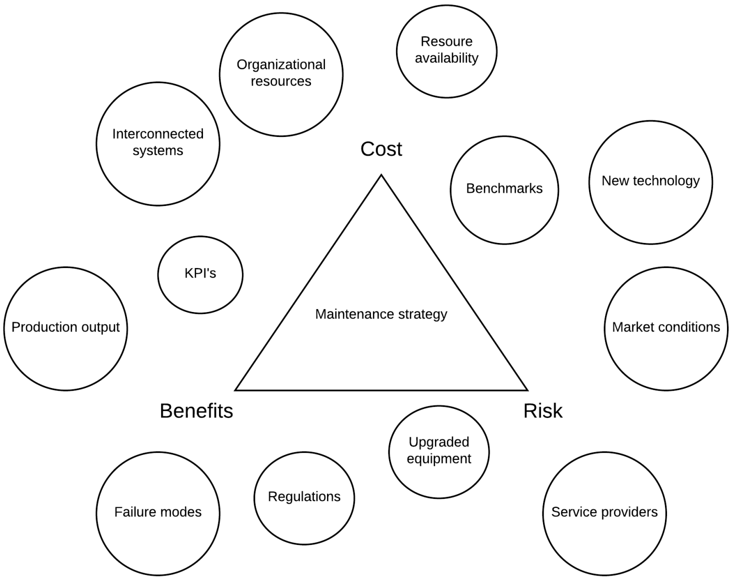


Figure 20 – Affecting factors in the optimization process

The following lists for both internal and external factors are adapted from ISO 55002 (P.3-4). The list items are adaptable to “affecting factors in a maintenance optimization process”, even though they are used by ISO 55002 in a different context.

Adapted from ISO 55002, the internal changes are, but not limited to:

- *Governance requirements*
- *Organizational structure, roles, accountabilities and authorities*
- *Policies, objectives, and the strategies that are in place to achieve them*
- *Resources and knowledge (e.g. capital, time, people, systems, and technologies)*
- *Information systems, information flows, and decision-making processes*
- *Relationships with, perceptions of, and values of internal stakeholders*
- *The culture in the organization*
- *Standards, guidelines, and models adopted by the organization*
- *The form and extent of contractual relationships*
- *Risk management*
- *Asset management practices and other management systems, plans, processes, and procedures*
- *Integrity and performance of the assets and asset systems*
- *Learning from investigation of previous asset and asset system failures, incidents, accidents, and emergencies*
- *Feedback from previous self-assessments, internal audits, third party reviews, and certification reviews*

(ISO, 2014c)(P.3-4)

Additional internal changes are: production output, KPI’s, interconnected systems/equipment, upgraded/new equipment, failure modes, maintainability, expected performance, and expected life. For instance, if the headcount in the organization is changed this might affect the feasibility of certain maintenance tasks. If a maintenance expert is lost, some maintenance activities might have to be outsourced to a service provider. Maintainability is also an important factor, because the people performing the maintenance should be able to do so in a safe and healthy way. The techniques for performing maintenance might change during the lifetime of the asset and are an important consideration during optimization.

Adapted from ISO 55002, the external changes are, but not limited to:

- *The social and cultural, political, legal, regulatory, financial, technological, economic, competitive and natural environment at international, national and local level*
- *Key drivers and trends having impact on the objectives of the organization*
- *Relationships with, perceptions of, and values of external stakeholders*

(ISO, 2014c)(P.3)

Certain changes are optional to adopt, but others are forced on the operator and have to be handled. For instance, if new technology becomes available but does not bring any benefit, it should not be acquired. If material availability change, the operator have to adapt because this is out of their hands and the change affects the maintenance strategy directly.

Step 6 - Predict new Reliability, Availability, Risk, and Cost

The question for this step is: how will the new strategy affect these figures? Will these figures remain the same, increase, or decrease? This part requires expert judgments, as these assumptions have to be tested for a new period before they can be verified. After several optimizations, a knowledge base is built and should be used for future optimization.

There are several ways of assuming the new reliability, availability, and risk. There should be a link between the updated strategy and these figures. For instance, if VIB (vibration) is the dominating failure mode, and the new strategy have implemented measures to remove all these failures, the failure characteristics could be simulated by removing all the failures connected to the failure mode VIB. This should yield new parameters and calculated results. While this approach is at the parameter level, another approach could be to just assume the new reliability, availability, risk, and directly without calculations.

If the changes affect the consequence probabilities, they should be updated accordingly. For instance, if new condition monitoring equipment is assumed to reduce the likelihood of a very serious case, the probability should be updated to reflect the change.

When the new strategy and assumptions are defined, the cost is calculated the same way as previously described. By updating the number of expected preventive maintenance, corrective maintenance, and condition monitoring man-hours, the same equations are applicable to predict the cost. If more complicated adjustments are made, the cost equations might need to be changed.

Step 7 - Comparison

The reason for comparing the results is to justify the changes through reliability, availability, risk, and cost in combination with internal and external changes. The results of the comparing strategies shall be listed to show increases and decreases in the different areas. Often, one strategy performs better in one area and worse in another, such as reducing cost may result in lower reliability. As long as the lower reliability is accepted, the results are justified by the improved cost. Compromises shall always be justified by the objectives, current status and the asset requirements.

After next period (e.g. one year) under the optimized strategy, the maintenance data will verify if the predictions and assumptions were accurate. Then the learning should enable better accuracy during the next optimization process.

Chapter 4 – Case study

The purpose of this chapter is to show the relevance of the assessment method. The method was applied to data from an asset at an offshore facility on the NCS. The data was provided by Apply Sørco as an test case. The asset is a compressed air system, referred to by the operator as system 63. The field and operator are confidential, and the information will be referred to as “reference information” or similar.

System 63 – Compressed air system

The test case was chosen because Apply Sørco recognized it had seen a lot of failures. The compressed air system is not considered critical, and has little condition monitoring. While Apply Sørco is familiar with this type of system, they seldom experience this many failures in such a short time. The system experienced 22 failures in approximately 17 months, causing nine equipment shutdowns, and one system shutdown.

The function of system 63 is to deliver dry and filtered air, which is free of oil. There are requirements to the pressure, temperature and dewpoint of the air. The compressed air is distributed to instruments, nitrogen production, and work-air (e.g. air-driven tools).

Process description

The compressed air system is made up of 3x50% air compressors, 2x100% air dryer packages, and a 1x100% air receiver. The system is capable of running all three compressors when both air dryers are in operation.

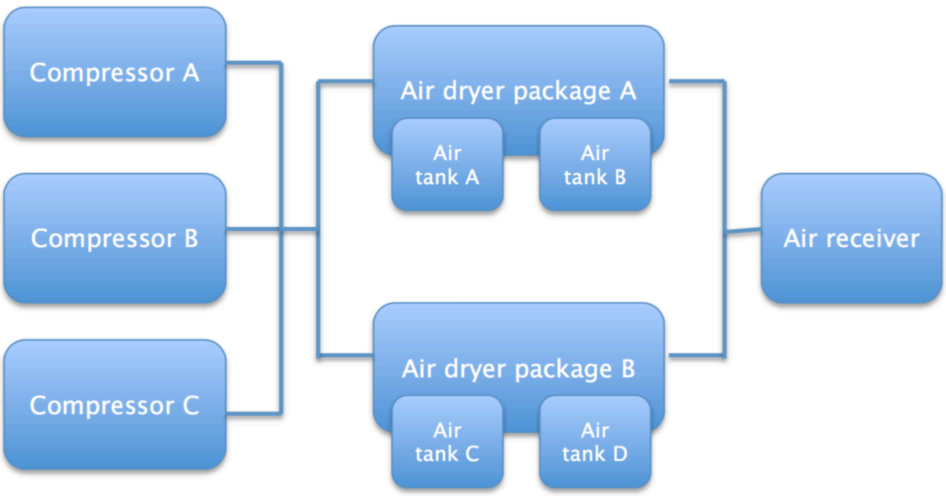


Figure 21 – Process description for System 63

The distribution priority for the compressed air is:

1. Instruments
2. Nitrogen production
3. Work-air

Air for nitrogen production and work-air will in events of low pressure be closed to prioritize the instrument air. In the analysis, the system is assumed working or not working.

Each compressor has a capacity of 1700 Sm^3/hour, with output pressure and temperature of 11 barg and 20˚C. From the compressors, the air is led to the air dryer packages that have two tanks each. The configuration is such that one air dryer tank is in in operation while the other regenerates (the other air dryer package is standby). Each air dryer tank handles 3000 Sm^3/hour. The dry air is led to the air receiver that has capacity to supply the instrument air-system for 5 minutes without air-supply from the compressors.

System assessment

The system is placed on a relatively new facility with limited time in operation. For these reasons the reference data are a bit inconsistent, poorly recorded, and represents mostly the "burn-in" phase of the system.

Spreadsheet application

The measurable parts of the method were built in MS Excel, a spreadsheet software. A spreadsheet application was built such that the reliability, availability, cost, and risk analysis was calculated and illustrated graphically in a more automated and seamless process. The application, as of now, is only suited for the assessment of system 63, but may be built to handle all types of systems. The application relies on the input from the requirement analysis, maintenance and failure data, and manual parameter estimation. Based on this, the spreadsheet application calculates the results and plots in the case study. The output will be presented in the following sections. While the assessment process is more or less automated, the analysis of the optimized strategy requires manual adjustment of the input data. Little effort was put in to automating the analysis of the optimized strategy due to the endless ways of predicting the input. A partial view of the application is shown in Figure 22, as it contains several sheets.

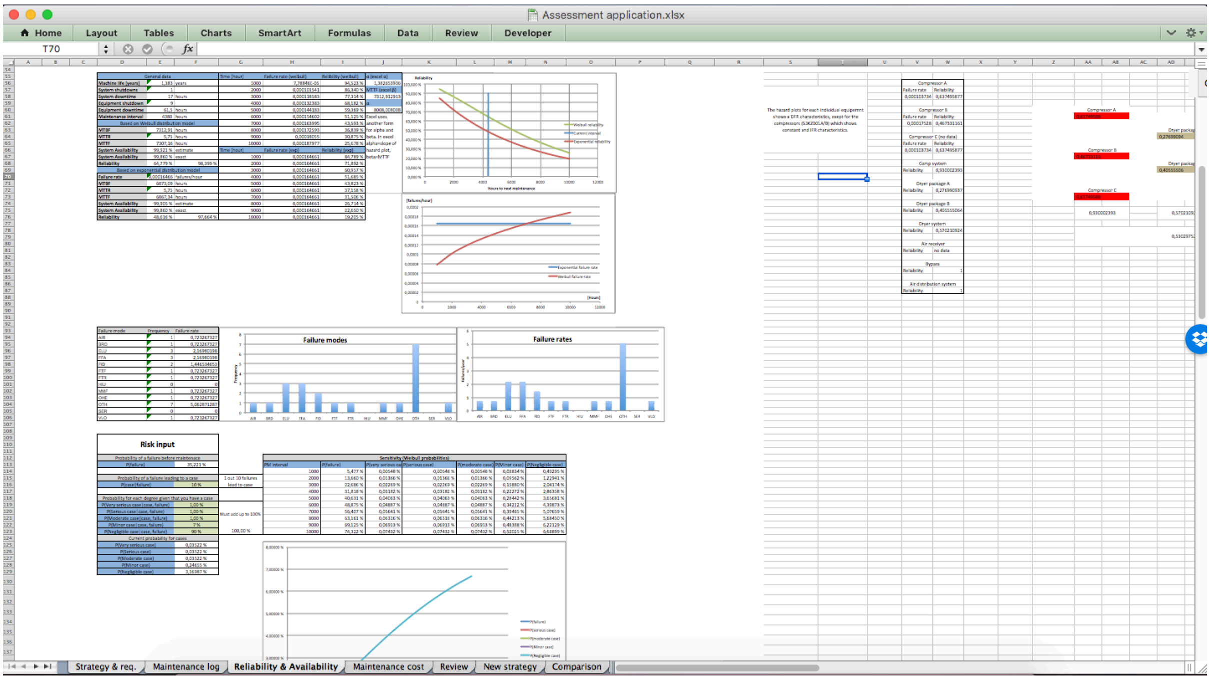


Figure 22 – Partial view of spreadsheet application

Simplifications and assumptions

Simplifications had to be done, mostly because the data was missing or unavailable. The reference data lacked a lot of the prerequisites, and the only available information was the maintenance routines and the maintenance log. Asset requirements, cost rates and consequence costs had to be assumed. The internal and external elements could neither be assumed, nor assessed. The analysis was therefore aimed at the cost, risk, and benefit factors.

Assumptions:

- The period under assessment used in case study is the whole system life, approximately 17 months.
- The failure happened at or close to the date of the corrective maintenance
- The whole system is maintained during a short period of time (e.g. within a week).
- The preventive maintenance interval starts at t=0 for all components.
- The system is working or not working.
- Only one failure can happen before repair is performed.
- No cost of deferred production

Step 1 - Current strategy and requirements

The current strategy for the selected test case is a preventive maintenance program with condition monitoring for certain parts. Corrective maintenance is performed upon failures. All three components have daily operational inspections and risk based inspections. In addition, the compressors and the air dryer skid have preventive maintenance programs consisting of a 6 and 12-months routine as well as a 60-months overhaul.

The condition monitoring equipment consists of vibration and parameter monitoring. This equipment is covered by a 12-months routine. The parameter monitoring is connected throughout the whole system, but only the air compressor units utilize vibration monitoring.

Compressor packages 63KZ001A/B/C	6-12-60 months routine 1200 hours lubrication service Daily operational inspections Risk based inspections Condition monitoring
Air dryer skid 63XX001	6-12-60 months routine Daily operational inspections Risk based inspections Condition monitoring
Air receiver	Daily operational inspections Risk based inspections Condition monitoring
Condition monitoring equipment	12 months routine
PSV valves	12 months routine

The asset requirements for the system are not available and will have to be assumed. For this assessment the required **availability** is set to **98%** and required **reliability** to **90%.** The availability is based on continuous operation for a full year (8760 hours). **Maintenance budget** is set to **800.000 NOK** per year, and **expected lifetime** is set to **30 years**.

Step 2 – Collect maintenance data

The operating company's reporting system is not fully implemented due their short time in operation, and therefore, the historical data has some shortcomings. The process of creating a logging tool needs to be reversed to capture and remove data.

For the case study, the list below shows the relevant data for the analysis. The data is recorded using the MS Excel software, and imported from the reference data. Due to the inconsistency in the reference data, some adjustments have been made.

- Start date
- Date finished
- Days to complete (auto generated in excel)
- Main tag
- Failed object
- Type of maintenance
- Shutdown description
- Maintenance description
- Failure mode
- System downtime
- Equipment downtime
- Repair time
- Number of men
- Machine life (auto generated in Excel)
- Discipline

"Start and finish date" is used to pinpoint when the maintenance and failure found place, to estimate the time to finish the maintenance, and to estimate machine life (time since installation). "Main tag" and "failed object" is used to identify where and which component that failed. The reason for recording both, is to see if there is a specific component that fails more than the others, and if there is a specific object in that component that is the troublemaker.

"Type of maintenance" is recorded to see what kind maintenance that dominates in reducing availability. "Type of maintenance" is useful for programming purposes in Excel, and is recorded using the pre-defined descriptions CM (corrective maintenance), CMSD (corrective maintenance with system shutdown), PM (preventive maintenance), and PMSD (preventive maintenance with system shutdown). "Shutdown description" is recorded using pre-defined descriptions, also for programming purposes. The pre-defined options are: System operating, no shutdown, equipment shutdown, and system shutdown. System operating means the system has to be in operation when the maintenance is performed. No shutdown means the system can remain as is, whether running or not, while the maintenance is performed. Equipment shutdown means the equipment receiving maintenance needs to be shut down, but the system may still operate. System shutdown means the full system needs to be shut down during the maintenance.

"Maintenance description" is a short description of what maintenance/repair that is performed. This could be 6-months routine on compressor A, or fixed valve-leak in air dryer B. "Failure mode" is used to record the effect of failure, and to show the dominating effect of failure for the system.

"System downtime" is the time in hours the system is out of function, and used for calculating the availability of the system. "System downtime" should not be mistaken with "Equipment downtime", because many systems have redundancies that allow a system to stay in operation even though a component fail. "Equipment downtime" is the time in hours the equipment is out of function. "Maintenance/Repair time" is the time in hours the whole maintenance crew uses to maintain and repair the failed object. “Number of workers”, in combination with repair time, will yield the man-hours the maintenance crew used. “Machine life” is generated in Excel by the start date of the maintenance, and the installation date of the system. The machine life is used in the reliability calculations. Discipline is recorded by the pre-defined options: Mechanical, Electrical, and Automation. This is relevant for seeing the required competence for the performed maintenance.

Step 3 - Reliability, Availability, Risk and Cost calculation

The system is assessed as a whole, and not broken down to equipment level. The theoretical foundation for the calculations is explained in chapter 2 and 3, together with the corresponding equations.

Hazard plot

To find a suitable lifetime distribution, the method of hazard plotting was used. By using Excel, the corrective maintenance data is listed in ascending order by the machine life at failure (see Appendix A3.1.1 for plotting data). The Nelson estimator is calculated from:

$$\hat{Z}(t) = \sum_{j:\delta_j=1,T_j \leq t} \frac{1}{n-j+1}$$

Further, the hazard plot is plotted by the cumulative hazard rate (Y-axis) and the machine life (X-axis).

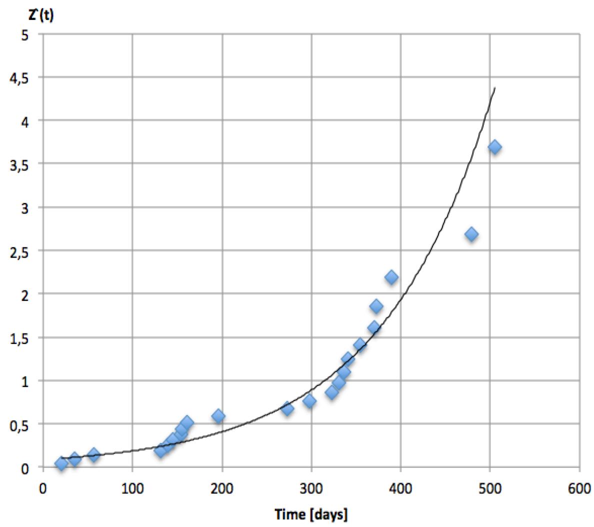


Figure 23 – Cumulative hazard plot for system 63

The trend curve in Figure 23 shows an increasing failure rate (IFR), which imply that the exponential distribution is not suited for modeling reliability. The IFR is not corresponding to the burn-in phase, but rather a system that deteriorates. An IFR suggests doing a logarithmic hazard plot, and calculating the logarithmic values of T and $\hat{Z}(t)$ yields the plot:

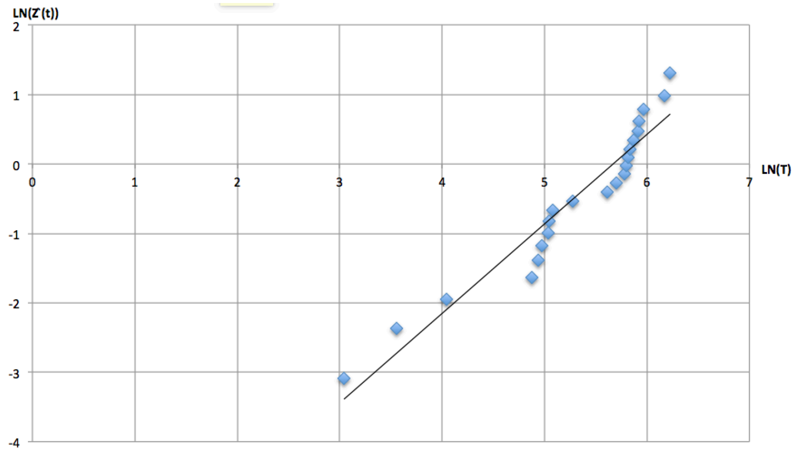


Figure 24 – Logarithmic cumulative hazard plot

The linear characteristic in Figure 24 suggests that a weibull distribution is suited for modeling the lifetime of the system. Graphical estimation yields β=1,3826 and α = 8008 and MTBF = 7313 hours.

Reliability and Availability calculations

Using the Weibull function in Excel, the reliability for next maintenance interval is calculated. Figure 25 shows the reliability of both the Weibull distribution and the exponential distribution for the next maintenance interval.

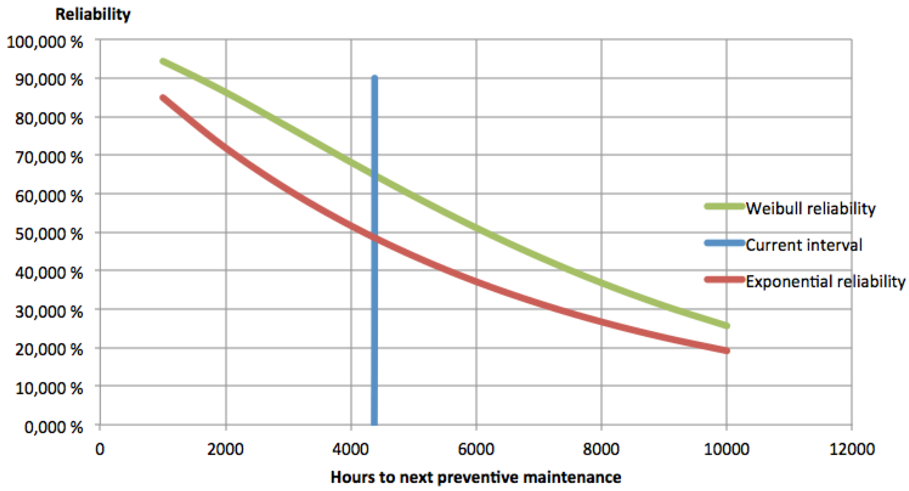


Figure 25 – Reliability plot

The current maintenance strategy is to perform preventive maintenance every sixth month (for most parts), 4380 hours, which yields a Weibull reliability of ≈ 65% according to the calculation. The machine life is approximately 17 months, and the system has seen one system shutdown, nine equipment shutdowns. This results in a MTBF of 7313 hours, MTTR of 5,75 hours, and a system availability of 99,86%. The plot shows the importance of using the best-suited distribution model as the exponential distribution shows substantial deviation. Comparable estimates are presented in the Appendix A3.1.2.

The calculations have a weakness; because this system is built with redundancy the estimates only show the characteristics of equipment failure. The redundancy in this system has avoided system shutdowns 21 out of 22 times, and therefor the reliability of the system to perform its function is a lot higher. By combining the P(failure)=F(4380) and P(function loss|failure), yields a probability of system functioning until time t ($R_{SF}(t)$):

$$R_{SF}(4380) = 1 - F(4380) * P(function\ loss \mid failure)$$

$$R_{SF}(4380) = 1 - 0{,}35221 * \frac{1}{22} = 0{,}98399 = 98{,}399\%$$

The calculations use the Weibull distribution and the frequentist probability of 1 out of 22 failures leading to loss of function. $R_{SF}(t)$ will be in the range [95,45%,100%] because of the assumption that only one failure can happen before the system is repaired to a good-as-new state.

Consequence probabilities

Assuming that a failure doesn't require loss of function to have a consequence, P(failure) is used for calculating risk probabilities. For different conditions, $R_{SF}(t)$ could have been used instead. Figure 26 shows the calculation of the consequence probabilities. The green fields mark an assumed probability.

Probability of a failure before maintenace	
P(failure)	35,221 %
Probability of a failure leading to a case	
P(case|failure)	10 %
Probability for each degree given that you have a case	
P(Very serious case|case, failure)	1,00 %
P(Serious case|case, failure)	1,00 %
P(Moderate case|case, failure)	1,00 %
P(Minor case|case, failure)	7 %
P(Negligible case|case, failure)	90 %
Current probability for cases	
P(Very serious case)	0,03522 %
P(Serious case)	0,03522 %
P(Moderate case)	0,03522 %
P(Minor case)	0,24655 %
P(Negligible case)	3,16987 %

Figure 26 – Consequence probabilities

The probability of failure before next maintenance (F(4380)) equals 35,221%. P(case|failure) is assumed to be: 1 out of 10 failures lead to a case (10%). The probabilities of each degree of severity are assumed in the same manner. For instance, 1 out of 100 failures that lead to a case, are "very serious" (1%). The logic of the calculation is shown in Figure 27.

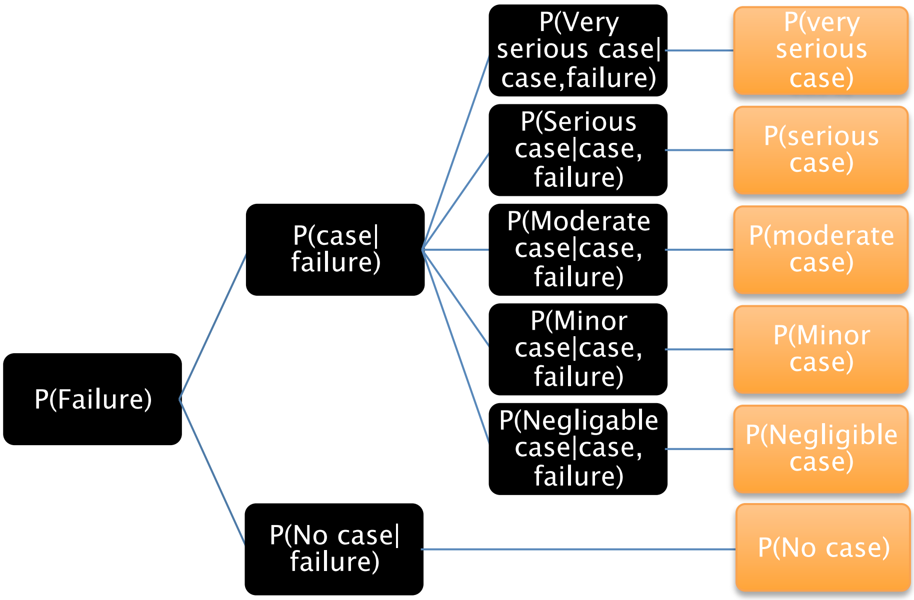


Figure 27 – Event tree

The probability of each degree of severity can be calculated using the rules of conditional probabilities:

$$P(very\ serious\ case) = 35{,}221\% * 10\% * \ 1\% = 0{,}03522\%$$

Risk calculation

Figure 28 shows the risk spectrum and expected loss for the current reliability. The green fields are the estimated costs for each case, and the column to the right is the connected risk.

Severity	Probability	Consequence cost	Risk cost	Expected cost
Very serious case	0,03522 %	kr 1 000 000 000,00	kr 352 207,72	kr 574 098,58
Serious case	0,03522 %	kr 500 000 000,00	kr 176 103,86	
Moderate case	0,03522 %	kr 50 000 000,00	kr 17 610,39	
Minor case	0,24655 %	kr 5 000 000,00	kr 12 327,27	
Negligible case	3,16987 %	kr 500 000,00	kr 15 849,35	

Figure 28 – Risk costs and expected loss

The risk costs are what make up the risk spectrum, and the expected loss per maintenance interval is 574.099 NOK. This is caused by the more severe cases that have high cost of consequence.

Cost calculation

Figure 29 shows the man-hour cost at system 63, where the green fields are assumed numbers. Man-hour rates and condition monitoring data where not given in the reference data. Kayrbekova (2011) estimates a man-hour rate of 650 NOK at the NCS, which is hereafter used in the cost calculations.

PM MHr cost	Number of PM	53	kr	265 200,00
	MTTM [hours]	7,70		
	MHr rate	kr 650,00		
CM MHr cost	Number of CM	22	kr	82 225,00
	MTTR [hours]	5,75		
	MHr rate	kr 650,00		
Condtion monitoring MHr cost	Number of mhrs	20	kr	20 000,00
	MHr rate	kr 1 000,00		

Figure 29 – The man-hour cost for system 63

The major man-hour expense is the cost of preventive maintenance man-hours due to large number of performed work orders. The total man-hour cost is 367.425 NOK.

Figure 30 shows the spare part consumption cost. The average spare part consumption per maintenance is assumed to be 5.000 NOK for preventive maintenance, and 10.000 NOK for corrective maintenance. It is assumed that corrective maintenance spare part cost is twice as expensive as preventive maintenance spare part cost, because a repair is expected to be more extensive than a preventive activity.

PM spare parts	Number of PM	53	kr	265 000,00
	Avg. SP consumption/PM	5000		
CM spare parts	Number of CM	22	kr	220 000,00
	Avg. SP consumption/CM	kr 10 000,00		

Figure 30 – Spare part consumption cost

While the preventive maintenance spare part cost is of the same magnitude as the man-hour cost, the corrective maintenance spare part cost is the major cost-driving element in the total corrective maintenance cost. Total spare part consumption cost is 485.000 NOK.

Figure 31 shows the logistic and support cost. For the material overhead costs, an overhead of 25% is assumed for preventive maintenance spare parts (parts that are expected and planned for) and 30% for corrective maintenance spare parts (de Decker, 1998). The overhead cost for corrective maintenance spare parts is assumed to be 5% higher because these are parts that are difficult to plan for, and might be needed in very short notice. For the same reason, it is assumed that planning and reporting of the corrective work order consume more time (1 more hour) than the preventive work order.

PM Material overhead	Storage	25 %	kr	66 250,00
	Transport			
	Handling			
PM Planning and reporting	#Work orders	53	kr	68 900,00
	Manhours/WO	2		
	Manhour rate	650		
CM Material overhead	Storage	30 %	kr	66 000,00
	Transport			
	Handling			
CM Planning and reporting	#Work orders	22	kr	42 900,00
	Manhours/WO	3		
	Manhour rate	650		

Figure 31 – Logistic and support cost

The preventive maintenance logistic and support cost is only 24% larger than the corrective maintenance logistic and support cost, even though there are performed 2,4 preventive work orders per corrective work order. The total logistic and support cost is 244.050 NOK.

The total maintenance cost, for the period the system has been in operation, is 1.096.475 NOK. That equals an annual average maintenance cost of 793.045 NOK, and an average of 396.523 NOK per maintenance interval.

Step 4 - Review

While the system has seen a lot of failures in its lifetime, the redundancy has still kept the reliability of the system function at a very good level. Even though repairs and reactive maintenance are costly, they are small expenses compared to production-losses and consequence-costs.

System 63 performs better than required in Availability and Budget, while the Reliability underperforms. The required availability, reliability and budget for the period were 98%, 90%, and 1.106.090 NOK. The calculations yielded system availability of 99,86%, reliability of 64,8%, and total cost of 1.096.475 NOK. In addition, calculations yielded MTBF of 7313 hours, MTTR of 5,75 hours, and probability of surviving 6 months without a system shutdown of 98,4%,

The redundancy makes it possible to maintain and repair equipment while the system is in operation. This is the main reason the system is able to meet the required availability. A clarification of why Reliability underperforms is needed, as the performance gap can't account for the redundancy. The reliability of ≈64,8% describes the probability of system 63 surviving the maintenance interval without having any equipment failure. This reliability is used to calculate the expected loss because it is assumed that there could be a consequence-cost upon equipment failure even if the system is able to function. The probability (reliability) of system 63 surviving the maintenance interval without a failure causing system shutdown is much higher, 98,4%. This is because of the redundancy, and therefore, it could be argued that the requirement of 90% reliability is met.

Figure 32 shows the effect on the consequence probabilities when increasing or decreasing the length of the maintenance interval. Especially the probability of a negligible case increases rapidly as the interval is extended.

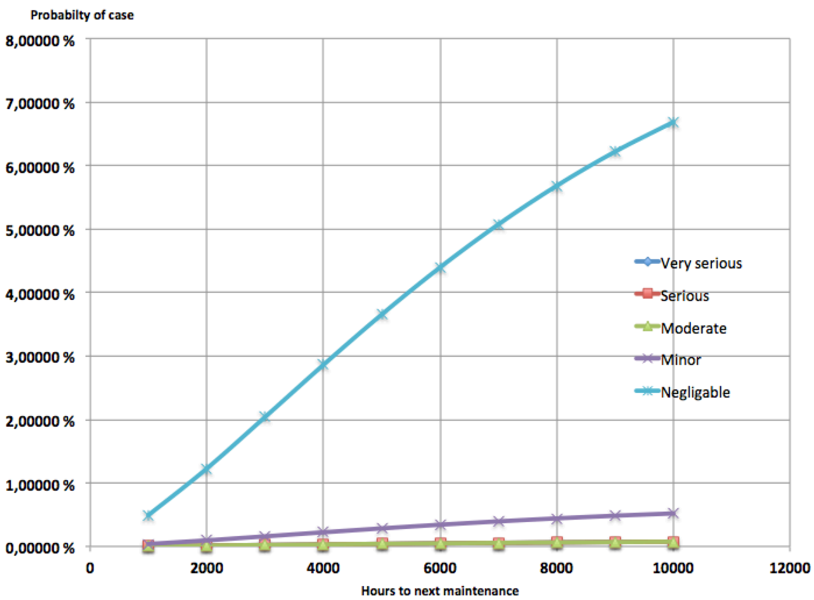


Figure 32 – Probability of case for next maintenance interval

For instance, increasing the maintenance interval from 4000 hours to 8000 hours will increase the probability of a negligible case with nearly 3%. While the more serious cases don't increase that much, their high consequence-costs will still result in a major impact (see Figure 36).

Figure 33 shows each cost driver and the total maintenance cost. The total preventive maintenance cost is 665.350 NOK, for 53 preventive maintenance work orders. The average cost of a preventive maintenance is 12.554 NOK. The total corrective maintenance cost is 411.125 NOK, for 22 corrective maintenance work orders. The average cost of a corrective maintenance is 18.688 NOK.

PM Manhour cost	kr 265 200,00	PM spare parts	kr 265 000,00	PM logistic support cost	kr 135 150,00
CM Manhour cost	kr 82 225,00	CM spare parts	kr 220 000,00	CM logistic support cost	kr 108 900,00
Condtion monitoring manhour cost	kr 20 000,00	Total cost		kr	1 096 475,00

Figure 33 – Maintenance cost

The major cost drivers are the preventive man-hour cost, and the preventive and corrective spare parts cost. The large number of work orders drives the preventive costs, and the corrective costs are driven by the more expensive nature of repairs. Calculations show that a corrective maintenance is on average 49% more expensive than a preventive maintenance. Of the total number of work orders, 70% is preventive maintenance and 30% is corrective maintenance. The total maintenance cost is 1.096.475 NOK

Figure 34 shows the expected loss and risk spectrum per maintenance interval for the current strategy. The expected loss could either be improved by doing measures that prevent all types of cases, or just prevent the cases that contribute the most to the expected loss.

Risk spectrum		
Very serious case	kr	352 207,72
Serious case	kr	176 103,86
Moderate case	kr	17 610,39
Minor case	kr	12 327,27
Negligible case	kr	15 849,35
Expected loss	kr	574 098,58

Figure 34 – Expected loss and risk spectrum

Measures towards the very serious and serious case should be taken such that the expected loss gets lowered.

The expected loss for the different interval-lengths is presented in Figure 35, and the connected risk spectrum is presented in Figure 36.

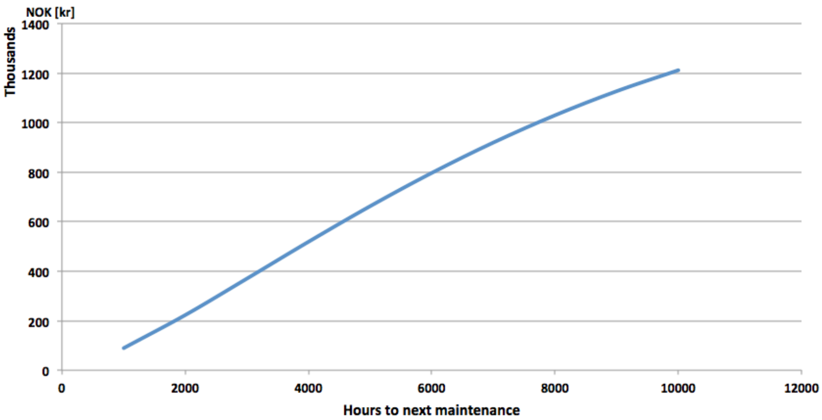


Figure 35 – Expected loss for next maintenance interval

Figure 35 shows that increasing the interval by 1000 hours increases the expected loss by approximately 140.000 NOK until the interval reaches 7000 hours, then the ΔExpected loss gradually decreases.

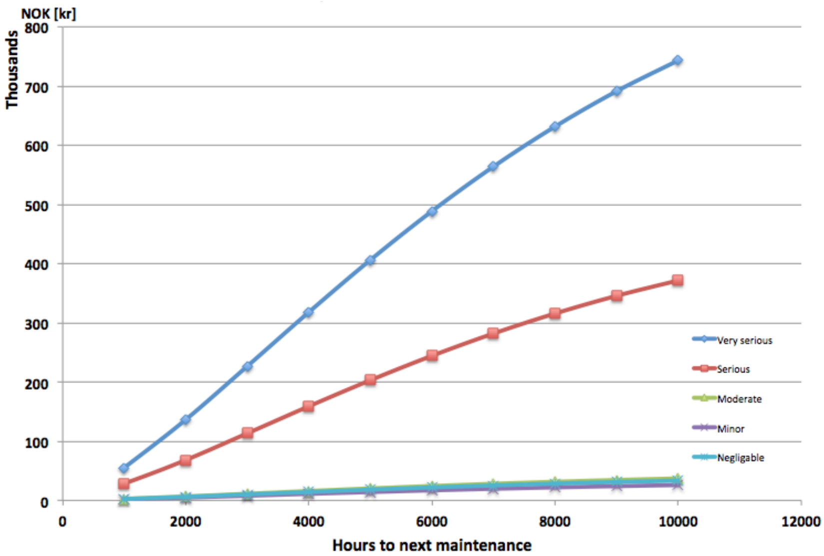


Figure 36 – Risk spectrum for next maintenance interval

Figure 36 shows how the risk spectrum changes for different intervals, and that the very serious and the serious case are the major contributors to the expected loss regardless of interval length.

Figure 37 shows the number of failures per main tag, that is the main components in system 63. The tag codes are broken into identifiable figures; see Appendix A2 for detailed explanation. The first two digits refer to the system, which in this case is system 63 for every tag. The next letters refer to the function type. KZ means compressor package, VL means receiver and surge drums, XX means miscellaneous equipment skid and is used for the air dryer skid, and ZZ is used as a main tag for objects that are not belonging to any main component in the system, but is within the system boundaries. The next three numbers refer to the sequence, and last letter is only used for parallel items. The XX function code makes for inconsistency in the maintenance analysis. While it is easy to check in which air dryer package the failure happened for a few failures, it is very time consuming for a great number of failures. VK is the function code for air dryers, but there is no function code for air dryer packages. This, among other things, is some of the inconsistency in the reference data.

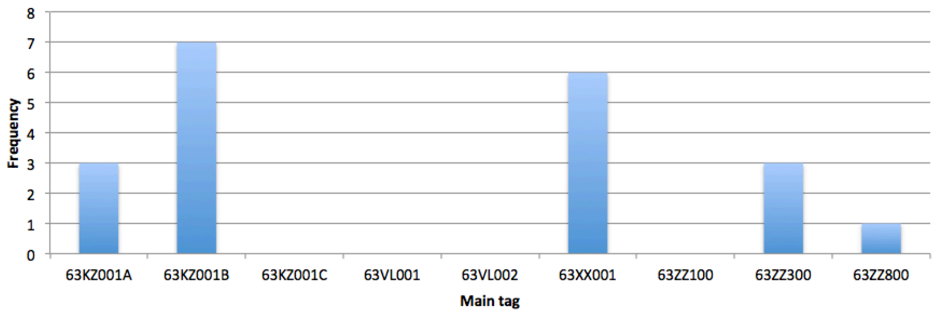


Figure 37 – Number of failures per main tag

Compressor package B, 63KZ001B, is showing the most failures followed by the air dryer skid. The six failures at the air dryer skid are divided equally between air dryer package A and B, according to the maintenance data.

Figure 38 shows number of failures per object tag. Most tags are having one or two failures, but there are tags that can be connected.

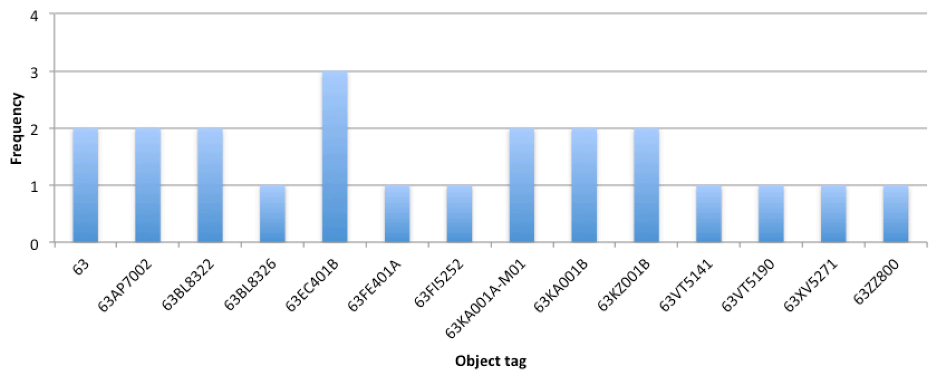


Figure 38 – Number of failures per object tag

Compressor B (63KA001B) and compressor package B (63KZ001B) is identified with a total of 4 direct failures at object level, and may be considered as a troublesome component. Two of the failures are leaks, and the others are vibration and broken sub-component.

63EC401B, which show three failures, is one of the control panels for the electrical heaters. This part would typically be changed, rather than maintained if it sees any more failures.

Figure 39 shows the number of failures per failure mode (see Appendix A1 for list of failure modes).

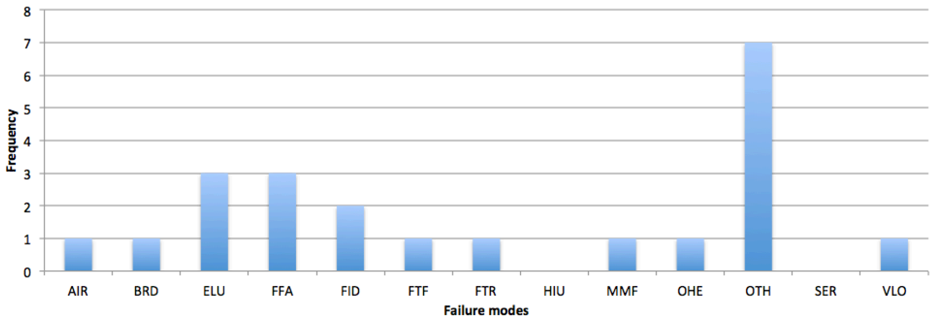


Figure 39 – Number of failures per failure mode

Besides the failure mode OTH (other), the ELU (External Leak of Utility medium) and FFA (Functional Failure) are the most frequent failure modes.

Another sign of poor maintenance recording is the dominating use of the failure mode OTH. An example from the reference data is an inspection of a triggered vibration alarm at compressor B, which is recorded as OTH and not VIB (vibration). The inconvenience of using OTH as failure mode is because it is not descriptive and useful in a maintenance and trend analysis.

Step 5 - New maintenance strategies

The current strategy has resulted in a total of 75 work orders at a 70%/30% ratio between preventive and corrective maintenance. In the optimization process, the ratios 80%/20% (strategy 1) and 60%/40% (strategy 2) is being analyzed and compared to original results. The simulations are assuming that one more preventive activity leads to one less failure and vice versa. Essentially, it means recognizing some of the failures, and handle them under the preventive regime. The interval of 6 months remains the same.

Step 6 - Reliability, Availability, Risk, and Cost predictions

Assuming that the Weibull distribution still is the best-suited model, the MTBF is increased by 10% for strategy 1 and decreased by 10% for strategy 2. β=1,3826 is kept the same. The MTTR is assumed to remain the same as for the current strategy.

Reliability and availability calculations of strategy 1 yield: MTBF= 8044 hours, Availability= 99,93%, and Reliability= 68,35%. Strategy 2 yields: MTBF= 6582 hours, Availability= 99,91%, and Reliability= 60,52%. As expected, strategy 1 yields better MTBF, reliability and availability than strategy 2. The availability is calculated as:

$$Availability = \frac{MTTF}{MTBF}$$

This availability is not comparable to the exact availability of the current strategy because of the redundancy.

Figure 40 presents the reliability characteristics for both strategies. The blue curve illustrates simulated strategy 1 and the red curve illustrates simulated strategy 2.

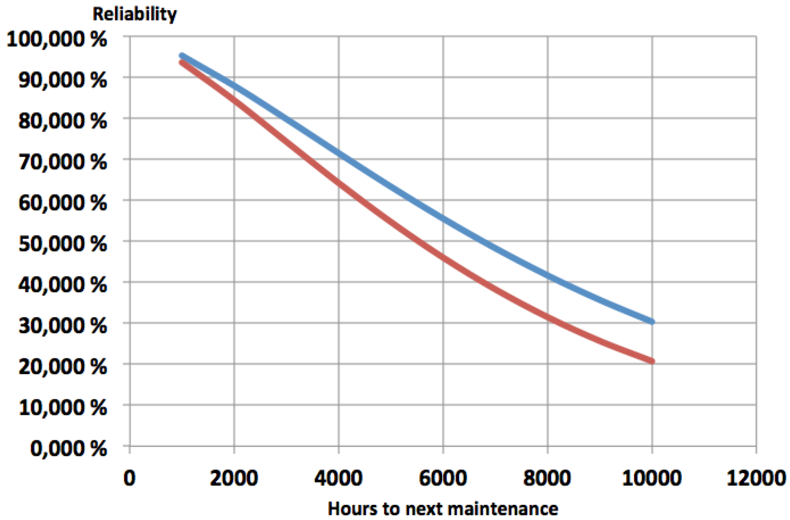


Figure 40 – Reliability of the new strategies for next interval

At short intervals the difference is small, but as the interval increases the difference gets bigger. At a six months maintenance interval, 4380 hours, the difference is ≈7,8%.

Figure 41 and Figure 42 presents the probabilities of each case, based of the new reliabilities. The probability of a case given failure (10%), and the probability of each degree of severity given a case remains the same as for the current strategy.

Strategy 1 probability for cases	
P(very serious case)	0,03165 %
P(serious case)	0,03165 %
P(moderate case)	0,03165 %
P(Minor case)	0,22157 %
P(Negligible case)	2,84880 %

Figure 41 – Probability of each case for strategy 1

Strategy 2 probability for cases	
P(very serious case)	0,03948 %
P(serious case)	0,03948 %
P(moderate case)	0,03948 %
P(Minor case)	0,27639 %
P(Negligible case)	3,55363 %

Figure 42 – Probability of each case for strategy 2

Figure 43 shows that a higher ratio of preventive maintenance decreases cost, which is expected as a preventive work order costs 49% less than a corrective work order.

PM Manhour cost	kr 300 226,42	PM spare parts	kr 300 000,00	PM logistic support cost	kr 153 000,00
CM Manhour cost	kr 56 062,50	CM spare parts	kr 150 000,00	CM logistic support cost	kr 74 250,00
Condtion Monitoring Manhour cost	kr 20 000,00	Total cost		kr	1 053 538,92

Figure 43 – Maintenance cost of strategy 1

The preventive cost contribution is the major cost driver in the man-hour cost, the spare part consumption cost, and the logistic and support cost. Total cost for strategy 1 is 1.053.539 NOK.

Figure 44 shows the exact opposite of Figure 43, that less preventive maintenance increases total cost.

PM Manhour cost	kr 225 169,81	PM spare parts	kr 225 000,00	PM logistic support cost	kr 114 750,00
CM Manhour cost	kr 112 125,00	CM spare parts	kr 300 000,00	CM logistic support cost	kr 148 500,00
Condtion Monitoring Manhour cost	kr 20 000,00	Total cost		kr	1 145 544,81

Figure 44 – Maintenance cost of strategy 2

In strategy 2, the corrective cost contribution is the major cost driver in the spare part consumption cost and the logistic and support cost. Total cost for strategy 2 is 1.145.545NOK, approximately 90.000 NOK more than Strategy 1.

Figure 45 and Figure 46 shows the expected loss and risk spectrum of both strategies.

Risk spectrum	
Very serious case	kr 316 533,49
Serious case	kr 158 266,74
Moderate case	kr 15 826,67
Minor case	kr 11 078,67
Negligible case	kr 14 244,01
Expected loss	kr 515 949,58

Figure 45 – Expected loss and risk spectrum strategy 1

Risk spectrum	
Very serious case	kr 394 847,78
Serious case	kr 197 423,89
Moderate case	kr 19 742,39
Minor case	kr 13 819,67
Negligible case	kr 17 768,15
Expected loss	kr 643 601,88

Figure 46 – Expected loss and risk spectrum strategy 2

The figures show that strategy 1 has a lower expected loss than strategy 2. This is caused by the lower probability of failure during each maintenance interval for strategy 1. The characteristic of the “serious” and the “very serious case” being the driver in expected loss is present here as well.

Step 7 - Comparison

Figure 47 shows the comparison of the current strategy and the new strategies. Strategy 2 performs worse than the current strategy at a higher maintenance cost and would not be an optimized strategy. Strategy 1 shows better performance at a lower maintenance cost and would be the preferred strategy out of these three.

	Current strategy	Strategy 1	Strategy 2
MTBF [hours]	7313	8044	6582
MTTR [hours]	5,75	5,75	5,75
Availability	99,921 %	99,929 %	99,913 %
Reliability	64,779 %	68,347 %	60,515 %
R(SF)	98,399 %	98,561 %	98,205 %
Total PM cost	kr 665 350	kr 753 226	kr 564 920
Total CM cost	kr 411 125	kr 280 313	kr 560 625
Condition monitoring mhr cost	kr 20 000	kr 20 000	kr 20 000
Total maintenance cost	kr 1 096 475	kr 1 053 539	kr 1 145 545

Figure 47 – Comparison of strategies

All three strategies show availability at the 99,9% mark, due to the redundancy. Reliability and cost sees a bigger change, due to being more affected by the added/mitigated failures.

Strategy 1 sees a ≈4% increase in reliability and ≈40.000 NOK decrease in cost compared to the current strategy. Strategy 2 sees the opposite, ≈4% decrease in reliability and ≈ 50.000 NOK increase in cost.

Figure 48 and Figure 49 shows the risk spectrum and expected loss for all three strategies.

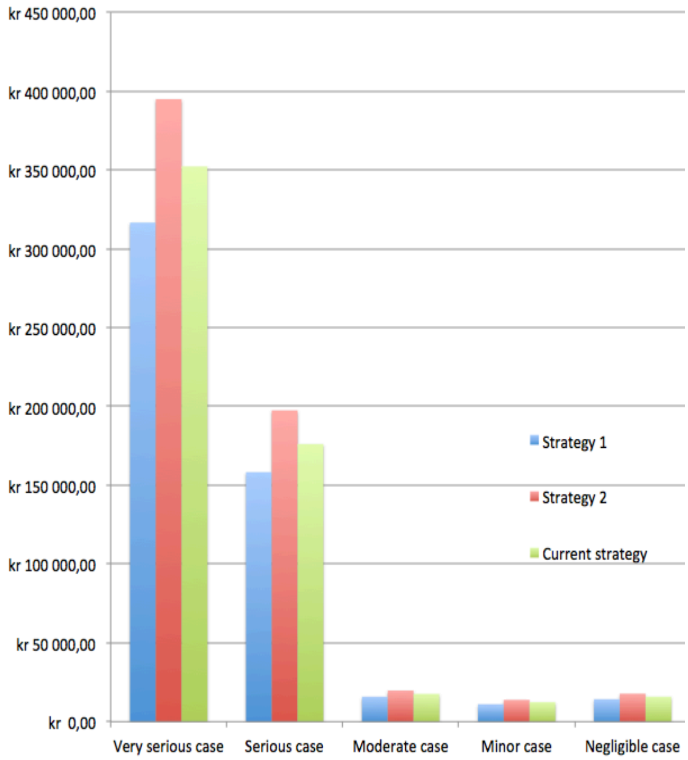


Figure 48 – Comparison of risk spectrum

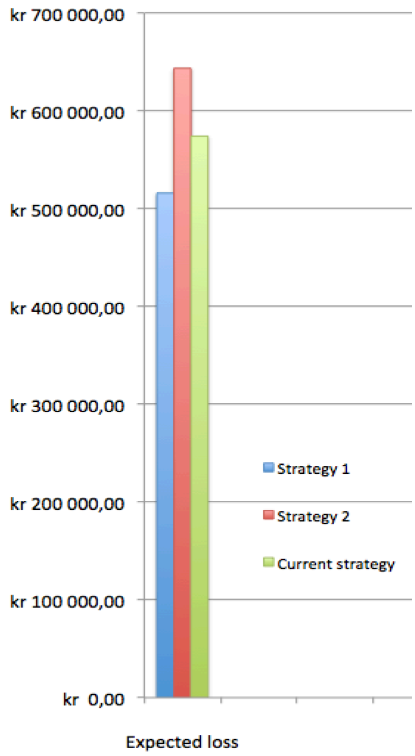


Figure 49 – Comparison of expected loss

Strategy 1 spent 31.779 NOK more on preventive measures per interval, which led to a decrease of 58.149 NOK in expected loss per interval. Statistically, the operator will save 26.370 NOK per interval on average in the long run.

Strategy 2 spent 36.319 NOK less on preventive measures per interval, which led to an increase of 69.503 NOK in expected loss per interval. Statistically, the operator will spend 33.184 NOK more per interval on average in the long run.

Based on the aforementioned, the decision to be made is if the operator should continue with the current strategy or move to strategy 1. Strategy 1 costs 15.527 NOK less for every interval, has approximately 4% better reliability, and has 58.149 NOK less in expected loss every interval.

In a lifetime perspective this adds up to (undiscounted) 931.620 NOK in cost savings, 4% better reliability for a total of 60 maintenance intervals, and 3.488.940 NOK less in expected loss for strategy 1.

The current strategy performs well relative to the assumed requirements, but there is still room for improvements. Strategy 1 shows better performance at a lower maintenance cost with a lower risk and is the preferred strategy. The assumptions are made by a student with no maintenance experience and should therefor be threated as such (the intention was to show the methodology on a case).

The operator should review and optimize their strategy every 12 months to maintain good performance and control of their asset. More data means more knowledge, and the next time the strategy gets reviewed the prior assumptions could be verified and adjusted such that the next optimization will be even more accurate. For instance, it might show that an increase of 12% in MTBF for strategy 1 is more accurate.

Discussion of case study

The test case was chosen because Apply Sørco recognized it had seen a lot of failures. The compressed air system is not considered critical, and has little condition monitoring. While Apply Sørco is familiar with this type of system, they seldom experience this many failures in such a short time. The system experienced 22 failures in approximately 17 months, causing nine equipment shutdowns, and one system shutdown. Due to the redundancy, availability was quite unaffected. Reliability and maintenance cost was directly affected, causing bad performance. The assumed requirements used in the test case were "best guesses", as the operator was reluctant to share this information. Therefore, the results of the analysis were within the assumed asset requirements. In reality this would not be the case, because as mentioned, the system was chosen due to having many failures. This raises questions if the method is suitable to assess maintenance strategies, but conclusion is that the quality of the results is down to the quality and availability of the necessary data. This is also the issue for other methods that are driven by historical data.

Based of the available information, the operator should define their asset requirements, update their recording tool, record the maintenance and failures properly, and define how often they want to optimize their strategy. This information is required if the assessment is going to provide any value.

Whether or not the operator has defined some asset requirements, they need to share that information to the people developing their maintenance strategy (the operator makes for silo thinking when the service provider is put to make maintenance strategies without really knowing the requirements). Also, relevant cost data should be supplied such that a strategy can be developed based on the best compromise of available recourses and technical, economical, and HSE perspectives.

For this analysis, where the system has a mix of standalone equipment packages and skids containing multiple equipment packages, trending based on parent tag instead of main tag could be beneficial. The parent tag is thought of as the level between the object and the main tag, see Figure 50. If a skid/package is the "failed object", main tag, parent tag, and object tag is then going to be the same. This should rarely be the event, as the true failing object (in the skid) should be possible to identify.

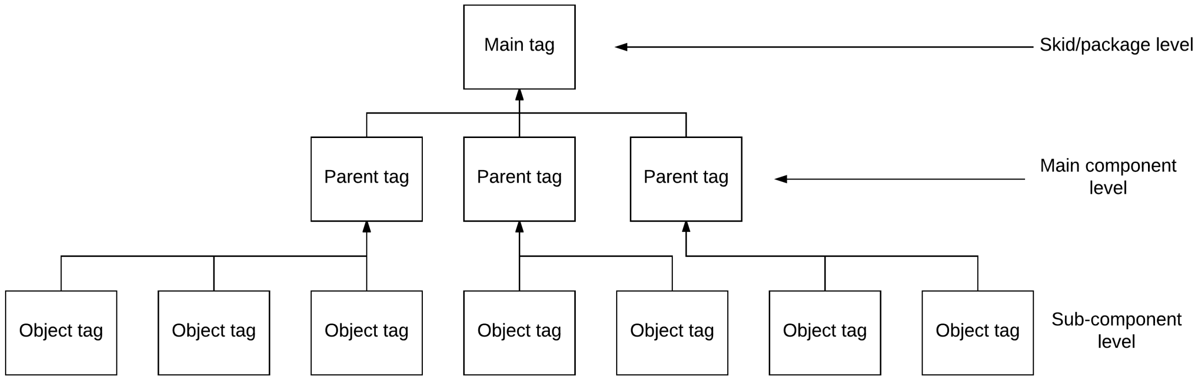


Figure 50 – Tag hierarchy

The issue encountered was connected to the air dryer skid, which contained two air dryer packages. The main tag referred to the whole skid, which did not identify the air dryer package that encountered the failure.

Because of the redundancy, the components might have spent different time in operation, or is not even been used yet. This could alter the failure characteristic of the system, and as mentioned, this system is in its burn-in phase, but the increasing failure rate does not indicate this. Another reason could be that the equipment in the test case has been tested and checked by the OEM before delivery, as accountabilities in this industry could be huge.

There is some uncertainty connected to the Weibull parameter estimation, due to the method of estimating the parameters. The graphical method of estimating α and β showed to be inaccurate. Using the Excel add-in "StatPlus", a regression analysis tool, the Weibull parameters were estimated mathematically. The graphical parameter estimation yielded β=1,3826, α = 8008 and MTBF = 7313 hours. The mathematical approach using "StatPlus" yielded β=1,28969, α = 6952,3 and MTBF = 6431,4 hours (see Appendix A3.1.6). The shape parameter β deviated 7% and the scale parameter α deviated 13,2% resulting in a reduced MTBF of 881,6 hours. The reliability from the graphical parameters resulted in a reliability of ≈64,8%, while the mathematical parameters resulted in a reliability of ≈57,6%. This deviation is connected to the challenge of being accurate in the process of finding the figures graphically. This deviation makes for a big difference in expected loss, which would increase from 574.099 NOK to 690.593 NOK per maintenance interval.

The method of median rank plotting was performed to verify the Weibull parameters and fit (see Appendix A3.1.3 and A3.1.4). The median rank plot also showed a good fit for the Weibull distribution. The median rank plot is plotted by LN(LN(1/(1-MR))) on the y-axis and LN(Time) at x-axis. While the shape parameter β=1,363 was close to the graphical β=1,3826 parameter, α and MTBF deviated. A regression analysis of the median rank figures yielded α=7139 and subsequently MTBF= 6535 hours (see Appendix A3.1.5). The median rank parameters yielded a reliability of ≈59,8%. The reliability characteristics are presented in Figure 51, and the importance of choosing the best-suited distribution model is still evident.

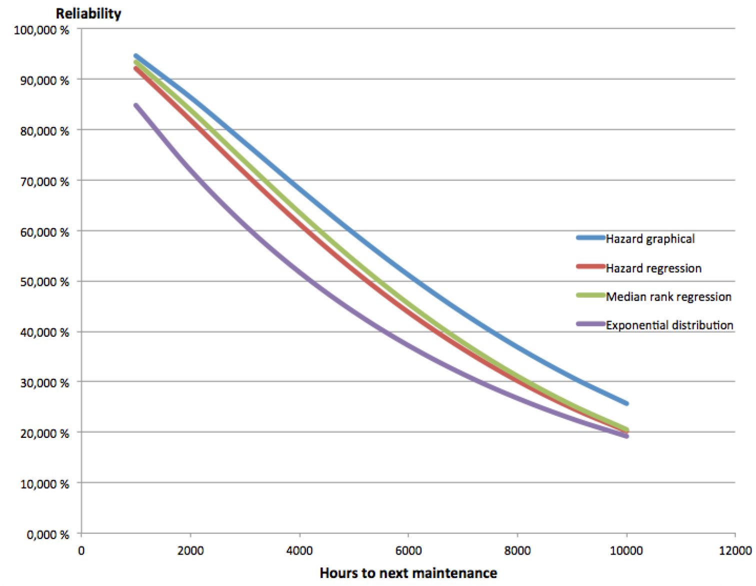


Figure 51 – Reliability comparison

The graphical parameter estimation shows to be optimistic compared to the mathematical parameter estimations. The conclusion is that graphical parameter estimation should be avoided since more certain solutions are equally simple to use and easier to integrate into an application.

Chapter 5 – Discussion

Overview

The main objective of the thesis was to develop an assessment method for optimizing maintenance strategies at system and equipment level. Overall, all the objectives were reached and fulfilled within the scope. The assessment method lets the asset-owner review an asset, either at system level or equipment level, and reveal if it fulfills the requirements. It also reveals if there are any returning trends from either faulty components or failure modes. The benefit of this method is that when predicting the performance of the new strategy, it is based on the results of the current strategy. Presenting technical, economical, and risk measures in the same analysis will help prevent “silo-thinking” and allow collaboration towards an optimal solution.

The challenge of this method is the need for consistent maintenance and failure recording. All the challenges encountered during equipment identification will most likely emerge in the maintenance data and affect the analysis as well.

If a general application is built, the whole process could be performed in three steps. The application uses a database to extract and present the data such that the first step is to choose the best-suited distribution model. This step might even be automated using the goodness-of-fit models that choose the best-suited distribution model. Then the application calculates and presents cost-risk-benefit results. Second is to assess the results of the asset performance, and based on this the third step is to build the new strategy.

Learning

The learning from the thesis work has been great, time consuming and demanding. Maintenance is a large and complex field of management and engineering. It requires comprehensive understanding of technical aspects, risk aspects, organizational aspects, human factors, environmental aspects, and management aspects. Broad and multi disciplinary experience and knowledge is required to perform the right maintenance at the right time.

Challenges in the industry emerge from different angles, but the most prominent issues seem to be the lack of collaboration and sharing of knowledge. While out of scope for the thesis, the author got the impression of that the industry is aware of these issues, but the workers down the hierarchy who execute these work tasks or possess these skills are not committed to sharing this with others in fear of becoming unnecessary.

The common perception of MS Excel might be as non-advanced spreadsheet software, but it allowed for advanced calculations and functional programming within certain boundaries. It works as a powerful tool, and the vast library of functions allows for solving calculations in an efficient manner. The author had good knowledge within Excel prior to the thesis work, but it still required learning more complicated programming to develop the spreadsheet application. To make the method fully database-driven, additional programming is needed. There may exist software better suited for this kind of work, and should be explored if integration is considered. The core of the assessment method is still applicable.

Overall, the study and understanding of theories and practices have been both challenging and rewarding.

Challenges

The challenge in solving the thesis objectives was the major study of literature, standards, and practices prior to starting the work. Also, finding the direction of the thesis was a challenge due to the wish for contributing with new ideas in the subject of maintenance. There already exist studies and techniques within most areas of maintenance, but methods combining cost-risk-benefit performance and considering condition changes were rare. The final path resulted in a cost-risk-benefit method combined with an assessment of changing elements. The cost-risk-benefit part aimed at using reliability theory, costing techniques, and risk techniques to present performance figures, and combine this with changing internal and external conditions. A challenge of verifying the method occurred because the real case lacked relevant information for optimizing the maintenance strategy. The available information only allowed for an assessment of cost-risk-benefit performance, and was even insufficient for a true assessment. Several assumptions had to made for the missing figures.

Outcome

Results from the case study shows a small benefit of optimizing, but it is evident that this strategy performs well (relative to assumed requirements). It should be interesting to follow the development of this system as it matures and the learning from the optimization process becomes even better.

The system in the case study was assessed as a whole, and the challenge was all the different maintenance intervals and that maintenance was performed continuously. When assessing the system as whole, certain assumptions have to be applied in the reliability calculations, and that makes for uncertainty in the results. This means the method of assessing the system as a whole only yields a rough reliability estimate.

The important considerations of internal and external elements are often forgotten or taken for granted. The changes are also harder to keep track of in large organizations, but are without doubt affecting the performance of the assets.

Chapter 6 – Future study

Chapter 6 presents future studies that could be implemented in the presented method, or is closely related to this subject.

Systems and equipment are often designed for a certain expected lifetime. Comparing expected performance/behavior to actual performance/behavior could tell if the asset is "older" or "younger" than it should be at that time. A method of how to predict where systems or equipment are in its lifetime (condition-wise) could be studied.

Spare part management is an essential part for both maintenance and operation. A combination of maintenance and spare parts optimization could make for savings if the strategy can be optimized as a whole. A method of how to optimize this combination could be studied.

The Gordon-Loeb model, a mathematical economic model, is used to analyze the optimal investment level in information security. This method, or the principles, could be studied to find the optimal investment in maintenance measures to reduce risks and expected loss.

Modern costing methods, such as activity-based costing, have typically been more precise than traditional cost accounting. Resource consumption in maintenance management could be studied using modern costing methods.

Finally, the assessment method should be tested, verified, and refined through more case studies.

Suggestion for maintenance engineers

This new digitized environment requires everything to be integrated. This method could be developed to a database driven application, able to communicate maintenance and failure data from a CMMS tool. Such an analysis tool is of great benefit for tailoring maintenance strategies for specific systems and equipment.

Chapter 7 – Conclusion

The method is able to tell performance and trends, which combined with changing internal and external elements should enable optimization of maintenance strategies and subsequently asset performance. The performance is not able to tell what's wrong, but shows if there is something wrong. Trends may show the problem, but the root cause could stem from internal or external factors. The assessment method is therefore a great tool for managing and controlling performance, properly in line with the relevant key principles of asset management.

For the method to be truly simple and user-friendly, it should be computer aided. The first time building the method into a spreadsheet or another application, it might be time-consuming. When the application is created, the method is simple, relevant and user friendly.

In regards to the accuracy of the method, reliability calculations will carry uncertainty if big systems are assessed as a whole, but so will reliability calculations at equipment level if the equipment has little historical data. The least uncertain calculations will be at equipment level with proper maintenance and failure data and a properly defined maintenance strategy. Availability may stay unaffected by the reliability calculations if equipment and system shutdown times are available. Otherwise, the uncertainty from the reliability calculations will affect the availability as well. Cost calculations will carry little uncertainty as long as the correct costing data is provided (MHr rates, etc.). Cost calculations stay independent of both reliability and availability.

Based on the aforementioned, and the case-study assumptions, the test case will benefit from updating its strategy to "Strategy1". "Strategy 1" is expected to perform better in all analyzed aspects and is therefore the recommended strategy.

Bibliography

AVEN, T. 1992. *Reliability and Risk Analysis*, Elsevier.

BARRINGER, P. 2004. Can reliability software solve other statistical problems. Available: http://www.barringer1.com/jun04prb.htm [Accessed 30.05.17].

BARRINGER, P. 2013. *Reliability tools* [Online]. http://www.barringer1.com. Available: http://www.barringer1.com/nov07prb.htm [Accessed 30.05. 2017].

BEVILACQUA, M. & BRAGLIA, M. 2000. The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and System Safety*, Vol. 70, pp. 71-83.

BLOOM, N. B. 2006. Preparation and Tools. *Reliability Centered Maintenance.* McGraw-Hill Education.

BORGES, V. 2015. Opportunistic maintenance. Available from: http://blogs.dnvgl.com/software/2015/08/opportunistic-maintenance/ 03.04.2017].

BRITISH STANDARD 1994. BS 5760-11:1994 Reliability of systems, equipment and components. *Part 11: Collection of reliability, availability, maintainability and maintenance support data from the field.* Great Britain: British Standard.

COOPER, R. & KAPLAN, R. S. 1991. Profit Priorities from Activity-Based Costing. *Harvard Business Review.*

DE DECKER, B. 1998. *What does that inventory really cost* [Online]. Conklin & de Decker. Available: https://www.conklindd.com/t-whatdoesinventoryreallycost.aspx [Accessed 10.04. 2017].

DHILLON, B. S. 1999. Maintenance Models and Warranties. *Engineering maintainability: How to design for Reliability and Easy maintenance.* Elsevier.

DNV GL. 2017. *Asset integrity management* [Online]. http://www.dnvgl.com. Available: https://www.dnvgl.com/services/asset-integrity-management-1380 [Accessed 01.06. 2017].

DOGAN, K. V. 2014. *Creating an Integrated Digital Platform for Asset Integrity Tools.* Master of Science, University of Stavanger.

DORNER, W. 1999. *Using Microsoft Excel for Weibull Analysis* [Online]. Available: https://www.qualitydigest.com/magazine/1999/jan/article/using-microsoft-excel-weibull-analysis.html [Accessed 29.05. 17].

FOSKETT, S. n.d. *Defining failure: What is MTTR, MTTF, and MTBF?* [Online]. minibiz. Available: https://gouache-design.ru/mttr-of.php [Accessed 07.05. 2017].

GUPTA, M. & GALLOWAY, K. 2003. Activity-based costing/management and its implications for operations management. *Technovation*, 23, 7.

HAKIM, G. J. 2009. *Probability & Statistics Primer*, University of Washington.

HERRING, A. & GEORGE, A. 2016. Oil Industry Safety, Maintenance at Risk in Wake of Price Falloff. Available: http://www.brinknews.com/oil-industry-safety-maintenance-at-risk-in-wake-of-price-falloff/ [Accessed 04.04.17].

IAM. 2008. *Key principles of Asset Management* [Online]. The Institute of Asset Management. Available: https://theiam.org/knowledge/diagrams/key-principles [Accessed 28.04. 2017].

ISO 2000. ISO 15663-1:2000 Petroleum and natural gas industries - Life-cycle costing- Part 1: Methodology. Switzerland: The International Organization for Standardization,.

ISO 2006. ISO 14224:2006 Petroleum, petrochemical and natural gas industries - Collection and exchange of reliability and maintenance data for equipment. Switzerland: The International Organization for Standardization,.

ISO 2008. ISO 20815:2008 Petroleum, petrochemical and natural gas industries - Production assurance and reliability management. Switzerland: The International Organization for Standardization.

ISO 2014a. ISO 55000:2014 Asset Management - Overview, principles and terminology. Switzerland: The International Organization for Standardization,.

ISO 2014b. ISO 55001: 2014 Asset Management - Management systems - Requirements. Switzerland: The International Organization for Standardization.

ISO 2014c. ISO 55002: 2014 Asset management - Management systems - Guidelines for the application of ISO 55001. Switzerland: The International Organization for Standardization.

KAPLAN, R. S. & ANDERSON, S. R. 2004. Time-Driven Activity-Based Costing. *Harward Business Review.*

KARTFJORD, S. J. 07.04.17 2017. *RE: Risk and cost in today's maintenance management.* Type to OLSEN, F. W.

KAYRBEKOVA, D. 2011. *Activity-Based Life-Cycle Cost Analysis.* Philosophiae Doctor, University of Stavanger.

MILLS, S. 2008. Developing a Maintenance Strategy and Setting Performance Targets. *Maintenance & asset management.* https://www.avtreliability.com/wp-content/uploads/tech_article_104costeffectivemain.pdf: ME.

MINITAB. 2016. *What is a probability plot?* [Online]. Minitab. Available: http://support.minitab.com/en-us/minitab/17/topic-library/basic-statistics-and-graphs/graphs/graphs-of-distributions/probability-plots/probability-plot/ [Accessed 15.05. 2017].

MOBLEY, R. K., HIGGING, L. R. & WIKOFF, D. J. 2008. Economics of Reliability. *Maintenance Engineering handbook.* 7th ed.: The McGraw-Hill Companies.

MOUBREY, J. 1997. *Reliability centred maintenance.* 2nd ed. Oxford: Butterworth/Heinemann.

NEMA, D. A. K. N.D. *Failure rate* [Online]. Available: http://web.iitd.ac.in/~arunku/files/CEL899_Y13/Failure_rate.pdf [Accessed 05.05. 2017].

NORSOK 1996a. NORSOK O-CR-001: 1996 Life Cycle Cost for Systems and Equipment - Common requirements. Norway: Standards Norway.

NORSOK 1996b. NORSOK O-CR-002: 1996 Life Cycle Cost for Production Facility - Common requirements. Norway: Standards Norway.

NORSOK 1996c. NORSOK Z-DP-002:1996 Coding system - Design principles. Norway: Standards Norway.

NORSOK 2011. NORSOK Z-008:2011 Risk based maintenance and consequence classification. Norway: Standards Norway.

OLOFSSON, O. N.D. *Preventive maintenance* [Online]. http://www.riboparts.com. Available: http://www.riboparts.com/changeBlogsite.asp?changeInfo=Forum for Lean Production&changeClass=Lean Production&changeName=TPM/TQM/Value Stream Mapping&id=2239 [Accessed 10.03. 2017].

PAN, J. 1999. Bathtub cruve. *In:* BATHTUB-CURVE (ed.). Carnegie Mellon University.

PILTELTON, L., GELDERS, L. & VAN PUYVELDE 1997. Maintenance as a business function. *Maintenance management.*

PSA 2015. Risk level in the Norwegian Petroleum industry (RNNP). The Norwegian Petroleum Safety Authority.

PSA. 2016. *Aging and producing life extension* [Online]. Petroleum Safety Authoroty. Available: http://www.ptil.no/aging-and-life-extention/category1032.html [Accessed 01.06. 17].

R-TECH. N.D. *The issue of RBM, RBI, RCM* [Online]. http://www.risk-technologies.com. Available: http://www.risk-technologies.com/home.aspx?lan=230&tab=3&itm=8&pag=44 [Accessed 02.05. 2017].

RAZA, J. 2017. *RE: Guidance in MSc thesis work.* Type to OLSEN, F. W.

RELIAWIKI.ORG. N.D. *Parameter estimation* [Online]. http://www.reliawiki.org. Available: http://reliawiki.org/index.php/Parameter_Estimation [Accessed 29.05. 17].

SALONEN, A. & DELERYD, M. 2011. Cost of poor maintenance. *Journal of Quality in Maintenance Engineering,* Vol. 17, 10.

SINTEF & NTNU 2015. *OREDA*, OREDA participants.

STARR, A., AL-NAJJAR, B., HOLMBERG, K., JANTUNEN, E., BELLEW, J. & ALBARBAR, A. 2010. Maintenance Today and Future Trends. *E-maintenance.* Springer.

TIRABOSCO, P. 2001. Risk based maintenance. *ICOMS-2001.*

VESTVIK, D. H. 2012. *Development of FMEA/RCM methodology to be implemented in Generic Maintenance Concepts.* Master of Science, University of Stavanger.

WALPOLE, R., MYERS, R., MYERS, S. & YE, K. 2007. *Probability & Statistics for Engineers & Scientists*, Pearson Prentice Hall.

Appendix

A1 List of failure modes

The list present common failure modes, and their description (Vestvik, 2012).

AIR	Abnormal instrument reading
BRD	Breakdown
DEX	Defect EX barrier
ELP	External leakage - process medium
ELU	External leakage - utility medium
ERO	Erratic output
FCO	Failure to connect
FDC	Failure to disconnect
FFA	Functional failure
FOF	Faulty output frequency
FOV	Faulty output voltage
FRO	Failure to rotate
FTC	Failure to close on demand
FTF	Failure to function on demand
FTI	Failure to function as intended
FTL	Failure to lock/unlock
FTO	Failure to open on demand
FTR	Failure to regulate
FTS	Failure to start on demand
HIO	High output
IHT	Insufficient heat transfer
INL	Internal leakage
LBB	Loss of buoyancy
LBP	Low oil supply pressure
LCP	Leakage in closed position
LOA	Load drop
LOB	Loss of barrier
LOO	Low output
LOP	Loss of performance
LOR	Loss of redundancy
MOF	Mooring failure
NOI	Noise
NON	No immediate effect
NOO	No output
OHE	Overheating
OTH	Other
PDE	Parameter deviation
PLU	Plugged / Choked

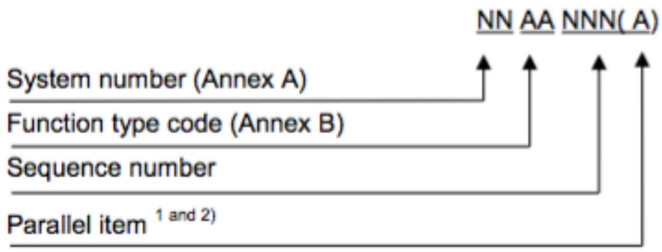
POD	Loss of function on both PODs
POW	Insufficient power
PTF	Power/signal transmission failure
SER	Minor in-service problems
SET	Failure to set/retrieve
SHH	Spurious high alarm level
SLL	Spurious low alarm level
SLP	Slippage
SPO	Spurious operation
SPS	Spurious stop
STD	Structural deficiency
STP	Failure to stop on demand
UNK	Unknown
UST	Spurious stop
VIB	Vibration
VLO	Very low output

A2 Operator's engineering numbering system

Copied directly from the operator's reference data.

A2.1 Main function (equipment)

The tag code format for main functions shall be:



1) Parallel item shall only be used when applicable.

2) Not relevant for this thesis.

The sequence number shall start from 001 within each system and main function code.

NB! Manual valves are not regarded as instrument function and shall be given a sequence number as described under section "Tagging & valves", Section 6.7.7.

A2.1.1 Equipment Package/Skid coding

Tag numbers shall be assigned to package/skids. Tag numbers for package/skids shall have function Code "X".

NB! Skids are not to be confused with module.

A2.1.2 System number

Code	NORSOK Main System Name
00-09	Reserved for systems that are specific to a particular plant
10-19	Drilling, well and subsea related systems
20-29	Main process systems
30-39	Export and by-product handling
40-69	Process support and utility systems
70-79	Safety systems
80-89	Electrical Power Generation and Distribution Systems, Automation and Telecommunication Systems
90-99	HVAC, Structural, civil, marine and architectural systems

A2.1.3 Function type codes

(NN AA NNN(A))

A Architectural

B Drilling

C Miscellaneous mechanical

D Driver and power transmission

E Electrical

F Heating, boiling, furnaces and flaring

G Heating, ventilation and air conditioning (HVAC)

H Heat transfer

I Instrumentation

K Compression, blowing and expansion

L Transferring and controlling

M Material and product handling

N Mechanical- solids

P Pumping

R Telecommunication

S Safety/escape and fire fighting

T Storage tanks/Containment - atmospheric

U Subsea

V Vessel and column – pressurized

W Wellhead – surface completion

X Miscellaneous package units

Y Mooring and Marine

The function type codes present in the case study are:

EC Control Functions (Control Panels, Local/ Stations, Relay Boxes, etc.)

FE Electric Heaters

KA Centrifugal Compressors

KZ Compressor package

VL Receiver and surge drums

XX Miscellaneous equipment skid

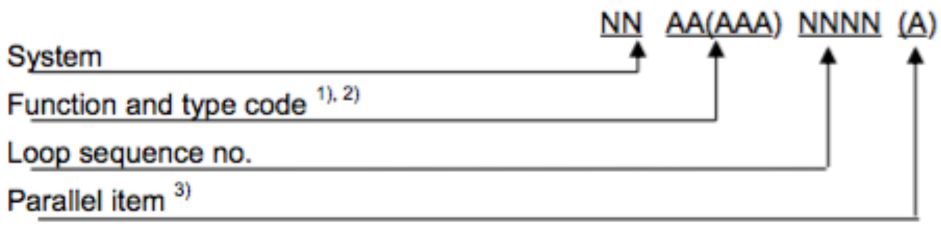
ZZ Imaginary parent code

A2.2 Instrument & telecommunication functions – field functions and main control functions

Main instrumentation functions (remote operated valves etc.) shall be given a sequence number unique within the system, starting from 0001.

Example: If the first valve in the system is numbered 50XV0001, there will not be an instrument 50LV0001. It will be 50LV0002.

The tag format for instrument functions shall be:



1) See annex B.4 Instrumentation function type codes (two letter example: PT, three letter example: PIC).

2) Not relevant for this thesis.

3) Not relevant for this thesis.

Project specific table of legal combinations of Annex B.4 shall be made.

Instruments shall be tagged according to the function in the process. For a pressure measurement in the bulk airline the tag will be:

63PT0001. Loop no. for instrument is defined as 63-0001 (system number and sequence number).

The instrument function codes present in the case study are:

AP Analysis point

FI Flow indicator

VT Vibration transmitter

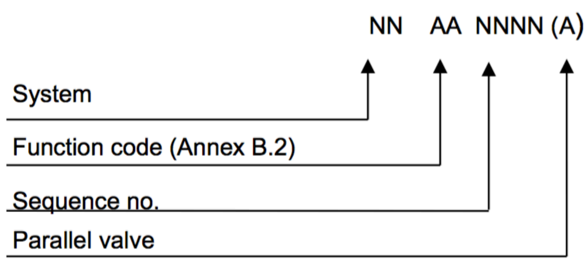
XV Unspecified valve

A2.2.1 Function and type code for instruments

First Letters			Succeeding Letters		
Measured of Indicating		Modifier	Readout of Passive	Output Function	Modifier
A	Analysis		Alarm		
B	Burner/Combustion/ Blow down		User's Choice	User's Choice	User's Choice
C	Conductivity	Modulating		Control	
D	Density	Differential			
E	Emergency		Sensor-Primary Element		
F	Flow	Ratio (Fractin)			
G	HVAC	Glass, Viewing Dev.			
H	Hand				High
I	Current (electrical)		Indicate		
J	Power	Scan			
K	Time, Schedule	Time Rate of CH.		Control Station	
L	Level		Light		Low
M	Moisture	Fire damper			Middle, Intermed.
N	Viscosity		User's Choice	User's Choice	User's Choice
O	Corrosion	Orifice, Restriction			
P	Pressure		Point, Test Connection		
Q					Totalizer
R			Record		
S	Speed, Frequency	Safety		Switch, Sequence	
T	Temperature	Combined fire and shutoff damper		Transmit	
U	Multivariable	Combined gas and shutoff damper	Multifunction	Multifunction	Multifunction
V	Vibration Mech. Analysis			Valve, Damper Louver	
W	Weight, Force		Well		
X	Unspecified	X-axis	Unclassified	Unclassified	Unclassified
Y	Event, State or Presence	Y-axis		Relay, Compute Convert	
Z	Position, Dimension	Z-axis		Drive, Actuator Contr. Element	

A.2.3 Manual valves

The tag code format for manual valves shall be:



The sequence no. shall run consecutively within each system, function and type code combination. Parallel valves shall be used for identical valves with same service function.

Example: 62BL2002 Ball valve diesel system.

FTC	Description
BL*	Ball Valve
GT*	Gate Valve
PG*	Plug Valve
GB*	Globe Valve
BU*	Butterfly Valve
NL*	Needle Valve
CH*	Check Valve

* Code not in compliance with NORSOK

A3 Case study calculations

A3.1 Case study figures

A3.1.1 Hazard plot data

j	T [days]	n-J+1	Z(t)
1	21	22	0,045454545
2	35	21	0,093073593
3	57	20	0,143073593
4	131	19	0,195705172
5	139	18	0,251260728
6	145	17	0,310084257
7	154	16	0,372584257
8	155	15	0,439250924
9	161	14	0,510679495
10	196	13	0,587602572
11	273	12	0,670935905
12	298	11	0,761844996
13	323	10	0,861844996
14	331	9	0,972956107
15	336	8	1,097956107
16	341	7	1,24081325
17	354	6	1,407479917
18	370	5	1,607479917
19	373	4	1,857479917
20	390	3	2,19081325
21	479	2	2,69081325
22	505	1	3,69081325

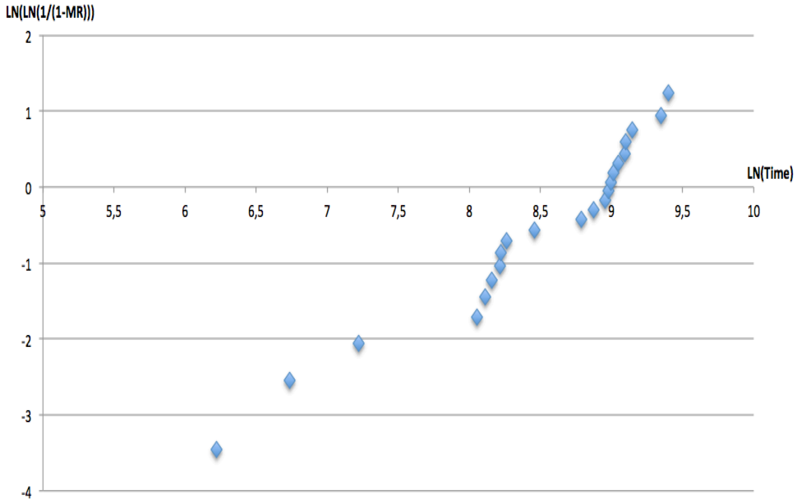
A3.1.2 Comparable calculation result

General data		
Machine life [years]	1,383	years
System shutdowns	1	
System downtime	17	hours
Equipment shutdown	9	
Equipment downtime	61,5	hours
Maintenance interval	4380	hours
Based on Weibull distribution model		
MTBF	7312,91	hours
MTTR	5,75	hours
MTTF	7307,16	hours
System Availability	99,921 %	estimate
System Availability	99,860 %	exact
Reliability	64,779 %	98,399 %
Based on exponential distribution model		
Failure rate	0,00016466	failures/hour
MTBF	6073,09	hours
MTTR	5,75	hours
MTTF	6067,34	hours
System Availability	99,905 %	estimate
System Availability	99,860 %	exact
Reliability	48,616 %	97,664 %

A3.1.3 Median rank data

Time	Rank	Median ranks	1/(1-MR)	LN(LN(1/(1-MR)))	LN(Time)
504	1	0,03125	1,032258065	-3,449903552	6,222576268
840	2	0,075892857	1,082125604	-2,539228628	6,733401892
1368	3	0,120535714	1,137055838	-2,052275323	7,221105098
3144	4	0,165178571	1,197860963	-1,711817127	8,053251154
3336	5	0,209821429	1,265536723	-1,446059995	8,112527763
3480	6	0,254464286	1,341317365	-1,225359071	8,154787573
3696	7	0,299107143	1,426751592	-1,03451067	8,215006433
3720	8	0,34375	1,523809524	-0,864615531	8,221478947
3864	9	0,388392857	1,635036496	-0,709957432	8,259458195
4704	10	0,433035714	1,763779528	-0,56658684	8,45616849
6552	11	0,477678571	1,914529915	-0,431595374	8,787525626
7152	12	0,522321429	2,093457944	-0,302704726	8,875147317
7752	13	0,566964286	2,309278351	-0,178008782	8,955706154
7944	14	0,611607143	2,574712644	-0,055789775	8,980172206
8064	15	0,65625	2,909090909	0,065638507	8,99516499
8184	16	0,700892857	3,343283582	0,18809936	9,009936308
8496	17	0,745535714	3,929824561	0,313784508	9,047350743
8880	18	0,790178571	4,765957447	0,445645905	9,091556836
8952	19	0,834821429	6,054054054	0,588191105	9,09963225
9360	20	0,879464286	8,296296296	0,749437333	9,144200569
11496	21	0,924107143	13,17647059	0,947181737	9,349754428
12120	22	0,96875	32	1,242924992	9,40261226

A3.1.4 Median rank plot



A3.1.5 Median rank regression analysis

Linear Regression

Regression Statistics

R	0,96928					
R-square	0,9395	Alpha	7138,80971	Gamma function	0,915384	
Adjusted R-square	0,93648	Beta	1,36303	MTTF	6534,752188	
S	0,29695	Reliability (4380)	59,819 %			
N	22					

LN(LN(1/(1-MR))) = - 12,09456 + 1,36303 * LN(Time)

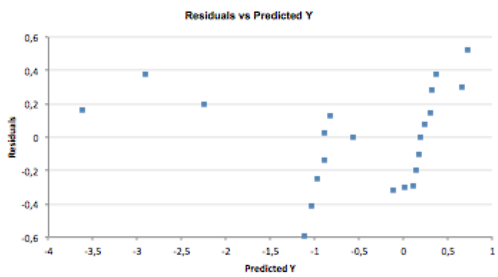
ANOVA

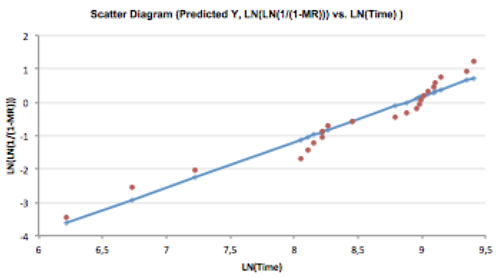
	d.f.	*SS*	*MS*	*F*	*p-level*
Regression	1,	27,38709	27,38709	310,58188	0,
Residual	20,	1,7636	0,08818		
Total	21,	29,15069			

	Coefficient	*Standard Error*	*LCL*	*UCL*	*t Stat*	*p-level*	*H0 (5%)*
Intercept	-12,09456	0,65831	-13,46777	-10,72135	-18,37211	0,	*rejected*
LN(Time)	1,36303	0,07734	1,2017	1,52436	17,62333	0,	*rejected*
T (5%)	2,08596						

LCL - Lower value of a reliable interval (LCL)

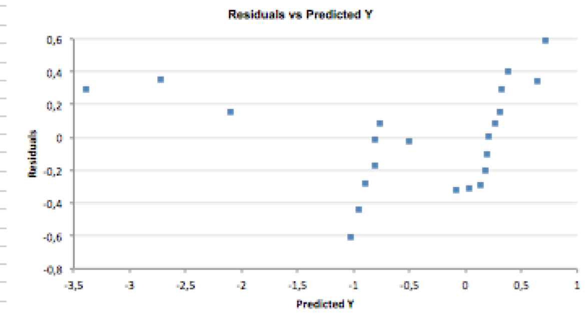
UCL - Upper value of a reliable interval (UCL)

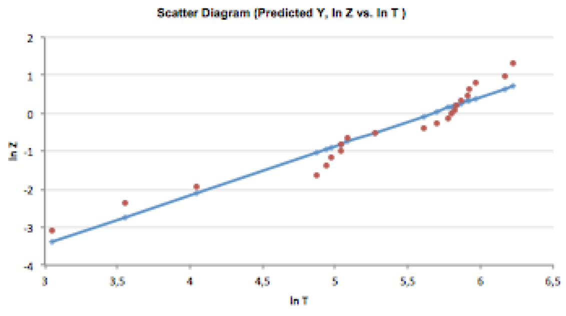




A3.1.6 Nelson estimator regression analysis

Linear Regression										
Regression Statistics										
R	0,96191									
R-square	0,92526					Alpha	6952,268851	Gamma function	0,92508	
Adjusted R-square	0,92153					Beta	1,28969	MTTF	6431,405	
S	0,31469					Reliability (4380	57,632 %			
N	22									
			ln Z = - 7,31098 + 1,28969 * ln T							
ANOVA										
	d.f.	*SS*	*MS*	*F*	*p-level*					
Regression	1,	24,51942	24,51942	247,60419	0,					
Residual	20,	1,98053	0,09903							
Total	21,	26,49995								
	Coefficient	*Standard Error*	*LCL*	*UCL*	*t Stat*	*p-level*	*H0 (5%)*			
Intercept	-7,31098	0,43907	-8,22687	-6,3951	-16,65103	0,	*rejected*			
ln T	1,28969	0,08196	1,11873	1,46066	15,73544	0,	*rejected*			
T (5%)	2,08596									
LCL - Lower value of a reliable interval (LCL)										
UCL - Upper value of a reliable interval (UCL)										





A3.2 Regression parameters

The formulas for calculating parameters and point of interception are:

$$x_j = \ln(t_j)\; and\; V_j = \ln\left(ln\left(\frac{1}{1-\frac{j-0{,}3}{n+0{,}4}}\right)\right) or\; V_j = \ln\,(\hat{Z}(t))$$

$$\beta = \frac{k\sum_{j=1}^{k} x_j V_j - (\sum_{j=1}^{k} x_j)(\sum_{j=1}^{k} V_j)}{k\sum_{j=1}^{k} x_j^2 - (\sum_{j=1}^{k} x_j)^2}$$

$$\alpha = \exp\left(\frac{(\sum_{j=1}^{k} V_j)(\sum_{j=1}^{k} x_j^2) - (\sum_{j=1}^{k} x_j)\,(\sum_{j=1}^{k} x_j V_j)}{-\beta\left(k\sum_{j=1}^{k} x_j^2 - (\sum_{j=1}^{k} x_j)^2\right)}\right)$$

$$Interception = \left(\frac{(\sum_{j=1}^{k} V_j)(\sum_{j=1}^{k} x_j^2) - (\sum_{j=1}^{k} x_j)\,(\sum_{j=1}^{k} x_j V_j)}{(k\sum_{j=1}^{k} x_j^2 - (\sum_{j=1}^{k} x_j)^2)}\right)$$

Ref: Nema (N.D.)(P.7)