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Estimation of the Economic Effect of Implementing Reliabilty-Centred Maintenance onboard a Maritime Vessel

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Preface

This master's thesis is the finalisation of my Master of Science degree in Marine Technology from the Norwegian University of Science and Technology. The study has been conducted during the spring semester of 2016. The thesis corresponds to 30 credits.

The work with the thesis started already during the summer of 2015, when I sailed with one of Klaveness' container vessel for five weeks in the South China Sea. During this period, I was able to get familiar with how the maintenance organisation in Klaveness Ship Management operates. I also got a basic understanding of the systems that are analysed in this thesis. Then, I used the autumn of 2015 to write my project thesis, titled "Improving Maintenance in Deep Sea Shipping – A Pre-Study". That thesis acted as a literature study and preparation for this master's thesis.

The thesis has been written with guidance from Klaveness Ship Management and MainTech AS. I would like to thank Christoffer Bøhmer and Jarle Kverneggen at Klaveness for providing me with the data used in the analysis. I would also like to thank Sverre Wattum at MainTech for good advice and being a sparring partner since before the project work started. A thank you is also due to Captain Cocos and his crew onboard Balsa.

Finally, I would like to thank my supervisor, Ingrid Utne, at the Department of Marine Technology, for her advice and pushing me into improving the final result of the thesis.

Aleksander Vold Kristiansen

Trondheim, June 10th 2016

Executive Summary

This master's thesis presents estimations of the economic effect of implementing reliability-centred maintenance (RCM) onboard a maritime vessel in order to help shipping operators with maintenance strategy decision making. It answers two research questions:

- How will RCM affect the ship system reliability?
- How will the maintenance related life-cycle costs change by implementing RCM on maritime vessels?

The recent halt in the global economic growth, combined with an increase in the ship supply capacity, has led to challenging conditions for ship-owners competing in the container freight market. As their revenues decline, they need to find new areas where they can save costs in order to stay competitive. A new approach to maintenance management may help achieve such cost savings. The results of this thesis show that the maintenance related life-cycle costs of certain shipboard systems may be reduced by up to 75 % by implementing RCM. The savings seem to be increasing with the criticality of the system.

Most ship-owners are currently following the recommendations from their equipment suppliers when they plan the onboard maintenance. These suggestions do normally not consider the equipment's operating context, and often call for system overhaul with pre-defined intervals. This approach is considered to belong in the second of the three generations of maintenance. It is believed that any organisation can achieve several benefits by advancing to the third generation, including cost savings, better safety records and more satisfied employees. RCM is considered an effective tool to help the organisation take this step.

The abovementioned benefits are mainly based on qualitative statements, so this thesis presents a method for providing quantified values, as well as using the method in a case study. First, two shipboard systems, the anti-heeling system (AHS) and the starting air system (SAS), are analysed using the RCM process, to develop alternative maintenance schedules. The behaviour of these schedules, as well as the currently used maintenance plans, are then evaluated by use of Monte Carlo simulation (MCS). Finally, the performances of the different plans are compared against each other, with regard to life-cycle costs and the occurrence of failures.

The resulting maintenance schedules show that the RCM plans call for approximately the same amount of planned maintenance activities, but they shift the focus from calendar based overhauls to condition based interventions. Allowing more condition controls causes a reduction in the number of complete system failures and an increase in the amount of deteriorated performances identified.

Reducing the severity of the failures also affects the maintenance related life-cycle costs. The RCM based schedule for the anti-heeling system achieves savings of 22 % related to the current plan. The more complex starting air system gains even larger cuts, reducing the life-cycle costs with around 75 %. Sensitivity analyses indicate that the RCM schedules may bring additional savings when the economic consequences of a failure get more severe. The economic effect of implementing RCM on safety or environmentally critical systems is still unclear.

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1. Introduction

1.1 Background

The global economy did not develop as expected in 2015. Regression in countries like Brazil and Russia, as well as reduced expansions in China, South Africa and other emerging states, led to lower global growth in 2015 compared to 2014 (World Bank Group, 2016). This decline in world advancement rate especially affects the fight against poverty, as fewer people than expected are able to break free from the underdevelopment. A consequence is that the global buying power comes to a halt as well.

When the improvement of the global economy slows down, international trading suffers. This can be seen from several of the major exporting countries. The United States, China, Japan and India all reported a reduction in export income in 2015 (Trading Economics, 2016). Even though other countries, such as Germany, experienced increased exports, the total global trade growth rate remained the same as in 2014 (World Bank Group, 2016). In other words, the demand for transportation of goods has not reached the levels anticipated.

The ship-owners invested for a future as expected, however. Major players in the container market, like Maersk, CSCL and MSC, invested in giant vessels. This led to an increase in the supply capacity in container shipping. According to the statistics portal Statista (2016), the capacity soared from 15.4 to 19.6 million twenty-foot equivalent units (TEU) from 2011 to 2015. Market theory states that when the supply increases more than the demand, the prices drop. This is also valid for the container ship market. Companies competing in the market struggle to make a profit, and the situation does not seem to improve in 2016 (Clarkson Research, 2016).

To stay competitive in such markets, operators need to focus on cutting costs. In container shipping, the focus has normally been on reducing the fuel consumption and improving logistics when it comes to cost reducing measures (The Journal of Commerce, 2013). Managers have normally overlooked the potential of savings related to maintenance. Most ship-owners base their maintenance schedules on the equipment manufacturer’s recommendations and class regulations (Shorten, 2012). These instructions are usually developed on a general basis, and do not consider the given equipment’s role in the vessel. Instead, they are typically more frequent than necessary to ensure that the equipment does not break down. By studying the shipboard systems and their relative criticality in the operating context, a well-reasoned, and often more efficient program, may be developed. The resulting schedule may lead to reduced costs, better safety and improved operational performance.

1.2 Purpose of the Study

The purpose of this study is to compare the life-cycle cost (LCC) of a reliability-centred maintenance (RCM) based plan against the current schedule to simplify maintenance management decision making for ship-owners in the container shipping segment. Chapter 2 will compare RCM to other strategies, and argue why the method is chosen in this thesis.

As the growth in the global economy has been lower than expected, the amount of traded goods has also halted. A consequence has been that the intense competition in the container shipping market has reduced the revenues for the involved actors, forcing them to find areas where they can cut costs. The focus has normally been on fuel consumption and logistics. However, most ship-owners have a somewhat old-fashioned approach to maintenance, and it is believed that there is a potential of savings related to the maintenance management as well.

To investigate the abovementioned potential, this study will calculate the life-cycle costs related to a maintenance schedule based on both RCM and the plan currently used by the Norwegian ship operator Klaveness Ship Management (KSM), and compare the results. Plans will be developed by the use of the RCM process described by Moubray (1997) and Smith and Hinchcliffe (2004), and their performance will be evaluated by simulating them over the expected lifetime of the vessel.

It is expected that the ship-owner can save considerable costs by performing the correct maintenance as suggested from the RCM process, while still keeping the system reliability at the required level.

1.3 Research Questions

The thesis will answer two research questions:

- How will RCM affect the ship system reliability?
- How will the maintenance related life-cycle costs change by implementing RCM on maritime vessels?

These are both wide questions that are challenging to answer. The thesis will therefore analyse two shipboard systems, and answer these questions to see if the systems show a trend. Chapter 2 will provide the necessary background and explain why there is a need to answer these questions.

1.4 Significance of the Study

As the benefits of RCM traditionally have been described in a qualitative manner, the background for making the decision to implement the approach has been limited. This study presents a method for quantifying the effect of a maintenance schedule. It also introduces a case study that produces such values to aid the decision making process. It can be considered a start in estimating the effect of maintenance strategies, and the student encourages others to build on the study.

1.5 Scope and Limitations

Due to the time limitations related to master's thesis, the study will only consider RCM's effect on reliability and life-cycle costs. As chapter 2 will describe, it is believed that RCM also will have an impact on the systems' safety level and environmental integrity. However, developing models and performing analyses of these aspects as well is viewed to be too time consuming, and is therefore left out.

The analysis will find the effect of an initial RCM program. This means that it will not introduce any interval optimisation procedures to find the maximal effect potential, but rather use the activities and intervals resulting from the RCM analysis in the calculations.

Additionally, the RCM process will be performed by the student alone. As this is the first time the student performs such an analysis, and that his first-hand experience with the analysed systems is rather limited, it is expected that the RCM results will include minor errors. However, the schedules will be reviewed by RCM experts, which ensures that the product should be at an acceptable level. The values presented in the results section should therefore not be considered as true values, but they should nevertheless show a realistic trend.

1.6 Definitions and Abbreviations

1.6.1 Definitions

- Corrective maintenance: "Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function" (EN 13306, 2010).
- Deteriorated performance: The system performance has started deviating from the initial capability.
- Failure mode: "Any event which causes a functional failure" (Moubray, 1997).
- Key performance indicators: Measured characteristics that assess the evolution of important operational areas (EN 15341, 2007).

- Life-cycle costs: All costs accumulated during a system's lifetime, including initial investments, operational costs, revenue impacts and decommissioning costs.
- Maintenance: "The combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EN 13306, 2010).
- Maintenance strategy: "A management method used in order to achieve the maintenance objectives" (EN 13306, 2010).
- Monte Carlo Simulation: "A methodology for obtaining estimates of the solution of mathematical problems by means of random numbers" (Zio, 2013).
- P-F interval: The time interval between an occurring failure can be identified and the function reaches functional failure.
- Predictive maintenance: "Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item" (EN 13306, 2010).
- Preventive maintenance: "Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item" (EN 13306, 2010).
- Reliability: "The ability of an item to perform a required function under given conditions for a given time interval" (EN 13306, 2010).
- Reliability-centred maintenance: "A specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context" (SAE JA1011, 2009).
- Total failure: The system delivers no output at all.

1.6.2 Abbreviations

- CM: Corrective Maintenance
- FBD: Functional Block Diagram
- FMEA: Failure Mode and Effect Analysis
- FMECA: Failure Mode, Effect and Criticality Analysis
- GT: Gross Tonne
- IMO: International Maritime Organisation
- ISM: International Safety Management
- KSM: Klaveness Ship Management

- KPI: Key Performance Indicator
- MCS: Monte Carlo Simulation
- O&M: Operations & Maintenance
- PdM: Predictive Maintenance
- PM: Preventive Maintenance
- QSM: Quality Standard Management
- RCM: Reliability-Centred Maintenance
- TEU: Twenty-foot Equivalent Unit
- TPM: Total Productive Maintenance
- USD: US Dollar
- VaR: Value at Risk

2. Literature Review

2.1 Introduction

Chapter 1 described how container shipping companies are looking for ways to cut costs to stay competitive, and how a new approach to maintenance may help them achieve their goals. It also introduced the purpose of the study, which is to compare the LCC of a RCM based plan with the present schedule to aid decision making.

This chapter will introduce important maintenance concepts, describe how maintenance thinking has evolved through the years, and argue why RCM is the chosen method in this thesis. Further, it will suggest different ways of evaluating the performance of a given maintenance strategy, before it ends with discussing the status in shipping and where the industry is heading.

2.2 Maintenance Management Strategies

2.2.1 Important Concepts

Maintenance is defined in the EN 13306 standard (2010) as “the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”. Figure 2-1 shows how the organisation needs to consider several aspects in order to ensure it has a well-functioning maintenance department. The figure will be brought up several times through the thesis.

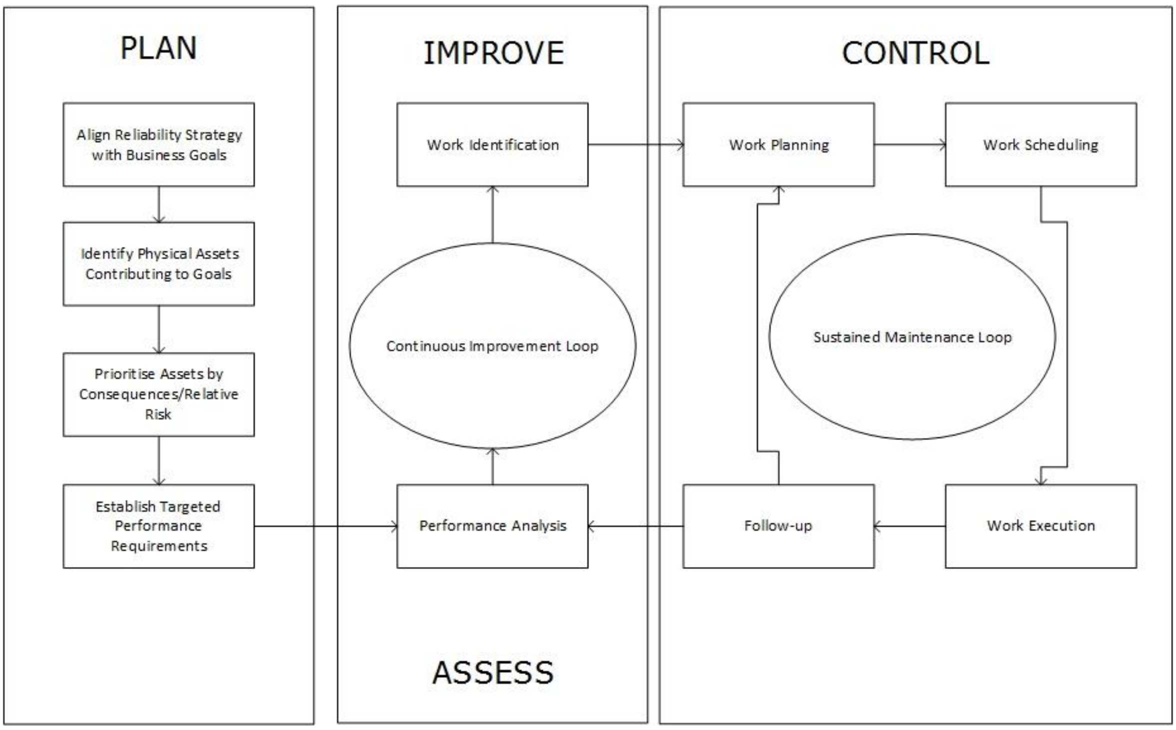


Figure 2-1. Important Aspects for a Well-Functioning Maintenance Department. Adapted from Smith and Mobley (2008).

There are numerous strategies developed to manage the maintenance function, but as this chapter will show, many of them are mainly focused around the work planning aspect. Some of the most common ideas are corrective, preventive and predictive maintenance, as well as RCM (Sullivan et al., 2010). These strategies will affect the reliability of the system or equipment in question, which consequently will influence the costs, safety and availability related to the same system. They differ from each other in how they treat equipment failures (EN 13306, 2010):

- Corrective maintenance (CM) means that maintenance activities are only performed after an asset failure.
- Preventive maintenance (PM) activities are executed at pre-defined intervals, based on the idea that this reduces the chance of equipment failure.
- Predictive maintenance (PdM) implies that the condition of the asset is monitored, and maintenance activities are then chosen based on the evaluated performance.
- The RCM process considers the relative importance of asset performance, and then decides whether CM, PM or PdM is the best option (SAE JA1012, 2011).

Another important maintenance concept is total productive maintenance (TPM). This is a strategy that takes the idea of maintenance a step further, and illustrates how the entire company needs to consider maintenance, and how the maintenance department needs to think about the total production (Mobley, 2002). All these theories and their relevance for this thesis will be described further in the following sections and sub-sections.

2.2.2 The Evolution of Maintenance

According to John Moubray (1997), one of the RCM pioneers, one can describe the evolution of maintenance through three generations. He places the first generation in the period before the Second World War. Here, industries relied on manual labour instead of autonomous production, which meant that equipment downtime was not a big concern. Combined with the fact that most equipment was simple and over-dimensioned, a more advanced strategy than CM was not really needed.

During the World War, the supply of manpower to the industry declined heavily, which switched the focus to mechanisation. With more mechanisation, downtime became an important aspect of production. More complex equipment also meant more capital invested. These two aspects led to the idea of preventing failures from happening and increasing the equipment lifetime. Therefore, companies started with introducing preventive maintenance plans to reduce failures and maintenance. This is considered as the second generation of maintenance.

The evolution of the third generation started to gain momentum in the mid-seventies. Moubray (1997) claims this was based on changes within three areas:

- New expectations: As industries adapted to just-in-time systems, fighting downtime became even more important. Stricter demands from safety and environmental regulations was introduced, which led to an increased focus on reliability improvements. Additionally, rising globalisation hardened the competition for many businesses, forcing them to make their entire organisation, including the maintenance department, more cost-effective.
- New research: An important assumption in PM strategies is that assets have increasing failure rates over time. However, data from Nowlan and Heap (1978) suggests that only one tenth of all failure modes have such failure distributions, which is shown in Figure 2-2 below. In other words, such a program is likely to call for both too much and incorrect maintenance. With the new findings, industries started to understand that many of their maintenance activities achieved nothing, and could even be counterproductive.
- New technologies: There has been a development in maintenance concepts and techniques, based on the requirements from the research and increasing expectations. New decision-support tools, such as failure mode, effect and criticality analyses (FMECA) and technical innovations allowing for condition monitoring have made it easier to develop and implement improved maintenance plans.

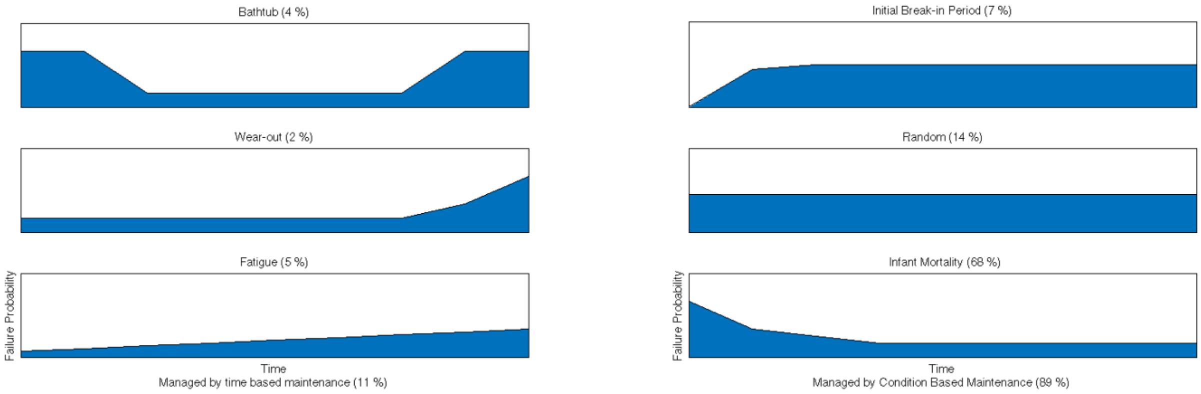


Figure 2-2. Failure Pattern Distribution. Adapted from Nowlan and Heap (1978).

The new condition monitoring technologies aim to identify failures that are about to occur. When such occurring failures are identified, it is a matter of time before the function reaches a failed state. This period of time is called the P-F interval (Moubray, 1997), which is illustrated in the figure below. An important idea of the third generation of maintenance is to ensure that condition control activities are executed with such intervals that they identify the failures in the P-F interval.

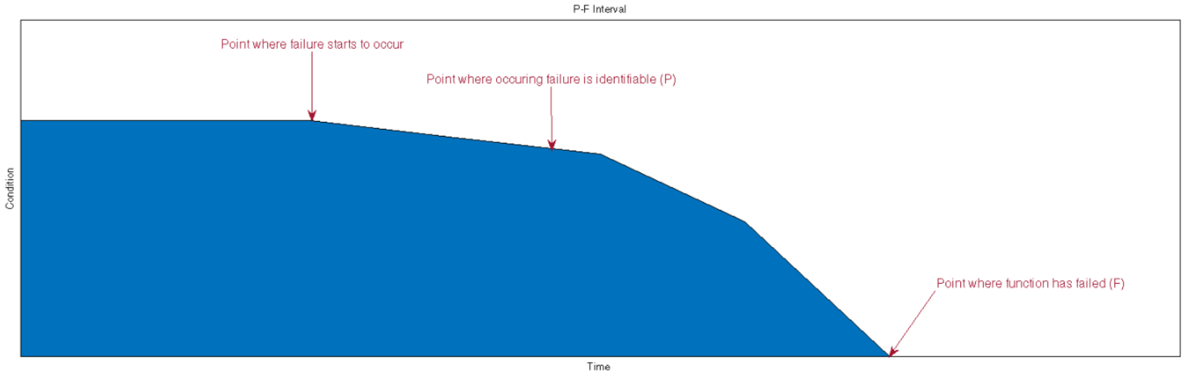


Figure 2-3. P-F Interval. Adapted from Moubray (1997).

2.2.3 Reliability-centred Maintenance

One tool that considers the three bullet points described above to aid decision making in maintenance planning is RCM. This tool was developed by United Airlines, who enjoyed great success from it. Several other industries have later profited on the benefits of implementing the strategy (Moubray, 1997). This will be described further in subsection 2.3.2.

RCM is defined by the SAE JA1011 (2009) standard as “a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context.”

An important part of the RCM process is the focus on the operating context. This means that where and how the asset is being used has significant influence on the final result. The redundancy level, quality and environmental standards, and safety hazards are all critical aspects that need consideration in the maintenance planning process.

The RCM method asks seven basic questions, in which the answers can result in a well-reasoned maintenance plan (Moubray, 1997):

1. What is the asset's functions and at what levels is it required to perform in the current operating context?
2. How can it fail to do what the user requires?
3. What causes these failures?
4. What is the effect of these failures?
5. What are the consequences?
6. Can the failures be predicted or prevented?
7. If not, what should be done?

The key to a good result is to answer the first question in a detailed manner. The more an engineer knows about the required performance of the asset, the easier it is to prescribe a maintenance plan for it. This should include quantified values where possible. As an example, when creating plans for a pump, one should as a minimum include information about whether there exist standby pumps, what fluid the pump transfers and the required transfer rate. The answer to question 2 is then the different ways the asset may operate without fulfilling the requirements.

Then a failure mode, effect and criticality analysis (FMECA) is developed by answering questions 3 through 5. The two final questions can be combined into one step. Here, the severity of the consequences is evaluated, and the best activity is chosen based on this evaluation and a cost-benefit analysis. These activities can range from corrective maintenance to re-design. I.e., a failure mode that causes only low operational costs, while preventing the failure from happening may require an extensive overhaul effort, should probably just run till it fails. A failure mode with catastrophic consequences, however, would normally require a significant surveillance plan, or even re-design.

Figure 2-4 below summarises how the RCM process can be executed through three steps.

Figure 2-4. The Three Steps of the RCM Process.

2.2.4 Total Productive Maintenance

Another popular maintenance strategy is the ideas related to TPM. The concept was first introduced in the United States, but it has experienced most of its development in the Japanese industry. The car manufacturer Toyota are famous for how they have implemented the TPM ideas in their “Lean Manufacturing” strategy. However, as mentioned in subsection 2.2.1, this covers more organisation areas than just maintenance. A successful TPM company focuses on optimising production through quantifying values for availability, performance rate and product quality (Mobley, 2002). As Figure 2-5 shows, maintenance planning is just a part of this process.

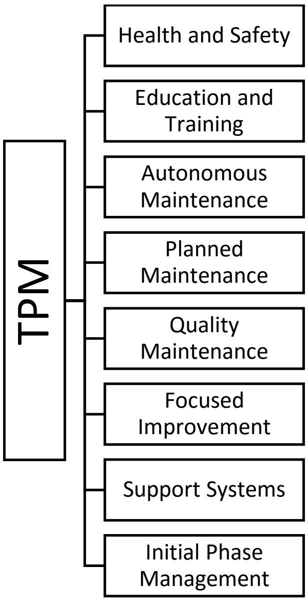


Figure 2-5. The Eight Pillars of TPM. Adapted from Borris (2006).

The figure is adapted from Borris (2006), and depicts how TPM is founded on eight pillars:

1. Health and Safety: Operators performing the technical tasks need to be protected.
2. Education and Training: If the operators do not have the required knowledge, production will probably not be optimal.
3. Autonomous Maintenance: Instead of waiting for expert technicians, asset operators can perform basic maintenance tasks themselves.
4. Planned Maintenance: Both PM and PdM activities are performed to prevent failures from happening.
5. Quality Maintenance: The product is supposed to be of a certain quality. Cross-functional teams co-operate to find and remove sources of quality variation.

6. Focused Improvement: Assets and processes are continuously analysed for potential improvements by cross-functional teams.
7. Support Systems: These techniques are used in support systems like warehouses and purchasing, as well as in the main production.
8. Initial Phase Management: The entire organisation and process, from the development of new ideas to customer support, need evaluation.

2.3 Measuring the Effect of Maintenance

2.3.1 The Effect of Maintenance

Reliability can be defined as the “ability of an item to perform a required function under given conditions for a given time interval” (EN 13306, 2010). Combining this definition with the one for maintenance in sub-section 2.2.1 gives a relationship between maintenance and reliability. One can say that the level of maintenance directly affects the reliability of an item. Depending on the equipment’s function, its reliability can influence important parameters like downtime costs, safety and product quality.

2.3.2 The Effect of Implementing New Maintenance Ideas

Subsection 2.2.2 explained how new expectations have influenced the evolution of maintenance planning through three generations. This part will describe the effect of advancing from one generation to the next one. The number of quantified values in the literature seems limited, but the figures found are presented below.

A company with a first generation maintenance organisation will experience several failures, causing high costs related to downtime, overtime work and equipment replacement, as well as potential damage to secondary equipment and the surrounding environment. Avoiding some of these failures through a preventive schedule will reduce the aforementioned costs. Sullivan et al. (2010) suggest that a transition to the second generation can lead to savings of 12 to 18 percent. The planning of such a schedule will include some related costs, which can influence the numbers presented. However, an analysis done by Stenström et al. (2015) showed that implementing a preventive plan over a pure corrective one in railway infrastructure would give a benefit-cost ratio of 3.3.

The use of a purely preventive maintenance plan will still, as can be seen in Figure 2-2, handle only a tenth of the expected failure modes in a correct manner. This means that critical failures are still likely to occur, and that the program includes performance of unnecessary activities. Handling the failure modes in the correct way through the use of predictive maintenance techniques may reduce costs with an additional ten percent, according to Sullivan et al. (2010). In some cases, however, implementing condition monitoring may involve large initial costs, due to investments and training, which may exceed the related benefits. This means that using predictive measures to handle every failure mode will most likely not be the optimal solution for any organisation.

By utilising RCM as a decision making tool, it is believed that one can get a cost-effective solution, while still sustaining the required system reliability. Based on analyses of what is worth doing, the process creates a program combining elements from the three generations. Both Sullivan et al. (2010) and Moubray (1997) list several benefits of implementing RCM in a qualitative manner:

- Better safety and environmental integrity.
- Improved operating performance.
- Improved cost-effectiveness.
- Prolonged equipment lifetime.
- Motivated employees.
- Better teamwork.

While neither Moubray (1997) nor Sullivan et al. (2010) back these statements with numbers, the following figure shows an interesting trend. The airline industry has, as mentioned earlier, been the frontrunner when it comes to implementing RCM. The figure depicts the reduction in fatalities due to airplane accidents against the increase in flying passengers after the implementation of RCM around 1980. This improvement in reliability can of course be due to improved equipment technology, but it is also probable that the use of RCM has some influence on the development.

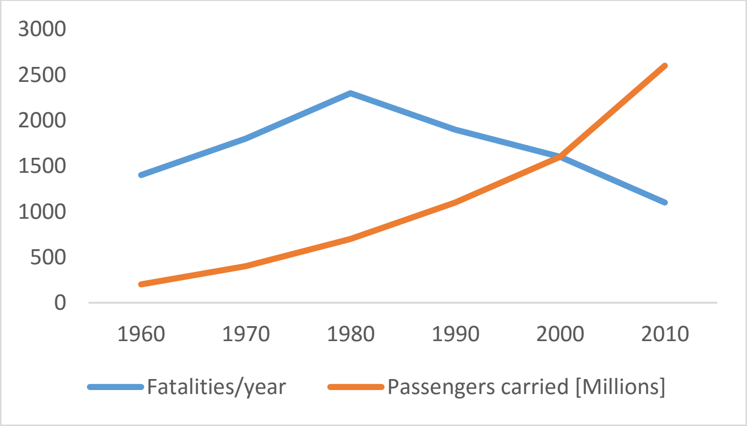


Figure 2-6. The Safety Development in the Air Transportation Industry. Adapted from Knutsen et al. (2014).

Starting an RCM process requires resources and effort from the organisation in question, both through training, equipment investments and implementation. Combining these initial costs with the lack of clarity when it comes to savings and benefits, it can be hard to convince an organisation operating in the transition between the second and third generation to take the final leap. In other words, there is a need for a study that can quantify the potential benefits of using RCM.

This is also valid for TPM. It is believed to be bring benefits, like improved product quality, reduced costs, and increased asset availability, but as the strategy covers more than just maintenance, the initial resource requirements are even greater than for RCM. Successful implementation of TPM requires commitment and support from the top management and may need a change of organisational structure and culture (Attri et al., 2013). Therefore, a company that still operates in the transition between the second and third generation of maintenance should start with implementing the ideas of RCM as an introduction to TPM. This is supported by Borris (2006), who states that RCM and TPM should not be considered as opposing strategies, but rather as complements to each other.

2.3.3 Quantifying the Costs

One common way of comparing different options is to analyse their corresponding life-cycle cost. An LCC analysis considers the accumulated costs of an option through its life-time. It does not consider potential revenues as positive aspects, but rather include lost income as costs. This makes it a fitting tool for comparing maintenance strategies. High asset reliability does not increase revenue, but failures may lead to both direct and indirect costs. The following equation shows how the LCC includes all costs related to the option that incurred during its life-time (ISO 15663-2, 2001).

$$LCC = C_{initial\ investment} + C_{operation} + C_{revenue\ impact} + C_{decommissioning} \qquad (1)$$

For maintenance strategies, the focus is on the operational and revenue impact costs. As different strategies distribute resources to maintenance activities in various ways, the operational costs will alter accordingly. The planned activities related to a condition monitoring based plan will have other cost drivers than a corrective schedule. This will also affect the amount of failures, which influences the LCC, both through direct repair costs, and the downtime related revenue impact.

The costs due to the planned activities can be calculated easily. The challenge lies in estimating the impact of the system reliability. The uncertainty related to equipment failure makes it hard to estimate the repair and downtime costs. However, as the next paragraphs show, a study by Kerres et al. (2015) presents a method for comparing the LCC of different maintenance plans based on Monte Carlo simulation (MCS).

Kerres et al. (2015) had identified that operation & maintenance (O&M) costs account for about 35 % of the LCC of wind turbines, and recognised the need to focus on these expenditures in order to reduce the cost of wind energy. They therefore developed a stochastic model to compare the LCC of different maintenance plans. Their study was based on an RCM analysis of a wind turbine, which identified the most critical components and failure modes of the system. They then proposed different plans to handle these failure modes, and used their model to find the most cost-effective option.

Based on typical actions related to the maintenance execution, all activities, both corrective and planned, was assigned a cost. This included revenue impact as well as operational costs. Then failure rates were attached to the system equipment, and random number Monte Carlo simulation was used to analyse the maintenance performance.

To include failure mechanisms in the model, Kerres et al. (2015) introduced two different deterioration processes: binary and delay-time deterioration. Binary deterioration means that the equipment can exist in two states – good or failed – while delay-time includes an intermediate defective state. This allowed them to include inspection activities in their model, as well as corrective and pre-defined replacement tasks. The failure rates were estimated as Weibull distributed values based on a large wind turbine reliability database.

Kerres et al. (2015) used their model to compare three different maintenance strategies: A pure run-to-failure strategy, an inspection based strategy and an online condition monitoring strategy. These strategies were then simulated 100 000 times over the turbine’s life-time, and their performance in four indicators were compared:

1. Unavailability
2. Downtime costs
3. O&M costs
4. Total LCC

The results indicated that the run-to-failure and the condition monitoring strategies had almost the same LCC, and they were both better than the inspection based strategy for the wind turbine in question. However, a sensitivity analysis showed that increasing electricity prices would increase the benefits of using condition monitoring, due to the increased costs related to downtime.

The abovementioned study illustrates how MCS can be used in the estimation of maintenance related life-cycle costs. Monte Carlo simulations is a valuable tool when it comes to estimation of the performance of systems with inherent levels of uncertainty. This is because it can take the uncertainty into account, and present the results as probability distributions. It also allows for use of sensitivity analyses, to see how the system reacts to potential changes in the input values (Williams et al., 2008).

This thesis will show how one can use MCS to evaluate the economic performance of a maintenance strategy, and compare different strategies against each other. Chapter 3 will present MCS further. Kerres et al. (2015) used their model to find the most cost-effective plan based on an RCM analysis. Shahata and Zayed (2013) used a similar approach to find the most cost-effective maintenance activity for water mains. None of them have used such a model to find the effect of RCM compared to other strategies, however, leaving a gap open for further research.

2.3.4 Performance Monitoring and Working for Continuous Improvement

This thesis is mainly focusing on the “plan” and “control” areas of Figure 2-1, and especially on “work planning”. However, as the figure shows, a well-functioning maintenance department also assesses its performance and searches for potential improvements. This can be done by using key performance indicators (KPI).

KPIs are measured characteristics that assess the evolution of important operational areas (EN 15341, 2007). In maintenance, KPIs are structured into economic, technical and organisational indicators. One can also divide KPIs into two groups based on what information they hold (Smith and Mobley, 2008):

- Leading indicators: These are indicators one can change, and they therefore help with managing the organisation. An example of a leading KPI is the percentage of work orders completed before the due date.
- Lagging indicators: These indicators show how the organisation has been managed, which makes them harder to influence directly. An example of a lagging KPI is the failure frequency.

The maintenance department should analyse its lagging indicators, compare the values to the performance goals and then focus on the KPIs that may help it reach the targets. Low failure frequency is a target that cannot be adjusted directly, but completing more work orders on time will probably affect the value. The student's project thesis gives more information about KPIs and presents a model that helps a manager to choose relevant indicators (Kristiansen, 2015).

Additionally, the organisation may learn and find improvement areas by investigating what went wrong when a failure has occurred. By truly understanding why a failure happens, the maintenance department can introduce measures that prevents the failure from occurring again, and thus affect the KPI values in a positive manner. This means that the organisation should perform root cause analyses to find the real problem. Andersen and Fagerhaug (2006) presents several tools to find the root cause, where the Five Whys might be the simplest one to implement. This method argues that asking why a failure happens through five levels should ensure that the root cause is identified.

2.4 Maintenance in Shipping

2.4.1 The Status of Shipping Maintenance

When it comes to maintenance in shipping, the International Maritime Organization (IMO) has defined requirements for vessels over 500 gross tonnes (GT) in the International Safety Management (ISM) code. Here, it is stated that a ship-owner should maintain its vessel in compliance with relevant rules and regulations. This means that inspections should be performed, appropriate corrective maintenance executed and that non-conformities and maintenance activities should be recorded and reported. The code does not state what strategy the organisation should choose when it comes to maintenance planning, leaving the decision to the ship-owner (International Chamber of Shipping and International Shipping Federation, 1996). This allows other agents to offer recommendations. The classification society DNV GL declare that maintenance "…shall be in accordance with applicable recognised standards in the industry or in accordance with procedures recommended by the manufacturer" (DNV GL, 2015).

In his position paper on shipping maintenance, Shorten (2012) describes how these minimal requirements have led the industry to become an industry of compliance. Instead of striving to optimise the performance and implement innovative solutions, most managers have focused on satisfying the requirements. Shorten (2012) presents numbers based on Lloyd's Register classified ships, showing that ship-owners mainly follow manufacturers' recommendations, and that only 2 % of the fleet pursue a predictive maintenance based scheme. DNV GL report a similar trend for their fleet, with a single percent registered with a condition monitoring class (Knödlseder, 2015).

Section 1.1 argued that the maintenance recommendations from the suppliers will most likely not be the optimal plan. However, the benefits of such a strategy is clear:

- The maintenance plan is already set, meaning that the organisation does not need to use resources on developing a schedule.
- The supplier often demands that the ship-owner follows the recommendations for the warranty to be valid (Shorten, 2012).

Most supplier-based maintenance plans are pre-defined based on calendar or running hours, which can be seen in the thesis' case study. This places the industry in the second generation of maintenance, with a few leading companies in the transition area to the third generation. Some important downsides related to the second generation were mentioned above, but there are also other disadvantages with following such a strategy. Strictly following generic recommendations from suppliers may also stifle the learning, understanding and development of both the shipboard crew and the management organisation. The crew will perform the tasks as they are told to, and seldom suggest improvements based on critical thinking, which may cause inefficient use of resources for the organisation in the long term (Knutsen et al., 2014).

The shipping industry should therefore strive to advance to the next generation, and sub-section 2.4.3 will present how this can be achieved.

2.4.2 The Approach in Klaveness Ship Management

This sub-section gives a short introduction to how KSM consider maintenance in order to understand the current situation and find potential improvement areas. It is mainly based on their Quality Standard Management (QSM) document, unless otherwise is stated. Section 5.7 of the QSM is dedicated to maintenance, and includes the following statement regarding the requirement of the maintenance function (Klaveness Ship Management AS, 2015b):

> *"The vessel shall at all times be kept in a seaworthy condition consistent with classification society requirements, and in compliance with relevant national and international regulations. Much emphasis shall be placed on maintaining the vessels as safe and pleasant working places for the crew, and avoiding the vessels becoming possible pollution and environmental hazards."*

The container vessels in KSM's fleet are all classed with DNV GL's "Machinery Continuous" scheme. This is a five-year survey plan that allows the Chief Engineer to perform some of the inspections. It does not require any maintenance plans, however. It only requires the documentation of performed maintenance (DNV GL, 2015).

KSM have set standards on how to differ the maintenance strategy based on the assumed life-time of the vessel. Table 2-1 shows how the approach changes with the investment period. This aims to find the equilibrium between availability and costs.

Table 2-1. Operational Maintenance Philosophy (Klaveness Ship Management AS, 2015b).

	Long Term	**Mid Term**	**Short Term**
Number of Years	> 7	4 - 7	0 – 3
Unplanned Off-Hire	1 - 4 days/year	4 – 8 days/year	6 - 12 days/year
Maintenance Strategy	Preventive and predictive	Preventive, predictive and planned corrective	Preventive and corrective

The table shows that KSM uses a combination of CM, PM and PdM. This implies a more advanced strategy than their class requires. However, Christoffer Bøhmer (2015) of KSM explains that this is a goal they are working towards achieving, and that condition monitoring is rarely in use per now. This means that KSM's preventive maintenance plans are mainly based on class requirements and manufacturer's recommendations.

The maintenance plan is implemented in the Kongsberg Consultas software. Here, the onboard crew can find their pending tasks with detailed instructions and due dates. It also allows the workers to share problems and improvement suggestions with the onshore office and the other vessels (Chief Officer Dulama, 2015).

In short, KSM are still operating in the second generation of maintenance. However, they have a stated goal of advancing to the third generation, and they have already introduced a computer system that easily allow the ideas of continuous improvement.

2.4.3 The Classification Societies' Visions

Stakeholders in the shipping industry are starting to see the limitations of the current approach to maintenance. DNV GL have published a position paper based around the following figure (Knutsen et al., 2014).

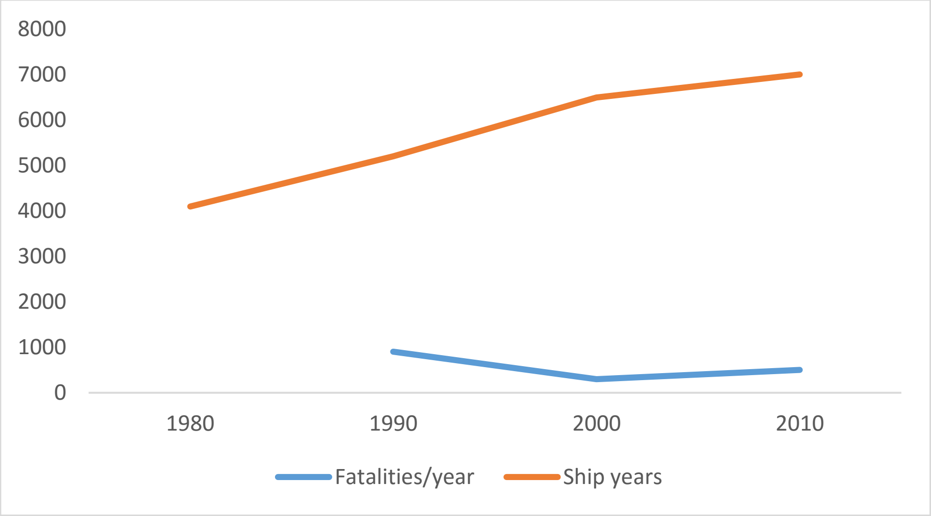


Figure 2-7. Fatalities per Year in Passenger Ships. Adapted from Knutsen et al. (2014).

Comparing this figure with Figure 2-6, one sees that the safety development in shipping has been far from the success of the aviation industry. DNV GL believe that the difference in maintenance strategies plays an important part in this deviation, and call for a new attitude to upkeep planning. In their position paper, they state that increased use of condition monitoring techniques is the future for operators in the deep sea shipping market as well. However, they acknowledge special challenges for this industry, in addition to the ones described in sub-section 2.3.2:

- Shipboard systems often consist of components from different manufacturers, making it harder to develop standardised monitoring equipment, software and techniques than for simpler systems.
- The aircraft industry produces planes in series of hundreds, or even thousands, while there are seldom more than ten equal sister ships. This affects the sizes of the important reliability databases that are needed for data-driven diagnostics and prognostics.
- The ship-to-shore data transfer capabilities are limited. The bandwidth is increasing steadily, but there are still problems related to transfer of online data.

To counter these challenges, DNV GL recommend managers to modernise their maintenance department through three stages (Knutsen et al., 2014):

1. Identify the most critical systems and components onboard, and implement condition monitoring techniques to handle their failure modes. RCM can be used to select these systems.
2. Develop reliability databases to help determine the remaining useful life of the equipment, and to help understand when, and what kind of, maintenance should be performed. These databases should preferably be developed in co-operation with other ship-owners, to ensure a comprehensive background that can provide trustworthy data.
3. Include the ideas of condition monitoring in the design process. Ensure that the systems allow for online tracking, and develop algorithms that recognise initiated failure mechanisms.

In the previously mentioned Lloyd’s Register paper, Shorten (2012) advocates the same need for implementation of predictive techniques. In addition to the abovementioned benefits of the modern ideas, he stresses the potential in shifting the maintenance expertise onshore. According to Shorten, this can reduce the size of the crew and allow the remaining manpower to focus on their core functional activities.

Classification societies have started promoting these ideas through their range of survey schemes. DNV GL focuses on predictive maintenance, and offer relaxed surveying to ship operators using well-reasoned condition monitoring procedures (2015). ABS (2003) and Lloyd’s Register (2013) recognise the potential in RCM as well, and give benefits to companies that follow this strategy.

2.5 Summary

During the last century, the ideas related to maintenance have evolved through what can be called three generations. Many ship-owners are still operating in the second generation, however, and have yet to implement the most modern techniques. There is a common belief that the benefits of enforcing condition monitoring make this the way to go for shipping operators as well. Such a modernisation process will face challenges, however, both organisational and technical. The literature provides no quantified information on the ratio between the benefits and challenges, which makes it harder to convince operators that this is a process worth undertaking.

This study aims to aid making this decision. By performing an RCM analysis on shipboard systems, one takes the first step towards a modern maintenance approach. It will then use MCS to evaluate the performance of the resulting schedule.

3. Methods

3.1 Introduction

Due to the recent decline in global economic growth, companies operating in the container shipping market need to cut costs to stay competitive. It is believed that implementing modern maintenance ideas can help operators achieve substantial cost reductions. However, there is a shortage of values backing the theory. This study therefore aims to quantify the economic effect of using the RCM method for a ship-owner. Specifically, the thesis will answer two research questions, which are presented in section 1.3.

To be able to answer these questions, the thesis will first use RCM to develop a maintenance plan for two shipboard systems. These schedules, as well as the present strategy, will then be simulated over a ship's life-time, and their performance will be evaluated against each other.

This chapter shows how the researcher has used the RCM method and developed a simulation program. The RCM technique described by Moubray (1997) and the SAE JA standards (2009, 2011) is presented in section 3.3. The process requires that the analyst has a certain knowledge of the systems in question, however, so section 3.2 presents how an RCM engineer can prepare for the analysis. This is based on the ideas of Smith and Hinchcliffe (2004). Then, section 3.4 introduces how Monte Carlo simulation is used to analyse the performance of the maintenance schedules.

3.2 Preparation for the RCM Analysis

3.2.1 System Hierarchies

To get a basic understanding of how the system and its equipment interact, the preparation starts with drawing asset and functional hierarchies. This idea is supported by both Moubray and Smith & Hinchliffe. An asset hierarchy shows how a system is made up of major equipment and components. Figure 3-1 depicts an asset hierarchy with three levels. A hierarchy can consist of both more and fewer levels than three.

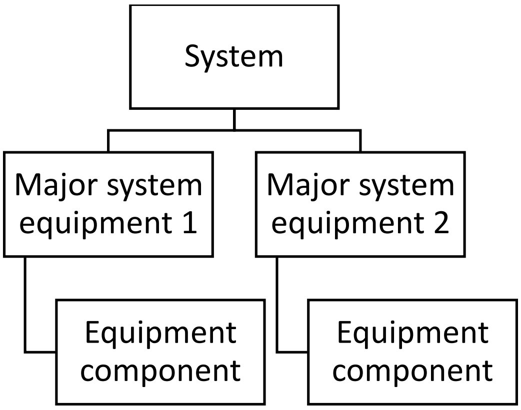


Figure 3-1. Asset Hierarchy Example.

This hierarchy can then be transformed to a functional hierarchy. Such a hierarchy defines the primary function of the system, equipment and components, which helps the maintenance engineer understand the system's role, what it consists of and how the equipment interacts. This knowledge is the basis for the next steps. Figure 3-2 shows a functional hierarchy based on Figure 3-1.

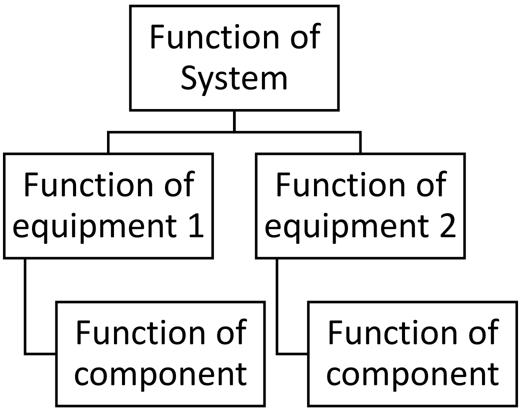


Figure 3-2. Functional Hierarchy Example.

3.2.2 Boundaries and the Operating Context

After the development of the hierarchies has given a basic understanding of how the system works, the analysis boundaries should be defined. This means that the engineer lists the major equipment that will be included in the analysis, and the medium, signals and similar that comes in to, and leaves, the system. Smith and Hinchcliffe (2004) present two reasons that explain the importance of such a definition:

- By listing the equipment, the engineer ensures that the same equipment is not included in different system analyses, and that the foundation for the analysis is clear for future revision. This is important for successful implementation of RCM, as sub-section 3.3.6 will describe further.
- An overview of the system's inputs and outputs gives a further understanding of how it works, and will help design the functional block diagram. The next sub-section introduces these diagrams.

Additionally, the boundaries help defining the system's operating context. Sub-section 2.2.3 introduced how the operating context influences the final result of an RCM process. This means that the planner needs to understand the redundancy level, quality, environmental and safety standards, protection and key control features before starting the analysis. Therefore, the engineer should develop a thorough functional description, including the aforementioned aspects.

3.2.3 Functional Block Diagram

After the creation of the system hierarchies and the definition of the boundaries and operating context, the engineer has enough information to design a functional block diagram (FBD). This is a drawing that depicts the functions of the system, and how the equipment and input interacts with each other. Figure 3-3 shows how an FBD for the example system can look like, where the dotted box indicates the boundary of the system.

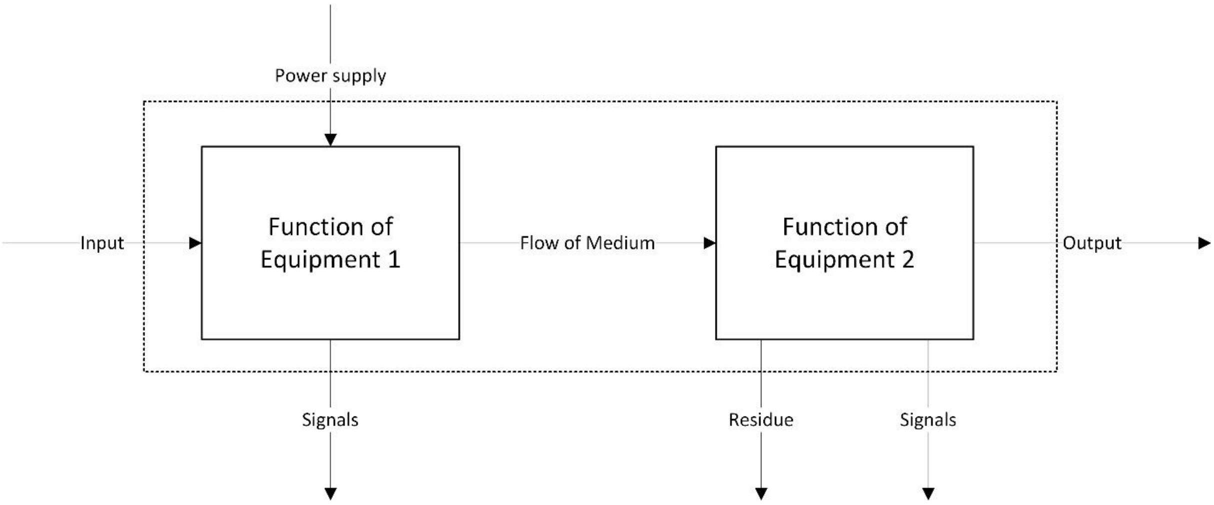


Figure 3-3. Functional Block Diagram (FBD) Example.

Using an FBD will aid identifying functions and functional failures in the RCM process.

3.2.4 Failure History and the Current Maintenance Plan

As section 3.3 will describe, an RCM analysis should include all probable failure modes. Moubray (1997) states that it should at least cover failures that have happened before, as well as failure modes already covered by a proactive maintenance program. An overview of these aspects should therefore be prepared before starting the analysis. The more details included in this preparation, the easier it is to perform the assessment.

3.3 The RCM Analysis

3.3.1 Introduction

Chapter 2 described how RCM is a tool that is closely related to the third generation of maintenance, and how DNV GL recommend implementing the method as a first step towards a modern maintenance organisation. Sub-section 2.2.3 introduced how an RCM maintenance plan is developed from the answer of seven questions. This section presents how the researcher has answered these questions in this thesis based on Moubray's (1997) method.

3.3.2 The Functions

In order to decide how to maintain a system or an asset, the engineer needs to know what the system is supposed to do. Therefore, the first question asked is "What is the asset's functions and at what levels is it required to perform in the current operating context?". If the analyst has done a thorough job with the RCM preparations, and developed a detailed FBD, this process is straightforward. The blocks and arrows of the FBD indicate what the user requires of the system.

The analysis should include all functions, both primary and secondary. Primary functions are the capacities that caused the user to acquire the asset. For a pump, this can be the ability to transfer fluids. Secondary functions are all the other duties the operator expect from the equipment. This include safety, comfort, efficiency and other aspects. An example is that the user may expect that the same pump delivers the fluid without any leakages.

The functions should also, where possible, include quantified performance requirements. This is an important aspect of the RCM process. A new asset may be able to perform better than what the user requires. In other words, the supplier delivers an asset that has an initial capability better than the desired performance. As Figure 3-4 shows, this means that there is an inherent margin for deterioration. However, as long as the asset delivers the desired performance, the initial capability is not important for an RCM engineer. The RCM process is about maintaining the desired performance. This shows the value of quantifying the performance requirements.

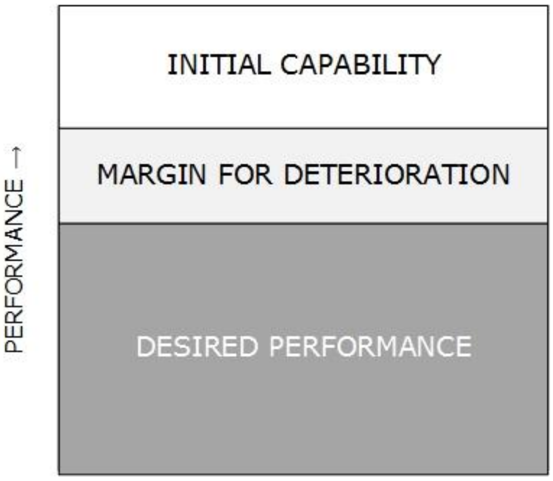


Figure 3-4. Initial Capability vs. Desired Performance. Adapted from Moubray (1997).

3.3.3 Functional Failures

The abovementioned performance requirement is also related to the second question: “How can it fail to do what the user requires?”. In RCM, a functional failure occurs when the capability line falls below the desired performance line in Figure 3-4. However, as different positions of the capability line are caused by different failure modes, and may cause different consequences, Moubray argue that the analysis should include both partial and total functional failures.

3.3.4 Failure Mode and Effects Analysis

Chapter 2 described how RCM questions 3 through 5 can be answered by performing an FMECA. However, in Moubray’s method, the consequence evaluation is performed in a special manner. Therefore, the next sub-section will consider the fifth question, while this part shows how a failure mode and effects analysis (FMEA) has been used to answer question 3 and 4.

The third question asks what causes the identified failures. This means that the analysis requires a recognition of the failure modes that can cause every functional failure. Moubray (1997) defines a failure mode as “any event which causes a functional failure”, and argue that the analysis should include failure modes that have occurred before, failure modes that are currently prevented by a maintenance plan and failure modes that are considered as probable to happen.

The failure modes have to be defined in a way that makes it possible to find an activity that counters them. This means that the analyser may need to ask “what causes the failure” through several levels. I.e., for a compressor, a possible failure mode can be that the electrical motor is unable to drive the compressor. This may be because the motor’s windings have burned out, which again may be caused by mechanical overload.

In an RCM process, several actors, such as the system operators, supervisors and external specialists, should be included in identifying the relevant failure modes. This has not been possible in this thesis. Instead, the researcher has used the failure history and current maintenance plan overview developed in the analysis preparation, as well as written sources and guidance from RCM experts, to describe the causes. The sources are presented in detail in chapter 4.

When the failure modes are listed, the analysis proceeds to answering the fourth question: “What are the effects of these failures?”. This means that the RCM engineer needs to describe what happens when each failure mode occurs. According to Moubray (1997), the failure effect should at least describe five points:

- Evidence of failure mode.
- How the failure mode affects safety and the environment.
- How the failure mode affects operations.
- How the failure mode affects other assets.
- How the failure mode can be repaired.

The failure effect part should be strictly descriptive. Its main purpose is to provide the analyst with the understanding required to evaluate the consequences in the next step.

3.3.5 Consequence Evaluation and Creating a Maintenance Plan

The fifth question of the RCM process is concerned with the consequences of each failure mode. It is these consequences that decide the required maintenance activities. The more severe consequences, the more important it is to keep the asset operating in a reliable manner. When evaluating consequences, Moubray (1997) classifies four groups:

- Hidden failure: Consequences that are harmless by themselves, but if they happen at the same time as others, the effects may be serious.
- Safety and environmental: Consequences that hurt or kill people, and/or breach any environmental standard.
- Operational: Consequences that affects production.
- Non-operational: Consequences that only involve direct repair costs.

These consequences are then ranked. A safety or environmental consequence is considered as unacceptable, and needs to be treated before the process give attention to operational effects, which again is handled before non-operational consequences. Whether the consequence is hidden or not does not affect this ranking, but only the maintenance activities that are available. As mentioned in the previous sub-section, the failure effect description should give enough information to define which group the failure mode belongs. The severity of a consequence is not considered directly by answering question five. Both a failure mode that injures one person and one that kills four operators have safety consequences. The answer of the last two questions may lead to different measures for these failure modes, however.

Question six and seven are respectively "Can something be done to predict or prevent the failure?" and "If not, what should be done?", which means that the RCM method prefers predictive PdM and PM techniques over CM. Figure 3-5 shows how a decision diagram is used to answer questions 5 through 7, and suggest a maintenance activity to counter the failure mode.

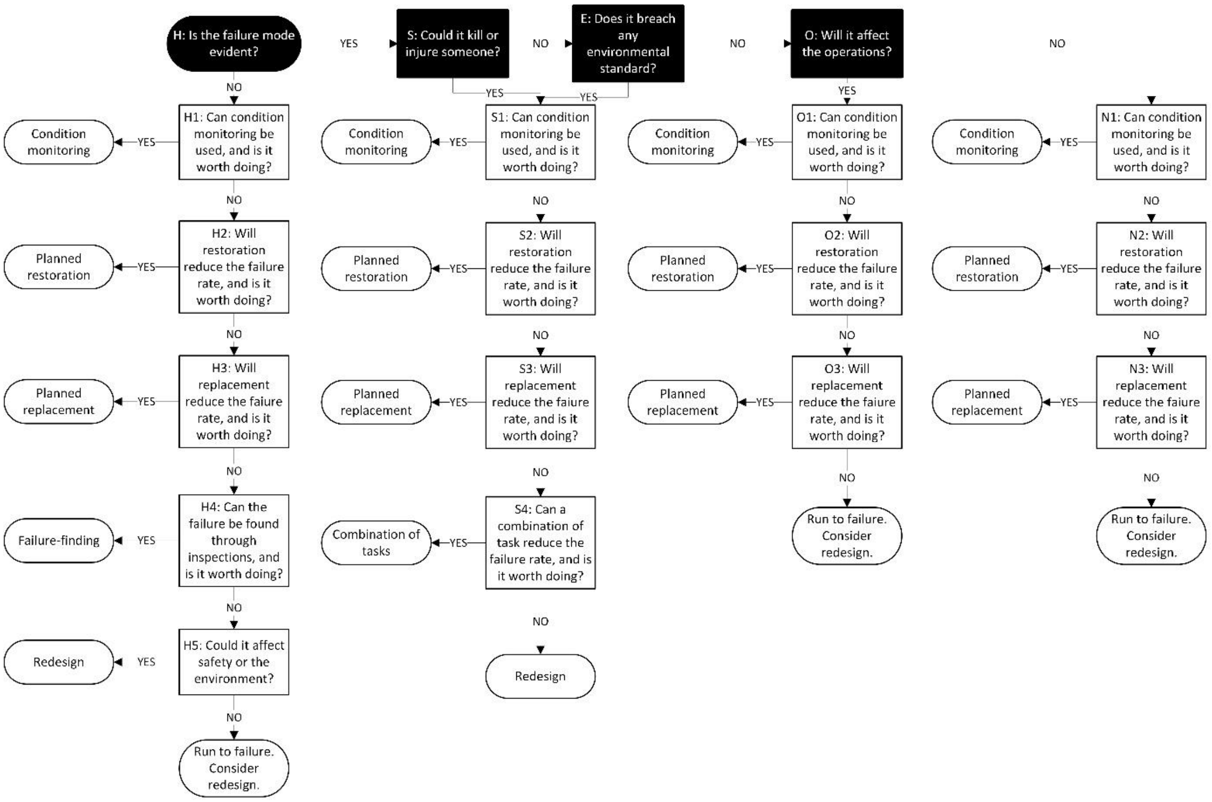


Figure 3-5. RCM Decision Diagram. Adapted from Moubray (1997).

The diagram shows the relative importance of the consequences and proposed tasks, and it asks whether a task is worth doing or not. This is where a failure mode that injures one person may be separated from one that kills four operators. An organisation may be more inclined to implement costly preventive measures if the consequences are fatal.

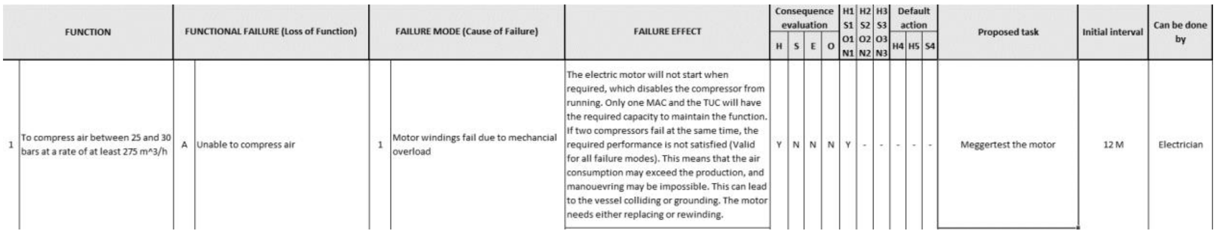
An optimal RCM process would evaluate the available maintenance options for each failure mode in the same way as the study by Kerres et al. (2015) presented in chapter 2. This would give input to whether the task is worth doing. Performing such an analysis is considered as too time consuming for this thesis, however. Instead, the researcher has focused on the feasibility of the task, and used a coarse common sense approach to whether it is worth doing or not.

Based on the outcome of the decision diagram, the researcher can suggest an RCM developed maintenance plan. This plan should include the proposed task, initial interval and the person responsible for executing the task. In this thesis, the researcher has independently defined these aspects, based on different input sources, as the following bullet points show:

- Proposed task: An evaluation of different possibilities based on the currently used maintenance activities, input from RCM experts and the researcher's understanding of the system in question.
- Initial interval: An evaluation of the system failure history data, compared with the potential consequences, regulations and input from RCM experts.
- Responsible operator: An evaluation of the complexity of the task, the crew member(s) that operate the system and who is responsible for similar tasks today.

3.3.6 RCM Framework

As a single function may have tens, and even hundreds, of failure modes, simply answering the seven questions without a systemised framework may lead to a chaotic process. The researcher has therefore used Microsoft Excel to create a structure based on Moubray's suggestions (1997). The scheme, which is depicted below, unites the entire RCM process in one table. The H, S, E, and O columns refer to the questions of the decision diagram.



FUNCTION		FUNCTIONAL FAILURE (Loss of Function)		FAILURE MODE (Cause of Failure)		FAILURE EFFECT	Consequence evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action			Proposed task	Initial interval	Can be done by
							H	S	E	O				H4	H5	S4			
1	To compress air between 25 and 30 bars at a rate of at least 275 m^3/h	A	Unable to compress air	1	Motor windings fail due to mechancial overload	The electric motor will not start when required, which disables the compressor from running. Only one MAC and the TUC will have the required capacity to maintain the function. If two compressors fail at the same time, the required performance is not satisfied (Valid for all failure modes). This means that the air consumption may exceed the production, and manouevring may be impossible. This can lead to the vessel colliding or grounding. The motor needs either replacing or rewinding.	Y	N	N	N	Y	-	-	-	-	-	Meggertest the motor	12 M	Electrician

Figure 3-6. The RCM Framework. Adapted from Moubray (1997).

Structuring the RCM process in this way simplifies future revisions of the analysis. Moubray recognises that the first edition will include errors and states that the analysis should be improved continuously. Following a similar framework as in Figure 3-6 allows any reviewer to follow the original analyst's line of thoughts, as well as to easily change and add more information when necessary. This idea of continuous improvement becomes obvious in the "initial interval" column. When performing an RCM analysis, the engineer suggests an interval for the task based on the available information, but admits that the period could, and even should, be changed when more data becomes available.

3.3.7 Benefits and Drawbacks of Using RCM as Described

Chapter 2 introduced several benefits a ship-owner could expect to achieve, and challenges it could expect to meet, by implementing the ideas of RCM. Those aspects were related to the effect of RCM. This sub-section focuses on the benefits and drawbacks related to performing the method as described.

One benefit of following the steps above is that it is a quite thorough method. This ensures that the analyst gets the required understanding of the system in question, and that the final result has considered the most important aspects related to the system. Another benefit comes from the RCM framework. This makes it easy for outsiders to understand what has been done and why it has been done, as well as to make revisions to ensure continuous improvement.

The thoroughness of the method also means that it is time-consuming, however. A lot of time needs to be committed in the process to provide a good result, both in the preparations and in the identification of functions and failure modes. Additionally, Moubray's method (1997) does not give clear instructions on how the analyst should deal with redundancy. It is only stated that it should be included in the operating context. This may cause different analysts to treat this aspect differently, which can lead to different end products.

3.4 Monte Carlo Simulation

3.4.1 Introduction to Monte Carlo Simulation

Monte Carlo Simulation can be defined as "a methodology for obtaining estimates of the solution of mathematical problems by means of random numbers". The method has its name from how the random numbers are generated by a machine similar to the roulettes of the casinos in Monte Carlo. These random numbers can be used to estimate how systems defined with given probability distributions will behave (Zio, 2013).

A coin toss gives an example of how MCS can be utilised. As the outcome of a coin toss is fifty-fifty, one can define all random numbers between 0 and 0.5 as heads, and all values between 0.5 and 1 as tails. Then, the generation of a random number gives a representation of the coin toss.

Zio (2013) describes how MCS can be used in system reliability analyses. As systems have a probability of failure, random numbers can be used to represent how their states are evolving over their lifetime. A simulation gives a reproduction of one possible fate of the system. This means that the lifetime should be simulated many times, in order to give statistical relevant quantities of how the system behaves.

In simulation, there are two basic methods for advancing in time and describing the behaviour of the system during the period (Hillier and Lieberman, 2010):

- Fixed-time incrementing: The time is advanced by a fixed amount, and the events that occurred during the interval are recorded. This method is useful for systems where there is a limited number of events that can happen in each interval.
- Next-event incrementing: The next event for the system is estimated, and the time is then updated to correspond with this event. This may require more computer power than fixed-time incrementing, but it makes it easier to keep track of complex systems. As the time between events in a reliability system may have large variations, this thesis will use next-event incrementing in its MCS.

3.4.2 Simulation of a Maintenance Plan

The MCS in this thesis simulates the behaviour of different maintenance plans. It estimates the performance of the jobs given by the schedules, where every job has a defined initial interval and is assigned to counter certain failure modes. All failure modes identified in the RCM process are included in the simulation. However, if similar failure modes are countered by the same job, they are merged to a single mode. I.e., the failure modes “bearing worn due to excessive radial thrust” and “bearing worn due to excessive axial thrust” will be handled as “worn bearing”. Additionally, failure modes that are allowed to run to failure are handled by a job with a very large planned interval. This lets them be included, without being disturbed by maintenance.

For each job, three possible events may cause the time to advance:

- Planned maintenance: Every job has a planned maintenance task, which is either predictive, preventive or corrective. This job has a fixed interval.
- Deteriorated performance: A deteriorated performance means that the performance line in Figure 3-4 has started moving from the initial capability. If this occurs in the simulation, it will be registered as a deteriorated failure. Where the job is a predictive task, the inspection may find that the equipment has deteriorated. This event can happen before the planned maintenance based on the related failure probability distribution, but it will not be discovered before the inspection. The time will advance with the planned

activity's fixed interval. It will, however, be registered as a failure and it will affect the performance parameters differently than planned maintenance.

- Total failure: This means failures where the equipment delivers no output at all. In other words, the performance line of Figure 3-4 is at the bottom. Every failure mode will have a "time to next occurrence", based on its failure probability distribution. If this time is lower than the time the next planned maintenance takes place, a total failure happens.

The simulation process can be described by the following flow chart.

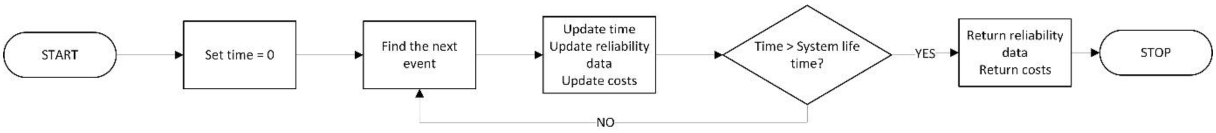


Figure 3-7. MCS Flow Chart.

Based on the flow chart, one sees that the MCS relies on a few key input parameters. The planned maintenance activity needs a pre-defined interval. Every failure mode has to have a defined failure probability distribution, and an indication on whether it is a critical failure or a started deterioration process. The simulation also requires that all events have a related cost.

The MCS has been programmed in MatLab. The MatLab script has been developed from scratch by the student. The script reads the input parameters described above, follows the flow chart presented in Figure 3-7, and returns reliability data and costs as output. Specifically, it presents the LCC of the maintenance plan, as well as the number of times a failure mode has occurred. The full script can be found in Appendix A.

The simulation includes six important assumptions:

- It is assumed that a total failure is identified and corrected immediately.
- All inspections are perfect. This means that if a deterioration process has started, the inspection will notice it.
- All necessary spare parts are available at all times.
- The time required to perform an event-related activity is considered negligible in the time advancement. It will affect the costs, however, as the next sub-section will explain.
- All activities leave the equipment as good as new. This means that every time an event happens, the time to a new failure, both critical and deteriorated, is recalculated.
- Additionally, every time an event happens, the time of the next planned activity will be defined by the fixed interval.

3.4.3 Definition of the Input Parameters

The previous sub-section introduced the input parameters required for the simulation to run. These data are listed in a Microsoft Excel worksheet, which is loaded as input to the simulation script. This sub-section describes how the parameters have been defined in the thesis:

- Job interval: This is given from the relevant maintenance plan.
- Failure probability distribution: This is based on historical failure data. The next chapter will describe how this thesis has encountered a lack of failure data, and has therefore implemented values from the Offshore Reliability Database (OREDA).
- Failure type: Whether the failure mode is indicated as a critical failure or a started deterioration process depends on whether the job is a predictive activity and if the failure mode is possible to find through an inspection.
- Costs: The cost of the event is based on three aspects. These aspects are labour costs, the costs of used equipment, and downtime costs.

3.4.4 Presentation of the Life-Cycle Costs

The last point of the previous sub-section introduced the aspects that make up the event costs. Every time a maintenance event occurs, the related costs are added to the system’s LCC. This means that the simulation only considers the operation and revenue impact costs of Equation 1 from sub-section 2.3.3, and that the initial investment costs are neglected. Then, when the simulation time reaches the vessel’s lifetime, the model presents the accumulated LCC as output.

However, one simulation only represents one possible fate of the system. As the randomness of the model will cause the system to behave differently every time, several simulations will be run to give an overview of the most likely scenarios. The model will then present a probability distribution of the life-cycle costs related to the maintenance schedules and the average LCC value.

As there is probability related to the accumulated costs, there is also an inherent risk involved. I.e., the simulations may state that the average LCC of a maintenance plan is 10 000 US Dollar (USD), but the worst case scenario causes an LCC of 50 000 USD. The model considers this by presenting the Value at Risk (VaR). This is a method used in financial decision making processes to give a simple illustration of the risk involved in a probabilistic situation. It states what the manager can expect to lose with a certain probability (Allen et al., 2009). In particular, this thesis will present the VaR at 95 %. In other words, it will present the value the ship-owner can, with 95 % probability, be certain that the LCC will not exceed.

3.4.5 Benefits and Drawbacks of Using Monte Carlo Simulation

Chapter 2 introduced the benefits of using MCS to estimate the life-cycle costs of systems with an inherent level of uncertainty. These benefits were related to how the method can take the uncertainty into account when presenting the results, and how the method opens up for easy use of sensitivity analyses.

The main drawback is related to the challenges of creating a model that represents the environment in a realistic way. To achieve this, the analyst needs to have knowledge about both programming, statistics and probability distributions, and system behaviour. This model development is a time-consuming process. When the model is completed, the simulations need to be performed. As several simulations need to be run to give a good estimation of the system behaviour, this also requires a lot of time.

4. Analysis and Results

4.1 Introduction

The previous chapters have introduced how RCM can be the first step towards a new maintenance strategy. This may help a container shipping operator to save the necessary costs to stay competitive in a challenging market. The uncertainty related to the benefits of implementing these ideas can make it hard to convince ship-owners to change, however. This thesis will therefore present quantified values of the effect of RCM to aid the decision making process.

Chapter 3 introduced the methodology used in the analysis. This part will show how the methods are applied on two shipboard systems, which are installed on seven sister ships operated by KSM. The vessels are from 2013. The chapter will also present the results from the simulation in a manner that may help answer the thesis' research questions, which were stated in Chapter 1.

The analysis will be displayed step-by-step, and the two systems will be shown side-by-side where possible.

4.2 Preparation for the RCM Analysis

The preparation starts with drawing asset and functional hierarchies for the systems to give a basic understanding of how they work. The asset hierarchies are developed based on the system drawings, which can be found in Appendix C, and explanations from the crew of Balsa. The following figures show the asset hierarchy for the AHS and SAS.

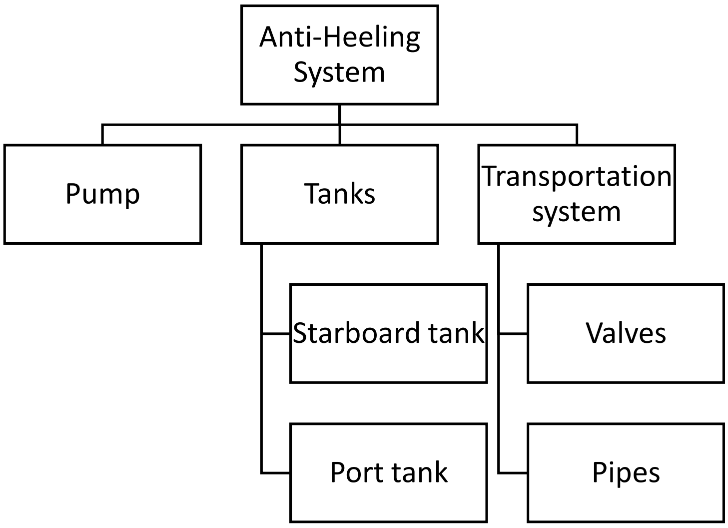


Figure 4-1. AHS Asset Hierarchy.

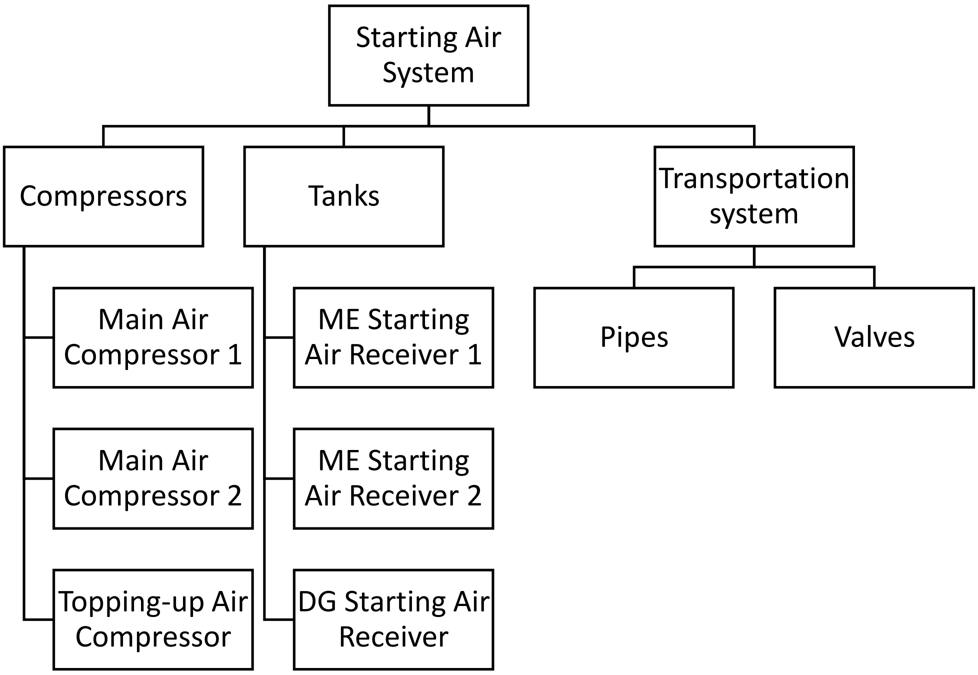


Figure 4-2. SAS Asset Hierarchy.

These figures are then transformed into functional hierarchies to give an understanding of the systems' primary functions, and how the equipment interact. This transformation is performed on the same basis as the asset hierarchy development. The functional hierarchies are shown below.

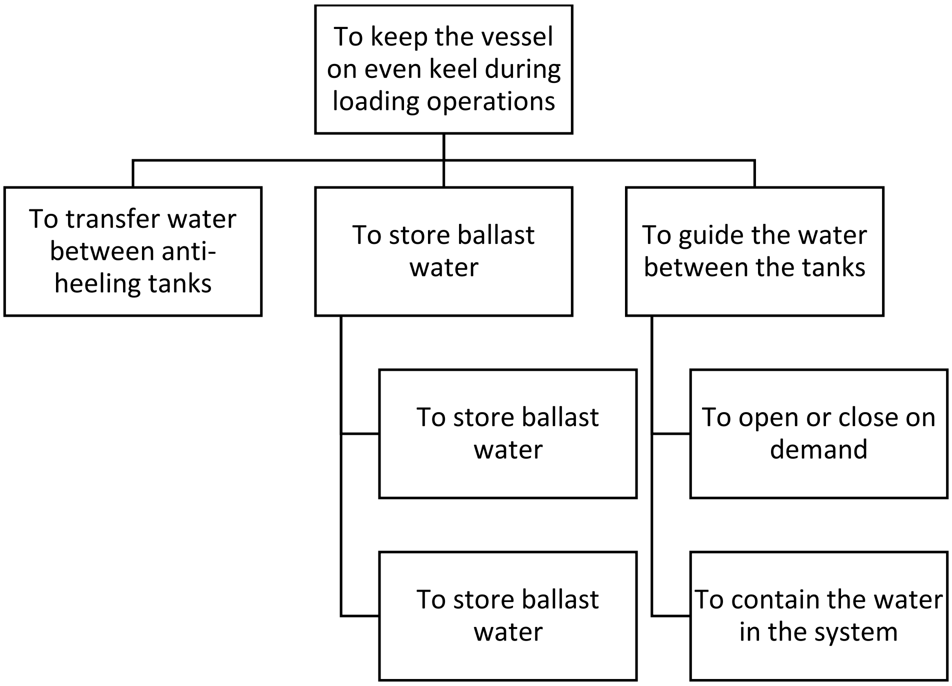


Figure 4-3. AHS Functional Hierarchy.

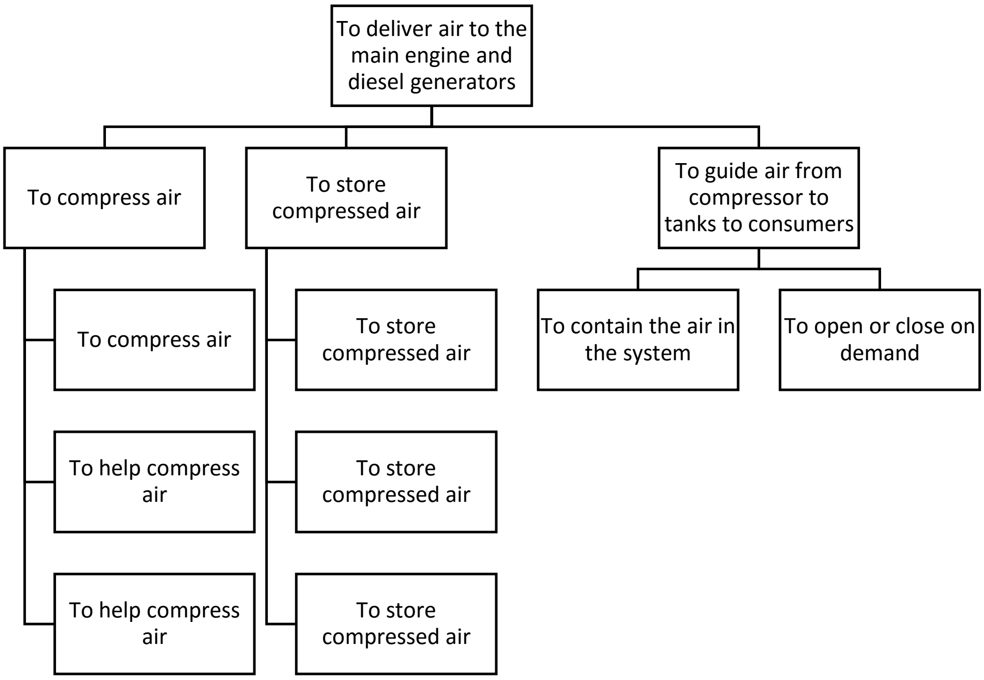


Figure 4-4. SAS Functional Hierarchy.

With the hierarchies developed, the systems' boundaries need to be defined in order to clarify the scope of the analysis. The boundary definitions can be seen in the Table 4-1.

Table 4-1. System Boundary Definitions.

Boundary	AHS	SAS
Start with	Water enters from ballast water system Working air enters from air system Electricity enters from switchboard	Air enters from atmosphere Electricity enters from switchboard
Terminate with	Water exits to ballast water system Water exits to deck	Air exits the receivers Water exits to bilge water system

This means that, in this analysis, it is assumed that every aspect before the starting boundaries and every aspect after the termination boundaries are working as intended and will not be considered. I.e., the analysis will not consider the pipelines and valves between the compressed air receivers and the main engine. Once the air leaves the tanks, the air leaves the system.

Based on the hierarchies and boundaries, the preparation process calls for a description of the operating context. As the following tables show, the analysis divides the description into four parts:

- Functional description and key parameters
- Redundancy features
- Protection features
- Key control features

The information provided in the tables is based on the system drawings, comments from the shipboard crew and recommendations from the Norwegian Shipowners' Association (1999).

Table 4-2. Operating Context for the Systems.

	ANTI-HEELING SYSTEM
Functional description/ Key parameters	PUMP: The pump is a reversible propeller pump with an electrical driven motor. It transfers water from one tank to another as needed to maintain the list angle demanded from the Chief Officer during loading operations. When in automatic operation, this list angle is maximum 1 degree to either side. The output capacity of the pump is 600 m^3/h with a pressure of about 1 bar. The pump and switch box is located on the keel, many meters below deck. TANKS: There is a pair of tanks. One starboard and one portside tank. Both of these tanks have a capacity of 485 m^3. The tanks are connected both to the anti-heeling pump and to the ballast water system. VALVES: Two butterfly valves are installed to control flow into the pump; one on each side of it. The valves working pressure is maximum 2 bars. These valves are actuated by control air with a pressure between 7 and 10 bar.
Redundancy features	There is only one pump and two tanks connected to the anti-heeling control panel, so there is no direct redundancy. However, the ballast water system can be used to control the heel angle if the system fails. This kind of operation requires close attention from the Chief Officer, however.
Protection features	The pump stops and the valves close if the given limit values for list are exceeded. This also happens if the tank on the suction side is empty. An alarm sounds when the angle exceeds 2.5 degrees. The pump shuts off in case of leakage.
Key control features	A control panel is installed in the ship office. This control panel has its own inclinometer that measures heeling angles up to 5 degrees each way. The panel sounds an alarm when the vessel heels over 2.5 degrees and it turns the system off when the angle exceeds 5 degrees. The control panel allows for both manual and automatic operation. An additional slave panel is installed at the bridge.
	STARTING AIR SYSTEM
Functional description/ Key parameters	COMPRESSORS: There are two main compressors and a topping-up compressor. The compressors main function is to provide compressed air to the starting air receivers. This air is then used to start the main engine and diesel generators. Air is needed every time the main engine changes direction. According to the Ship-Owner Association, start air should be delivered between 25 and 30 bars supplied at a rate of at least 390 m3/h. Each main compressor can supply air at 30 bar with a rate of 275 cubic meters per hour. The topping-up compressor capacity is 101m3/h*30 bar. Compressor 1 normally runs, while compressor 2 and topping-up steps in when required. The compressors are located next to each other, almost directly outside the Engine Control Room (ECR). A lamp glows in the ECR when a compressor is running. The compressors start automatically.

	TANKS: There are two main engine (ME) start air receivers and one diesel generator (DG) receiver. The receivers are, respectively, 6.5 and 0.25 cubic meters and handles air up to 30 bar. Air can be transferred between the ME receivers and from the ME receivers to the DG receiver, but not vice versa.
Redundancy features	In normal operation, only one compressor would be capable to keep all the three tanks on a satisfying level. The two other works as stand-by and assisting compressors. In order to satisfy the safety recommendations from the Shipowners' Association, two compressors should always be available. One of the ME receivers are also used as standby, but always ready. The DGs can get starting air from the ME receivers, if the DG receiver is faulty. The system can also supply the work air system if required.
Protection features	An alarm sounds if the receiver pressure falls below 19 bars. The compressor discharges air through safety valves if the pressure exceeds a given level. The compressor shuts down if the oil pressure is below 1 bar.
Key control features	A switchbox is located close to the compressors.

The next step in the process is to use the gathered information, and develop functional block diagrams. As the figures below show, there is a clear connection between the FBDs, and the functional hierarchy and boundary definitions. Details from the operating context description is also included.

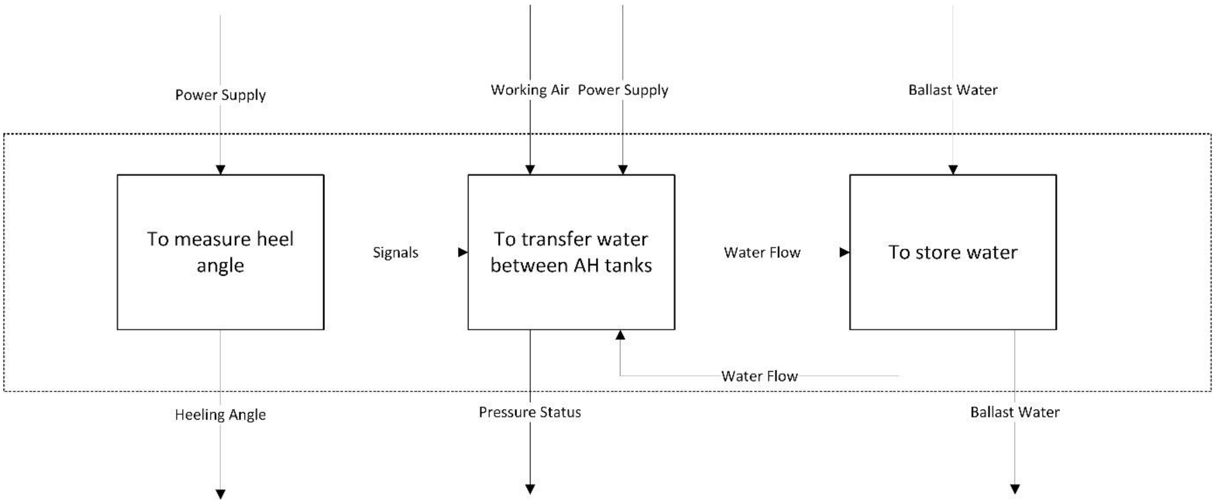


Figure 4-5. FBD of the AHS.

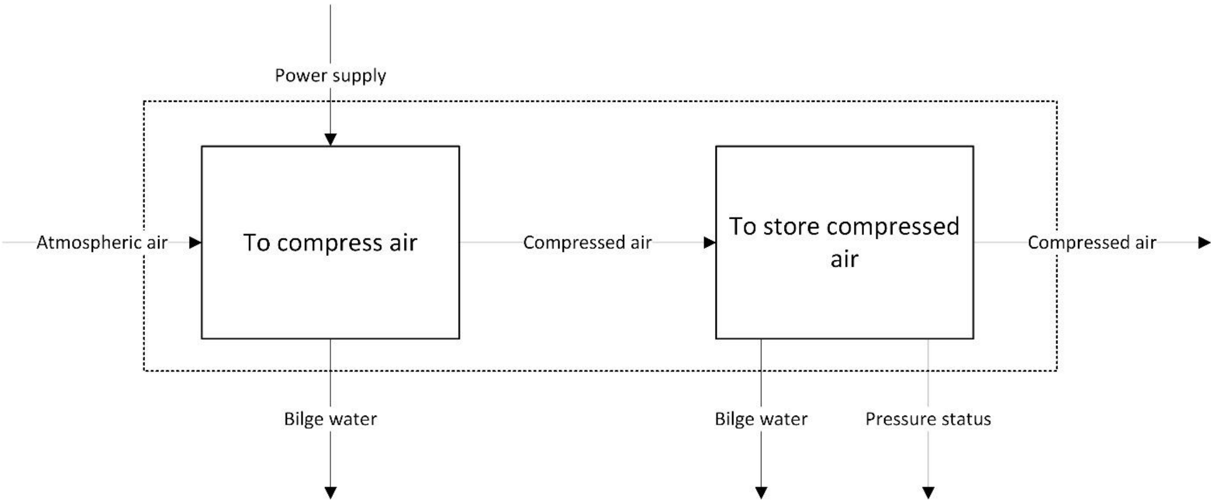


Figure 4-6. FBD of the SAS.

As the next section will show, these FBDs are crucial for the identification of functions in the RCM analysis.

The last step of the preparation before the analysis is to gather information of the systems' failure history and their current maintenance schedule. This data is given by KSM, and is presented in the tables on the next pages. Note that the targeted failure modes are added by the student to aid the identification process in the RCM analysis. The failure modes are based on Beebe (2004), Bloch and Geitner (2012), McKee et al. (2011), Shiels (1999) Tinga (2012) and WorkSafe Victoria (2008), as well as the manufacturer's operating manual (J.P. Sauer & Sohn Maschinenbau, 2008), the student's own judgement and inputs from the RCM experts at MainTech.

Table 4-3. The Current Maintenance Schedule.

System/ Equipment	Task	Interval	Targeted Failure Mode
AHS			
Pump	Lubricate bearings	1 month	Insufficient lubrication
	Vibration and sound monitoring	1 month	Faulty bearings, impeller and shaft
	Electric motor meggertest	3 months	Overloaded motor
	Electric motor overhaul	60 months	Worn bearings, shaft and windings
	Pump overhaul	8 000 h	Worn bearings, seals, impeller and shaft
Tank	Tank inspection	12 months	Corroded ballast tank
SAS			
Main Air Compressor	Electric motor meggertest	6 months	Overloaded motor
	Check screw connections	12 months	Improper installation and excessive vibrations
	Test/adjust safety valves	12 months	Faulty or incorrectly set safety valve
	Replace air filter cartridge	1 000 h	Dirty air filter
	Oil change	1 000 h	Compressor components worn by particles
	Check 1st and 2nd stage valves	2 000 h	Valves worn by damage, carbonisation, oiling, corrosion or moisture
	Replace 3rd stage valves	2 000 h	Valves worn by damage, carbonisation, oiling, corrosion or moisture
	Clean oil strainer	4 000 h	Compressor components worn by particles
	Replace 1st and 2nd stage valves	4 000 h	Valves worn by damage, carbonisation, oiling, corrosion or moisture
	Compressor overhaul	4 000 h	Worn gudgeon pin, bearings and piston rings
	Check condensate separator	4 000 h	Separator clogged by oil
	Overhaul drain valves	4 000 h	Valve leakages and stuck valve
	Renew flexible gear rim	4 000 h	Worn gear rim by installation error, lubrication error or overload
Starting Air Receiver	Internal inspection	12 months	Internal corrosion and build-up of contaminants
	Adjust safety valves	12 months	Safety valves incorrectly adjusted

The schedule for the topping-up compressor is equal to the one of the main air compressors, with an additional condition control every month. The diesel generator air receiver has the same plan as the main engine receivers. In addition, the compressors and air vessels are also subjects to DNV GL’s continuous inspection scheme. No such jobs are found for the AHS in KSM’s maintenance plans. It is also worth mentioning that every task for the compressor, except the meggertest and the safety valve test, are copied from the manufacturer's manual (J.P. Sauer & Sohn Maschinenbau, 2008). A similar manual has not been provided by the AHS supplier, so the reasoning behind the system's schedule is unclear.

The following table shows the failure history for the systems. All problems related to the AHS and SAS from all the seven sister vessels are listed (Klaveness Ship Management AS, 2015a).

Table 4-4. System Failure History.

System	Component	Reported failure	Cause of failure
AHS	Valve	"Broken valve" in July 2015	Unknown
	Pump air filter	"Replaced air filter" in January 2015	Unknown
	Electric motor	"Old oil showing some water contamination" in April 2015	Unknown
SAS	-	No failures reported in any vessel	-

Three failures reported in two years have caused challenges for the development of the RCM based maintenance schedules. In addition, the information in the reports are limited, with no causes included. This data should be a part of the foundation for the rest of the analysis, especially for estimating the initial intervals and failure rates. To counter these challenges, the student has, as mentioned in chapter 3, used other sources of information. These sources will be presented in the next sections.

4.3 The RCM Analysis

The first step of the RCM analysis is to define the systems' functions. The functions are identified in the preparation, and they are listed in the tables on the next pages. The information in the FBDs and the operating context description is the main input for the function definitions.

The reasoning behind the included functional failures is that all failures, both partial and total, should be covered. The tables contain all functional failures.

An example of a critical failure mode for each functional failure is also included in the tables. The failure modes have been defined based on the same written sources introduced in section 4.2, the student's understanding and input from MainTech engineers. The entire analysis, including all failure modes with corresponding failure effects, can be found in Appendix B. The effect descriptions are purely based on the student's judgement.

Table 4-5. Functions, Failures and Failure Modes for the AHS.

System	Function	Functional failure	Failure mode
AHS	To measure the heeling angle with an accuracy of +/- 0.1 degrees	Unable to measure the heeling angle	Inclinometer stuck
		Measures heeling angle with too large inaccuracy	Inclinometer affected by vibrations
	To transfer water from one side to the other at a rate of at least 500 m^3/h when the heeling angle exceeds a given limit	Does not transfer any water at all	Pump impeller worn by impact from foreign objects
		Transfers water at a rate less than 500 m^3/h	Leakage in piping between pump and demand tank
	To contain up to 485 m^3 of water in each tank	Unable to contain any water at all	Tank leaking due to corrosion
		Unable to contain 485 m^3 of water	Tank valves stuck open
	To sound an alarm when the heeling angle exceeds 2.5 degrees	Unable to measure the heeling angle	Inclinometer stuck
		Does not sound an alarm when the measured angle exceeds 2.5 degrees	Unable to send signal to alarm panel due to electrical breakdown
	To stop the anti-heeling pump when the angle exceeds 5 degrees	Unable to measure the heeling angle	Inclinometer stuck
		Does not stop the pump when the measured angle exceeds 5 degrees	Stop signal does not reach the pump due to electrical breakdown
	To stop the pump when leakage is detected at the pump gear box	Unable to detect leakage	Float switch fails due to electrical breakdown
		Unable to stop the pump	Stop signal does not reach the pump due to electrical breakdown
	To stop the pump when one of the tanks reaches low level	Unable to recognise low water level	Low level switch stuck in upright position
		Unable to stop the pump	Stop signal does not reach the pump due to electrical breakdown

Table 4-6. Functions, Failures and Failure Modes for the SAS.

System	Function	Functional failure	Failure mode
SAS	To compress air between 25 and 30 bars at a rate of at least 275 m^3/h	Unable to compress air	Motor windings fail due to mechanical overload
		Unable to reach 25 bar	Air escaping from compressed air lines due to connection gaskets or seals leaking
		Unable to deliver pressurised air at a rate of 275 m^3/h	Loose connections between electric motor and crankshaft
	To store respectively 6.5 m^3 and 0.25 m^3 of air with a pressure up to 30 bars in the ME and DG starting air receivers	Unable to store the required amount of pressurised air	Pressure relief valve installed incorrectly
		Stores pressure above 30 bars	Pressure relief valve stuck in closed position
	To automatically start the compressors when the receiver pressure falls below 21 bars	Does not start the compressors when the pressure falls below 21 bars	Pressure switch is set at too low level
		Starts the compressors when the pressure is above 21 bars	Pressure switch is set at too high level
	To automatically stop the compressors when the receiver pressure exceeds 26 bar	Does not stop the compressors when the pressure exceeds 26 bar	Pressure switch is set at too high level
		Stops the compressors when the pressure is below 26 bars	Pressure switch is set at too low level
	To deliver compressed air from compressors to receivers	The compressed air does not reach the receivers	Pipes are leaking due to corroded pipeline
	To sound an alarm in the ECR when the receiver pressure falls below 19 bars	Does not sound an alarm when the pressure falls below 19 bars	Pressure gauge damaged by vibration, overpressure, pulsation or corrosion
		Sounds an alarm when the pressure is over 19 bars	Pressure gauge installed incorrectly

A maintenance task is then suggested for every failure mode by following the decision diagram presented in Figure 3-5. The RCM analysis shows that, due to the inherent redundancy level of the SAS, and the limited severity related to the consequences of a failure for the AHS, neither of the systems can be considered critical for neither the safety, nor the environmental integrity, of the vessel. This means that the resulting schedules focus on finding a cost-effective solution only.

Sub-section 3.3.5 described how the proposed task, initial interval and responsible operator are determined based on different input sources, such as the current maintenance schedule, failure history, recommendations from RCM experts and the researcher's own evaluation. I.e., a meggertest of the compressors' electrical motor is currently performed every sixth month. The student recommends to continue to perform such tests, but as every inspection so far has shown perfect performance, the initial interval is set to 12 months instead of six. Table 4-7 shows the resulting maintenance schedules.

Table 4-7. The RCM Maintenance Schedules.

System	Task	Initial interval	Can be done by
AHS	Vibration and sound monitoring of the pump, and temperature monitoring of the bearings	6 months	3rd engineer
	Lubricate bearings	6 months	3rd engineer
	Monitor the pump's Ampere meter	12 months	3rd engineer
	Inspect pipe tunnel for water leaks	24 months	3rd engineer
	Inspect the pump for small leakages	60 months	3rd engineer
	Inspect anti-heeling tanks for corrosion	60 months	Chief officer
SAS	Monitor the pressure gauge in the ECR and compare to running status of compressor	Daily	Wiper
	Drain condensation from air receivers and evaluate the flow	Daily	Wiper
	Meggertest the electrical motor and check the supply voltage	12 months	Electrician
	Vibration monitoring of the compressor	12 months	3rd engineer
	Readjust the pressure relief valve and do an alarm/gauge test	12 months	3rd engineer
	External and ultrasound inspection of air receiver and pipes	24 months	3rd engineer
	Internal inspection of air receiver	48 months	3rd engineer
	Check oil level	500 h	Wiper
	Change oil	1 000 h	3rd engineer
	Monitor the 1st stage pressure gauge	1 000 h	Wiper
	Monitor the stage pressure gauges and thermometers	2 000 h	Wiper
	Take oil test and clean the oil filter	4 000 h	3rd engineer

Additionally, the process leads to the three following re-design suggestions for the AHS. Note that re-design does not necessarily mean a change of physical system design, but may imply a modification of operational procedures as well.

- During operations, the control panel angle should be compared to the analogue heeling angle.
- During operations, the water level displayed on the control panel should be compared to the level on the ballast overview.
- The crew should report to the Chief Officer as soon as they notice unnatural heeling angles.

As Moubray’s method (1997) does not state explicitly how to handle redundancy, the operating context is used actively in the RCM analysis. For the SAS, only two out of three compressors are needed to satisfy the relatively strict recommendations from the Norwegian Shipowners' Association (1999). This analysis therefore assumes that only one piece of equipment is needed for each block in the system’s FBD, and considers the redundancy level in the consequence evaluation.

The following figures show comparisons of the activities related to the current schedules and the RCM based maintenance plans, where the y-axis shows the number of related activities. The diagrams are split into three groups: condition monitoring, pre-defined PM tasks and run-to-failure. The RCM run-to-failure number is based on the failure modes that the process considers as not critical enough to warrant a preventive task. As the current schedule does not state that any failures should be run-to-failure, this number is developed from the failure modes identified in the RCM process that the present plan does not consider.

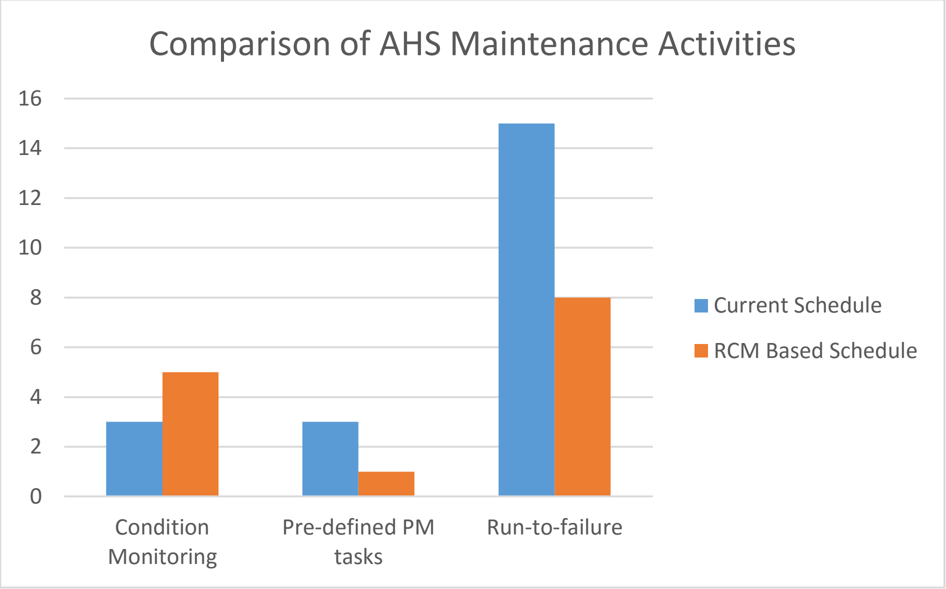


Figure 4-7. Comparison of AHS Maintenance Activities.

The comparison of the AHS maintenance activities shows that the RCM based and the current schedule both have six tasks. However, the figure shows how RCM prefers predictive maintenance over preventive overhauls, as five out of the six activities are based on condition monitoring techniques. The run-to-failure bars are mainly included to illustrate that the analysis has identified several failure modes that are unattended by the current schedule. A similar change of focus can be seen in the SAS comparison, which is depicted in Figure 4-8.

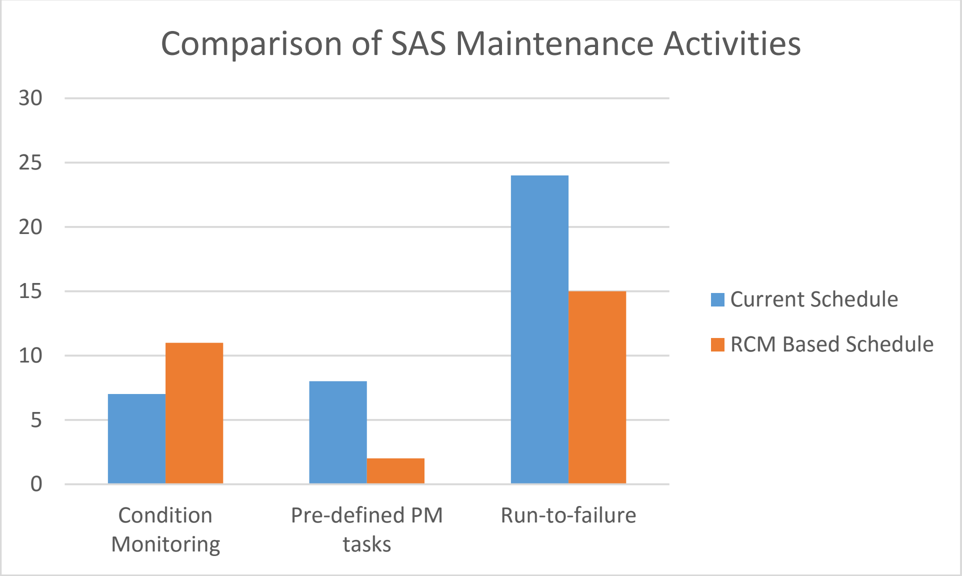


Figure 4-8. Comparison of SAS Maintenance Activities.

As for the AHS, the SAS schedules have a similar amount of prescribed activities, but there is a shift from pre-defined PM tasks to condition monitoring.

4.4 Simulation of the Maintenance Plans

4.4.1 The Time to Failure

The next step is to simulate the performance of the schedules, in order to get quantified values of the effect of RCM. Section 3.4 introduced that the simulation used next-event incrementing, and that the next event could be either planned maintenance, a deteriorated performance or a failure. It was also stated that the time to failure was based on historical data. However, as the analysis preparation shows, there is not enough failure data to use in such a simulation. The thesis therefore uses statistics from OREDA (SINTEF, 2009).

It should be noted that OREDA includes three types of failure, which are critical, degraded and incipient. As the condition control activities aim to find deviations from the initial performance of the equipment, both incipient and degraded failure rates are included in the estimation of deteriorated performances. This may cause the simulations to overestimate the number of failures related to the given schedules, as an incipient failure does not satisfy the definition of a functional failure. However, as the incipient failures should be removed before they evolve to a critical failure, the student believes that they should be included.

The OREDA database includes failure rates for machinery, and electric, mechanical and safety equipment. The failure rates are assumed to be constant, which means that they follow the exponential distribution with the parameter λ. Hillier and Lieberman (2010) describe how a random number can be used to determine when the next exponentially distributed failure will occur.

The exponential distribution's cumulative function can be defined as

$$F(t) = 1 - e^{-\lambda t} \tag{2}$$

Where t indicates time. By inserting a random number, r, in the function, we get an expression where the time depends on the arbitrary observation.

$$r = 1 - e^{-\lambda t} \tag{3}$$

This can be written as

$$t = \frac{\ln(1 - r)}{-\lambda} \tag{4}$$

Since $1 - r$ is a random number itself, the expression can be simplified to

$$t = \frac{\ln(r)}{-\lambda} \tag{5}$$

This expression has been used to define the time to the next failure in the Monte Carlo Simulation. The following figure depicts the cumulative function of the exponential distribution with a λ-value of 0.1 over a time interval ranging from 0 to 12 months. It shows an example of how the process works in practice. In the example the random number generator has produced the number 0.5, which corresponds to a time of 6.9 months.

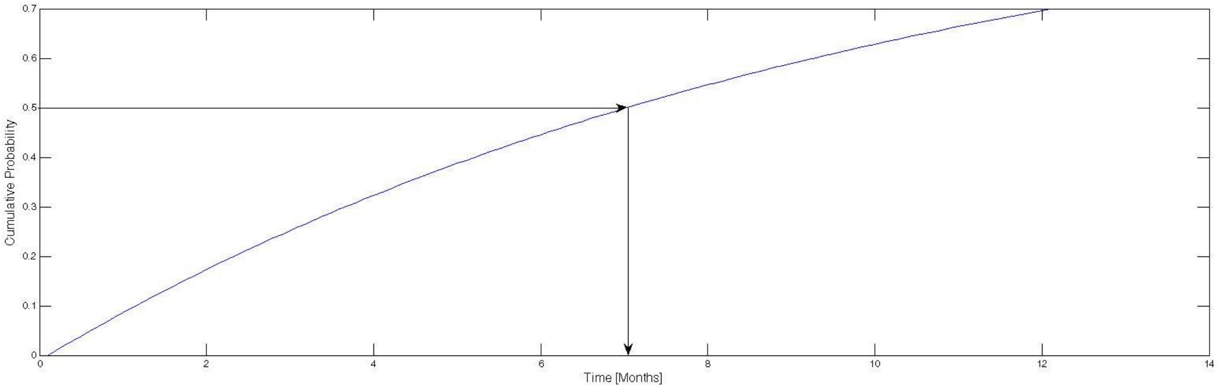


Figure 4-9. The Cummulative Function of the Exponential Distribution.

4.4.2 The Input Values

Section 3.4 also introduced how the simulation program depends on intervals, costs and failure probabilities as input values. This sub-section shows how these numbers were quantified for the maintenance programs.

The job intervals are given by the maintenance schedules. The simulation program runs in months, which means that the activities that are based on running hours need their intervals transformed. Table 4-8 shows the running hours per month for the pump and compressors (Klaveness Ship Management AS, 2015a). As an example, the current SAS maintenance plan calls for a compressor oil change every 1 000 hours. Since the compressor runs an average of 95 hours per month, the simulation program initiates an oil change every 10.5 months.

Table 4-8. Running Hours per Month for AHS and SAS equipment (Klaveness Ship Management AS, 2015a).

	Anti-Heeling Pump	**Main Air Compressor 1**	**Main Air Compressor 2**	**Topping-up Compressor**
Running hours per month	7	95	82	36

The costs consist, as previously mentioned, of three categories:

- Labour costs: These costs depend on the time required to perform the task and the salary of the responsible operator. The man hours required to restore a failure back to function are based on values from OREDA (SINTEF, 2009). The man hours include the time from the failure occurs, to the failure mode is identified and the system is running again. The reliability database is divided into critical, degraded and incipient failures. In the simulation, a weighted average of the degraded and incipient failure rate gave the value for the “deteriorated performances”, while the failure rate of a “failure” came from the critical number. OREDA also lists values for different failure modes. Such a failure mode is chosen if it matched the one being analysed. If not, the simulation uses the general number. I.e., a broken compressor driveshaft gathers data from OREDA’s “structural deficiency” row. The time required for the planned activities are defined by the student’s judgement. The salaries are given by KSM’s wage overview (Kverneggen, 2016), and the values needed for the analysis are presented in Table 4-9.
- Equipment costs: This is the costs of the equipment required to perform the given task. For a planned lubrication, this is the cost of the needed oil, while for a failed electrical motor, it may be the price of an entire new motor. The student does not, in the majority of the cases, have access to true values for these costs, since KSM’s suppliers were unwilling to share the price of the spare parts. This means that the values in the thesis are estimations based on prices from suppliers of similar equipment found online.
- Downtime costs: These costs depend on the downtime hours. KSM operates with a cost of $ 7 000 per day (Bøhmer, 2016). As the SAS is a redundant system, it is assumed that it will have no related downtime costs, except when one of the receivers are critically corroded. It is then assumed that the vessel is not allowed to leave port without replacing it. For the AHS, it is assumed that the Chief Officer will start using the ballast water system instead, as mentioned earlier. As it might take some time before the failure is recognised, and keeping the vessel stable manually is a more complex task, it is believed that the loading procedure will cause a 2-hour prolongation of the port time.

Table 4-9. Salary Values used in Analysis (Kverneggen, 2016).

Crew member	Salary [$/month]	Working hours [h/month]	Salary [$/h]
Chief Officer	3 165	224	14.1
2nd Engineer	3 463	224	15.5
3rd Engineer	2 836	224	12.7
Electrician	2 526	261	9.7
Able Seaman	1 367	261	5.2
Wiper	1 036	261	4.0

The failure rates are mainly given by OREDA. The values are chosen on the same basis as the man hours, however these also included the database's "maintainable item versus failure mode" information. The following example shows how the failure rates are calculated.

OREDA includes 192 degraded and 256 incipient failures with a failure rate of, respectively, 54.87 and 62.23 per 10^6 hours for centrifugal pumps. Of all failures, 0.43 % are due to the impeller. We know from the maintenance history, that the Anti-Heeling Pump (AHP) runs 7 hours per month. This gives a failure rate per month for a deteriorated AHP impeller failure of

$$Failure\ rate = \frac{54.87 * 192 + 62.23 * 256}{192 + 256} * 0.0043 * \frac{7}{10^6} = 2 * 10^{-6} \tag{6}$$

Even though the database gives values for similar equipment as the ones analysed, such as centrifugal pumps and reciprocating compressors, the numbers will be wrong. This is because the operating context is different. A large centrifugal pump running 10 hours a day on an offshore platform will behave differently than an anti-heeling pump which operates for seven hours per month. This causes the simulations to represent an incorrect world. The results will not show the true behaviour of the systems; however, they do give an indication on what the operator can expect.

The four tables below show the values used in the simulations. The tables also include the sources where OREDA cannot provide failure rate values. The input simplifies the failure modes from the RCM analysis. I.e., the RCM analysis identifies several failure modes related to the AHS bearings, but as many of them calls for the same activity, they are gathered as "worn bearings". This means that the simulation does not separate between the various causes of a bearing failure. The calculations behind the costs, as well as the input spreadsheets used in the simulations, are added in Appendix D.

Table 4-10. Input Values for Current AHS Schedule.

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
Lubricate bearings	1	20	Insufficient lubrication (SKF)	0.0004	1 424
Vibration and sound monitoring	1	25	Worn impeller – Total Worn impeller – Deter. Worn driveshaft – T Worn driveshaft – D Worn bearings – T Worn bearings – D Stuck suction valve – T Stuck suction valve – D	0.000001 0.000002 0.000002 0.000003 0.000002 0.000004 0.001 0.007	1 524 524 1 204 204 1 424 424 1 305 152
Meggertest electric motor	3	15	Motor overload – T Motor overload – D	0.0001 0.00006	2 864 826
Ballast tank inspection	12	50	Corroded ballast tank – Deteriorated (Garbatov and Guedes Soares, 2009)	0.003	26 757
Electric motor overhaul	60	1 192	All failure modes already handled by other jobs	-	-
Pump overhaul	1 143	1 073	Worn seals. Other failure modes already handled.	0.0001	1 216
Run-to-failure	300	-	Leaking pipes – T Faulty float switch – T Faulty inclinometer – T (Posital Fraba, 2012) Pump unable to start due to electrical problems – T Stuck discharge valve – T Tank valves stuck open – T Faulty low level switch – T	0.003 0.0001 0.0005 0.001 0.001 0.001 0.004	634 780 1 032 681 1 305 756 680

The electric motor overhaul in Table 4-10 above shows a special case. In the preparations, this job is identified to prevent worn bearings, windings and driveshaft. These failure modes are also handled by inspection activities with shorter intervals. As mentioned in chapter 3, all activities are assumed to leave the system as good as new. This causes the job to be superfluous in the simulation, since all failure modes are already handled.

Table 4-11. Input Values for RCM Based AHS Schedule.

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
Comparison of analogue and digital inclination	1/30	1	Faulty inclinometer (Posital Fraba, 2012)	0.0005	1 032
Vibration and sound monitoring	6	25	Worn driveshaft – T	0.000002	1 204
			Worn driveshaft – D	0.000003	204
			Worn impeller – T	0.000001	1 524
			Worn impeller – D	0.000002	524
			Stuck suction valve – T	0.001	1 305
			Stuck suction valve – D	0.007	152
Temperature monitoring	6	25	Worn bearings – T	0.000002	1 424
			Worn bearings – D	0.000004	424
Lubricate bearings	6	20	Insufficient lubrication (SKF)	0.0004	1 424
Monitor Ampere meter	12	13	Motor overload – T	0.0001	2 864
			Motor overload – D	0.00006	826
Inspect pipe tunnel	24	25	Leaking pipes – T	0.003	634
			Leaking pipes – D	0.005	25
Inspect pump for small leakages	60	13	Worn seals – T	0.0001	1 216
			Worn seals – D	0.0096	571
Ballast tank inspection	60	50	Corroded ballast tank – D (Garbatov and Guedes Soares, 2009)	0.003	26 757
Run-to-failure	300	-	Faulty float switch – T	0.0001	780
			Pump unable to start due to electrical problems – T	0.001	681
			Stuck discharge valve – T	0.001	1 305
			Tank valves stuck open – T	0.001	756
			Faulty low level switch – T	0.004	680

A comparison of the two previous tables shows that the same failure modes will be included in the simulations, but the RCM schedule will handle them in another manner than the current plan. The same is valid for the SAS, as the two following tables indicate. The simulation only considers one compressor and one tank, due to how the analysis recognise the redundancy level and operating context, as explained in section 4.3.

Table 4-12. Input Values for Current SAS Schedule.

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
Meggertest electric motor	6	10	Motor overload – T Motor overload – D	0.006 0.003	2 165 777
Check screw connections	12	13	Loose connections – T Loose connections – D	0.0007 0.0008	316 62
Test safety valves	12	6	Faulty safety valve – T Faulty safety valve – D	0.001 0.003	174 151
Replace air filter	10.5	43	Dirty air filter – T	0.005	170
Oil change	10.5	267	Dirty oil leading to worn bearings, shaft and pistons – T	0.0002	1 596
Check stage valves	21	19	Worn valves – T Worn valves – D	0.004 0.004	320 212
Replace 3rd stage valves	21	181	Worn valves – T	-	-
Clean oil strainer	42	13	Dirty strainer leading to dirty oil leading to worn bearings, shaft and pistons – T	0.0002	1 596
Replace stage valves	42	331	Worn valves – T	-	-
Check condensate separator	42	13	Clogged separator – T Clogged separator – D	0.0002 0.005	301 25
Overhaul drain valves	42	73	Leaking, clogged or stuck valve – T	0.0001	112
Renew flexible gear rim	42	73	Worn coupling – T	0.0002	266
Overhaul compressor	42	5 093	Worn seals and piston ring - T	0.0003	4 369
Internal vessel inspection	12	38	Internal corrosion and build-up of contaminants – T Internal corrosion and build-up of contaminants – D	0.001 0.003	5 903 650

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
Test/adjust vessel safety valves	12	6	Faulty safety valve – T	0.004	174
			Faulty safety valve – D	0.02	151
Run-to-failure	300	-	Faulty cooling fan – T	0.0001	344
			Incorrect voltage supply – T	0.0009	165
			Leaking pipes – T	0.003	201
			Faulty pressure gauge – T	0.012	417
			Faulty oil pump – T	0.002	241
			Faulty stop check valve – T	0.001	131
			Faulty pressure switch – T	0.012	346
			Unable to send stop signal due to electrical problems - T	0.0004	68

As for the AHS, the table above indicates that some of the current jobs are superfluous, due to already performed inspection activities.

Table 4-13. Input Values for the RCM Based SAS Schedule.

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
Meggertest electric motor and check supply voltage	12	10	Motor overload – T	0.006	2 165
			Motor overload – D	0.003	777
			Incorrect voltage supply – T	0.0009	167
			Incorrect voltage supply – D	0.003	77
Vibration monitoring	12	13	Worn coupling – T	0.0002	266
			Worn coupling – D	0.0002	112
			Loose connections – T	0.0007	316
			Loose connections – D	0.0008	62
Readjust safety valve	12	13	Faulty safety valve – T	0.001	174
			Faulty safety valve – D	0.003	151
Pressure gauge test	12	13	Faulty pressure gauge – T	0.008	417
			Faulty pressure gauge – D	0.04	38
			Faulty pressure switch – T	0.008	346
			Faulty pressure switch – D	0.04	25

Job	Interval [months]	Cost of Job [$]	Failure Modes Handled	Failure Rate [per month]	Cost of Failure [$]
External inspection of vessel and pipes	24	13	Corroded tanks – T	0.001	5 903
			Corroded tanks – D	0.003	650
			Leaking pipes – T	0.003	201
			Leaking pipes – D	0.0005	25
Internal vessel inspection	48	38	Internal corrosion and build-up of contaminants – T	0.001	5 903
			Internal corrosion and build-up of contaminants – D	0.003	650
Check oil level	5.25	0.7	Worn bearings – T	0.0002	516
			Worn bearings – D	0.0002	362
Change oil	10.5	267	Dirty oil leading to worn bearings, shaft and pistons – T	0.0002	1 132
Monitor 1st stage gauges	10.5	0.7	Air intake problems – T	0.01	169
			Air intake problems – D	0.01	51
Monitor 2nd and 3rd stage gauges	21	0.7	Worn valves – T	0.004	320
			Worn valves – D	0.004	212
			Leaking seals and piston rings – T	0.0001	370
			Leaking seals and piston rings – D	0.0001	262
Oil test and clean oil filter	42	213	Piston seizure – T	0.0002	1 216
			Piston seizure – D	0.0002	1 062
Drain condensation from receiver	1/30	0.3	Leaking, clogged or stuck drain valve – T	0.0001	112
			Leaking, clogged or stuck drain valve – D	0.0007	81
Run-to failure	300	-	Faulty cooling fan – T	0.0001	344
			Faulty oil pump – T	0.002	241
			Faulty stop check valve – T	0.001	131
			Unable to send stop signal due to electrical problems - T	0.0004	68

4.5 The Simulation Results

4.5.1 Number of Failures

One of the research questions is concerned with how the ship system reliability is affected by the maintenance strategy. This sub-section will answer this by presenting how the number of failures differ between the current schedule and the RCM based plan.

All four maintenance plans are simulated 100 000 times. It is assumed that the lifetime of a vessel is 25 years. Figure 4-10 below shows the mean number of failures occurring for each schedule. This includes both total and deteriorated performances.

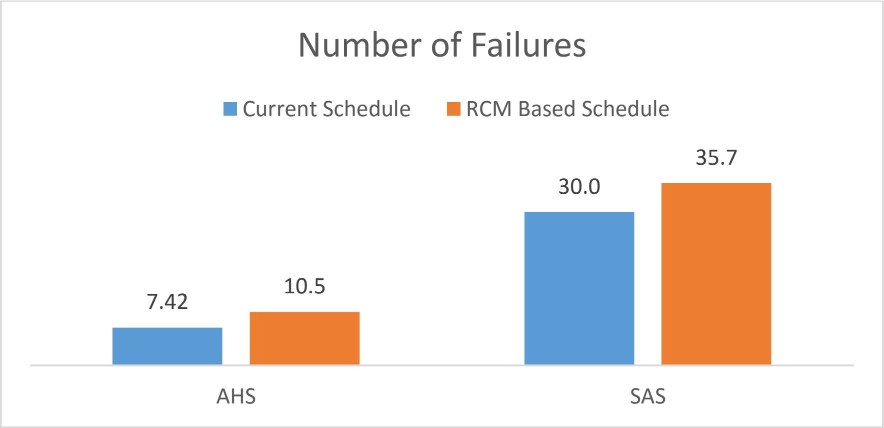


Figure 4-10. Comparison of Failures.

The numbers imply that the RCM based schedules will cause more failures than the current strategy. This contradicts the theories presented throughout this thesis. To highlight why this happens, a more thorough analysis of the failure modes is required. The following diagram splits total from deteriorated performances.

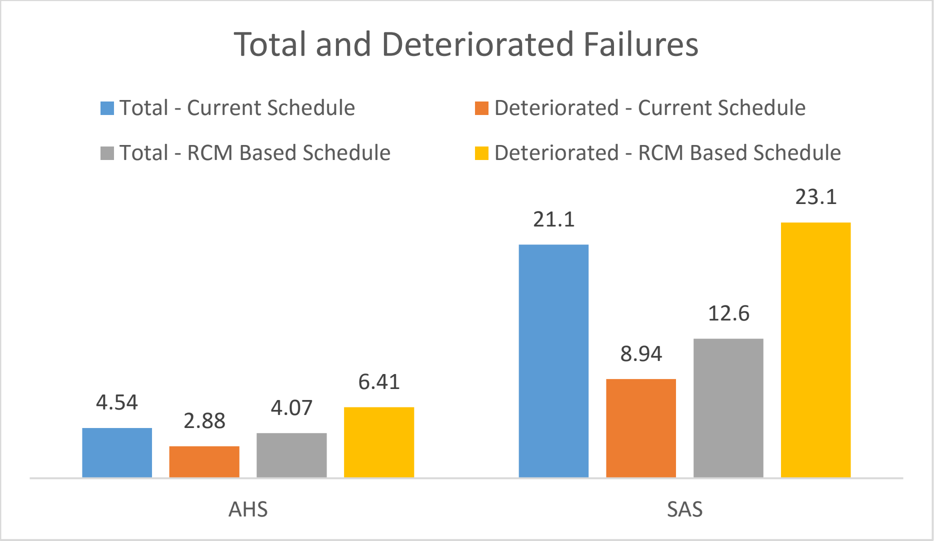


Figure 4-11. Comparison of Total and Deteriorated Failures.

The figure shows that the RCM schedules increase the number of deteriorated performances, while they reduce the amount of total failures.

4.5.2 Life-Cycle Costs

The other research question is related to the economic effect of implementing RCM on a maritime vessel. This sub-section presents the life-cycle costs accumulated during the life-time of a vessel. The four following figures depicts the probability distribution of the LCC for the maintenance schedules.

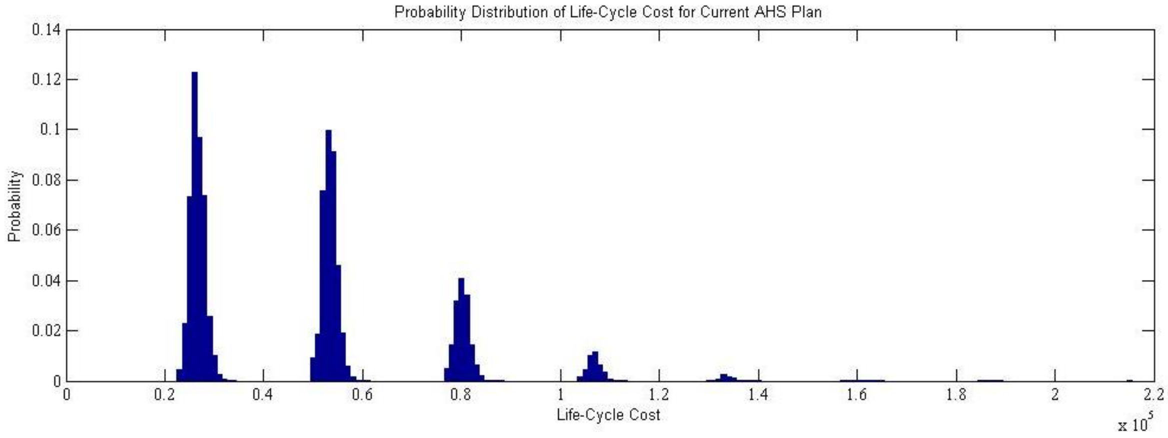


Figure 4-12. Probability Distribution of LCC for Current AHS Plan.

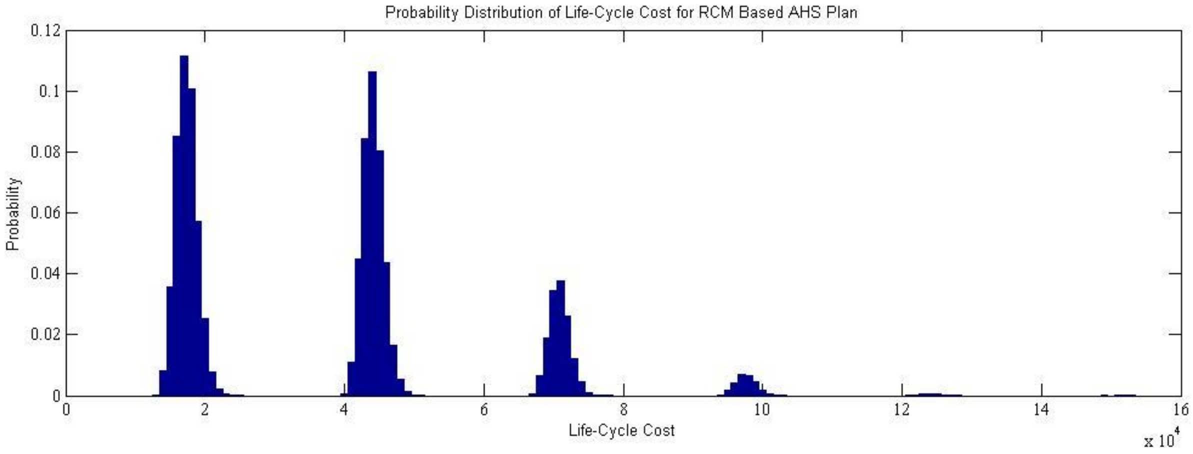


Figure 4-13. Probability Distribution of LCC for RCM Based AHS Plan.

Figures 4-12 and 4-13 above show the probability distributions for the AHS schedules. The bars in the figures are shifted towards lower costs for the RCM based plan, implying that RCM may involve a cost reduction. Detailed differences are presented in the table below. The reason for the piecewise distributions is mainly due to the corroded ballast tank failure mode and its high failure cost.

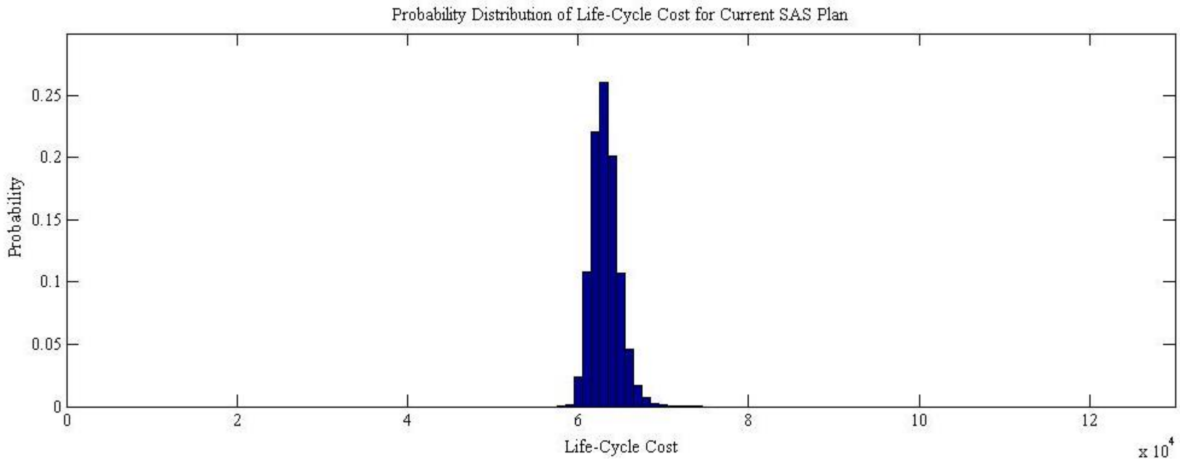


Figure 4-14. Probability Distribution of LCC for Current SAS Plan.

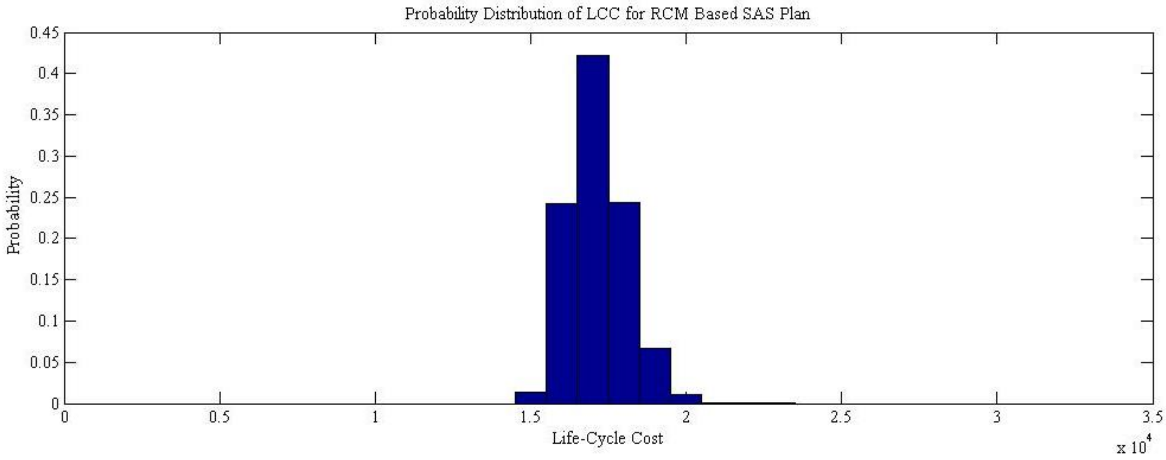


Figure 4-15. Probability Distribution of LCC for RCM Based SAS Plan.

None of the SAS plans include failure modes with similar costs as the corroded ballast tank in the AHS, which makes the probability distributions gathered. As for the AHS, the entire RCM based distribution is shifted towards lower costs. Table 4-14 lists important details.

Table 4-14. Mean and Upper Bound LCC.

Schedule	Mean LCC [kUSD]	LCC VaR 95% [kUSD]
AHS: Current	48.6	83.7
AHS: RCM	37.9	72.4
SAS: Current	63.2	65.9
SAS: RCM	15.9	18.8

The data in the table suggest that a ship-owner may reduce costs by implementing RCM. Note the assumption of only one compressor and one receiver, as mentioned in section 4.3. This affects the LCC values, as there are actually three compressors and two receivers behaving in this manner. However, as this is valid for both the current schedule and the RCM based plan, the relative effect should be correct. The mean LCC is reduced with 22.0 and 74.8 % for the AHS and SAS respectively. Similar numbers are valid for the upper bound values.

4.6 Sensitivity Analysis

4.6.1 Simulations without Incipient Failures

The previously presented simulations consider both incipient and degraded failures as deteriorated performances. In other words, as soon as a condition control identifies a performance different from the "initial capability" line in Figure 3-4, a failure is registered, even if the performance is still in the "margin for deterioration". Even though the failure rates of incipient and degraded failures are weighted, this will most likely cause the simulation to register more failures than actual functional failures. This is because the failure rates given by OREDA are normally higher for incipient failures.

Simulations without incipient failures included are executed to find their relative importance. Table 4-15 shows the results from these simulations. The AHS numbers are similar to the results from the original simulation, while the SAS experience less failures. The RCM schedules still cause an increase in the number of failures.

Table 4-15. Average Number of Failures without Incipient Failures Included.

	AHS Current	**AHS RCM**	**SAS Current**	**SAS RCM**
Average number of failures	7.62	10.5	25.8	31.8

4.6.2 Different RCM Intervals

As the RCM intervals used in the simulation are mainly based on the student's intuition, additional simulations with different maintenance intervals are executed. Specifically, the intervals are both halved and doubled for both systems. This is done to show the importance of the intervals. The figure below shows how the intervals affect the amount of failures.

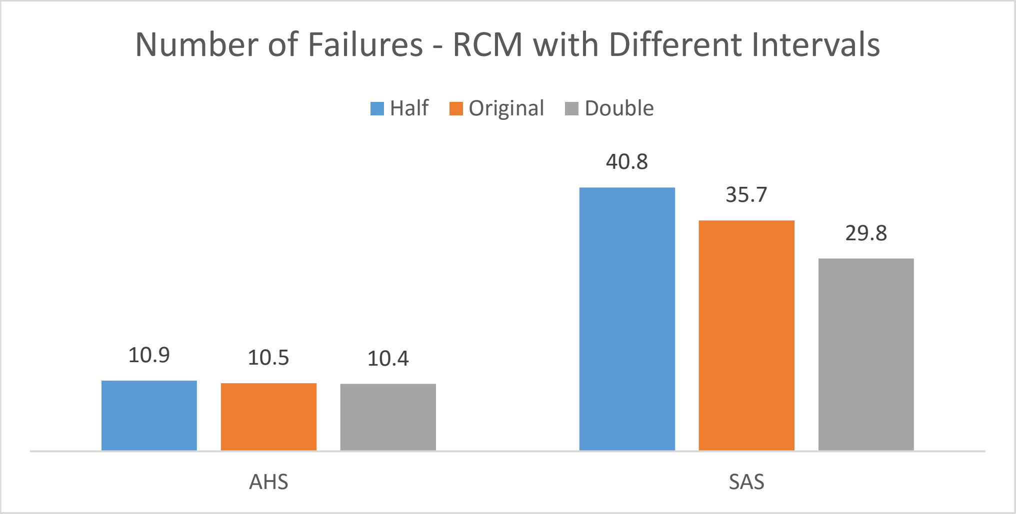


Figure 4-16. Number of Failures - RCM with Different Intervals.

This graph shows the same trend for both systems. Shorter intervals increase the number of failures. Normally one would expect the number of failures to decrease with shorter intervals. Therefore, the following diagram splits between deteriorated performances and total failures to find why this happens.

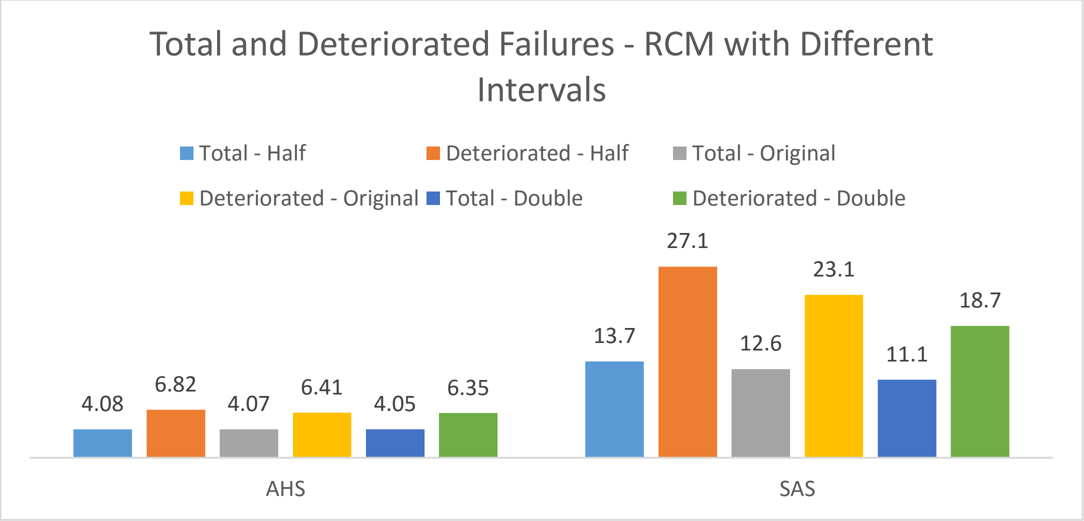


Figure 4-17. Total and Deteriorated Failures - RCM with Different Intervals.

This implies that the number of deteriorated performances is the factor that is most affected by the interval. The effect of the intervals on the LCC is summarised in Table 4-16 below.

Table 4-16. LCC - RCM with Different Intervals.

Schedule	Mean LCC [kUSD]	LCC VaR 95 % [kUSD]
AHS: Half	43.4	77.9
AHS: Original	37.9	72.4
AHS: Double	37.9	70.1
SAS: Half	28.2	29.8
SAS: Original	15.9	18.8
SAS: Double	11.6	13.1

The same trend as for the amount of failures is valid for the accumulated costs: Increased intervals mean lower costs. The reasons behind these trends will be discussed in the next chapter.

4.6.3 Increased Day Rates

In the initial analysis, it is assumed that failures in the AHS could lead to downtime costs. These costs are proportionate to the day rate of a container vessel, which is set to 7 000 USD. As these rates represent the low demand in the container shipping market, an additional analysis is performed to investigate how a market improvement would affect the results. This is done by increasing the day rate to 14 000 USD, and simulating AHS' current and original RCM schedules 100 000 times. The table below lists the results.

Table 4-17. LCC of AHS with Increased Day Rates.

Schedule	Mean LCC [kUSD]	LCC VaR 95% [kUSD]
AHS: Current with double DT costs	51.1	88.6
AHS: RCM with double DT costs	39.7	75.1

The results indicate that both schedules will be affected by the increase in day rates, and almost by the same amount. The original analysis implies that the RCM schedule would cause a cost reduction of 22.0 %, while this simulation gave a cut of 22.3 %.

4.6.4 Varying Cost of Ballast Tank Corrosion

So far, the analyses have assumed that a deteriorated failure mode looks the same every time, and always costs the same to repair. This assumption is rarely valid in real life. Additional simulations are therefore performed where the cost of a deteriorated failure mode varies with the inspection interval.

The figures depicting the LCC probability distribution for the AHS in sub-section 4.5.2 show that the cost of repairing the ballast tank had a large impact on the results. In that analysis, it is assumed that the entire tank needed repair every time a bit of corrosion was spotted. Now, it is assumed that the cost increases linearly with the time the corrosion is allowed to grow.

The failure rate used earlier implies that the tank needs a complete overhaul every 30 years. A corrosion allowed to grow one year therefore correspond to a cost of 1/30 of the previously used failure cost. The following table shows how this affects the LCC.

Table 4-18. LCC with Varying Ballast Tank Corrosion Costs.

Schedule	Mean LCC [kUSD]	LCC VaR 95% [kUSD]
AHS: Current	27.3	30.2
AHS: RCM	20.8	27.7

This new assumption leads to large reductions in LCC for both schedules. The relative change is not affected in the same way, however. The new cost reduction of implementing RCM is at 23.8%, while the original analysis implies savings of 22.0 %. The upper bounds are closer in this scenario.

4.6.5 Change in Regulations and Spare Part Inventory

The original analysis assumes that the redundancy level in the SAS would ensure that a failure did not lead to any downtime. The results from the analysis show that the RCM schedule will lead to 31.8 failures, which means a failure around every 10 months. If any failure would take 7 days to repair, this would give an availability of 97.7 % yearly. This means that the probability of two simultaneous failures is 0.05 %, which implies that the original assumption holds.

However, a scenario that does not acknowledge this assumption is also simulated. This scenario assumes that there has been a change in regulations, which states that if a part of the system is in a failed state, the vessel is not allowed to leave port. It also assumes that no spare parts are available onboard, so the system can only be repaired while the vessel is at port. This leads to downtime, and the downtime hours are taken from the active repair hours data in OREDA. The simulation results are shown below.

Table 4-19. LCC of SAS with Downtime.

Schedule	Mean LCC [kUSD]	LCC VaR 95 % [kUSD]
SAS: Current	81.3	91.4
SAS: RCM	18.4	21.5

The results are similar to the ones in the original analysis. The savings related to implementing RCM is now 77.4 %, versus 74.8 % earlier.

5. Discussion and Conclusions

5.1 Introduction

Ship-owners operating in the container freight market are facing tough times, with several competitors and reduced revenues. This forces the operators to find areas where they can save costs in order to stay competitive. While savings have been achieved through improved logistics and less fuel consumption, it is believed that the ship-owners can realise additional cost-reductions through a well-reasoned maintenance strategy.

Many shipping companies follow maintenance strategies that land-based industries consider as outdated. This idea is supported by several classification societies, such as DNV GL, Lloyd's Register and ABS. They call for a new approach in the shipping industry, and they argue that RCM may be the first step towards an improved future. However, the benefits of implementing RCM have traditionally been backed by qualitative statements, which makes it hard to convince ship-owners that this is the way to go. This study therefore aims to provide values that quantify the effect of implementing RCM onboard a maritime vessel. The analysis is limited to reliability and economic aspects, and does not consider the safety level and environmental integrity.

To achieve this, two shipboard systems onboard Klaveness' container vessels are analysed by using Moubray's (1997) RCM method. The resulting maintenance plans' behaviour are then simulated 100 000 times to give a representative description of the schedules' performance. The schedules are finally compared to the currently used plan with regard to life-cycle cost and number of failures.

5.2 Discussion

5.2.1 The RCM Based Schedules

The figures comparing the RCM based schedules to the current plans show that the total level of planned maintenance activities remains the same. However, there is a change when it comes to the type of activities. For both systems, the figures show a trend where the RCM based schedules have an increase in the number of condition based activities, and a reduction in pre-defined overhauls compared to the currently used plans. As the RCM method promotes condition monitoring over other techniques by nature, and as the present strategy is based on second generation of maintenance ideas, this difference is as expected.

5.2.2 Number of Failures

The results presented in chapter 4 show that using RCM to develop maintenance schedules may increase the number of functional failures for the anti-heeling and starting air systems. However, they also show that the amount of total failures is reduced, and that the increase is due to the added number of identified deteriorated performances. As RCM promotes condition monitoring techniques over other maintenance activities, this development is logical. Considering the definition of reliability given earlier, one may say that RCM worsens the shipboard system reliability in these cases.

An important aspect in RCM is how the method considers the relative importance of the system or equipment in question. As long as a failure mode does not affect safety or the environment, the process may encourage the operator to let equipment run to failure, as it only considers the cost-efficiency of the available options. Since neither of the systems in this study are critical for the safety or environment due to the inherent level of reliability, this could have been a reason for the increase in failures. If so, the reduced reliability would need to be considered closely with the change in LCC. However, the diagrams in Figure 4-7 and Figure 4-8 imply that the RCM schedules have fewer failure modes that are allowed to run to failure. A thorough evaluation of the occurring failure modes shows that the increase is not due to run-to-failure failure modes, but rather the modes that are identifiable through condition monitoring.

The increase in number of failures can be explained by that the rate of deteriorated performances are normally higher than for total failures. This means, as an example, that a degradation may occur and be fixed three times in the same period as two total failures would happen for a scheme that does not use condition monitoring techniques. As the RCM based schedules developed in this study are both based on frequent use of condition monitoring, the increase in deteriorated failures is understandable. Combining this with the reduction in total failures, one can see that the RCM schedules identifies and repairs the failures at an early stage, before the entire performance is lost.

The reasons behind the increase of failures in total can additionally be explained by limitations in the exponential distribution and the simulation model. This is also valid for the unexpected development when changing the RCM intervals. These limitations are further explained in section 5.3.

5.2.3 Life-Cycle Costs

Both systems analysed showed the same trend. The RCM schedules bring lower life-cycle costs than the currently used plans. This is considered as an expected consequence of the reduction of total failures. The results also show that the potential cost-reduction increases with higher downtime costs. Based on the two systems analysed, one can say that the maintenance related life-cycle costs will be reduced by implementing RCM on a maritime vessel.

An important factor to consider when assessing these results is the criticality of the systems involved. As neither of the systems have any significant impact on safety or the environment, the RCM process has mainly been focused on finding a cost-efficient schedule. This study has therefore not been able to assess how safety or environmental critical failure modes affect the life-cycle costs. As RCM works to avoid safety and environmental consequences at all costs, the LCC of another system might increase.

The results also show that the relative savings vary from 22 to 75 %, where the SAS achieves the largest cost-reductions. This system is more complex than the AHS, both when it comes to the amount of equipment involved, and the size of the current and RCM based maintenance schedules. As presented in the analysis, the current SAS plan includes several overhaul activities with pre-defined intervals, in addition to condition monitoring tasks, and some of these tasks override each other. By implementing a RCM based schedule, the ship-owner gets better understanding and control of the complex system. The system may experience less total failures, and the deficiencies are rather repaired at an earlier stage. It seems that RCM may have larger economic impact on complex systems.

The number of, and the type of, failures directly affects the LCC. As the input value tables in chapter 4 show, the costs of total failures are normally larger than the costs of repairing deteriorated failures. This is mainly due to the level of overhaul, and the work hours, needed to repair the breakdown. As a consequence, the failures should be identified at an early stage to reduce the maintenance related life-cycle costs. RCM excels at this stage.

This becomes clear when the costs of downtime increases. Total failures normally take longer to repair than deteriorated performances, which may mean more downtime hours. So, when the negative consequences of downtime increases, it becomes more important to avoid total failures. In other words, RCM seems to deliver better results when the downtime costs increase.

5.3 Limitations

The study displays encouraging results, but it includes some limitations. First of all, the analysis does not consider any critical systems. This means that failures do not cause any severe consequences, due to the systems' primary functions and their level of redundancy. As an example, when the student was onboard on of KSM's vessels, the chief officer stated that he did not worry if the AHS failed, as he could easily use the ballast water system instead. The previous section describes how the system criticality can affect the life-cycle costs. This study shows that RCM may lead to cost-reductions for non-critical systems, but it does not state anything about more important systems.

Secondly, the entire RCM process was performed by the student alone, with revisions from RCM consultants at MainTech. No vessel crew members, nor onshore employees of KSM, were involved in the analysis. This is, according to Moubray (1997), an example of how RCM should not be applied. As no single person can have full understanding of all functions, failures modes and consequences, the process is bound to include weaknesses. Additionally, the crew will not feel any ownership to the new schedule, and may consider it as more unwanted paperwork. This means that the RCM based plans used in the simulations will most likely be erroneous: important failure modes may have been neglected, consequences wrongly evaluated and inefficient tasks may have been proposed.

The input cost values can also be considered as a limitation. As mentioned in chapter 4, since actual cost data is hard to come by, most of the failure and job cost inputs were based on OREDA and online sources. The costs are also constant regardless of maintenance interval. A direct consequence is that the output life-cycle cost will not represent the true value. The failure mode input values are similar for the both the RCM based and the current schedule, however, which means that the relative savings should give a good representation of the plans' performance.

The increase in failures in the RCM based schedules, and the unexpected variation of failures depending on the intervals presented in chapter 4, also indicate an important limitation in the study. As one increases the number of inspections, one would not expect the number of failures to increase, and especially not the number of total failures. However, the SAS values presented in sub-section 4.6.2 show that dividing the initial intervals in two would lead to an average of 2.6 more failures than by doubling the same intervals. This is due to a flaw in the combination of the exponential distribution and the simulation model. The following figure depicts the main problem caused by the exponential distribution.

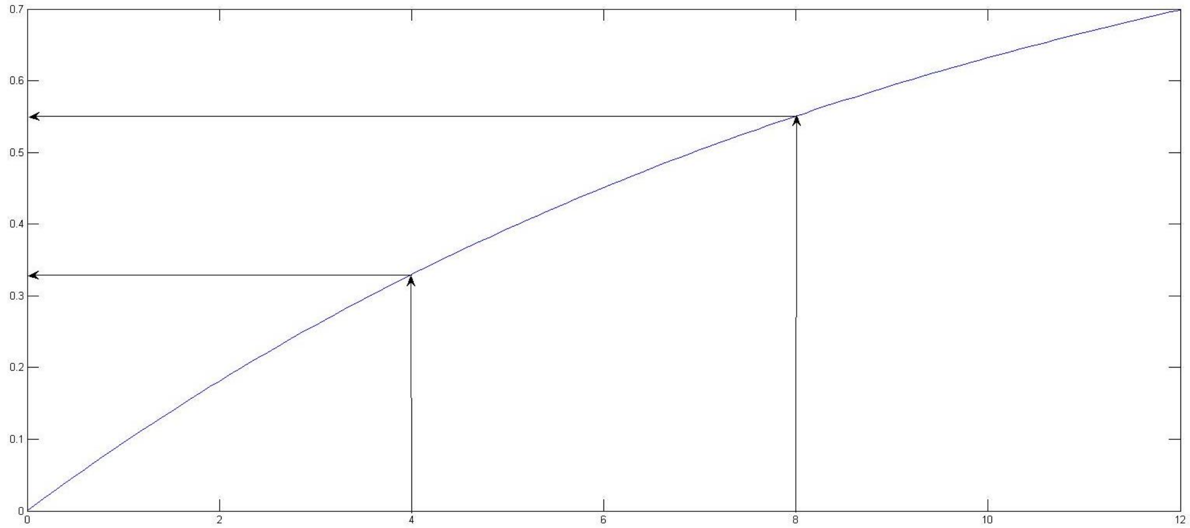


Figure 5-1. The Exponential Distribution's Cumulative Function with Limitation Indicators.

The figure represents an example of the cumulative function of a failure mode which failures are exponentially distributed. The failure rate is 0.1 per month, and the figure shows the 12 first months. This failure mode is currently treated by condition monitoring techniques every eight months. As the figure indicates, a failure will occur and be found by an inspection 55 % of the time. By dividing the inspection interval by two, to every four months, the probability of a failure occurring in between intervals is reduced to around 33 %. In other words, there is less chance of a failure to occur before the inspection when the interval is reduced. However, the number of inspections is doubled, and this affects the amount of failures, as the following calculations show.

$$E(failures)_{8m} = 0.55\ \frac{failures}{inspection} * 37\frac{inspections}{lifetime} = 20\ \frac{failures}{lifetime} \tag{7}$$

$$E(failures)_{4m} = 0.33\ \frac{failures}{inspection} * 75\frac{inspections}{lifetime} = 25\ \frac{failures}{lifetime} \tag{8}$$

The combination of this attribute of the exponential distribution and the model assumption where the time to the next failure is recalculated every time an activity is performed will lead to more failures by introducing shorter intervals. The limitation becomes even clearer when considering that the model does not connect deteriorated and total failures, such that frequent inspections do not actually prevent total failures – they just find deteriorated failures at an early stage. A way to counter this limitation is proposed in section 5.4.

Other assumptions also bring weaknesses to the study. It is assumed that every inspection is perfect, and will identify a failure mode if it has occurred. Even though better condition monitoring techniques are presented continuously, assuming that all failure modes will be identified every time is still an optimistic idea. In a real situation, one would therefore expect to see an increase in total failures at the expense of the number of deteriorated failures.

It is also assumed that every needed spare part is always available onboard the vessel. This is seldom the case in real life. Normally, a spare part is ordered when it is needed, in order to minimise the inventory costs. This means that the time from the failure occurs until it is repaired would most likely increase, which makes the system more prone to the consequences of unavailability. Sub-section 4.6.5 showed how removing this assumption would affect the results.

5.4 Conclusions

This thesis has analysed how RCM affects the reliability and the maintenance related costs of two shipboard systems. Based on the results, three conclusions can be drawn:

- RCM appears to reduce the amount of severe failures from the analysed systems. The failures are rather identified at an earlier stage, leaving the number of failures at a similar level as earlier.
- The maintenance related LCC seems to decrease by implementing RCM on maritime vessels. For the two systems analysed, these savings are at 22 % and 75 % respectively.
- The economic effect of RCM may improve with more severe financial failure consequences. When the unavailability costs increase, the RCM based schedules deliver even better results.

A comparison of the number of failures occurring by following the RCM based and the currently used maintenance schedules shows that the system may experience more failures with an RCM scheme. This contradicts the results given by the airline industry, which have seen impressive reliability improvements. The numbers achieved in the aviation industry focus on safety, however, and the systems analysed in this study are not critical when it comes safety issues. RCM’s main goal for such systems is to find the most cost-effective solution, and not to reduce the amount of failures. Additionally, the results show that RCM will most likely identify the failures at an early stage. This supports the qualitative theory, which states that RCM may lead to prolonged equipment lifetime. The numbers achieved are hampered by limitations in the simulation model, however. It is believed that a better model may show less failures by following the RCM schedules.

The second conclusion states that the life-cycle costs seem to decrease by implementing RCM. Both systems analysed show lower LCC when following the RCM based schedules, both on an average level and in a risk-averse approach. This is mainly due to the fact that the increased use of condition monitoring techniques advocated by RCM, leads to the failures being identified at a stage where the cost of repair is relatively low. It also causes fewer downtime hours, which has a large impact on the costs. This coincides with the theories of RCM leading to improved operating performance and cost-effectiveness.

These cost-savings may increase when the economic consequences of a failure get more severe. The results show that an increase in the unavailability cost, either due to higher costs per hour or more hours out of operation, can lead to better performances from RCM based schedules.

It appears to be clear benefits of implementing RCM onboard maritime vessels. However, the method's effect on the safety level and environmental integrity is still uncertain. A ship-owner considering to initiate RCM in its organisation should therefore investigate these effects first. If the results are encouraging, the process should be applied to the most complex and critical systems at first. This is because the RCM process needs commitment, in both time and resources, and the critical systems seems to be where the organisation can reap the largest benefits. Then, more systems can be gradually analysed with time. It is important that the manager implements the analysis and then thinks the work is done. In order to achieve success from the process, the analysis needs to be revised regularly, and the entire organisation needs to search for improvement areas continuously.

The study is a start when it comes to evaluating the effects of RCM. Unfortunately, realistic data is hard to come by, and the model developed proves to include certain limitations. This means that the analysis does not represent true values. However, the student believes that the results display a realistic representation when it comes to the cost-reduction potential in maintenance management. An increase in the use of condition monitoring techniques appears to be the future, also in deep sea shipping, and RCM is an effective tool to decide when these techniques should be used.

5.5 Recommendations for Future Work

5.5.1 Recommendations for Future Research

This sub-section will recommend which procedures the next researcher should focus on changing, and in which areas he or she should expand the analysis, in order to improve the significance to the field of study. It will therefore be closely related to the limitations presented in section 5.3.

First of all, an analysis of the performance of safety and environmental critical systems should be performed. This could be systems like the ballast water treatment system or the fire water system. These systems' maintenance schedules should be analysed with regard to reliability and LCC, like this study has done, but also include how RCM affects the safety level and environmental integrity of the container ship.

Secondly, the RCM should be performed together with operators with thorough knowledge and understanding of the system in question. This would enhance the credibility of the resulting RCM based maintenance plans, and ensure more realistic results. Additionally, their expertise could lead to better cost input values.

Section 5.3 also presented the limitations related to the model and the exponential distribution. This is crucial to improve in similar studies in the future. One way to do this is to create a relation between the deteriorated and total failures. In other words, if a deteriorated failure has occurred, the model should set a time where the function reaches the point of no performance. One could also adjust the assumption of all activities leaving the equipment as good as new. This assumption now causes the model to recalculate the time to a failure every time an activity, both inspections, planned overhauls and corrections, is performed. An inspection would not leave the equipment as good as new, so by limiting this assumption to overhaul and corrective activities could improve the model. This would reduce the problem described by Figure 5-1 and equations 7 and 8 in section 5.3. As the number of recalculations are only dependent on actual failures, the value corresponding to inspections/lifetime is expected to decrease. Combining these two improvements would most likely lead to a more realistic model and more correct results. The student wanted to implement these ideas. However, the scope of the thesis caused the problem to be identified too late, as the improvements would take a lot of time, due to PF-interval estimations, model re-programming and simulations.

Further, it would be interesting to use the ideas presented by Kerres et al. (2015) in sub-section 2.3.3 to optimise the RCM based schedule. Performing such an analysis could highlight the inherent potential in RCM in an even better way.

Another way to take the study to the next level, is to include the spare parts availability and its effect on the maintenance schedules' performance. The student's project thesis (Kristiansen, 2015) discussed the importance of a well-planned spare part inventory strategy for a deep sea shipping company, and presented a model by van Jaarsveld and Dekker (2011) that uses data available from an RCM study to optimise the spare parts inventory. Including this model in the analysis could improve the credibility of the results, and help ship-owners making the right decisions.

How RCM affects the need for onboard manpower is also of interest. The transition RCM brings from pre-defined overhauls to condition based maintenance implies that many activities can be planned to be performed by experts while in port, supporting the classification societies' vision of a future with reduced shipboard manpower.

Finally, the student would recommend the future researchers to investigate the costs of implementing RCM. This study has only focused on the operational costs, such as job and failure costs. The costs related to performing the RCM analysis, and the new approach to maintenance management has been neglected. To give a true indication on the real economic effect of RCM, these costs need to be considered.

5.5.2 Recommendations for Future Development of the Maintenance Organisation

This part is related to the last paragraph of the previous sub-section. It will present the student's recommendations for a ship-owner that wants to implement the RCM ideas. It will not discuss the associated costs.

After an RCM analysis has been performed, the organisation has ideally discussed and defined all aspects in the "plan" and "control" boxes of Figure 2-1. Now, it has to focus on assessing the performance and find areas of improvement through the continuous improvement loop. One way to handle this, is to use key performance indicators. When the RCM based plans are running, they should be measured with lagging KPIs to evaluate their performance, and with leading KPIs to find potential areas for improvement.

Another way to cultivate continuous improvement is to ensure that the entire organisation is included and learns from the occurring errors. As the RCM process argues that it need constant revisions and updates, commitment from both operators and managers is necessary for a successful implementation. Bringing in the ideas of Total Productive Maintenance could help enhance this process.

With an initial approach to the improvement loop in order, the ship-owner should focus on following the recommendations by DNV GL, which were presented in sub-section 2.4.3. This means developing databases to help determine the remaining useful life of the equipment, and to help understand when, and what kind of, maintenance should be performed. As these databases are based on the failure history of the systems, it is important that the ship-owner truly understands why the failure modes have occurred. The student therefore recommends that a root cause analysis tool, such as Five why, is used for every appearing failure.

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APPENDIX

A. MatLab Scripts

A.1 The Simulation Script

```
% This script calculates the costs related to a maintenance strategy. It considers the failure
rate, task interval, failure costs and planned task costs related to a system's failure modes.
% The performance of the system and strategy are then simulated over the system's lifetime.
The script delivers the accumulated costs as output.

% The script is made by Aleksander Vold Kristiansen in the spring of 2016 as part of the
Master's Thesis in Marine Technology at NTNU.

data = dataFromExcel;                                                       % Load the data
from an Excel spreadsheet
N_jobs = max(data(:,1));                                                    % Define the
number of jobs in the spreadsheet
t = zeros(1,N_jobs);                                                        % The time passed
for every job starts at zero
N_months = 25 * 12;                                                         % Define the
number of months
interval = zeros(1,N_jobs);                                                 % One interval for
each job
nextPlanned = zeros(1,N_jobs);                                              % Every job has
one next interval slot
nextFailure = zeros(1,N_jobs);                                              % Every job has
one next failure slot
timeToFailure = ones(1,length(data(:,2)))*inf;                              % Every failure
mode has a slot for time to next failure
failureCosts = data(:,6);                                                   % Define the cost
of every failure mode
jobCosts = zeros(1,N_jobs);                                                 % One cost for
each planned job
failureRate = data(:,3);                                                    % Define the
failure rate of every failure mode
N_planned = zeros(1,N_jobs);                                                % Every job has a
number of executed activities
N_failures = zeros(1,N_jobs);                                               % Every job has a
number of failures
failureCounter = zeros(N_jobs,length(data(:,2)));                           % Create a matrix
to count occurances of specific failure modes
conditionControl = data(:,5);                                               % Define whether
the failure mode can be identified through condition control
costOfJob = zeros(1,N_jobs);                                                % Every job has a
cost slot
N_failureModes = length(data(:,2));                                         % Define the
number of failure modes


for i = 1:N_jobs                                                            % For every job
    firstIndex = find(data(:,1)==i,1);                                      % Find the first
line job number i appears
    lastIndex = find(data(:,1)==i+1,1)-1;                                   % Find the last
line job number i appears

    if isempty(lastIndex) == 1                                              % If the line
found as last is empty...
```

```
        lastIndex = length(data(:,1));                                      % ...the last line
is defined as the last entry
    end

    while t(i) < N_months                                                   % While the time
is less than 300 months
    for j = firstIndex:lastIndex                                            % For all failure
modes related to the job
        interval(i) = max(data(j,4));                                       % The interval is
given by the Excel file
        jobCosts(i) = max(data(j,7));                                       % The costs are
given by the Excel file
        nextPlanned(i) = t(i) + interval(i);                                % The next planned
activity is the current time plus the interval
        timeToFailure(j) = log(rand)./(-failureRate(j));                    % The time to
failure for each failure mode is given by the exponential distribution
    end

        nextFailure(i) = t(i) + min(timeToFailure(firstIndex:lastIndex));   % The next failure
happens at the current time plus the time to the failure that happens first
        [C,I] = min(timeToFailure(firstIndex:lastIndex));                   % Find the vector
position of the next failure mode

        if nextPlanned(i) < nextFailure(i)                                  % If the next
planned activity happens before the next failure...
            N_planned(i) = N_planned(i) + 1;                                % ...the number of
planned activities increases with one...
            t(i) = nextPlanned(i);                                          % ...and the new
time is the time where the next planned activity occurs
            costOfJob(i) = costOfJob(i) + jobCosts(i);                      % ...and the job
cost is added
        elseif conditionControl(j) == 1                                     % Or if the next
failure is a degraded failure caught by a condition control...
            N_failures(i) = N_failures(i) + 1;                              % ...the number of
failures increases with one...
            failureCounter(i,I) = failureCounter(i,I) + 1;                  % ...and the
occurances of the particular failure mode increases with one...
            t(i) = nextPlanned(i);                                          % ...but the new
time is the time of the next condition monitoring activity
            costOfJob(i) = costOfJob(i) + failureCosts(j) + jobCosts(i);    % ...and the job
and failure costs are added
        else                                                                % If not...
            N_failures(i) = N_failures(i) + 1;                              % ...the number of
failures increases with one...
            failureCounter(i,I) = failureCounter(i,I) + 1;                  % ...and the
occurances of the particular failure mode increases with one...
            t(i) = nextFailure(i);                                          % ...and the new
time is the time where the next failure occurs
            costOfJob(i) = costOfJob(i) + failureCosts(j);                  % ...and the
failure costs are added
        end

    end
end
LCC = sum(costOfJob);
failureCounter(:,1:8);
```

A.2 The Script that Runs the Simulation Several Times

```
LCCVector = zeros(1,100000);                                                % Create a vector
to store all the simulations' LCC
failuresPerSimulation = zeros(15,30,100000);                                % Create a matrix
to store the occurring failures
meanFailures = zeros(15,30);                                                % Create a vector
to calculate the average number of failures

for a = 1:100000                                                            % For the
spesified number of times
    simulationv2                                                            % ...run the
simulation script
    LCCVector(a) = LCC;                                                     % ...add the
resulting LCC to the vector
    failuresPerSimulation(:,:,a) = failureCounter;                          % ...and add the
number of failures to the matrix
    if a == 1000 || a == 10000 || a == 25000 || a == 50000 || a == 75000    % If the process
reaches the given number
        disp(a)                                                             % ...display the
number to indicate how far the process has come
    end
 end

meanLCC = mean(LCCVector);                                                  % Calculate the
mean LCC
sortedLCC = sort(LCCVector);                                                % Sort the LCC
values from lowest to highest


for b = 1:15                                                                % For all jobs
    for d = 1:30                                                            % ...and for all
failure modes
        meanFailures(b,d) = mean(failuresPerSimulation(b,d,:));             % ...find the mean
value of the failure mode
    end
end
```

B. The RCM Analyses

B.1 Anti-Heeling System

	FUNCTION		FUNCTIONAL FAILURE (Loss of Function)		FAILURE MODE (Cause of Failure)	FAILURE EFFECT	Consequence evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action			Proposed task	Initial interval	Can be done by
							H	S	E	O				H4	H5	S4			
1	To measure the heeling angle with an accuracy of +/- 0.1 degrees	A	Unable to measure the heeling angle	1	Inclinometer stuck	The angle indicated on the control panels will not change. This makes automatic operation of the system impossible, and may cause heavy heeling if not discovered. The heeling angle will be discovered by the crew during loading operations, and countermeasures can be initiated.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
		B	Measures heeling angle with too large inaccuracy	1	Mounting plate installed with tilt	The system will treat a heeling angle as if the vessel is on even keel. A constant list can cause trouble with loading operations. The inclinometer needs to be installed evenly.	N	-	-	-	Y	-	-	-	-	-	During operations, the control panel angle should be compared to the analog heeling angle. Installation procedure must be well described to prevent tilted inclinometer.	Once every operation	Chief Officer
				2	Inclinometer affected by vibrations	The system may start to distribute water even if the vessel is on even keel. Installation of vibration damping around the inclinometer could be installed.	N	-	-	-	Y	-	-	-	-	-	During operations, the control panel angle should be compared to the analog heeling angle. Vibration damping should be installed on the inclinometer.	Once every operation	Chief Officer
2	To transfer water from one side to the other at a rate of at least 500 m^3/h when the heeling angle exceeds a given limit	A	Does not transfer any water at all	1	Pump does not receive start signal from control panel due to electrical breakdown	The vessel's heel angle may continue to increase until an angle where it can affect safety and loading operations. If the angle exceeds 2.5 degrees, an alarm sounds. This allows the C/O to start straighten the vessel with the ballast water system. The light on the switch box will remain dark, but this switch box is located far from operating areas. The electric connection between the control panel and the switch box needs fixing.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
				2	Supply tank is empty	A low water level alarm will sound. This will also shut down the AH pump. Water can then be transferred from the ballast water system.	Y	N	N	Y	Y	-	-	-	-	-	During operations, the water level displayed on the control panel should be compared to the level on the ballast overview	Once every operation	Chief Officer
				3	Seal incorrectly installed	The AH pump shuts down due to pump leakage. The pump needs to be checked for damage, and the external seal needs replacement.	Y	N	N	Y	Y	-	-	-	-	-	Inspect the pump for small leakages shortly after installation	-	3rd Engineer

				4	Seal worn due to tear and wear	The AH pump shuts down due to pump leakage. The pump needs to be checked for damage, and the external seal needs replacement.	Y	N	N	Y	Y	-	-	-	-	-	Inspect the pump for small leakages	60 M	3rd Engineer
				5	Electric motor has tripped due to overload	The AH pump is unable to start as the electric motor has tripped. This load has been increasing over time.	Y	N	N	Y	Y	-	-	-	-	-	Monitor the pump's Ampere meter	12 M	3rd Engineer
				6	Shaft between motor and pump has broken due to fatigue	The engine will start, but the electrical power will not be transferred to pump motion. This will lead to the same effect as in 2A1. The pump will need to be replaced.	Y	N	N	Y	Y	-	-	-	-	-	Vibration monitoring	6 M	3rd Engineer
				7	Suction valve stuck closed	The supply water will not reach the pump. This may lead to the pump running dry, causing it to break down. The system needs to be shut down and the valve opened.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
				8	Leakage in piping between supply tank and pump	Water will accumulate in the pipe tunnel. This may lead to a free surface effect, affecting the vessel's stability, and further increase heel angles. The tanks need to be closed and the pipes tightened.	Y	Y	-	-	Y	-	-	-	-	-	Inspect pipe tunnel for small leaks	24 M	3rd Engineer
				9	Impeller clogged by foreign object	The impeller will work against the object, causing damage to the impeller. The pump may vibrate heavily, leading to further damage to other equipment, such as the bearings. The pump needs to be opened and inspected, and the object removed.	Y	N	N	Y	N	N	N	-	-	-	Run to failure. The filter design in the ballast water system should be reviewed if this failure mode occurs.	-	-
				10	Impeller worn by impact from foreign objects	The pump will operate out of design, causing vibrations, which may lead to damage to other equipment, i.e. worn bearings or motor breakdown. The impeller needs replacement.	Y	N	N	Y	Y	-	-	-	-	-	Vibration monitoring. The filter design in the ballast water system should be reviewed if this failure mode occurs.	6 M	3rd Engineer
				11	Impeller worn by corrosion	See 2A10.	Y	N	N	Y	Y	-	-	-	-	-	Vibration monitoring	6 M	3rd Engineer
				12	Impeller worn by cavitation	See 2A9. In addition, the cavitation will create noice. If an increased level of cavitation occurs at the pump's BEP, failure may be imminent.	Y	N	N	Y	Y	-	-	-	-	-	Vibration and sound monitoring	6 M	3rd Engineer
				13	Excessive radial thrust	High radial thrust can lead to packing and seal problems, and shaft failure. The temperature in the bearings may increase, leading to the bearing seizing.	Y	N	N	Y	Y	-	-	-	-	-	Measure the bearing temperature. Install temperature logging equipment. Train personnel in correct use of pump.	6 M	3rd Engineer

				14	Excessive axial thrust	The temperature in the bearings may increase, leading to the bearing seizing. The shaft may fail due to fatigue.	Y	N	N	Y	Y	-	-	-	-	-	Measure the bearing temperature. Install temperature logging. Pump re-design should be considered if this failure mode occurs.	6 M	3rd Engineer
				15	Wrong lubrication oil	The wrong lubrication oil may cause an increase in bearing temperature, causing the bearing to wear down faster. A failed bearing causes vibrations and needs to be replaced before it affects the rest of the pump.	Y	N	N	Y	Y	-	-	-	-	-	Vibration and temperature monitoring	6 M	-
				16	Too much lubrication	Too much lubrication oil may cause an increase in bearing temperature, causing the bearing to wear down faster. A failed bearing causes vibrations and needs to be replaced before it affects the rest of the pump.	Y	N	N	Y	Y	-	-	-	-	-	Vibration and temperature monitoring	6 M	-
				17	Insufficient lubrication	Too little lubrication oil may cause metal-to-metal contact, which shortens the bearing life. A failed bearing causes vibrations and needs to be replaced before it affects the rest of the pump.	Y	N	N	Y	N	Y	-	-	-	-	Lubricate bearings. Train personnel in correct use of lubricating oil.	6 M	3rd Engineer
				18	Bearings installed incorrectly	Shortens the bearings life and causes vibrations.	Y	N	N	Y	Y	-	-	-	-	-	Check for excessive vibrations shortly after installation. Train personnel in correct installation of bearings.	Next operation	3rd Engineer
				19	Discharge valve stuck closed	The discharged water will gather in the pipeline and pump, increasing the pressure. This will cause the valve to slam open.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				20	Leakage in piping between pump and demand tank	Water will accumulate in the pipe tunnel. This may lead to a free surface effect, affecting the vessel's stability, and further increase heel angles. The tanks need to be closed and the pipes tightened.	Y	Y	-	-	Y	-	-	-	-	-	Inspect pipe tunnel for small leaks	24 M	3rd Engineer
		B	Transfers water at a rate less than 500 m^3/h	1	Suction valve not entirely open	The vessel's heel angle may continue to increase until an angle where it can affect loading operations. If the angle exceeds 2.5 degrees, an alarm sounds. This allows the C/O to start straighten the vessel with the ballast water system. The reduced suction can lead to pump cavitation and vibration.	N	-	-	-	Y	-	-	-	-	-	Vibration and sound monitoring	6 M	3rd Engineer
				2	Leakage in piping between supply tank and pump	See 2A8	N	-	-	-	Y	-	-	-	-	-	Inspect pipe tunnel for small leaks	24 M	3rd Engineer
				3	Impeller worn by impact from foreign objects	See 2A10	N	-	-	-	Y	-	-	-	-	-	Vibration monitoring. The filter design in the ballast water system should be reviewed if this failure mode occurs.	6 M	3rd Engineer

				4	Impeller worn by corrosion	See 2A10	N	-	-	-	Y	-	-	-	-	-	Vibration monitoring	6 M	3rd Engineer
				5	Impeller worn by cavitation	See 2A12	N	-	-	-	Y	-	-	-	-	-	Vibration and sound monitoring	6 M	3rd Engineer
				6	Excessive radial thrust	See 2A13	N	-	-	-	Y	-	-	-	-	-	Measure the bearing temperature. Train personnel in correct use of pump.	6 M	3rd Engineer
				7	Excessive axial thrust	See 2A14	N	-	-	-	Y	-	-	-	-	-	Measure the bearing temperature. Pump re-design should be considered if this failure mode occurs.	6 M	3rd Engineer
				8	Wrong lubrication oil	See 2A15	N	-	-	-	Y	-	-	-	-	-	Vibration and temperature monitoring	6 M	-
				9	Too much lubrication	See 2A16	N	-	-	-	Y	-	-	-	-	-	Vibration and temperature monitoring	6 M	-
				10	Insufficient lubrication	See 2A17	N	-	-	-	N	Y	-	-	-	-	Lubricate bearings. Train personnel in correct use of lubricating oil.	6 M	3rd Engineer
				11	Bearings installed incorrectly	See 2A18	N	-	-	-	Y	-	-	-	-	-	Check for excessive vibrations shortly after installation. Train personnel in correct installation of bearings.	Next operation	3rd Engineer
				12	Seal incorrectly installed	The pump will have a leakage, which reduces the output. The leak may affect the electronics. This should be handled by the leakage protection before it breaks the pump.	N	-	-	-	Y	-	-	-	-	-	Inspect the pump shortly after installation	-	3rd Engineer
				13	Seal worn due to tear and wear	See 2B12	N	-	-	-	Y	-	-	-	-	-	Inspect the pump for small leakages	60 M	3rd Engineer
				15	Leakage in piping between pump and demand tank	Water will accumulate in the pipe tunnel. This may lead to a free surface effect, affecting the vessel's stability, and further increase heel angles. The tanks need to be closed and the pipes tightened.	N	-	-	-	Y	-	-	-	-	-	Inspect pipe tunnel for small leaks	24 M	3rd Engineer
3	To contain up to 485 m^3 of water in each tank	A	Unable to contain any water at all	1	Tank leaking due to corrosion	The water level in the tank will not rise no matter how much the pump runs. This wil show on both the AH control panel and the tank overview. If the tank has corroded on the outside, external water may intrude the tank. If the tank has corroded on the inside, water will gather in open areas, affecting the stability of the vessel. In either case, the system needs to be shutdown, and the tank fixed in dry docking.	Y	Y	-	-	Y	-	-	-	-	-	Inspect the AH tanks for corrosion damage to both coating and steel	60 M	Chief Officer
		B	Unable to contain 485 m^3 of water	1	Tank leaking due to corrosion	See 3A1.	Y	Y	-	-	Y	-	-	-	-	-	Inspect the AH tanks for corrosion damage to both coating and steel	60 M	Chief Officer
				2	Tank valves stuck open	Assuming the butterfly valves work as intended, the water will leave the system and enter the ballast water system. However, this also means that ballast water intended for other tanks may enter the tank. This may cause unintended heeling angles, causing problem for the crew and loading operations.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-

4	To sound an alarm when the heeling angle exceeds 2.5 degrees	A	Unable to measure the heeling angle	1	Inclinometer stuck	The angle indicated on the control panels will not change. This means that the system will not recognise that the heeling angle is reaching critical values, and this may affect operations.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
		B	Does not sound an alarm when the measured angle exceeds 2.5 degrees	1	Unable to send signal to alarm panel due to electrical breakdown	The angle will show on the control panel, but the critical value may be overlooked. The C/O may not be aware of the increasing heeling angle, and there is a chance that no countermeasures are initiated. However, as soon as the heeling angle leads to problems for the loading crew, countermeasures will be taken.	Y	N	N	Y	Y	-	-	-	-	-	Check in on the heeling angle during operations. The crew should report to the C/O as soon as they notice unnatural heeling angles.	-	Chief Officer
5	To stop the anti-heeling pump when the angle exceeds 5 degrees	A	Unable to measure the heeling angle	1	Inclinometer stuck	The angle indicated on the control panels will not change. This means that the system will not recognise that the heeling angle is reaching critical values, and this may affect operations. When the angle exceeds 5 degrees, this could affect the safety of the crew as well. However, the crew should be able to recognise such angles naturally before they get too critical.	Y	Y	-	-	Y	-	-	-	-	-	During operations, the control panel angle should be compared to the analog heeling angle. The crew should report to the C/O as soon as they notice unnatural heeling angles.	Once every operation	Chief Officer
		B	Does not stop the pump when the measured angle exceeds 5 degrees	1	Stop signal does not reach the pump due to electrical breakdown	See 4B1.	Y	Y	-	-	Y	-	-	-	-	-	Check in on the heeling angle during operations. The crew should report to the C/O as soon as they notice unnatural heeling angles.	-	Chief Officer
6	To stop the pump when leakage is detected at the pump gear box	A	Unable to detect leakage	1	Float switch fails due to electrical breakdown	The pump will continue to run in unsafe conditions. This will at first reduce the pump performance, and in time cause the pump to break down. Pump replacement is costly, and a pump out of function may affect operations.	N	-	-	-	N	N	N	Y	-	-	Function test the float switch	60 M	3rd Engineer
		B	Unable to stop the pump	1	Stop signal does not reach the pump due to electrical breakdown	A leakage alarm will sound, however the pump will continue to run in unsafe conditions. This will at first reduce the pump performance, and in time cause the pump to break down. Pump replacement is costly, and a pump out of function may affect operations.	Y	N	N	Y	N	N	N	-	-	-	Run to failure. The ECR crew should shut check the running status of the pump as soon as the alarm sounds and shut down the pump.	-	-
7	To stop the pump when one of the tanks reaches low level	A	Unable to recognise low water level	1	Low level switch stuck in upright position	The system keeps running, even though the tank is empty. This may cause the pump running dry, which will harm the pump. The water level should be indicated on the control panel and ballast water overview. The pump needs to be shut down as soon as possible, the switch loosened or replaced and the tank filled.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
				2	Low level switch fails due to electrical breakdown	See 7A1.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-
		B	Unable to stop the pump	1	Stop signal does not reach the pump due to electrical breakdown	A low level alarm will sound, however the pump will continue to run in unsafe conditions. This will at first reduce the pump performance, and in time cause the pump to break down.	Y	N	N	Y	N	N	N	-	-	-	Run to failure	-	-

B.2 Starting Air System

FUNCTION		FUNCTIONAL FAILURE (Loss of Function)		FAILURE MODE (Cause of Failure)		FAILURE EFFECT	Consequence evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action			Proposed task	Initial interval	Can be done by
							H	S	E	O				H4	H5	S4			
1	To compress air between 25 and 30 bars at a rate of at least 275 m^3/h	A	Unable to compress air	1	Motor windings fail due to mechancial overload	The electric motor will not start when required, which disables the compressor from running. Only one MAC and the TUC will have the required capacity to maintain the function. If two compressors fail at the same time, the required performance is not satisfied (Valid for all failure modes). This means that the air consumption may exceed the production, and manouevring may be impossible. This can lead to the vessel colliding or grounding. The motor needs either replacing or rewinding.	Y	N	N	N	Y	-	-	-	-	-	Meggertest the motor	12 M	Electrician
				2	Motor windings fail due to thermal overload	See 1A1.	Y	N	N	N	Y	-	-	-	-	-	Meggertest the motor	12 M	Electrician
				3	Bearings seize due to wrong bearing lubrication oil	The wrong lubrication oil may cause an increase in bearing temperature, causing the bearing to wear down faster. The electric motor starts, but is unable to run the compressor. This will cause heavy vibrations and noise at the compressor.The failure mode may cause damage to other compressor components as well. The bearings need replacement.	Y	N	N	N	Y	-	-	-	-	-	Vibraiton monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				4	Bearings seize due to too much lubrication	Too much lubrication oil may cause an increase in bearing temperature. See 1A3.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				5	Bearings seize due to insufficient lubrication	Too little lubrication oil may cause metal-to-metal contact, which shortens the bearing life. See 1A3.	Y	N	N	N	Y	-	-	-	-	-	Check oil level	500 h	Wiper
				6	Bearings seize due to incorrect installation	Incorrect installation may cause metal-to-metal contact and heavy vibrations, leading to shorter bearing life. See 1A3.	Y	N	N	N	Y	-	-	-	-	-	Check for excessive vibrations shortly after installation. Train personnel in bearing installation.	Next operation	3rd Engineer

				7	Flexible gear rim seize due to wrong lubrication oil	The compressor starts, but is unable to compress any air. It will probably make more noice than normal. When the receiver pressure drops, the second and third compressor will start. The gear rim needs replacement, and the compressor needs to be inspected for secondary damage.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				8	Flexible gear rim seize due to too much lubrication oil	See 1A7.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				9	Flexible gear rim seize due to insufficient lubrication	See 1A7.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				10	Flexible gear rim seize due to incorrect installation	See 1A7.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring. Train personnel in correct use of lubrication oil.	12 M	3rd Engineer
				11	Flexible gear rim seize due to overload	See 1A7.	Y	N	N	N	Y	-	-	-	-	-	Vibration monitoring	12 M	3rd Engineer
				12	Compressor does not start due to blown fuses	The electric motor will not start when required, which disables the compressor from running. The fuses need replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				14	Oil pressure sensor activated due to oil level too low	The electric motor will not start when required, which disables the compressor from running. A lamp will glow locally. MAC2 and TUC will start without the start of MAC1, indicating this in the ECR. The compressor needs more oil.	Y	N	N	N	Y	-	-	-	-	-	Check oil level	500 h	Wiper
				15	Oil pressure sensor activated due to too viscous oil	See 1A14. The oil needs to be changed.	Y	N	N	N	N	Y	-	-	-	-	Change oil	1 000 h	3rd Engineer
				16	Oil pressure sensor activated due to blocked oil filter	See 1A14. The oil filter needs to be cleaned.	Y	N	N	N	N	Y	-	-	-	-	Clean oil filter	4 000 h	3rd Engineer
				17	Oil pressure sensor activated due to blocked oil pipe	See 1A14. The oil pipe needs to be cleaned.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				18	Oil pressure sensor activated due to failed oil pump	See 1A14. The oil pump needs to be fixed or replaced.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				19	Motor overcurrent sensor activated due to incorrect supply voltage	The electric motor will not start when required, which disables the compressor from running. A lamp will glow locally. MAC2 and TUC will start without the start of MAC1, indicating this in the ECR. Check the supply voltage.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				20	Motor overcurrent sensor activated due to loose connections	See 1A14. Check if crankshaft can be easily rotated by hand. Disconnect coupling to see whether motor or compressor is at fault.	Y	N	N	N	Y	-	-	-	-	-	Vibration Monitoring	12 M	3rd Engineer
				21	Motor overcurrent sensor activated due to piston seizure	See 1A14. Check cylinders and pistons for score marks, and replace as necessary.	Y	N	N	N	Y	-	-	-	-	-	Oil test	4 000 h	3rd Engineer

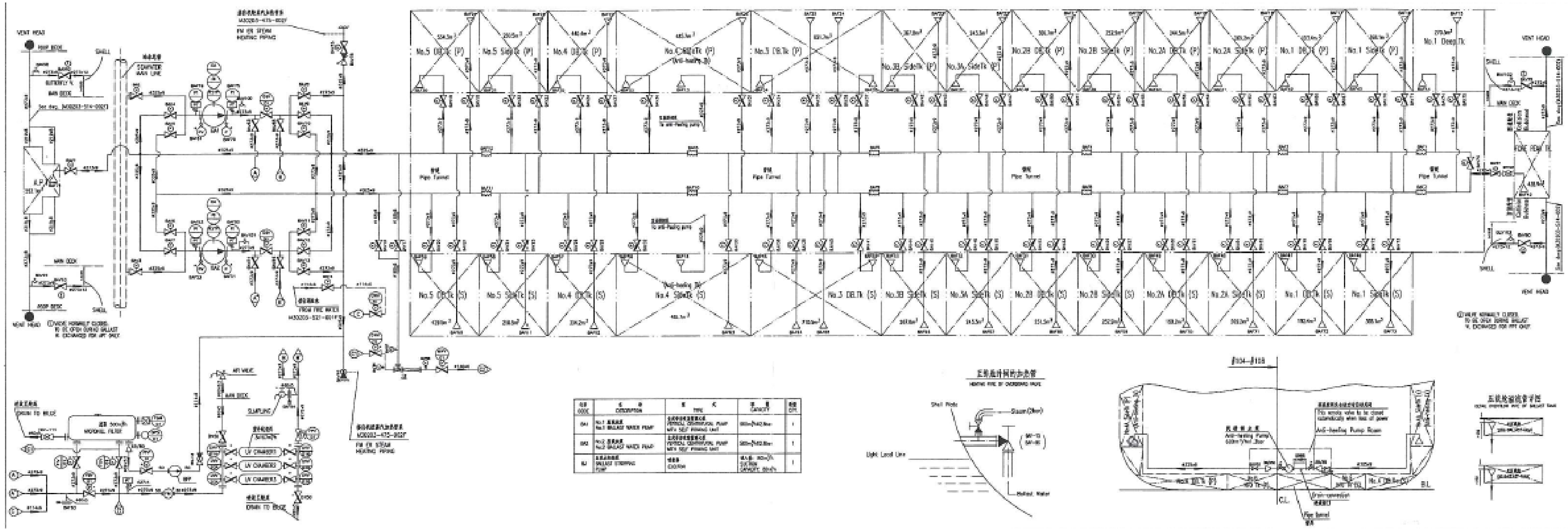
				22	Air temperature sensor activated due to failed cooling fan	The electric motor will not start when required, which disables the compressor from running. A lamp will glow locally. MAC2 and TUC will start without the start of MAC1, indicating this in the ECR. The fan needs replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the compressor thermometers	2 000 h	Wiper
				23	Air temperature sensor activated due to restricted cooling air intake	See 1A17. Remove blocking objects and clean the cooling air intake.	Y	N	N	N	Y	-	-	-	-	-	Monitor the compressor thermometers	2 000 h	Wiper
				24	Air intake filter is blocked	The electric motor and compressor starts, but is unable to deliver any pressure. This will show on the compressor gauges. The air intake cartridge needs cleaning or replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the 1st stage pressure gauge	1 000 h	Wiper
				25	Compressor valves worn by damage, carbonisation, oiling, corrosion or moisture	See 1A19. The worn valves need replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
				26	Air escaping from compressed air lines due to connection gaskets or seals leaking	The compressor runs as intended, but is not able to maintain the pressurised air. This will show on the compressor gauges. The gasket and/or seal needs replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	4 000 h	Wiper
				27	Air escaping from compressed air lines due to piston rings leaking	See 1A21. Check piston rings for damage. Tighten or replace as necessary.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
				28	Air leaking between cylinder and valve cover due to gasket leaking	See 1A21. Replace the gasket.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	4 000 h	Wiper
				29	Air leaking between cylinder and valve cover due to O-ring of the liner above or beneath the relief groove leaking	See 1A21. Replace the faulty O-ring.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
				30	Piston not moving due to worn gudgeon pin	The compressor runs, but the pressure is not increasing. This will shoe on the compressor gauges. The pin needs replacing.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	4 000 h	Wiper
		B	Unable to reach 25 bar	1	Air intake filter is blocked	The compressor runs as intended, but is unable to reach the required level. This will show on the compressor's pressure gauge. Filter cartridge needs cleaning or replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the 1st stage pressure gauge	1 000 h	Wiper
				2	Compressor valves worn by damage, carbonisation, oiling, corrosion or moisture	See 1B1. The worn valves need replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
				3	Air escaping from compressed air lines due to connection gaskets or seals leaking	The compressor runs as intended, but is unable to maintain the required level. This will show on the compressor's pressure gauge. The gasket and/or seal need replacement.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	4 000 h	Wiper
				4	Air escaping from compressed air lines due to piston rings leaking	See 1B3. Check piston rings for damage. Tighten or replace as necessary.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
				5	Air leaking between cylinder and valve cover due to gasket leaking	See 1B3. Replace the gasket.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	4 000 h	Wiper
				6	Air leaking between cylinder and valve cover due to O-ring of the liner above or beneath the relief groove leaking	See 1B3. Replace the faulty O-ring.	Y	N	N	N	Y	-	-	-	-	-	Monitor the stage pressure gauges	2 000 h	Wiper
		C	Unable to deliver pressurised air at a rate of 275 m^3/h	1	Compressor RPM does not reach neccessary numbers due to incorrect voltage supply	The other compressors will start and the function will be maintained. The voltage supply must be corrected.	N	-	-	-	N	N	N	Y	-	-	Check the voltage supply	12 M	Electrician
				2	Loose connections between electric motor and crankshaft	See 1C1. The connections need tightening.	N	-	-	-	Y	-	-	-	-	-	Vibration Monitoring	12 M	3rd Engineer

2	To store respectively 6.5 m^3 and 0.25 m^3 of air with a pressure up to 30 bars in the ME and DG starting air receivers	A	Unable to store the required amount of pressurised air	1	Pressure relief valve installed incorrectly	The pressurised air will constantly leak out of the valve, which may cause lack of air for manoeuvring operations. One ME receiver holds enough air for 12 starts. The valve needs to be installed correctly. Replace if damaged.	Y	N	N	N	N	N	N	-	-	-	Run to failure. Train personnel in correct installation of valve.	-	-
				2	Pressure relief valve broken when opening	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				3	Angle stop check valve installed incorrectly	See 2A1. The valve needs to be installed correctly. Replace if damaged.	Y	N	N	N	N	N	N	-	-	-	Run to failure. Train personnel in correct installation of valve.	-	-
				4	Close signal does not reach stop check valve	See 2A1. Investigate where the electronics fail.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				5	Stop check valve does not respond to close signal due to valve stuck mechanically	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				6	Stop valve installed incorrectly	See 2A1. The valve needs to be installed correctly. Replace if damaged.	Y	N	N	N	N	N	N	-	-	-	Run to failure. Train personnel in correct installation of valve.	-	-
				7	Close signal does not reach stop valve	See 2A1. Investigate where the electronics fail.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				8	Stop valve does not respond to close signal due to valve stuck mechanically	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				9	Pressure relief valve leaking air	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				10	Angle stop check valve leaking air	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				11	Stop valve leaking air	See 2A1. The valve needs replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
				12	Pressure relief valve adjusted wrong	See 2A1. The valve needs to be readjusted.	Y	N	N	N	Y	-	-	-	-	-	Control the valve settings	12 M	3rd Engineer
				13	Corrosion of receiver wall	The pressurised air will constantly leak out of the hole, which may cause lack of air for manoeuvring operations. The receiver's integrity must be strengthened, or the whole receiver needs replacement.	Y	N	N	N	Y	-	-	-	-	-	Visual (external/internal) and ultrasound inspection	24 M / 48 M	3rd Engineer
				14	Condensation not emptied by operator	The room for pressurised air is diminishing, leading to a bigger loss of pressure when the motor receives air from the tank. This leads to less than 12 starts per tank. May cause lack of air during manoeuvring operations. Condensation must be removed from tank.	Y	Y	-	-	N	Y	-	-	-	-	Drain condensation	Daily	Wiper
				15	Condensation drain valve clogged	See 2A14. Clean the drain valve. Replace if necessary.	Y	Y	-	-	Y	-	-	-	-	-	Evaluate flow when draining condensation	Daily	Wiper
		B	Stores pressure above 30 bars	1	Pressure relief valve adjusted wrong	The pressure increases in the tank, and may increase over design pressure. The pressure can be seen in the ECR and on a local gauge. It will not harm the engine, but it may lead to damage to other receiver components, and even to a receiver explosion. The valve needs readjustment.	Y	Y	-	-	Y	-	-	-	-	-	Control the valve settings	12 M	3rd Engineer
				2	Pressure relief valve stuck in closed position	See 2B1. The valve needs replacement.	Y	Y	-	-	Y	-	-	-	-	-	Monitor the pressure gauge in the ECR	Daily	Wiper
				3	Pressure relief valve installed incorrectly	See 2B1. The valve needs to be installed correctly. Replace if necessary.	Y	Y	-	-	Y	-	-	-	-	-	Monitor the pressure gauge in the ECR. Train personnel in valve installation.	Daily	Wiper

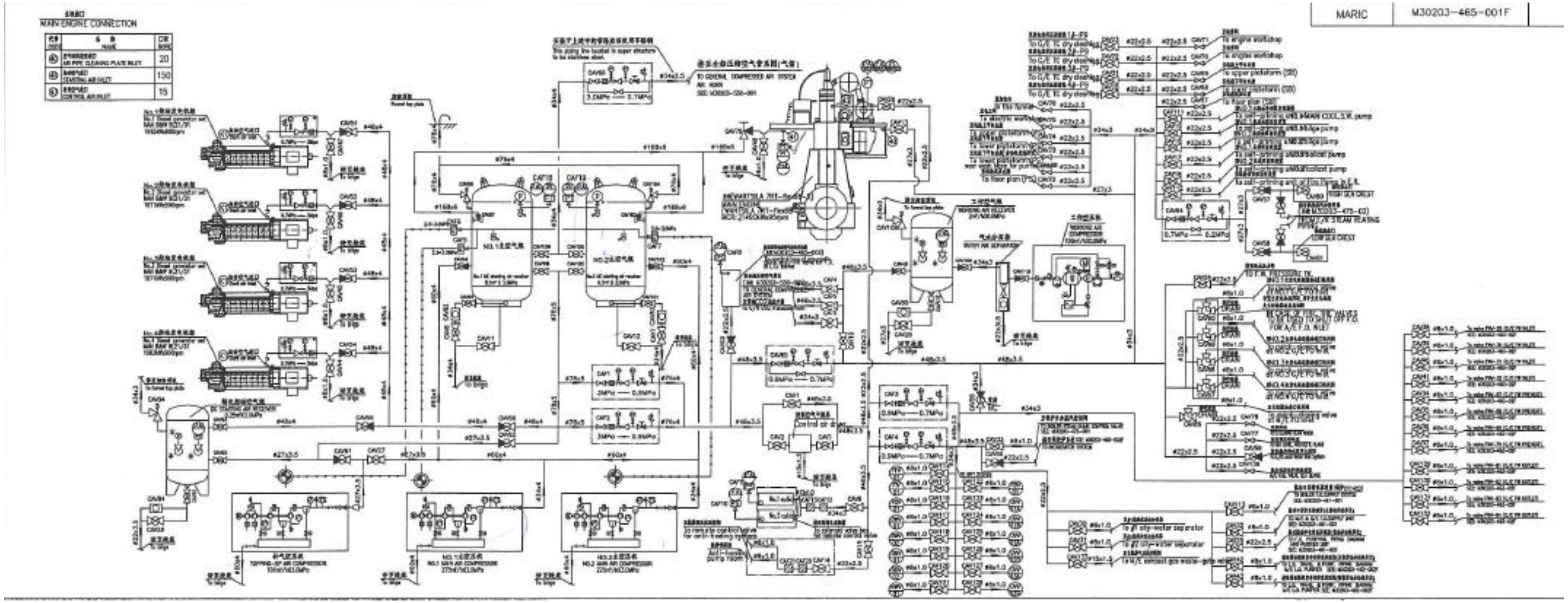
3	To automatically start the compressors when the receiver pressure falls below 21 bars	A	Does not start the compressors when the pressure falls below 21 bars	1	Pressure switch is set at too low level	The pressure will continue to decrease as the engine requires air to start. An alarm will sound at 19 bars. The compressors will eventually start, depending on the switch settings. Two air receivers above 19 bars have enough air for plenty of starts. If pressure switch has failed, the compressors can be started manually. Readjust pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
				2	Pressure switch worn out	See 3A1. Replace the pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
		B	Starts the compressors when the pressure is above 21 bars	1	Pressure switch is set at too high level	The pressure will be kept at a high level. Requires unnecessary amount of energy. Readjust the pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
4	To automatically stop the compressors when the receiver pressure exceeds 26 bar	A	Does not stop the compressors when the pressure exceeds 26 bar	1	Pressure switch is set at too high level	The pressure increases in the tank, which can blow the pressure relief valve. The pressure in the tank and the running status can be seen both in the ECR and locally. Readjust pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
				2	Pressure switch worn out	See 4A1. Replace the pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
		B	Stops the compressors when the pressure is below 26 bars	1	Pressure switch is set at too low level	The pressure will never reach desired levels, which may cause problems for manoeuvring operations. Two tanks with pressure over 21 bars have enough air for plenty of starts. Pressure can be read in the ECR and locally. Readjust pressure switch.	Y	N	N	N	Y	-	-	-	-	-	Monitor the pressure gauge and the running indicator of the compressor in the ECR	Daily	Wiper
5	To deliver compressed air from compressors to receivers	A	The compressed air does not reach the receivers	1	Pipes are leaking due to corroded pipeline	The pressure in the receivers does not increase even though the compressors are running. The leakage can be seen and heard by inspection. Without air, there will be problems related to manoeuvring. The pipelines need replacement.	Y	Y	-	-	Y	-	-	-	-	-	Visual and ultrasound inspection	24 M	3rd Engineer
				2	Compressed air returns to compressor due to leaking stop check valve	The pressure in the receiver does not increase even though the compressors are running. Returning compressed air will blow a safety valve in the compressor. The valves need replacement.	Y	N	N	N	N	N	N	-	-	-	Run to failure	-	-
6	To sound an alarm in the ECR when the receiver pressure falls below 19 bars	A	Does not sound an alarm when the pressure falls below 19 bars	1	Pressure gauge installed incorrectly	The local and ECR pressure gauge will indicate wrong pressure. The pressure in the tank may decrease to critical levels for manoeuvring operations. The gauge needs to be reinstalled correctly. Replaced if damaged.	N	-	-	-	N	N	N	Y	-	-	Allow the compressor to start by the pressure switch set at 17 bar, and read the pressure gauge when it starts	12 M	3rd Engineer
				2	Pressure gauge damaged by vibration, overpressure, pulsation or corrosion	See 6A1. The gauge needs replacement.	N	-	-	-	N	N	N	Y	-	-	Allow the compressor to start by the pressure switch set at 17 bar, and read the pressure gauge when it starts	12 M	3rd Engineer
				3	Unable to send alarm signal to ECR due to electrical issues	The pressure gauge in the ECR will indicate pressure below the green area. The compressors will run to increase the pressure. The electrical path needs failure investigation.	N	-	-	-	Y	-	-	-	-	-	Monitor the pressure gauge in the ECR	Daily	Wiper
		B	Sounds an alarm when the pressure is over 19 bars	1	Pressure gauge installed incorrectly	An alarm will sound in the engine room. The pressure gauge needs to be reinstalled correctly. Replace if damaged.	N	-	-	-	N	N	N	N	N	-	Run to failure	-	-
				2	Pressure gauge damaged by vibration, overpressure, pulsation or corrosion	See 6B1. The gauge needs replacement.	N	-	-	-	N	N	N	N	N	-	Run to failure	-	-

C. System Drawings

C.1 Ballast Water and Anti-Heeling System

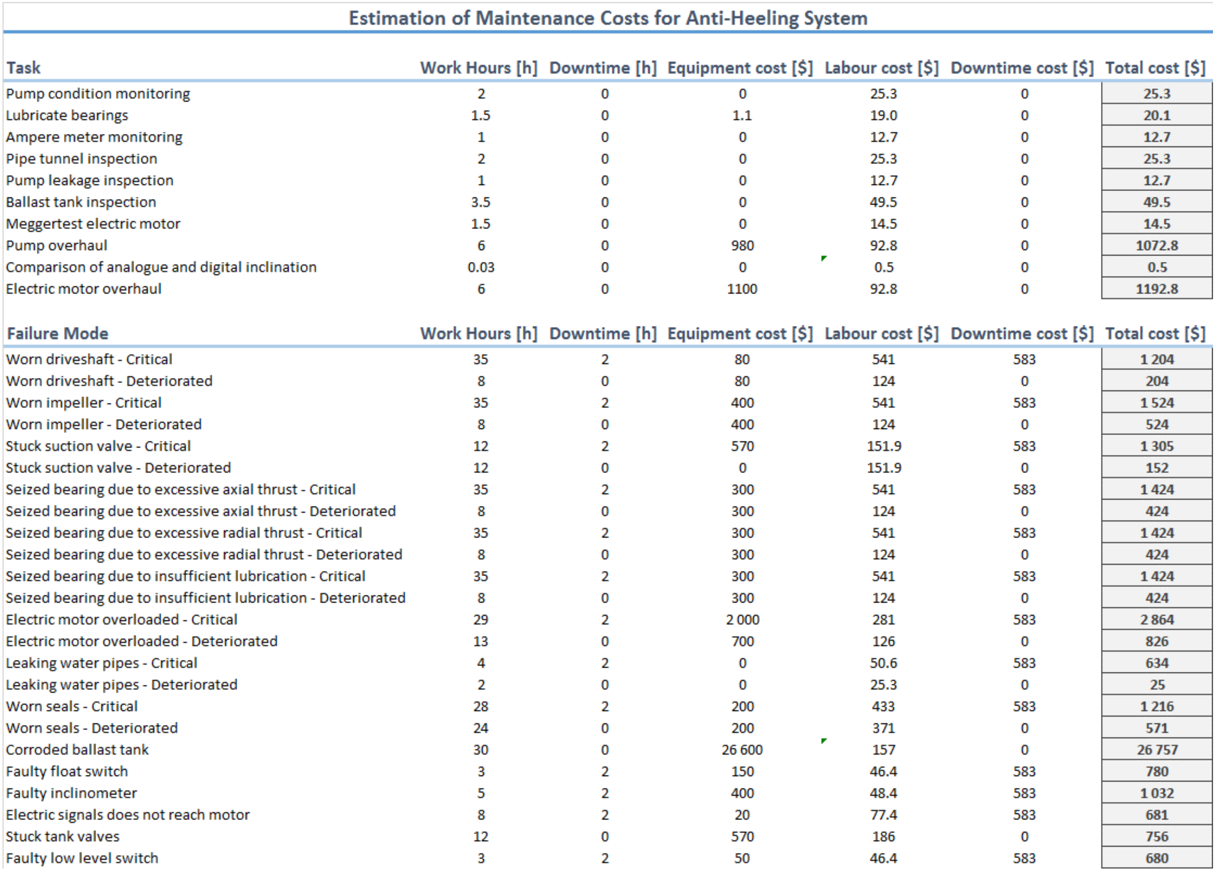


C.2 Starting Air System



D. Cost Estimations

D.1 Anti-Heeling System



Estimation of Maintenance Costs for Anti-Heeling System

Task	Work Hours [h]	Downtime [h]	Equipment cost [$]	Labour cost [$]	Downtime cost [$]	Total cost [$]
Pump condition monitoring	2	0	0	25.3	0	**25.3**
Lubricate bearings	1.5	0	1.1	19.0	0	**20.1**
Ampere meter monitoring	1	0	0	12.7	0	**12.7**
Pipe tunnel inspection	2	0	0	25.3	0	**25.3**
Pump leakage inspection	1	0	0	12.7	0	**12.7**
Ballast tank inspection	3.5	0	0	49.5	0	**49.5**
Meggertest electric motor	1.5	0	0	14.5	0	**14.5**
Pump overhaul	6	0	980	92.8	0	**1072.8**
Comparison of analogue and digital inclination	0.03	0	0	0.5	0	**0.5**
Electric motor overhaul	6	0	1100	92.8	0	**1192.8**

Failure Mode	Work Hours [h]	Downtime [h]	Equipment cost [$]	Labour cost [$]	Downtime cost [$]	Total cost [$]
Worn driveshaft - Critical	35	2	80	541	583	**1 204**
Worn driveshaft - Deteriorated	8	0	80	124	0	**204**
Worn impeller - Critical	35	2	400	541	583	**1 524**
Worn impeller - Deteriorated	8	0	400	124	0	**524**
Stuck suction valve - Critical	12	2	570	151.9	583	**1 305**
Stuck suction valve - Deteriorated	12	0	0	151.9	0	**152**
Seized bearing due to excessive axial thrust - Critical	35	2	300	541	583	**1 424**
Seized bearing due to excessive axial thrust - Deteriorated	8	0	300	124	0	**424**
Seized bearing due to excessive radial thrust - Critical	35	2	300	541	583	**1 424**
Seized bearing due to excessive radial thrust - Deteriorated	8	0	300	124	0	**424**
Seized bearing due to insufficient lubrication - Critical	35	2	300	541	583	**1 424**
Seized bearing due to insufficient lubrication - Deteriorated	8	0	300	124	0	**424**
Electric motor overloaded - Critical	29	2	2 000	281	583	**2 864**
Electric motor overloaded - Deteriorated	13	0	700	126	0	**826**
Leaking water pipes - Critical	4	2	0	50.6	583	**634**
Leaking water pipes - Deteriorated	2	0	0	25.3	0	**25**
Worn seals - Critical	28	2	200	433	583	**1 216**
Worn seals - Deteriorated	24	0	200	371	0	**571**
Corroded ballast tank	30	0	26 600	157	0	**26 757**
Faulty float switch	3	2	150	46.4	583	**780**
Faulty inclinometer	5	2	400	48.4	583	**1 032**
Electric signals does not reach motor	8	2	20	77.4	583	**681**
Stuck tank valves	12	0	570	186	0	**756**
Faulty low level switch	3	2	50	46.4	583	**680**

D.2 Starting Air System

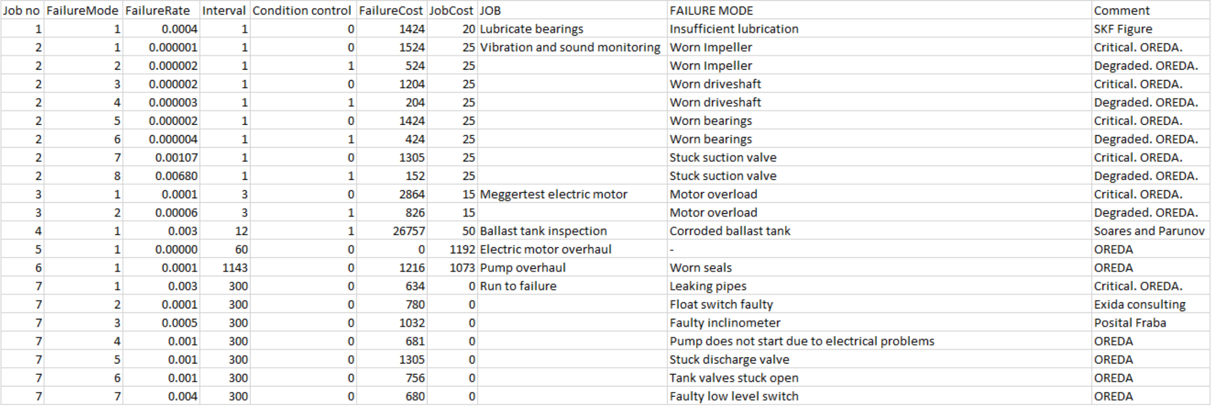
Estimation of Maintenance Costs for Starting Air System

Task	Work Hours [h]	Downtime [h]	Equipment cost [$]	Labour cost [$]	Downtime cost [$]	Total cost [$]
Monitor pressure gauge in ECR	0.1	0	0	0.3	0	0.3
Drain receivers	0.1	0	0	0.3	0	0.3
Meggertest electrical motor	1	0	0	9.7	0	9.7
Vibration monitoring	1	0	0	12.7	0	12.7
Readjust pressure relief valve	1	0	0	12.7	0	12.7
External receiver inspection	1	0	0	12.7	0	12.7
Internal receiver inspection	3	0	0	38.0	0	38.0
Check oil level	0.2	0	0	0.7	0	0.7
Change oil	0.5	0	261	6.3	0	267
Monitor local pressure gauges and thermometers	0.2	0	0	0.7	0	0.7
Check screw connections	1	0	0	12.7	0	12.7
Test safety valve	0.5	0	0	6.3	0	6.3
Replace air filter	1	0	30	12.7	0	42.7
Check compressor valves	1.5	0	0	19.0	0	19.0
Replace compressor valve	2	0	150	30.9	0	180.9
Renew flexible gear rim	1.5	0	50	23.2	0	73.2
Overhaul compressor	6	0	5 000	92.8	0	5092.8
Overhaul drain valve	1.5	0	50	23.2	0	73.2
Oil test and clean oil filter	1	0	200	12.7	0	213

Failure Mode	Work Hours [h]	Downtime [h]	Equipment cost [$]	Labour cost [$]	Downtime cost [$]	Total cost [$]
Electric motor overloaded - Critical	17	0	2 000	165	0	2165
Electric motor overloaded - Deteriorated	8	0	700	77	0	777
Incorrect voltage supply - Critical	17	0	0	164.5	0	164.5
Incorrect voltage supply - Deteriorated	8	0	0	77.4	0	77.4
Loose connections - Critical	14	0	100	216	0	316
Loose connections - Deteriorated	4	0	0	61.8	0	61.8
Faulty safety valve - Critical	8	0	50	124	0	174
Faulty safety valve - Deteriorated	8	0	50	101	0	151
Faulty pressure indication - Critical	16	0	170	247.4	0	417
Faulty pressure indication - Deteriorated	3	0	0	38.0	0	38.0
Corroded receiver - Critical	18	9	3 000	278	2 625	5903
Corroded receiver - Deteriorated	11.5	0	504	146	0	650
Leaking pipes - Critical	4	0	150	50.6	0	200.6
Leaking pipes - Deteriorated	2	0	0	25.3	0	25.3
Worn bearings - Critical	14	0	300	216	0	516
Worn bearings - Deteriorated	4	0	300	62	0	362
Worn shaft	14	0	80	216	0	296
Air intake problems - Critical	11	0	30	139.3	0	169.3
Air intake problems - Deteriorated	4	0	0	50.6	0	50.6
Worn valves - Critical	11	0	150	170	0	320
Worn valves - Deteriorated	4	0	150	62	0	212
Leaking seals - Critical	11	0	200	170	0	370
Leaking seals - Deteriorated	4	0	200	62	0	262
Piston seizure - Critical	14	0	1 000	216	0	1216
Piston seizure - Deteriorated	4	0	1 000	62	0	1062
Clogged separator - Critical	13	0	100	201	0	301
Clogged separator - Deteriorated	2	0	0	25	0	25
Clogged drain valve - Critical	4	0	50	61.8	0	112
Clogged drain valve - Deteriorated	2	0	50	30.9	0	81
Faulty cooling fan	8	0	220	123.7	0	344
Worn gear rim - Critical	14	0	50	216.4	0	266
Worn gear rim - Deteriorated	4	0	50	61.8	0	112
Blown fuses	2	0	10	19.4	0	29
Faulty oil pump	13	0	40	201	0	241
Faulty check valve	2	0	100	30.9	0	131
Faulty pressure switch - Critical	3	0	300	46.4	0	346
Faulty pressure switch - Deteriorated	2	0	0	25.3	0	25
Electric signals does not reach motor	5	0	20	48.4	0	68

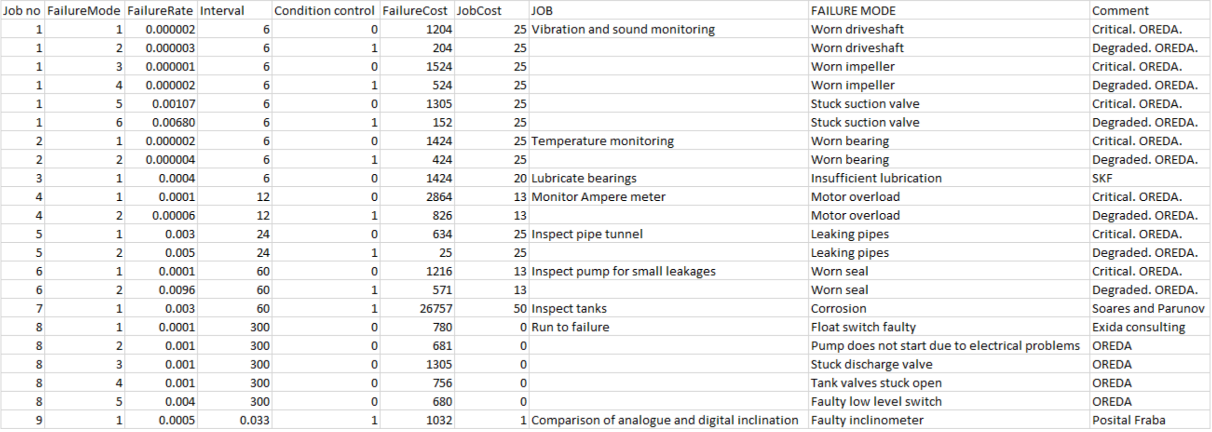
E. Input Tables

E.1 Anti-Heeling Current



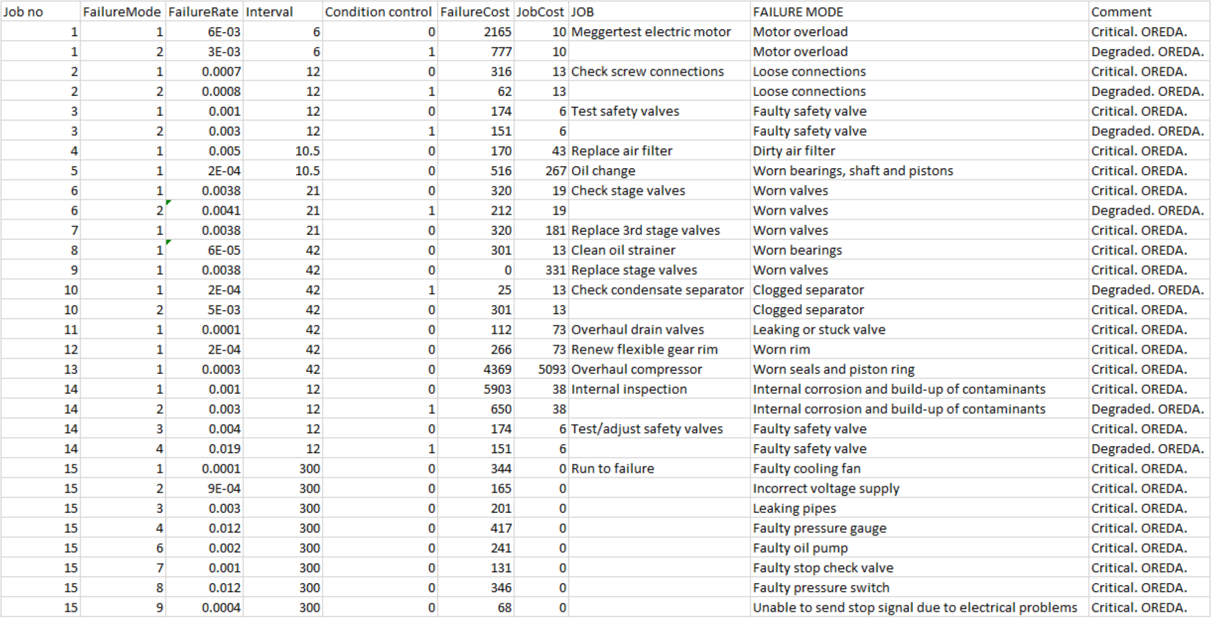
Job no	FailureMode	FailureRate	Interval	Condition control	FailureCost	JobCost	JOB	FAILURE MODE	Comment
1	1	0.0004	1	0	1424	20	Lubricate bearings	Insufficient lubrication	SKF Figure
2	1	0.000001	1	0	1524	25	Vibration and sound monitoring	Worn Impeller	Critical. OREDA.
2	2	0.000002	1	1	524	25		Worn Impeller	Degraded. OREDA.
2	3	0.000002	1	0	1204	25		Worn driveshaft	Critical. OREDA.
2	4	0.000003	1	1	204	25		Worn driveshaft	Degraded. OREDA.
2	5	0.000002	1	0	1424	25		Worn bearings	Critical. OREDA.
2	6	0.000004	1	1	424	25		Worn bearings	Degraded. OREDA.
2	7	0.00107	1	0	1305	25		Stuck suction valve	Critical. OREDA.
2	8	0.00680	1	1	152	25		Stuck suction valve	Degraded. OREDA.
3	1	0.0001	3	0	2864	15	Meggertest electric motor	Motor overload	Critical. OREDA.
3	2	0.00006	3	1	826	15		Motor overload	Degraded. OREDA.
4	1	0.003	12	1	26757	50	Ballast tank inspection	Corroded ballast tank	Soares and Parunov
5	1	0.00000	60	0	0	1192	Electric motor overhaul	-	OREDA
6	1	0.0001	1143	0	1216	1073	Pump overhaul	Worn seals	OREDA
7	1	0.003	300	0	634	0	Run to failure	Leaking pipes	Critical. OREDA.
7	2	0.0001	300	0	780	0		Float switch faulty	Exida consulting
7	3	0.0005	300	0	1032	0		Faulty inclinometer	Posital Fraba
7	4	0.001	300	0	681	0		Pump does not start due to electrical problems	OREDA
7	5	0.001	300	0	1305	0		Stuck discharge valve	OREDA
7	6	0.001	300	0	756	0		Tank valves stuck open	OREDA
7	7	0.004	300	0	680	0		Faulty low level switch	OREDA

E.2 Anti-Heeling RCM



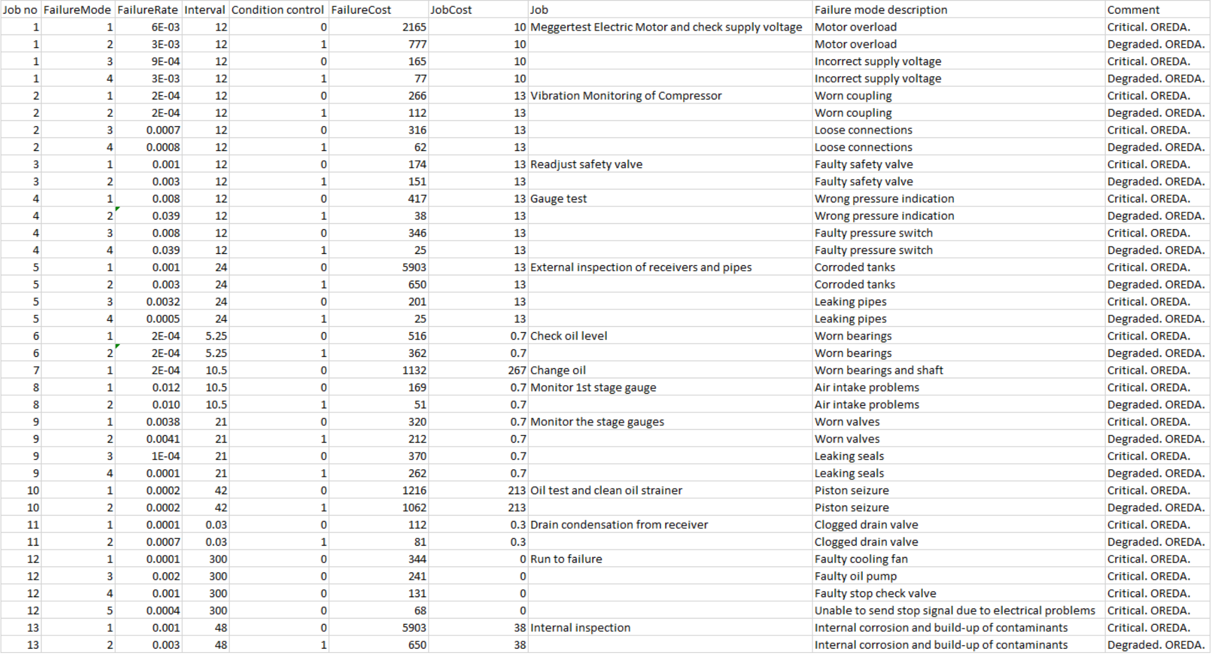
Job no	FailureMode	FailureRate	Interval	Condition control	FailureCost	JobCost	JOB	FAILURE MODE	Comment
1	1	0.000002	6	0	1204	25	Vibration and sound monitoring	Worn driveshaft	Critical. OREDA.
1	2	0.000003	6	1	204	25		Worn driveshaft	Degraded. OREDA.
1	3	0.000001	6	0	1524	25		Worn impeller	Critical. OREDA.
1	4	0.000002	6	1	524	25		Worn impeller	Degraded. OREDA.
1	5	0.00107	6	0	1305	25		Stuck suction valve	Critical. OREDA.
1	6	0.00680	6	1	152	25		Stuck suction valve	Degraded. OREDA.
2	1	0.000002	6	0	1424	25	Temperature monitoring	Worn bearing	Critical. OREDA.
2	2	0.000004	6	1	424	25		Worn bearing	Degraded. OREDA.
3	1	0.0004	6	0	1424	20	Lubricate bearings	Insufficient lubrication	SKF
4	1	0.0001	12	0	2864	13	Monitor Ampere meter	Motor overload	Critical. OREDA.
4	2	0.00006	12	1	826	13		Motor overload	Degraded. OREDA.
5	1	0.003	24	0	634	25	Inspect pipe tunnel	Leaking pipes	Critical. OREDA.
5	2	0.005	24	1	25	25		Leaking pipes	Degraded. OREDA.
6	1	0.0001	60	0	1216	13	Inspect pump for small leakages	Worn seal	Critical. OREDA.
6	2	0.0096	60	1	571	13		Worn seal	Degraded. OREDA.
7	1	0.003	60	1	26757	50	Inspect tanks	Corrosion	Soares and Parunov
8	1	0.0001	300	0	780	0	Run to failure	Float switch faulty	Exida consulting
8	2	0.001	300	0	681	0		Pump does not start due to electrical problems	OREDA
8	3	0.001	300	0	1305	0		Stuck discharge valve	OREDA
8	4	0.001	300	0	756	0		Tank valves stuck open	OREDA
8	5	0.004	300	0	680	0		Faulty low level switch	OREDA
9	1	0.0005	0.033	1	1032	1	Comparison of analogue and digital inclination	Faulty inclinometer	Posital Fraba

E.3 Starting Air Current



Job no	FailureMode	FailureRate	Interval	Condition control	FailureCost	JobCost	JOB	FAILURE MODE	Comment
1	1	6E-03	6	0	2165	10	Meggertest electric motor	Motor overload	Critical. OREDA.
1	2	3E-03	6	1	777	10		Motor overload	Degraded. OREDA.
2	1	0.0007	12	0	316	13	Check screw connections	Loose connections	Critical. OREDA.
2	2	0.0008	12	1	62	13		Loose connections	Degraded. OREDA.
3	1	0.001	12	0	174	6	Test safety valves	Faulty safety valve	Critical. OREDA.
3	2	0.003	12	1	151	6		Faulty safety valve	Degraded. OREDA.
4	1	0.005	10.5	0	170	43	Replace air filter	Dirty air filter	Critical. OREDA.
5	1	2E-04	10.5	0	516	267	Oil change	Worn bearings, shaft and pistons	Critical. OREDA.
6	1	0.0038	21	0	320	19	Check stage valves	Worn valves	Critical. OREDA.
6	2	0.0041	21	1	212	19		Worn valves	Degraded. OREDA.
7	1	0.0038	21	0	320	181	Replace 3rd stage valves	Worn valves	Critical. OREDA.
8	1	6E-05	42	0	301	13	Clean oil strainer	Worn bearings	Critical. OREDA.
9	1	0.0038	42	0	0	331	Replace stage valves	Worn valves	Critical. OREDA.
10	1	2E-04	42	1	25	13	Check condensate separator	Clogged separator	Degraded. OREDA.
10	2	5E-03	42	0	301	13		Clogged separator	Critical. OREDA.
11	1	0.0001	42	0	112	73	Overhaul drain valves	Leaking or stuck valve	Critical. OREDA.
12	1	2E-04	42	0	266	73	Renew flexible gear rim	Worn rim	Critical. OREDA.
13	1	0.0003	42	0	4369	5093	Overhaul compressor	Worn seals and piston ring	Critical. OREDA.
14	1	0.001	12	0	5903	38	Internal inspection	Internal corrosion and build-up of contaminants	Critical. OREDA.
14	2	0.003	12	1	650	38		Internal corrosion and build-up of contaminants	Degraded. OREDA.
14	3	0.004	12	0	174	6	Test/adjust safety valves	Faulty safety valve	Critical. OREDA.
14	4	0.019	12	1	151	6		Faulty safety valve	Degraded. OREDA.
15	1	0.0001	300	0	344	0	Run to failure	Faulty cooling fan	Critical. OREDA.
15	2	9E-04	300	0	165	0		Incorrect voltage supply	Critical. OREDA.
15	3	0.003	300	0	201	0		Leaking pipes	Critical. OREDA.
15	4	0.012	300	0	417	0		Faulty pressure gauge	Critical. OREDA.
15	6	0.002	300	0	241	0		Faulty oil pump	Critical. OREDA.
15	7	0.001	300	0	131	0		Faulty stop check valve	Critical. OREDA.
15	8	0.012	300	0	346	0		Faulty pressure switch	Critical. OREDA.
15	9	0.0004	300	0	68	0		Unable to send stop signal due to electrical problems	Critical. OREDA.

E.4 Starting Air RCM



Job no	FailureMode	FailureRate	Interval	Condition control	FailureCost	JobCost	Job	Failure mode description	Comment
1	1	6E-03	12	0	2165	10	Meggertest Electric Motor and check supply voltage	Motor overload	Critical. OREDA.
1	2	3E-03	12	1	777	10		Motor overload	Degraded. OREDA.
1	3	9E-04	12	0	165	10		Incorrect supply voltage	Critical. OREDA.
1	4	3E-03	12	1	77	10		Incorrect supply voltage	Degraded. OREDA.
2	1	2E-04	12	0	266	13	Vibration Monitoring of Compressor	Worn coupling	Critical. OREDA.
2	2	2E-04	12	1	112	13		Worn coupling	Degraded. OREDA.
2	3	0.0007	12	0	316	13		Loose connections	Critical. OREDA.
2	4	0.0008	12	1	62	13		Loose connections	Degraded. OREDA.
3	1	0.001	12	0	174	13	Readjust safety valve	Faulty safety valve	Critical. OREDA.
3	2	0.003	12	1	151	13		Faulty safety valve	Degraded. OREDA.
4	1	0.008	12	0	417	13	Gauge test	Wrong pressure indication	Critical. OREDA.
4	2	0.039	12	1	38	13		Wrong pressure indication	Degraded. OREDA.
4	3	0.008	12	0	346	13		Faulty pressure switch	Critical. OREDA.
4	4	0.039	12	1	25	13		Faulty pressure switch	Degraded. OREDA.
5	1	0.001	24	0	5903	13	External inspection of receivers and pipes	Corroded tanks	Critical. OREDA.
5	2	0.003	24	1	650	13		Corroded tanks	Degraded. OREDA.
5	3	0.0032	24	0	201	13		Leaking pipes	Critical. OREDA.
5	4	0.0005	24	1	25	13		Leaking pipes	Degraded. OREDA.
6	1	2E-04	5.25	0	516	0.7	Check oil level	Worn bearings	Critical. OREDA.
6	2	2E-04	5.25	1	362	0.7		Worn bearings	Degraded. OREDA.
7	1	2E-04	10.5	0	1132	267	Change oil	Worn bearings and shaft	Critical. OREDA.
8	1	0.012	10.5	0	169	0.7	Monitor 1st stage gauge	Air intake problems	Critical. OREDA.
8	2	0.010	10.5	1	51	0.7		Air intake problems	Degraded. OREDA.
9	1	0.0038	21	0	320	0.7	Monitor the stage gauges	Worn valves	Critical. OREDA.
9	2	0.0041	21	1	212	0.7		Worn valves	Degraded. OREDA.
9	3	1E-04	21	0	370	0.7		Leaking seals	Critical. OREDA.
9	4	0.0001	21	1	262	0.7		Leaking seals	Degraded. OREDA.
10	1	0.0002	42	0	1216	213	Oil test and clean oil strainer	Piston seizure	Critical. OREDA.
10	2	0.0002	42	1	1062	213		Piston seizure	Degraded. OREDA.
11	1	0.0001	0.03	0	112	0.3	Drain condensation from receiver	Clogged drain valve	Critical. OREDA.
11	2	0.0007	0.03	1	81	0.3		Clogged drain valve	Degraded. OREDA.
12	1	0.0001	300	0	344	0	Run to failure	Faulty cooling fan	Critical. OREDA.
12	3	0.002	300	0	241	0		Faulty oil pump	Critical. OREDA.
12	4	0.001	300	0	131	0		Faulty stop check valve	Critical. OREDA.
12	5	0.0004	300	0	68	0		Unable to send stop signal due to electrical problems	Critical. OREDA.
13	1	0.001	48	0	5903	38	Internal inspection	Internal corrosion and build-up of contaminants	Critical. OREDA.
13	2	0.003	48	1	650	38		Internal corrosion and build-up of contaminants	Degraded. OREDA.