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Application of RCM to Construct a Maintenance Program for a Maritime Vessel

Bruk av RCM til å utforme et
vedlikeholdsprogram for et maritimt fartøy

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Preface

This thesis is the finalisation of the M.Sc. degree in Marine Technology. It was written during the spring semester 2015, at the Norwegian University of Science and Technology, NTNU. The thesis corresponds to 30 credits.

The thesis examines the practice of reliability centred maintenance (RCM) in a maritime context. The method is utilized to analyse a machinery system installed on a vessel that Wilhelmsen Ship Management (WSM) operates. As a final outcome, an adequate maintenance program is developed, aiming to concentrate resources on those maintenance tasks that promote system reliability. Microsoft Office Excel has been applied to structure worksheets in the analysis.

The author has worked consistently throughout the semester. Yet, a great deal of data for the analysis was gathered during a workshop accomplished at the end of April. In retrospect, the author thinks that performing this workshop earlier in the semester would most likely have distributed the workload more evenly throughout the semester. The majority of work was done at the author's office at the Department of Marine Technology, but also some workdays were spent at the office of MainTech AS.

I would like to express my gratitude to my supervisor Ingrid Bouwer Utne at the Department of Marine Technology, for providing proper advice throughout the semester. I would also like to thank MainTech AS and Wilhelmsen Ship Management for participating in my work and attending the workshop in April. Specifically, I am very grateful for the expertise given by Sverre Wattum (MainTech AS), Yngve Beite (WSM) and Hans Petter Grønlund (WSM).

Furthermore, I would like to thank my fellow students for a fantastic and memorable time at NTNU. Support from my parents and family has given me will to work hard and achieve my goals. Finally, I would like to thank my true grit, Andreas, for affectionate guidance and support.

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Summary

In this thesis an assessment has been carried out to discover whether reliability centred maintenance (RCM) is an applicable method to construct a maintenance program for a specific system on board a vessel within Wilhelmsen Ship Management's (WSM) fleet. Constructing efficient and appropriate maintenance programs for technical equipment on ships has become a key concern in the maritime industry. This is a result of a growing concern towards environmental and safety aspects, as well as an increased usage of capital intensive vessels, giving large downtime costs if normal operation is interrupted (Rasmussen, 2003). Maintenance programs connected to technical ship systems are commonly defined by recommendations from manufacturers and classification societies (Mokashi et al., 2002).

Yet, it is not necessarily given that the recommended practices are outlined in an optimal manner considering the equipment in its operating context (Linton, 2011, Wang et al., 2010). Henceforth, the issue addressed within the present study is how the RCM practice can be employed as an alternative approach, which is of relevance to create a maintenance program more on the premises of the equipment. This has been achieved by analysing an engine and its auxiliary systems installed on a vessel operated by WSM. These included the engine's sea- and freshwater cooling system, lubrication oil system and fuel system. The purpose has been to evaluate the RCM applicability in a maritime context and discuss if the resulting maintenance program could obtain an improved effect for a vessel's operation compared to following the common trend in traditional maritime maintenance.

The development of the analysis is based on the RCM perspective of Moubray (1997) and criteria outlined in SAE International (1999). The technique provides advantages in handling various equipment and focuses on maintaining the function of a system in a cost effective manner (Selvik and Aven, 2011). The analysis was performed for the equipment through four stages. This involved establishing function descriptions, functional failures, failure modes, effects and criticality (FMECA) worksheets and proper maintenance tasks, focusing on each listed failure mode. System explanations were also included to describe the equipment being analysed. Criticality and risk evaluations were carried out in accordance with WSM's outlined

consequence parameters, frequencies and risk matrix. The majority of the data input was set during an RCM workshop at WSM's office. The first three stages founded the necessary basis to determine the final maintenance program.

Applying the RCM process on the engine determined that the most critical failure modes potentially leading to engine stop were failure of its auxiliary systems, disregarding any engine component failure. The FMECA pointed out that the majority of failure modes at the lowest causation level were considered to have low criticality. Failure modes obtaining the highest risk indexes were:

- Closing valve failure and blackout of switchboards in the seawater cooling system
- Lack of chemical dosing in the freshwater cooling system
- Contaminated oil, filter failure and old oil in the lubrication oil system
- Wear/fatigue and assembly error for the purifier in the fuel oil system

The information gathered in the FMECA enabled tailoring the maintenance to handle each evaluated failure mode, resulting in a program of both corrective and preventive actions. Further, the results were structured to provide a framework for continuous improvement and update of the maintenance program.

The results provided a thorough arrangement of equipment data applicable for legitimating the choice of tasks in the maintenance program. Most of the evaluated failure modes received low risk indexes, resulting in more corrective means than expected. This indicated that it could be relevant for WSM to evaluate the vessel's spare part program. The diversity of tasks in the maintenance program corresponded well to the perception of RCM prioritising actions that improve system reliability.

Due to limited time during the RCM workshop, the extent of equipment included in the analysis had to be reduced from the initial plan. However, this illustrated one of the known drawbacks of RCM, which is its extensive need for time and resources. From the analysis, it is clear that RCM may very well suit a maritime context. Constructing a maintenance program by employing this practice would provide beneficial results for a shipping company. Yet, the method is mainly considered applicable to fit equipment that by function failure would be critical towards safety and/or operation.

Sammendrag

I denne oppgaven har det blitt undersøkt om pålitelighetsbasert vedlikehold (RCM) er en anvendelig metode for å konstruere et vedlikeholdsprogram til et teknisk skipssystem på et fartøy innen Wilhelmsen Ship Managements (WSM) flåte. Å konstruere effektive og hensiktsmessige vedlikeholdsprogrammer for skipsteknisk utstyr har blitt viktig å ta i betraktning i den maritime næringen. Dette er et resultat av voksende interesse for miljø- og sikkerhetsaspekter, i tillegg til en økt bruk av kapitalintensive fartøyer, som resulterer i store nedetidskostnader ved stopp i normal operasjon (Rasmussen, 2003). Vedlikeholdsprogrammer knyttet til skipssystemer blir ofte utformet basert på anbefalinger fra leverandører og klasseselskap (Mokashi et al., 2002).

En usikkerhetsfaktor knyttet slike anbefalinger er at de ikke nødvendigvis er formet på et optimalt vis med tanke på hva som passer utstyret og dens operasjonelle kontekst (Linton, 2011, Wang et al., 2010). Problemstillingen som derfor belyses i denne oppgaven er hvordan RCM metoden kan benyttes som en alternativ tilnærming, for å skape et vedlikeholdsprogram som er utformet mer på utstyrets premisser. Dette blir gjort ved å analysere en motor og dens hjelpesystemer på et skip som WSM opererer. Dette inkluderer motorens sjø- og ferskvannskjølesystem, smøreoljesystem og drivstoffsystem. Hensikten har vært å evaluere om RCM er anvendbar i en maritim sammenheng og diskutere om det resulterende vedlikeholdsprogrammet kunne ha en positiv påvirkning for et operasjonelt fartøy sammenliknet med å følge den vanlige trenden i tradisjonelt maritimt vedlikehold.

Utviklingen av analysen er basert på RCM tilnærmingen til Moubray (1997) og kriteriene definert i SAE International (1999). Metoden er tilpasningsdyktig til å benyttes på ulike typer utstyr og fokuserer på å opprettholde funksjonen til et system på en kostnadseffektiv måte (Selvik og Aven, 2011). Analysen ble utført gjennom hovedsakelig fire stadier. Dette innebar etablering av funksjonsbeskrivelser, funksjonsfeil, utføre failure modes, effects and criticality analyse (FMECA) og opprette passende vedlikeholdsoppgaver, med fokus på oppførte feilårsaker. Utfyllende systemforklaringer er tatt med for å beskrive utstyret som blir analysert. Kritikalitet- og risikovurderinger ble gjort i samsvar med WSMs egne konsekvensparametere og risikomatrise. Mesteparten av det benyttede datagrunnlaget ble gitt under en RCM workshop på

WSMs kontor. De tre første stadiene av analysen dannet den nødvendige basisen for å kunne utforme det endelige vedlikeholdsprogrammet.

Ved å anvende RCM prosessen til å analysere motoren ble det fastslått at de mest kritiske feilårsakene som kan føre til motorstopp var svikt i et av hjelpesystemene, sett bort i fra motorkomponentsvikt. Resultater fra FMECAen påpekte at de fleste feilårsakene på nederste nivå var knyttet til lav kritikalitet. Feilårsaker som fikk de høyeste risikoindeksene var:

- Svikt i lukkeventilen og blackout av tavler i sjøvannskjølesystemet
- Mangel på kjemisk dosering i ferskvannskjølesystemet
- Forurenset olje, filtersvikt og gammel olje i smøreoljesystemet
- Slitasje-/-tretthet og monteringsfeil for separatoren i drivstoffsystemet

Informasjonen som ble etablert i FMECA oppsettet gjorde det mulig å skreddersy vedlikeholdet for å håndtere hver feilmodus, noe som gav et program med både korrigerende og forebyggende vedlikeholdstiltak. Resultatene ble strukturert slik at de kan benyttes som et rammeverk for kontinuerlig forbedring og for å holde vedlikeholdsprogrammet oppdatert.

Resultatene gjorde det mulig å etablere en gjennomført mengde med utstyrsdata som kan benyttes til å begrunne valget av tiltak i vedlikeholdsprogrammet. De fleste av de evaluerte feilårsakene har fått lave risikoindekser, noe som resulterer i flere korrigerende vedlikeholdstiltak enn forventet. Dette indikerer at det kan være relevant for WSM å vurdere fartøyets reservedelsprogram. Det ulike mangfoldet av tiltak i vedlikeholdsprogrammet samsvarer godt med oppfatningen av RCM som først og fremst fokuserer på å prioritere tiltak som forbedrer systemets pålitelighet.

På grunn av begrenset tid under RCM workshopen måtte omfanget og utstyrsmengden reduseres i forhold til hva som var opprinnelig planlagt. Dette korresponderer med en kjent ulempe ved RCM, knyttet til at det er en krevende prosess både med tanke på tid og ressurser. Analysen har vist at RCM godt kan passe i en maritim sammenheng og et vedlikeholdsprogram konstruert ved å benytte metoden vil kunne være fordelaktig for et rederi. Likevel er metoden i hovedsak ansett til å passe utstyr som ved funksjonssvikt vil være operasjons- og/eller sikkerhetskritisk.

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Abbreviations

C	Consequence
CA	Criticality Analysis
CBM	Condition Based Maintenance
CM	Condition Monitoring
DP	Dynamic Positioning
F	Frequency
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FO	Fuel Oil
FP	Failure Pattern
FW	Freswater
IHM	Inventory of Hazardous Materials
IMO	International Maritime Organization
ISM	International Safety Management
LO	Lubrication Oil
MDT	Mean Down Time
MTBF	Mean Time Between Failure
NPD	Norwegian Petroleum Directorate
PM	Preventive Maintenance
PMC	Planned Maintenance Committee
QCV	Quick Closing Valve
RCM	Reliability Centred Maintenance
RI	Risk Index
ROV	Remotely Operated Vehicle
RPM	Revolutions Per Minute
SFI	Senter for Forskningsdrevet Innovasjon, (Norwegian Ship Research Institute)
SW	Seawater

TT	Tunnel Thruster
WSM	Wilhelmsen Ship Management

1 Introduction

1.1 Background and motivation

Wilhelmsen Ship Management (WSM) is one of the main providers of third party ship management services in the world. By working as a third party, the company acts as an owner of the vessel in the period of the charter. WSM directs operations, provides crew in addition to paying operating and voyage costs. Maintenance work is an essential part of a vessel's operation and is consequently within the responsibility of WSM.

Outlining a vessel maintenance strategy that preserves reliable and safe operation is of great interest to third party companies, ship owners and the society. There are numerous motives for this conclusion. An evident reason is that accidents connected to maritime activity could result in large, harmful impacts towards people and the environment. From another perspective, an appropriate maintenance strategy helps in avoiding a vessel's downtime and off-hire, which is correlated with negative factors, such as large costs and undesirable publicity. Thus, considering these aspects it is obvious that establishing an appropriate maintenance strategy should be a key objective for a maritime company as WSM.

However, it is not necessarily straightforward to define and plan a vessel's maintenance tactic. The rapid growth of complex systems on maritime vessels, combined with comprehensive system interoperability requirements makes it challenging, but necessary to create a plan that is both thorough and effective. Essential elements in constructing a maintenance strategy are the development of a maintenance program, including planning and completing maintenance actions. Traditional maintenance programs connected to a ship's technical systems are often a result of recommendations from manufacturers, legislation and classification societies (Mokashi et al., 2002). Class approval of machinery and propulsion components are commonly based on inspection and condition monitoring performed after specific operating hours. Knowing that the manufacturer has obligations in case of claims, the shipping companies typically follow the recommended practices in terms of inspections and operating hours without further questions.

Yet, using a more analytical approach would facilitate a reduction in unnecessary maintenance work and better tailor the maintenance plan to its context.

Most knowledge connected to methods of achieving an optimal maintenance strategy originates from experiences in land-based industry (Murthy and Kobbacy, 2008). Consequently, transferring results and suitable maintenance methods into a maritime context cannot be done scrupulously as there are clear differences in operating onshore and at sea. MainTech AS has extensive experience from a variety of industries in facilitation of operation, maintenance and inspection. A maintenance method that the company has utilized to achieve successful maintenance programs is reliability centred maintenance (RCM). This is supported by several maintenance experts (Rausand, 1998, Rasmussen, 2003, Moubray, 1997). The methodology combines operational and technical data with information based on employees' experience. This creates a program that prioritises maintenance needs and concentrate resources on those tasks that promote system reliability. Consequently, this method may be an adequate approach as an alternative to the traditional maritime maintenance mind-set.

1.2 Objectives

The thesis aims to examine if the RCM practice can be utilized to achieve a successful maintenance program in a maritime context. The maintenance program intends to be an applicable element in a maintenance strategy at a higher level aiming for continuous improvement. Compared to traditional maritime maintenance, methods such as the RCM procedure could have an improved effect towards operational availability, safety, costs and reputation.

The main objectives of this thesis were:

1. Present the traditional maintenance practice that is common in the shipping industry, including challenges and areas suited for improvements
2. Describe the RCM method, what the essential steps of the process are, positive and negative aspects
3. Perform an RCM analysis on a machinery system for a ship operated by WSM, including illustrations and descriptions of relevant systems and equipment
4. Based on the results from the RCM procedure, establish an applicable maintenance program that suits the system under consideration and systematically facilitates execution and planning of maintenance tasks
5. Discuss whether the analysis results support that the RCM procedure suits a maritime context

1.3 Scope and limitations

The scope of this thesis is to exemplify the practice of RCM by analysing an engine on board one of WSM's operating vessels. Further, the assessed functional failure is shutdown of the engine due to failure of auxiliary systems. The evaluated auxiliary systems connected to the engine are the lubrication oil system, fuel oil system, seawater- and freshwater cooling systems. System illustrations corresponding to the vessel's arrangement along with a thorough description of the components included for each system is outlined. Additionally, in accordance with the RCM process, functional statements, identification of functional failures, failure modes and effects analysis (FMECA) worksheets and a final maintenance program for each auxiliary system are presented.

The RCM analysis focuses on failure modes that may cause engine stop and utilizes a decision tree procedure to outline suitable maintenance tasks for the final strategy. The included maintenance tasks are both preventive and corrective means. To facilitate proper communication, the resulting maintenance program is created in a manner that suits both the maintenance management planning the tasks and the personnel executing them. The RCM process and established maintenance program are utilized as basis to evaluate the applicability of the method in a maritime context.

1.4 Structure of report

The work of the thesis is mainly completed in four main steps; initial literature review, descriptions of the RCM method, RCM analysis of specific machinery equipment that constructs a maintenance program and evaluation of the results from the analysis.

Chapter 2 covers the literature review, discussing different aspects of maintenance, including demonstrating why maintenance is a key concern for companies, also in the maritime industry. Chapter 3 provides a proper description of the method utilized in the thesis, RCM. This involves all necessary steps and how information was gathered. Chapter 4 explains the systems and equipment that are analysed, by proper descriptions and illustrations.

Chapter 5 presents the results of the RCM analysis, including FMECA worksheets and a resulting maintenance program. Chapter 6 contains discussions and evaluations of the analysis results.

Chapter 7 presents the obtained conclusion and chapter 8 offers recommendations to WSM and comments for further work.

Appendix A provides the original problem description outlined in collaboration with the supervisor and cooperating companies.

2 The relevance of maintenance

In today's society there exist a fundamental expectation that businesses and organizations function in a reliable and efficient manner. A tendency to increase the pressure towards running operations with little to no downtime can be found in many sectors such as transportation, communication and manufacturing (Murthy and Kobbacy, 2008). Additionally, industries typically develop in a direction with continuous growth of the technical complexity level for important systems and arrangements (de Boer et al., 1997). To provide safe and well-functioning operation that meets requirements from both the society and regulatory authorities there has to exist a maintenance philosophy in the relevant organisation.

The general opinion of maintenance has changed greatly from a historical point of view. During the last century, the perception of maintenance has transformed from being a costly, unavoidable part of the production or operation, to more of a strategic choice. Most sectors seem to recognise that maintenance might contribute to beneficial results, thus making it highly relevant to implement as a key concern in the business (Alhouli et al., 2011). Nowadays, it is largely accepted that maintenance significantly affect environmental issues, safe operation, availability and energy economic factors (Rasmussen, 2003). However, maintenance is a wide field of study, and to achieve beneficial results necessitates constructing a proper maintenance strategy.

2.1 Constructing a maintenance strategy

Since the perception of maintenance has changed in a positive direction during the last decades, the connected field of study has also developed greatly. As a result, an increase of scientific research and theories concerning maintenance has successfully evolved. Yet, there exists potential for improvement in the use of terminological expressions. Maintenance terms are being used interchangeably, often causing confusion as the intended meaning of the expression is unclear. The following section shortly explains some of the key maintenance terms mentioned throughout the thesis. The last section includes a description of what the suggested structure of a maintenance strategy could be. Mainly, the thesis uses the terminology defined by Standard Norge (2010).

2.1.1 Explanation of relevant maintenance terms

In general, maintenance is connected to all actions that aim to restore or retain an item's condition so that it can perform a required function. The activities can be a combination of technical, administrative and managerial approaches, which is performed throughout the item's lifecycle. In this setting an item can be a part, component, subsystem, functional unit or system that can be individually described and considered (Standard Norge, 2010). Maintenance objectives correspond to the assigned target for maintenance actions, e.g. cost reduction, increased availability, safety etc. Determination of maintenance objectives, responsibilities and implementation of planning, controlling and improving maintenance activities are performed by the maintenance management.

The maintenance plan outlined by the management should be structured and include documents explaining the activities, procedures, resources and time scale required to carry out the maintenance work. Altogether, the management method utilized to achieve maintenance objectives is the maintenance strategy. I.e. the strategy more or less gathers all areas of responsibility within an organisation's maintenance work, including planning, managing and executing the maintenance activities. Establishing a proper maintenance strategy is challenging, requiring a clear and unambiguous structure. An approach suitable for managements of various sorts is suggested below.

2.1.2 Maintenance strategy model

The maintenance strategy should aim to reduce and/or exclude the chance of equipment and system failure that may lead to undesired consequences. In other words, clarifying a proper strategy for maintenance is an essential step towards creating a basis for safely operating complex systems in a way that ensures effectiveness, reliability and as little downtime as possible.

An applicable structure of a proper maintenance strategy is illustrated in Figure 1. This is a management model developed by the Norwegian Petroleum Directorate (NPD) through a maintenance strategy study performed in 1998. It also corresponds well with the maintenance strategy model outlined in the NORSOK Standard z-008 (2011). The model systematically shows a maintenance strategy loop that contains the elements necessary to obtain an organisation's maintenance objectives and goals. In other words, after the objectives are outlined the means of how to achieve them are defined in the maintenance strategy loop.

Firstly, performance standards and accept criteria are defined. A next step is to create a maintenance program suited for the systems under consideration. The next elements are related to planning and execution of maintenance activities. Furthermore, the last steps contain processes that facilitate continuous improvement of the maintenance strategy, i.e. reporting, analyses and improvements. These are essential elements necessary to ensure that the maintenance strategy is efficient and applicable as time passes. This reveals the dynamic nature of a maintenance strategy, i.e. it highly depends on feedback and updates to obtain best results.

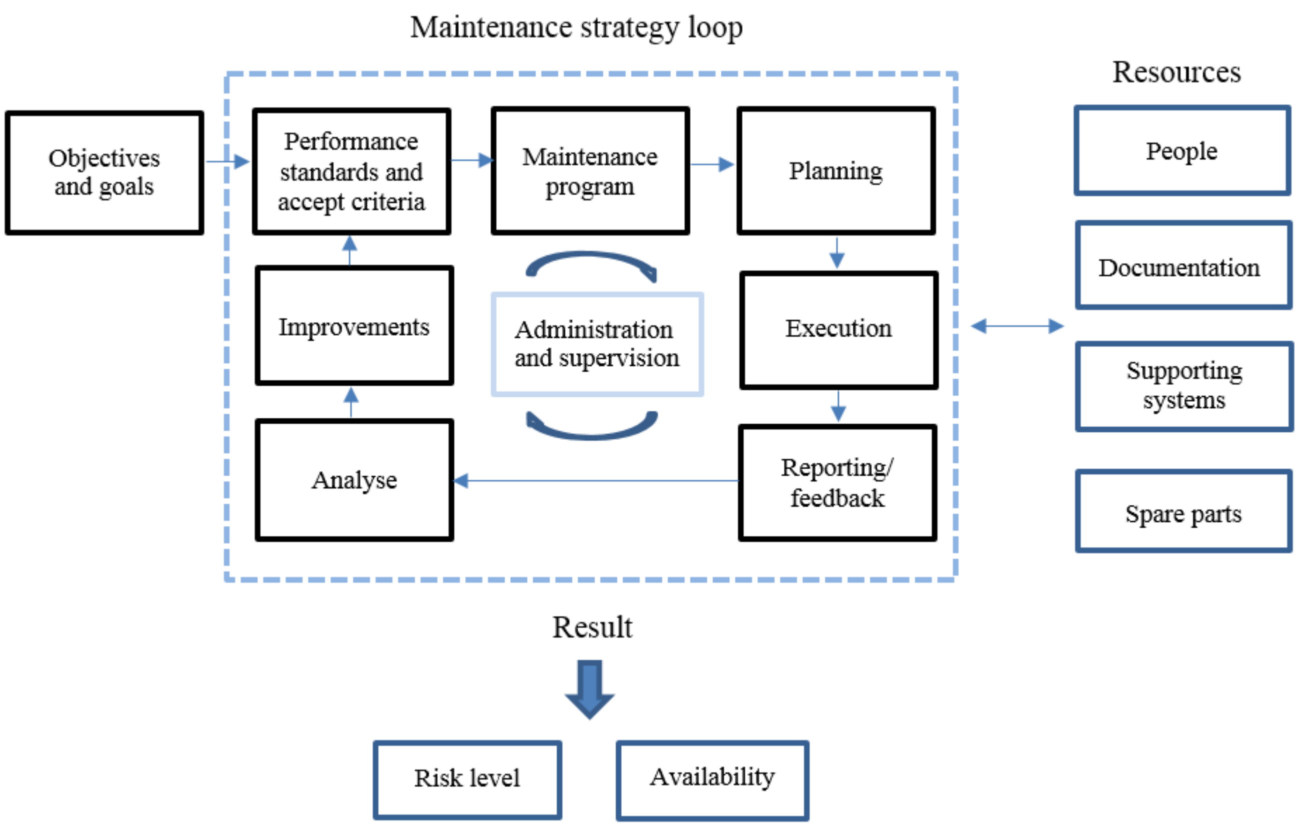


Figure 1. Maintenance strategy corresponding to the management model proposed by Norwegian Petroleum Directorate (1998).

Processes in the loop are made possible by resource input, such as people, documentation, supporting systems and spare parts. Every element in the loop may consist of several smaller progressions, resulting in an own specific output. Here, the general results are connected to risk level and availability. Yet, there may be different/additional results, mainly depending on which objectives being defined from the beginning. Added in the middle of the loop is administration and supervision. Firstly, these are parties responsible of leading and structuring the maintenance management. To ensure that every element in the maintenance loop is fulfilled, the administration must control its development. Typically, this requires supervision, but it is also possible to accomplish through encouragement and support. The latter is important to ensure that all relevant personnel understand the value of planned maintenance activities and are motivated to implement them. The maintenance strategy loop shows that managing maintenance is generally a learning process requiring an apparent administration that facilitates continuous enhancement.

The main concern further is mainly related to one of the elements in the maintenance strategy loop. Aspects of creating a maintenance program are discussed in the succeeding sections. NORSOK Standard z-008 (2011) refers to a maintenance program as a structure that includes maintenance intervals as well as written procedures for maintaining, testing and handling relevant components. Reliability centred maintenance (RCM) is one of several applicable methods to use for such intentions. One of the advantages of RCM is its ability to create a learning process where personnel from different backgrounds cooperate to achieve increased knowledge of operating equipment. This knowledge directly affects the maintenance program, which may be updated if necessary. Henceforth, the technique suits a dynamic maintenance strategy and can greatly help in attaining continuous improvement within maintenance management.

The method is widely exercised in land-based industry, but not in a similar extent within the maritime industry. The latter is an industry permeated with traditional perceptions of maintenance, thus having potential of constructing improved maintenance programs. However, several operating factors connected to maritime activity are non-existing for land-based industries. As a result, creating a suitable maintenance program may be more complex and challenging compared to onshore businesses.

2.2 Maintenance in the shipping industry

The maritime sector is an international industry and dominates global trading. Ships carry about 90% of all goods worldwide, and is the main transportation sector of the world (Bouwer Utne and Rasmussen, 2012). The global population is expected to continue its growth, signifying that maritime transport will remain as a major contributor for the international trade in the future. Increased focus on environmental friendly solutions, sustainable operation and improved safety has led to stricter regulations from the International Maritime Organization (IMO) and several class societies. Which regulations a vessel must comply with depend on class notation and the respective flag state (Wang et al., 2010). A central international directive is the international safety management (ISM) code. This is a global standard for safe maritime operation, by which a majority of the merchant fleet follows (Turan et al., 2011). It states several clear requirements to safety management systems and maintenance activities.

As discussed in the previous chapter, the pressure to avoid downtime is a common trend in several sectors. This is especially noticeable in the maritime industry, where the use of capital intensive installations and vessels leads to large downtime costs if normal operation is interrupted (Rasmussen, 2003). Consequently, containing a high level of operation reliability and safety at all times are essential objectives for maritime companies. In this context, executing appropriate maintenance is crucial to achieve such goals. Traditional maintenance procedures are often a result of recommendations from manufacturers, legislation and company standards (Mokashi et al., 2002). Maintenance models and data might also be utilized, although typically to a less degree (Rausand, 1998).

A common trend in maritime maintenance is addressed by Alhouli et al. (2011). After interviewing three major shipping companies, they all pointed out that a central factor influencing the maintenance program is what the manufacturer recommends. This is an available and reasonably trustworthy source to gather important information related to handling and maintaining equipment. It is also important to follow their instructions during the guarantee period. Not following the recommendations could remove the supplier from any obligations in case of a claim.

However, the manufacturers may have own motives for presenting their instructions. Fear of product liability claims may influence the recommended maintenance activities in a too conservative direction related to maintenance intervals and equipment interaction. This could lead to maintenance being performed too frequent, which is a waste of resources and inappropriate for the equipment. Linton (2011) demonstrates this aspect through experience from the US Coast Guard's fleet. Here, laboratory tests of a ship's engine were conducted. As a result, it was revealed that too excessive maintenance was recommended from the manufacturer. Yet, the manufacturer did not want to extend the maintenance intervals. As the Coast Guard was reluctant to ignore possible warrantee claims, the negotiation with the manufacturer stagnated.

Additionally, manufacturers might not receive much feedback from customers after the guarantee period is over. Therefore, guidelines are not necessarily based on experience data gathered over a period. As a result, it is plausible to assume that shipping companies may obtain profitable outcomes by optimizing their own maintenance strategy, merely basing it on the company's motives and experience. Wang et al. (2010) points this out as an improved solution compared to blindly complying with manufacturer's recommendations. The authors claim that manufacturers often lack of understanding the working environment. Consequently, the maintenance may not be adequate for the equipment in its operating context.

Economic aspects must be considered when attaining a suitable maintenance program. For instance, it is essential to evaluate how maintenance actions could lead to profitable results, versus the actual costs of implementing them. Improving the maintenance activities to be economically efficient and provide an appropriate safety level are therefore main concerns when constructing a maintenance program. Such improvement may be connected to spare part planning, costs of executing maintenance, reducing downtime costs, packing the maintenance actions in an efficient manner, etc. (Norden et al., 2013). Henceforth, there exist many possibilities in reducing operational costs if the maintenance program is optimized for its context.

Specifically for shipping companies there is an explicit advantage in creating a systematic and well-documented maintenance program. This is related to costs and procedures of a vessel's periodic class surveys. Several central classification societies, e.g. DNV GL and Lloyd's Register, have constructed specific class notations for vessels that operate with preventive means, such as utilizing condition monitoring maintenance (DNV, 2008, Lloyd's Register, 2013). The class notations are typically connected to vital equipment, for instance machinery and propulsion parts. The concepts of condition monitoring are thoroughly described in section 3.5.1. Yet, the essential point of condition monitoring is that such maintenance tasks involves working in a predictive manner, routinely measuring the equipment condition to help decide if there might be need for further maintenance interactions (Rasmussen, 2003).

Economically, obtaining such class notations may become very beneficial for the vessel operation. Mainly, this is because the class societies reward proactive maintenance approaches by adjusting their class survey procedures towards a flexible direction. As an example, Knödlseder (2015) explains how DNV GL has created such options. The class society has mainly four arrangements for surveys of machinery parts: renewal, continuous, planned maintenance system and condition monitoring. Vessels classified for renewal and continuous surveys require less comprehensive maintenance programs, but necessitate proper surveys every five years. This reduces the flexibility of the vessel as the survey includes opening up equipment and/or function test every machinery component, hence causing extensive downtime. Moreover, it is a costly process and increases the risk of assembly errors when equipment parts are interfered with.

The two latter arrangements for surveys; planned maintenance system and condition monitoring are more proactive alternatives that provide increased flexibility for the vessel. These surveys have yearly audits, but do not require opening up any equipment. The procedures focus on reviewing the situation on board and checking that the maintenance information corresponds to the machinery component’s real condition. Henceforth, these surveys offer clear advantages such as less downtime and reducing potentially harmful interaction with the equipment. As a result, there is potential for maintenance costs being reduced, especially in a long-term perspective. Additionally, it is plausible that the equipment’s reliability is improved compared to using the first class notations.

However, obtaining the proactive notations requires an extensive maintenance program that is developed by including crew, management and if relevant, third party managements (Knödlseder, 2015). Implementing procedures of the maintenance program on board must be done to reflect the real condition of the equipment in a best possible manner. Thus, constructing appropriate maintenance programs for this context necessitates the use of both time and resources. Despite clear advantages in using proactive alternatives, it is a truism that the traditional maritime approach is to perform extensive class surveys every five years. This can be seen in Figure 2, showing DNV GL's distribution of machinery survey arrangements within their legacy fleet.

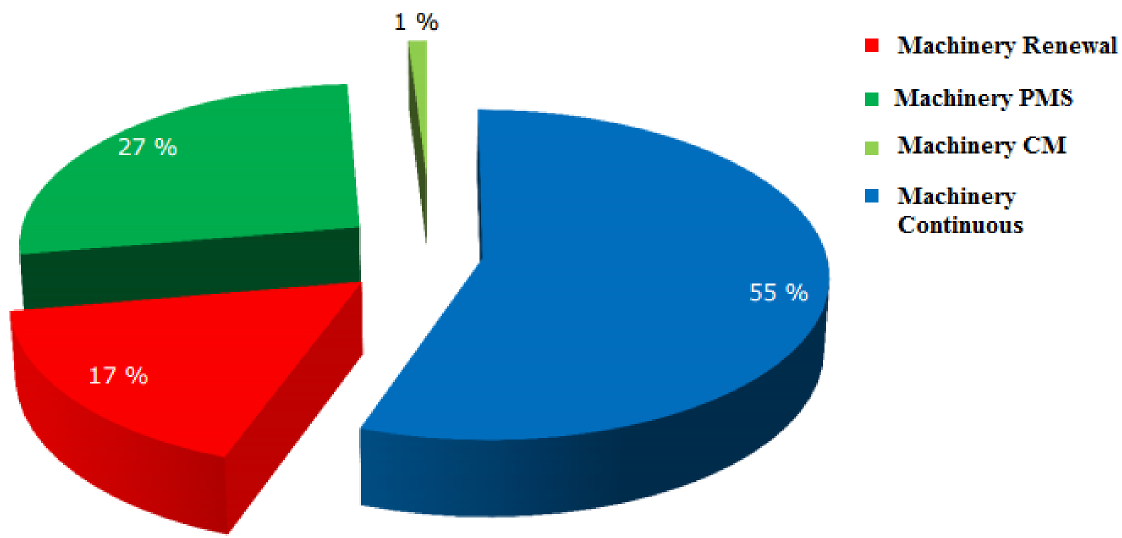


Figure 2. Distribution of machinery survey arrangements in accordance with DNV GL's legacy fleet (Knödlseder, 2015).

On the other hand, Algelin (2010) has gathered information related to which maintenance management techniques various Swedish shipping companies choose to utilize. Interviews with ten ship owners established statistics of which methods that their companies commonly used. The ones interviewed represented companies of large to medium size, in summary controlling 177 ships. Most of the shipping companies claimed that they were using a preventive planned maintenance strategy based on the operating hours of the equipment and general experience. Henceforth, one can reasonably assume that many shipping companies have proactive tactics in their business and it does exists a willingness to improve their maintenance procedures.

2.3 Wilhelmsen Ship Management (WSM)

Wilhelmsen Ship Management (WSM) is a shipping company that frequently encounter challenges towards obtaining an efficient and applicable maintenance program as well as strategy. The company provides third-party ship management services to an extensive range of vessel segments on a global level. Their ship management services include technical management, crew management and training, dry-docking services, new building supervision, technical consultancy, amongst others. Wilhelmsen Ship Management (WSM) is a department within Wilhelmsen Maritime Services, which is a Wilh. Wilhelmsen group company. Wilhelmsen Maritime Services includes WSM's ship management services along with port services, logistics, marine equipment and products to offer efficient solutions to the global maritime industry (Wilhelmsen Ship Management, n.d.-a). By working as a third party, the company acts as an owner of the vessel in the period of the charter. As maintenance work is an essential part of a vessel's operation, it is within WSM's areas of responsibility to supervise and organise the activities.

WSM states that their vision is to "..be the shaper of the ship management industry" (Wilhelmsen Ship Management, n.d.-b). Further, a mission is to deliver products and services which significantly improve customers' operational efficiency.

Wilhelmsen Ship Management operates the vessel that is studied further in the thesis. The company is in charge of managing the ship, including planning maintenance actions and strategies. After requisitions from the vessel owner, the ship is kept unnamed.

2.3.1 Maintenance requirements from the ISM code

WSM operates vessels in accordance to the ISM code along with ISO 9001:2000 and ISO 14001:2004 (Wilhelmsen Ship Management, n.d.-a). Chapter ten of the ISM code specifies maintenance requirements by which the company must follow. In general, it is stated that the company ought to form procedures that ensure maintenance activities in accordance with relevant rules and regulations. More specifically, to meet requirements WSM should ensure that (IMO, 2002):

10.2 .1 inspections are held at appropriate intervals;

.2 any non-conformity is reported, with its possible cause, if known;

.3 appropriate corrective action is taken; and

.4 records of these activities are maintained.

Furthermore, the ISM chapter clarifies that the company must have procedures of identifying which equipment and technical systems that could result in hazardous situations if failure would occur. These actions must be included in the company's safety management system, which additionally should provide specific measures of how to improve the reliability of such critical items. These measures should also include equipment that is not in continuous use, e.g. testing of stand-by arrangements. Finally, all procedures should be integrated into the ship's operational maintenance routine (IMO, 2002). ISO 9001:2000 and ISO 14001:2004 are not directly connected to maintenance regulations, but with requirements to quality and environmental management systems respectively. Consequently, these standards are not discussed further.

2.3.2 WSM's maintenance guidelines and procedures

WSM has outlined internal procedures in a maintenance manual corresponding to requirements defined in chapter ten of the ISM code. To structure their maintenance work, the company uses a software program named BASSnet. The program systematically categorises the vessel's equipment by SFI Coding. This is an international standard that classifies components in maritime systems (Xantic, 2001).

WSM's maintenance manual contains guidelines towards how the maintenance should be organised related to planning, responsibility and execution. Stated objectives are to ensure (Wilhelmsen Ship Management, 2013):

- Proper upkeep of the ship's structure and equipment
- Timely and safe execution of maintenance activities
- Reduced repair costs and downtime
- Extended machinery life due to a systematically planned preventive maintenance routine
- Effective inventory management

On board the vessel, supervision and coordination of maintenance procedures is the master's responsibility. Under the master's authority, there is a chief engineer, second engineer and chief officer. They all have their own responsibilities related to planning repair programmes and keep the master updated about the condition of the vessel. The chief engineer is responsible for the machinery maintenance and the chief officer has responsibilities towards the deck maintenance programme.

On all vessels, WSM states that a planned maintenance committee (PMC) is established. A committee comprises of the master as chairperson and members are typically the chief engineer, chief officer, second engineer and electrical officer. Other relevant staff may also be included if necessary. On a quarterly basis, the committee should inspect all areas of the vessel to construct a list of necessary maintenance activities during that period. If some planned maintenance needs external workers, e.g. activities that the crew on board cannot perform, then these should be listed and forwarded to the company. The PMC should meet weekly to plan the forthcoming week. The planning is required to be a documented process. The PMC records must be made available to the attending vessel manager and class surveyor upon request.

Certain factors are taken into consideration when planning the maintenance actions. Most importantly, WSM strictly follows the manufacturer's recommended schedule. Other important factors also influence priority decisions. Such factors can be the criticality of equipment in terms of safety and environmental protection, the amount of available time and available spare parts. Additionally, to save time and resources it is advantageous if new maintenance activities are planned around scheduled class/maintenance surveys.

Except from manufacturer recommendations, WSM sporadically uses condition monitoring and previous experience as input in the planning process. However, condition monitoring is not utilized for all vessels in the fleet, by which other preventive solutions are common as an alternative. Condition monitoring is thoroughly explained in chapter 3.5.1. The maintenance planning should also consider previous maintenance records and if suitable, change the maintenance plan according to those. However, the vessel manager or class society must approve the changes before implementation.

Operating vessels that are constantly on the move and often in remote places, can make it challenging to offer available onshore maintenance operators if needed. Failure of a specific item or system may not be possible to repair straightaway, which can be disastrous in some situations. Henceforth, WSM requires that the vessels have listed their critical systems and equipment. This provides a record of vessel equipment that by failure could lead to an ongoing or immediate hazardous situation towards the personnel, ship or environment. The identification of critical items should include directions for their inspection, testing, maintenance and spare part stock availability.

The record of critical items should be delivered and approved by the vessel manager in charge. The PMC should be aware of critical equipment, enabling that it is strictly inspected and given a minimum spare part inventory to be maintained. Thereby, the shipboard management should execute the identification process. The PMC along with the vessel crew prepares and executes maintenance plans to ensure the functional reliability of these systems. To identify the items, a few questions related to risk evaluation should be considered (Wilhelmsen Ship Management, 2013):

1. What is the function of this item?
2. How can it fail?
3. What could cause it to fail?
4. What happens if it fails?
5. Does it matter if it fails?
6. If the item is on the critical list, identify what components can cause it to fail, based on experience, probability, usage and stress, and then ask if anything can be done to predict or prevent failure?
7. What should be done if failure cannot be predicted or prevented?

Such risk evaluation of equipment is greatly connected to the process of reliability centred maintenance, which is discussed in subsequent sections.

The PMC under the master’s authority has the responsibility to supervise that the planned maintenance is done in a correct, efficient and punctual manner. Keeping in mind the importance of costs, quality, safety and environmental requirements should also be evident to the crew executing maintenance. Critical equipment is only maintained by licensed officers. The chief officer organises the maintenance of the hull, deck and lifesaving appliances. Maintenance in the machinery is delegated to engineer officers by the chief engineer. Both chiefs are responsible of keeping the maintenance records for their systems in order. Managing the spare parts is allocated between the master, chiefs and officers. Mandatory spares needed on board the vessel are outlined by the class society, making the crew on board responsible for the appropriate care and record of such equipment.

Henceforth, WSM has a structured framework for managing maintenance activities. Yet, the approach lacks definitions connected to how the organisation plans to meet their objectives. The personnel in charge of different tasks are clearly stated, as well as how often the on board maintenance planning is executed. However, it may seem like there is a lack in long-term planning of maintenance work and an overall maintenance strategy. Furthermore, it is evident that the quality of maintenance greatly depends on the competence of the on board crew. Systematically gathering their information is valuable for containing a maintenance strategy with updated records. It is also apparent that their maintenance program depends on the reporting procedures from the on-board crew. For WSM to supervise and administrate the maintenance program on board a vessel, the communication between the vessel and onshore personnel must be somewhat unrestrained. In order to identify whether a more analytical maintenance approach could be appropriate for the company, a maintenance method well known from land-based industries is applied on a machinery system on one of WSM's vessels.

3 Method - Reliability Centred Maintenance (RCM)

3.1 The procedure of RCM

"Reliability Centred Maintenance; a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating text." (Moubray, 1997, p. 7)

Reliability centred maintenance (RCM) is a method that provides guidelines of how to create a maintenance program applicable for various types of equipment and systems. RCM should result in a program that prioritises maintenance needs and concentrate resources on those tasks that promote system reliability. The method also provides results that facilitate maintenance planning and execution as well as further maintenance analyses. It is a technique originated within the aircraft sector and later successfully adapted to several other industries (Murthy and Kobbacy, 2008). Main principles of the methodology can be summarized by four features (Mokashi et al., 2002):

1. Preserving functions
2. Identify failure modes that can defeat desired functions
3. Prioritise function need (using failure modes)
4. Selecting only applicable and effective tasks

RCM focuses on maintaining the function of a system in a cost effective manner that meets both internal and external requirements (Selvik and Aven, 2011). Such requirements could be the company's own maintenance goals and objectives as well as regulatory aspects from classification societies, flag states etc.

When creating a maintenance strategy by the use of this approach, one may combine operational and technical data with information based on employees' experience (Bai, 2003). Working through the RCM procedure creates a platform for employees at all levels, sharing knowledge and attaining a renewed awareness about the equipment. The method may progress as a learning process that reveals maintenance issues not considered before. Therefore, RCM may be an applicable framework for systemising operational experience. As a result comes a proper understanding of the equipment's behaviour and background, making it possible to tailor the maintenance strategy to the appropriate context.

3.1.1 Seven questions

The RCM procedure utilized further in the paper involves asking seven fundamental questions about the asset under review. Answers to these questions form a suitable basis to construct an optimized maintenance program. The equipment overall should become more reliable as a direct effect. The basic questions goes as follows (Moubray, 1997):

1. What are the functions and associated performance standards of the equipment in its present operating context (functions)?
2. In what ways can it fail to fulfil its functions (functional failures)?
3. What is the cause of each functional failure (failure mode)?
4. What happens when each failure occurs (failure effects)?
5. In what way does each failure matter (consequences)?
6. What can be done to prevent each failure (proactive tasks and tasks interval)?
7. What should be done if a suitable preventive task cannot be found (default actions)?

Analysing an item by utilizing the RCM process should then establish comprehensive answers to each question.

3.1.2 Choosing stages of the RCM process

The global perception of what an RCM process should achieve is generally analogous. Even so, there exist various theories of how the procedure should be performed to attain desired results. Namely, as the methodology of RCM has developed, a variety of theories concerning the method's structure has evolved simultaneously.

There exist various alternatives for RCM processes. For instance, Rausand (1998) describes twelve steps. To start with, establishing which components that are critical in the relevant context. Performing this screening process ensures that non-essential components are excluded further in the analysis, saving vital time and resources. Mokashi et al. (2002) suggests analysing the ten most cost-exhaustive components or safety significant items.

Both of these approaches differ from the procedures discussed in the succeeding sections. The RCM steps outlined further are based on the view of Moubray (1997) and two standards defined by Society of Automotive Engineers (SAE), SAE JA1011 (SAE International, 1999) and SAE JA1012 (SAE International, 2002). As the popularity of using RCM has increased over the past years, there has developed an emerging demand towards creating an international standard of minimum criteria for an RCM process. SAE JA1011 is a standard that clarifies such criteria, setting out minimum principles that any process must comply with in order to be classified as RCM. The SAE JA1012 standard is utilized as a guideline towards the terms and key concepts utilized in SAE JA1011. Process descriptions and the terminology defined in the standards are unambiguous and well explained, creating a detailed procedure that is adjustable for several industries.

Following these standards in addition to Moubray (1997), the RCM stages progresses in compliance with the questions outlined in section 3.1.1. This includes working through each point, creating a systematic overview of the unanswered aspects within each of the seven question. As a result, more components are included from the beginning. Some may argue that this leads to unreasonable amount of work, raising questions whether all accomplished results are valuable information or not. However, excluding components early in the process could possibly hinder revealing weak and maintenance relevant components at a subsequent time in the analysis. Due to such different perspectives, one must consider which approach that may suit the specific situation and early in the process evaluate the amount of equipment necessary to analyse.

A proper description of each stage in the RCM practice is presented in the following chapters.

3.2 Functions

The first step of the RCM analysis is to establish a proper function description of the equipment under evaluation. SAE International (1999) suggests that four key concepts are covered in a functional description:

- Functional statements
- Performance standards
- Operating context
- Primary and secondary functions

Functional statements for the different items must be formulated in a manner that covers all relevant descriptive parameters, e.g. speed, output or product quality. One way of formulating the statements is by using an object, a verb and a desired performance standard. E.g., a specific water pump (object) should pump water (verb) by 10 l/min (performance standard). Classifying the functions in this manner makes it possible to cover several items in an intuitive manner. In addition, it is easier to discover potential deviations in expected output during normal operation.

Ideally, the performance standard consists of an upper and lower level of acceptance, i.e. creating an interval of permitted behaviour. This is helpful when addressing the failure states in the next step, as it is possible to have both complete and partial failure of equipment. The performance of an item can be divided into desired performance and built-in capacity. To establish suitable maintenance it helps to distinguish between the two concepts, i.e. what the item can do (built-in capacity) and what the users want it to do (desired performance). The built-in capacity should evidently be higher than the desired performance, otherwise the item is not maintainable.

ABS (2003) recommends creating a functional hierarchy that includes the functional groups with the main systems and subsystems at different levels. As a comment, systems categorized by classification codes, such as the SFI code, simplify the process of creating a functional hierarchy. This is due to how the SFI code is constructed to follow the same logic as a functional hierarchy. The hierarchy helps visualize a system’s functional structure and identifies smaller subsystem packages for application in the succeeding steps. In a machinery system, characteristic subsystems might include components associated with pumping, heating, cooling, purifying, lubricating, regulating and monitoring. Figure 3 illustrates an extract of how a functional hierarchy can be constructed for a ship's seawater cooling system.

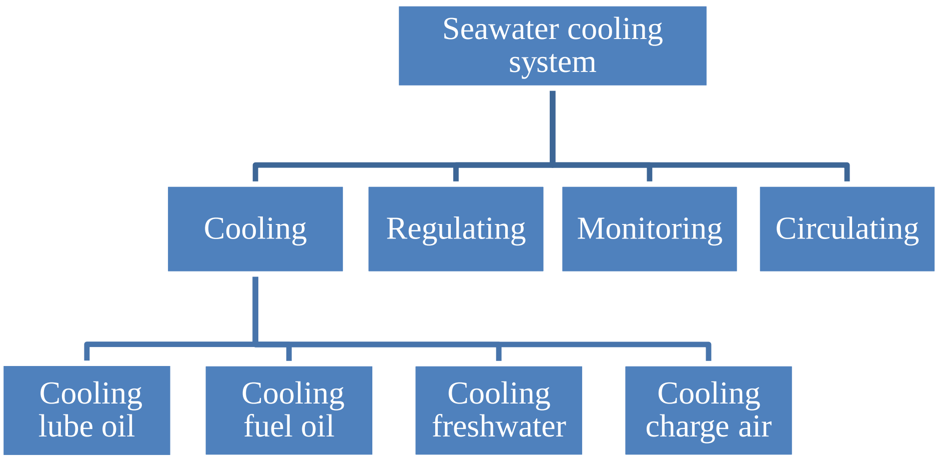


Figure 3. Excerpt of a functional hierarchy connected to the seawater cooling system.

Furthermore, the function description should include each relevant item and a clarification of what its users expect it to do in its specified operating context. Clarifying the context is of high relevance as this affects functions and performance expectations as well as the nature of the failure modes that may occur. Different factors are to be included when considering an item's operational context. Examples may be location, process intensity, redundancy and spare parts.

Particularly in the maritime industry, the context is an important and challenging topic. Compared to how the method is used in land-based industry, the operating context is one of the main concerns when utilizing RCM on ship systems. Vessels are constantly on the move, operating at different locations worldwide. This affects the ship systems, e.g. due to changing environmental conditions. For instance, a vessel's cooling systems greatly depend on seawater flow and temperature. If a vessel is operating in the North Sea one month and continuing in the South China Sea the next, seawater content and temperature change as the ship travels to its new location. This may affect the function and load of system parts, like pumps and pipework. Other changing parameters can be larger waves, currents, humidity and temperatures. In land-based industry, such changes for the operating context are not typical. This makes it easier to create a generic maintenance plan that can be transferred to similar systems and facilities.

Most types of equipment have more than one function. Consequently, it is necessary to identify the ones being relevant for the maintenance plan under development. Generally, it is typical to divide functions into two main categories, primary and secondary functions.

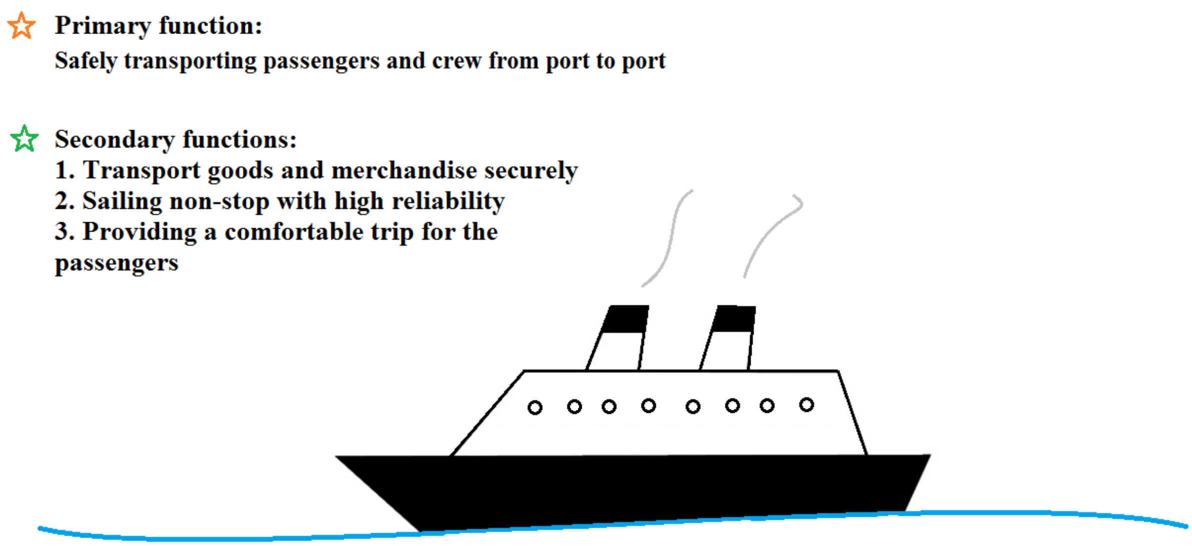


Figure 4. Primary and secondary functions connected to a passenger ferry.

Primary functions are the main reasons for why the item is acquired in the first place. Figure 4 shows an example of the primary and secondary functions for a passenger ferry. The ferry's primary function is to carry passengers and crew safely from port to port. On component level, primary functions are usually relatively easy to recognise. For instance, an item's name is likely to be based on its primary functions.

Secondary functions are those expected of the item additionally to its primary functions. These functions may not be as obvious to discover as the primary ones. Listing the secondary functions can create an extensive list, making it important to evaluate which ones being relevant to take further in the analysis. For instance, the passenger ferry illustrated in Figure 4 is likely to have supplementary secondary functions than those listed. Primary functions may very well be depending on secondary functions. Thus, cascading effects of secondary function failure could be severe. Consequently, the consequences following failure of a secondary function must not be underestimated. To evaluate such consequences, it is necessary to study potential functional failures.

3.3 Functional Failures

After establishing what the intended purposes of the equipment are, one must look into the situations where it may fail to fulfil these. Standard Norge (2010) defines failure as "termination of the ability of an item to perform a required function". Here, it is important to distinguish between the failure state, being the functional failure and the events that made the failure occur, i.e. the failure modes. RCM experts frequently interchange the terms failure mode and functional failure. Murthy and Kobbacy (2008) refer to failure modes as how items may fail to fulfil its purpose, i.e. as functional failures. However, Moubray (1997) refers to failure modes as the causes for functional failures. This is the terminology emphasized further.

Overall, this step should identify the different ways an item may fail to fulfil its intended functions. As discussed, an item typically has more than one function. Thus, in the event of a failure it can suffer from a diversity of different failure states. Figure 5 shows how a pump may operate normally for its primary function, pumping 500 L/min. However, if the secondary function is to deliver water at 5 bar, it fails due to a leakage in the pump. On the other hand, the pump could fail delivering 500 L/min, meaning that the primary function is unfulfilled. If the pressure is accurate, then the secondary function is acceptable.

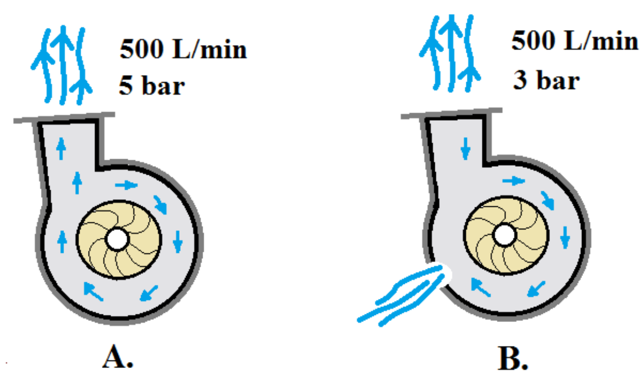


Figure 5. A. Centrifugal pump operating as wanted. B. Centrifugal pump leaking, not delivering required pressure.

Only addressing that an item has failed without any further explanation is a vague statement that holds back essential information about the equipment. For instance, pronouncing failure of a ship's main engine could mean that the entire engine is broken and completely shut down. On the other hand, it may also mean that it is usable, but partly broken in a way that makes it possible to run the engine as usual. Therefore, the importance of the first step should become clear at this stage. Here, the clarification of functions and especially performance standards is used systematically. In the case of a ship's main engine, a performance standard could be 'running continuously at 900 rpm' or 'delivering 3000 kW'. This means that a functional failure might be 'delivering less than 3000 kW', which could be intolerable depending on the defined upper and lower limits of performance acceptance. It is important to distinguish this step from defining failure causes, here referred to as failure modes (SAE International, 1999) .

3.4 Failure modes, effects and criticality analysis (FMECA)

When the functions and functional failures have been established it is necessary to study these further. The next steps in the RCM process define sources that lead to functional failures and evaluate the sequence of events following a failure. A failure modes, effects and criticality analysis (FMECA) is a fundamental part of the RCM process that systematically cover the next stages. The analysis method involves two main parts, the failure modes and effects analysis (FMEA) and the criticality analysis (CA) (Kim et al., 1996). The FMEA aims to identify potential failures, their modes and effects on performance. The CA ranks the significance of potential failures according to the failure pattern, mean time between failure (MTBF) and the severity of the failure consequence. In the performed analysis, MTBF is employed on both repairable and non-repairable units. However, the most consistent approach is to distinguish these two categories by also utilising mean time to failure (MTTF) for non-repairable items (Utne et al., 2012). MTBF denotes the time elapsing from when the unit is put into operation until it fails. Moreover, effects on relevant consequence parameters are studied, e.g. effects towards safety of the personnel, the environment, costs etc.

Constructing an FMECA is commonly obtained by gathering a team of relevant experts that have knowledge about the analysed equipment (Turan et al., 2011). Systemizing the FMECA by using worksheets is common practice, but the preferred structure and content varies. The table below is an excerpt of how an FMECA worksheet may be constructed. Function, functional failures, failure modes and effects are included.

Table 1. An excerpt of FMECA worksheet.

Function	**Functional failure**	**Failure mode Level 1**	**Failure mode Level 2**	**Failure mode Level 3**	**Effect**
1. Duetz engine generates 1140 kW	1. Engine stops during operation	1. Sea water cooling system failure	a. Sea strainer blockage	1. Plankton/schools of small fish/	No cooling effect, temp. increase of engine, shutdown of engine.
				2. Marine growth	No cooling effect, temp. increase of engine, engine shutdown.
				3. Closing valve failure	Not possible to isolate strainer, can't open nor close

Furthermore, consequences and risk indexes are included. The risk index (RI) is commonly referred to as a risk priority number. This value is often found by multiplying three factors, occurrence, severity and detection (Xiao et al., 2011). However, a simplified approach is utilized in the FMECA presented in the succeeding sections. Rausand (2011) defines the risk index connected to a hazardous event, as the logarithm of the risk associated with the occurrence. The index can then be found by adding the consequences (C) and frequency (F) of the failure mode, as shown below.

$$RI = C + F$$

This is considered as sufficient for the analysis that will be performed as frequency categories tend to be logarithmic (Utne et al., 2012). In a more extensive risk assessment, it could be appropriate to consider alternative methods to better rank the criticality and risk. The input for the risk priority number suggested by Xiao et al. (2011) compared with the input for the risk index utilized by Rausand (2011) has one main difference worth mentioning. The factor connected to detection is not included in the latter version, meaning whether the failure mode can be easily detected or not. Yet, SAE International (1999) covers this aspect by stating that the consequence categorization process should separate hidden and evident failure modes. Therefore, a column stating whether the failure mode is hidden or evident is included in the FMECA worksheets.

The values defined for the frequency and consequences vary from 1-5, hence resulting in risk indexes from 2-10. The risk index is utilized in a risk matrix, which is discussed further in section 3.4.3. Failure modes, effects and consequences are thoroughly explained in the subsequent sections.

3.4.1 Failure Modes

The functions of the equipment have now been established, together with what ways it may fail to deliver its purpose. A natural continuation is to decide the causes of each failure state. Hence, all likely causes to the functional failures should be listed. Events that cause the functional failures are often referred to as failure modes. SAE International (1999) outlines that it is the owner or user of the equipment that helps to identify and accept which failure modes that are considered as reasonably likely. Consequently, these are natural participants to include in an FMECA expert team.

Recognizing the causes makes it possible to tailor the maintenance program to better prevent them and reduce the likelihood of functional failures from happening in the first place.

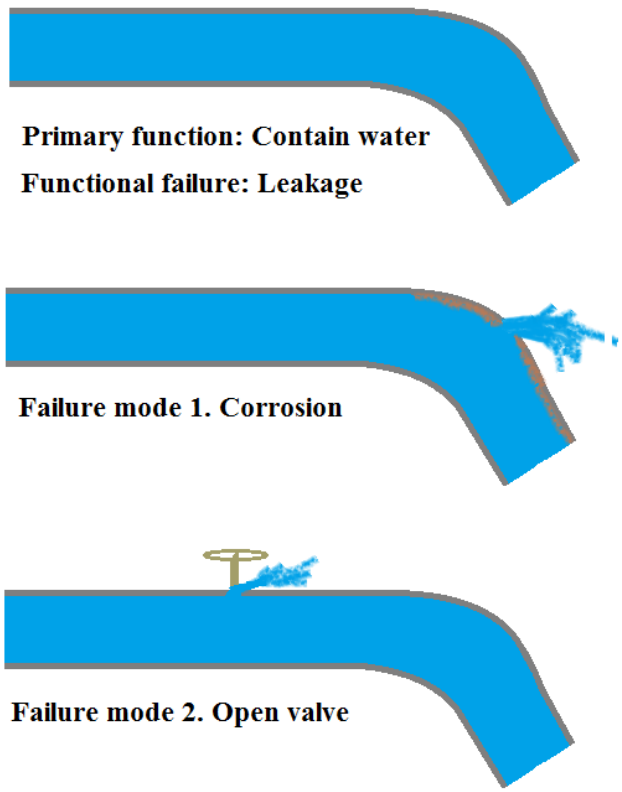


Figure 6. Different failure modes for a seawater pipeline.

The operating context should be apparent during this process, since it greatly affects the failure modes. Additionally, the context can be used systematically to organise similar items and their failure modes. A main challenge with this stage is to find a suitable limit for the detail level of the failure modes. Failure modes can be broken down into several causation levels, which might make it hard to decide when to stop analysing. The gathered information should be sufficient to cover all essential causes, without going into extensive detail. A rule of thumb is to go deep enough to enable the discovery of an appropriate maintenance strategy (SAE International, 1999).

3.4.2 Failure effects and consequences

Before studying the consequences of a functional failure, it is necessary to describe exactly what happens when each failure mode takes place. This is referred to as the failure effects. The effect descriptions should cover the development of a functional failure if no particular actions are performed to detect or prevent them from happening. A possible approach to explain the effects in a better way is to discuss five factors suggested by Moubray (1997):

- The indications implying that a failure has happened
- If the failure poses a threat to people and/or the environment,
- Whether the failure may be a threat to productivity or other operative relations
- How the failure may cause physical damage
- Which activities that are necessary to repair the failure

Studying the failure effects is closely related to studying the consequences. However, the main result should be knowledge about the sequence of events following a failure. I.e., not focusing too much on how large impact the failures may have, which is covered in the next step.

There are various methods of evaluating the consequences of failures. A common approach is firstly to distinguish between hidden and evident failures. Hidden failures are those that may occur in normal circumstances without being detected. The contrary is an evident failure, which on its own will be discovered naturally if it occurs. There are often challenges with hidden failures as their effects may become evident at a delayed point of time, possibly creating more severe consequences. As a result, such failures are generally suited for predictive means. Additionally, the failures resulting in consequences for people and/or the environment should be differentiated from the ones affecting only economic factors. To evaluate the consequences one must establish consequence and frequency parameters. These can be utilized to establish a risk matrix that shows the criticality of the various functional failures and/or failure modes.

3.4.3 Risk matrix, consequence and frequency parameters

A functional failure and its failure modes may have consequences of varying severity levels. When evaluating the consequences SAE International (1999) states that hidden and evident failure modes should be distinguished. It is of great importance to evaluate the severity level as it significantly affects how much a company is willing to invest in their maintenance program. Henceforth, the concept of risk and criticality are central aspects in this part of the analysis. It is important to evaluate which consequences that are most critical, resulting in a high risk level. Reducing the severity of these consequences is an obvious goal when shaping the maintenance program. This means that the critical consequences found at this stage will affect the decision-making at the end of the analysis.

Rasmussen (2003) defines criticality as a measurement of the risk that arises when a failure mode happens, which includes evaluating consequences and frequency of the failure. A risk matrix uses these as input values and systematically shows criticality levels of the different failure events. The criticality of the consequences is commonly categorized by using parameters such as: humans, environment, availability and costs. Yet, this may vary depending on company policies and type of operation. Figure 7 illustrates a risk matrix that shows by colour and number the criticality of events, corresponding to the matrix utilized in WSM. The risk index is presented in each cell and calculated as discussed in the introduction part of section 3.4.

		1	**2**	**3**	**4**	**5**
	Consequences → Frequency ↓	**Negligible**	**Minor**	**Moderate**	**Significan t**	**Severe**
5	**Very high (daily/weekly)**	6	7	8	9	10
4	**High (once a month)**	5	6	7	8	9
3	**Medium (twice a year)**	4	5	6	7	8
2	**Low (less than every year)**	3	4	5	6	7
1	**None (less than every 2 years)**	2	3	4	5	6

Figure 7. 5x5 risk matrix in accordance with the one outlined in WSM.

A minimum requirement towards a useful risk matrix is to differentiate between an outcome with low risk (green) and one with high risk (red). The region dividing these areas represents intermediate, medium risk levels (yellow). I.e. the green area represents a tolerable risk, the yellow may be tolerable with mitigation and the red is an intolerable level. Depending on the acceptance criteria, the yellow area may also be considered as intolerable. For instance, in the event of leakage in a seawater pipe due to corrosion, this may happen twice a year and have moderate consequences towards humans, environment and costs. The risk index becomes six, which is in the yellow region and mitigations might have to be evaluated.

Consequences and frequencies utilized in the risk matrix are divided into severity levels. The matrix above illustrates the result of consequences and frequencies categorized by five levels. The consequences and frequencies receive a value between 1-5, providing a risk index between 2-10. The utilization of severity levels decides how big the risk matrix becomes. If the consequence and frequency levels are divided into three levels instead, the risk matrix is 3x3 and not 5x5 such as the one above.

Characteristics connected to each consequence parameter may be tailored to the suitable context. A matter of categorizing consequences is shown in Table 2. The data is based on how WSM sort their parameters. This also applies for the classification of frequencies demonstrated in the risk matrix on Figure 7. Similar classification is utilized in succeeding sections.

Table 2. Categorizing of consequence parameters.

Categor. → Severity grade↓	**Human**	**Environment**	Off-hire	**Costs (maintenance and loss)**	**Reputation**
5	Fatality/ permanent disability	Long term impact on ecosystem. Restitution time > 10 years	More than a week	> 1 million $	Loss of charter
4	Lost work day	Medium long term impact. Restitution time 1-10 years	4-7 days	< 1 million $	Company exposed to society through media/detention
3	Restricted work	Short term, local impact Restitution time < 1 year	2-4 days	< 500 000 $	Major nonconformity
2	Medical treatment	Temporary impact. Restitution time < 1 month	12-48 hours	< 100 000 $	None conformities from external parties including customer complaints
1	First aid	Insignificant damage	Less than 12 hours	< 10 000 $	Minor observations from external parties

Risk matrices are utilized widely in organisations as appropriate tools to help identify, rank, and prioritize possible outcomes. The matrices also visualise what the risk of different events could be in a structured manner, which is easily understood. However, it is important to underline that risk matrices have its flaws. Thomas (2013) emphasizes that there are several deficiencies to be aware of, e.g. risk acceptance inconsistency, range compression issues and negatively correlated frequency and consequences. A conclusion may be that the risk matrix should not be used passively as a verifying mechanism to state that an activity is sufficiently safe. The results of real value lie within the discussion and process that initially creates the relevant risk matrix.

3.5 Maintenance task analysis

As one of the final steps in the RCM process, it is now possible to begin shaping a suitable maintenance program. Results from the FMECA, including the consequence analysis clarify which failure modes that lead to the most severe outcomes. These are essential during the decision process, as they need special attention when planning necessary maintenance tasks. This stage mainly forms a plan of how to prevent or predict each critical failure. The executed maintenance tasks may be of two primary sorts, preventive or corrective.

3.5.1 Maintenance task classifications

It is common to divide maintenance tasks into two classifications, whether it is corrective or preventive. Corrective maintenance is recognized as a mean to handle unforeseen occurrences, classically in cases where equipment have run to failure. Preventive maintenance (PM) intends to reduce wear or damage from evolving in the equipment in a more planned manner. Formally, one might categorize it as maintenance meant to avoid, reduce or eliminate the consequences of failures (Dai, 2013). Furthermore, preventive maintenance is typically divided into periodic overhauls or condition monitoring (CM).

Periodic overhauls are general inspections of an item to decide its need for repair or replacement and/or renewal of parts with limited life expectancy. This type of maintenance is often determined by a known relationship between time and reliability, i.e. operating hours/usage vs. wear/fatigue (Bai, 2003). Condition monitoring is a generic term where the item is regularly inspected and/or monitored to decide if the unit operates as required. This kind of monitoring should not interrupt normal operation and may include functional tests, general inspections and/or measurements of various parameters (Rasmussen, 2003). The measurements will be compared with predefined performance standards, hence revealing if the analysed item is operating as normal or indicating a deviating behaviour. Figure 8 demonstrates how the different maintenance tasks are connected.

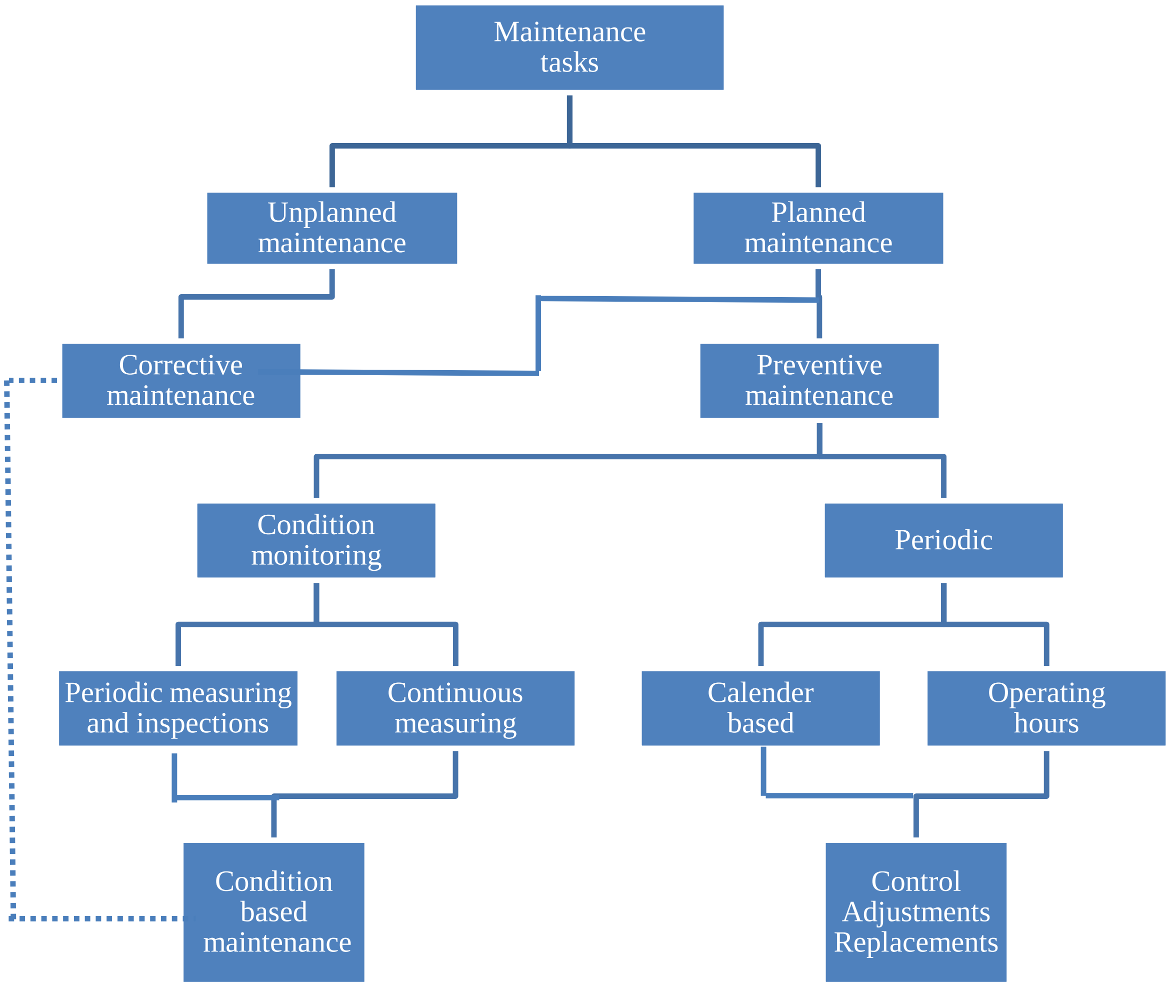


Figure 8. Classification of maintenance tasks in accordance with Dai (2013).

From a safety perspective, preventive maintenance is generally a wise choice as it continuously provides essential information about the status of the equipment. This might help to detect damage at an early stage. However, performing maintenance too often is not beneficial either. Apart from unnecessary costs of extensive maintenance work, it may not be appropriate for the equipment either. This is connected to the risk of executing maintenance incorrectly. Vinnem (2014) supports this aspect, stating that more than fifty percent of the hydrocarbon leakages from the offshore industry in the period 2001-2011 happen due to human intervention. On board a vessel, incorrect maintenance work might be connected to assembly errors (Chief engineer, May 2015). This can cause increased stress loads or operational errors for rotating parts. Thus, when utilizing preventive activities it must be clear that it is possible to gain an improvement of the system's reliability and/or that the former status of the equipment is obtained.

As an alternative, planned corrective maintenance can be appropriate in some cases. It is evident that this type of maintenance is often a last minute solution. However, it can also be the intention of a company to run parts of the equipment until it fails. This is illustrated in Figure 8 as corrective maintenance is categorised as either planned or unplanned, in addition to being associated with condition based maintenance. Whether corrective means are considered as ideal is mainly affected by the criticality level of the equipment (Selvik and Aven, 2011). I.e. if there are low consequences for the failure mode connected to a component, it might be economically efficient simply to repair the part after it has failed. However, a suitable functional hierarchy or similar grouping structures of the equipment should be included to justify the use of corrective means. As a result, it is clarified what function and interactions the item has related to other equipment. This is important for illustrating the additional components and/or systems that may be affected by the item's functional failure.

The strategy formulated by the use of this final step should provide information about all planned maintenance means. Moubray (1997) continues by recommending the practice of decision trees to help establish efficient and applicable maintenance tasks.

3.5.2 Decision tree

Decision trees are commonly used to select the type of maintenance that is suitable for different failures, e.g. the one illustrated on page 41. The content of the decision trees are based on a predefined logic, depending on the system and context of the analysis.

Generally, there are a few important principles that must hold when constructing a maintenance program, independently of the decision tree or approach utilized. Firstly, the proposed maintenance actions must be applicable, i.e. the activities must either reduce the impact of a failure, reduce the probability or completely prevent it from occurring. Secondly, the maintenance activities must be cost-effective. It is very unlikely that a company is willing to invest in maintenance tasks if the costs of doing so are higher than the costs following a failure.

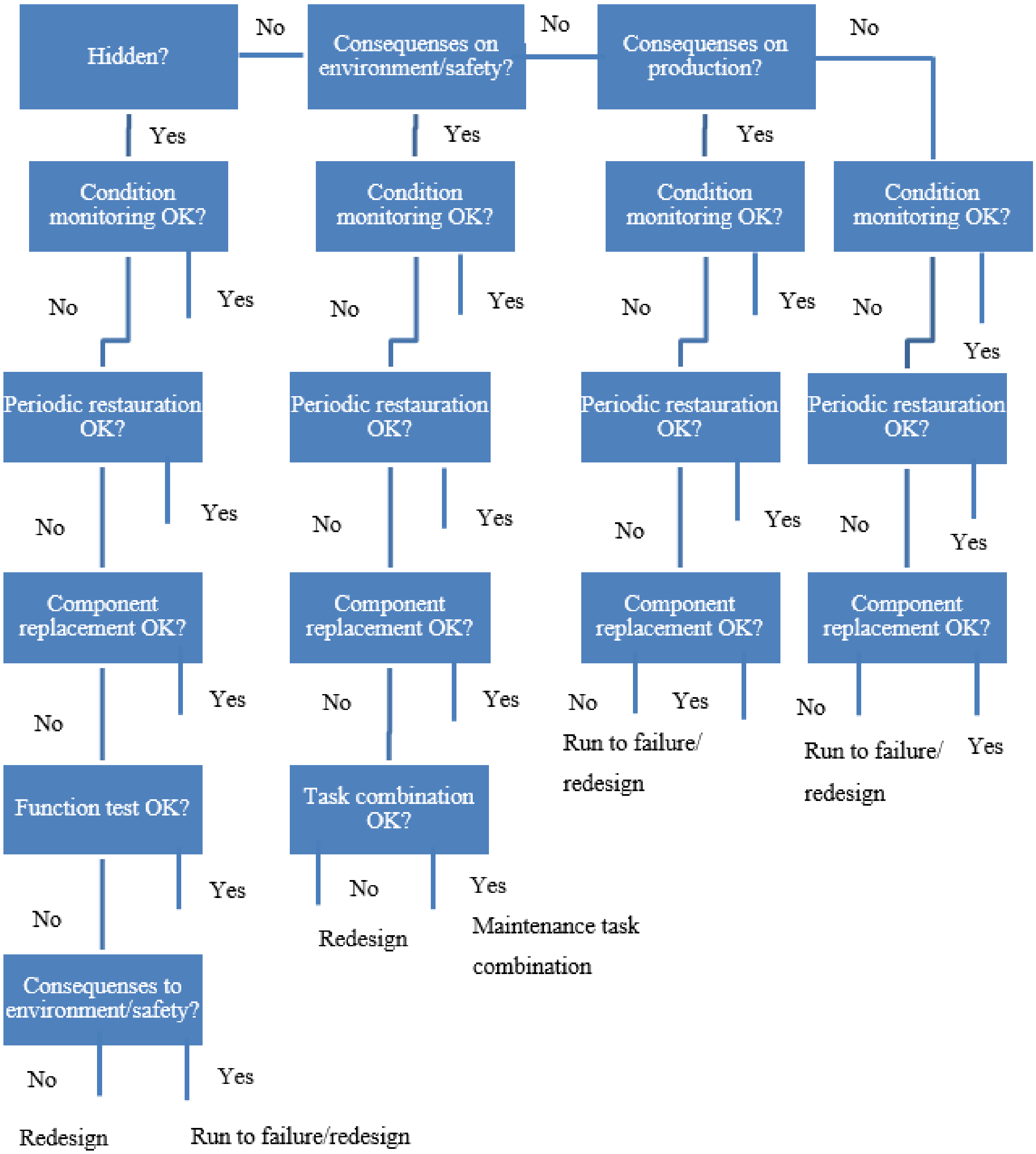


Figure 9. Simplified version of the decision tree utilized to establish applicable maintenance tasks.

Figure 9 is a simplified description of the decision tree utilized further in the analysis, inspired by the RCM approach at MainTech AS and Moubray (1997). Appendix B demonstrates the complete version of the decision tree. To establish maintenance tasks for each failure mode the

RCM expert team starts in the top left corner. The decision procedure is driven forward by assessing binary options at each question box. By working through the decision tree, data for appropriate maintenance tasks is gathered. The decision tree shows that not all paths lead to preventive maintenance solutions. This is connected to the fact that planned corrective maintenance may sometimes be the most cost-effective solution, given that there are minor consequences of letting the component run to failure. The decision tree process complies with the criteria outlined by SAE International (1999), especially when it comes to dealing with safety/environmental consequences before evaluating economic consequences.

3.5.3 Failure patterns

Another essential aspect is to take the probability of function failures into consideration. This may change as time goes by, resulting in a specific failure rate pattern. This means that some failures are closely related to the age of the equipment, thus making it possible to better foresee when the failure may occur. There exist different types of failure patterns as illustrated in Figure 10.

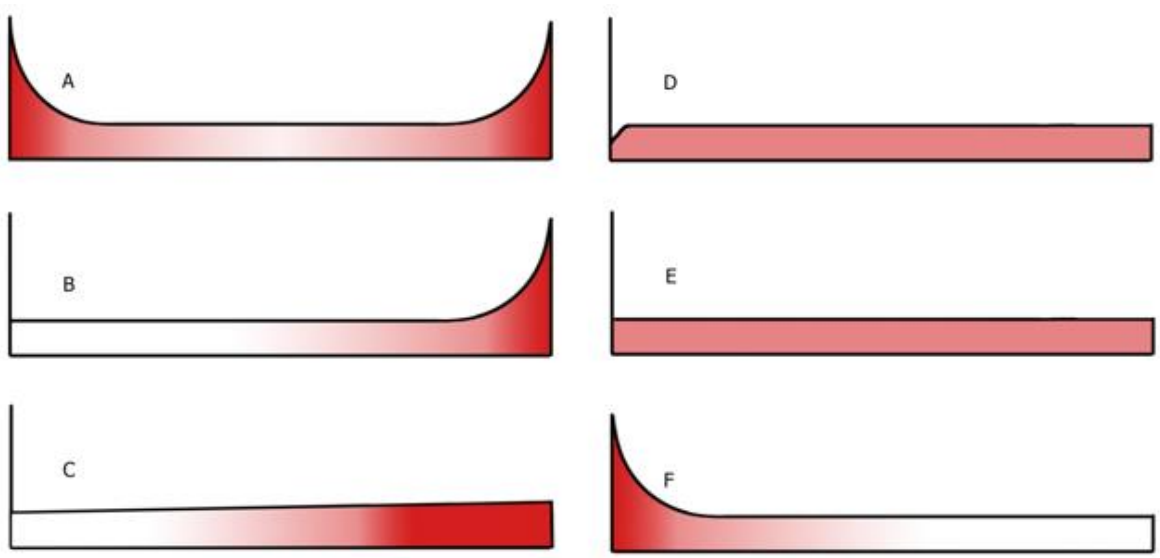


Figure 10. Different failure rate functions, versus time (Moubray, 1997).

The six different patterns show the failure rate function on the vertical axes and time on the horizontal. Wheeler (2007) explains the different patterns:

- Pattern A illustrate a typical 'bathtub curve'. This shows that some equipment may just as likely fail in the beginning of its lifetime, as in the wear out period in the end
- Pattern B is age-related, connected to an increasing probability of failure throughout the lifetime of the equipment
- Pattern C illustrate the characteristic failures affected by component wear-out phenomena
- Pattern D reflects a condition-related form, e.g. connected to wear-out due to environmental conditions
- Pattern E denotes random failure, meaning that the functional failure may occur at any time
- Pattern F is connected to infant mortality, meaning a high number of early failures

These diagrams clearly show that foreseeing the point at which the equipment may fail is challenging for some sorts of equipment, as one cannot always predict when the failure is likely to occur. Consequently, determining an optimal maintenance interval may be very difficult. Still, if the point of failure is possible to discover, establishing a P-F interval is necessary for outlining when the maintenance tasks should optimally be performed.

3.5.4 P-F interval

Utilizing preventive maintenance presupposes certain requirements. Firstly, it must be possible to identify equipment conditions that indicate functional failure, or that a failure is likely to happen in the near future. In other words, there must exist a possibility for detecting the failure by preventive measures for the interaction to be effective in the first place. Additionally, to justify the use of such maintenance actions, a P-F interval ought to be established. This is an interval illustrated by the curve in Figure 11. It gives an estimate of the time it takes from a point where a potential failure may be detected to the point where it deteriorates into a functional failure. The time between the preventive maintenance actions should then be less than the P-F interval (SAE International, 1999).

When proactive tasks are infeasible and not worth doing, it may be a better solution to perform default and corrective actions.

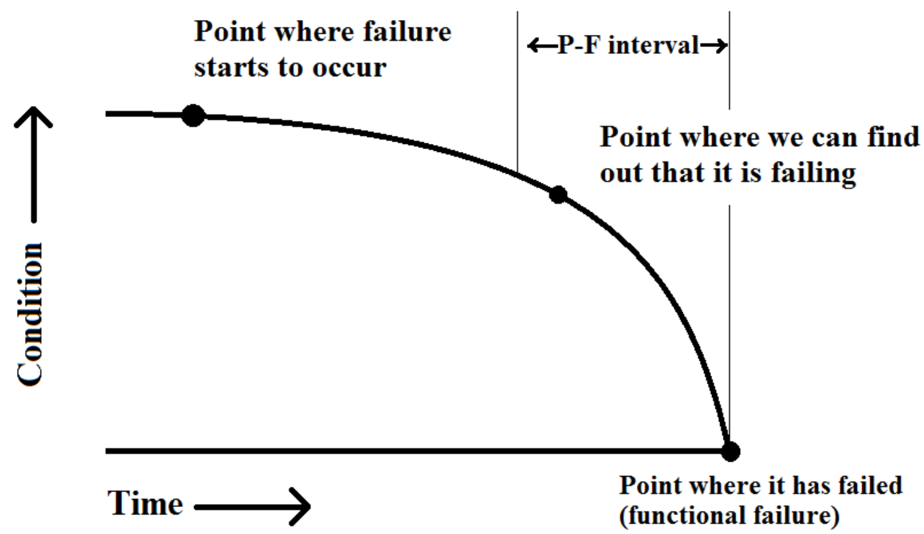


Figure 11. P-F curve with the related P-F interval in accordance with Moubray (1997).

3.5.5 Corrective activities

The last and final step in the RCM process concerns the equipment that does not suit a proactive approach. Typically, this means that corrective maintenance could be applicable. As pointed out in section 3.5.1, corrective activities can be a planned procedure. Moubray (1997) suggests applying default actions for equipment that does not fit any other effective or applicable task. Alireza et al. (2010) suggests the following default actions:

- No scheduled maintenance, i.e. letting equipment run to failure
- Redesign

Possible candidates suited for default tasks are components with a random failure pattern, i.e. those with functional failures difficult to predict. Consequently, this makes it challenging to plan an effective maintenance interval. Working through the decision tree on page 41, the default maintenance tasks are placed on the lowest level in the tree. Ending up at this level means that the above maintenance alternatives were not adequate options, such as periodic component replacement or condition monitoring. Thus, it illustrates that this approach planned corrective maintenance is only chosen by eliminating preventive measures first.

Letting the equipment run to failure is a cost-effective solution that avoids spending money on unnecessary preventive activities. Nonetheless, for such equipment failures there must exist no doubt that the outcomes are close to negligible. As for ships, choosing this maintenance alternative often necessitates available spare parts. This is another aspect especially challenging in the maritime industry, as the vessels in their operating context are constantly on the move.

3.6 Pros and cons of RCM

3.6.1 Positive aspects of RCM

The development of RCM in the aviation industry has delivered amazing results and inspired other industries to improve their maintenance practices (Dhillon, 1999). Since then it has become an acknowledged process, being well known in the field of maintenance. The method is highly adaptable for many types of systems and can provide technical maintenance analyses throughout an item's lifetime (Siddiqui and Ben-Daya, 2009). An option is using RCM during the operation phase to adjust existing maintenance strategies. New experiences related to failure rates, causes and consequences might develop throughout the equipment's operation, thus making it necessary to keep the maintenance program updated. RCM makes this possible by being a dynamic method that creates a framework for continuous flow of information.

In a maritime context, RCM may be useful due to different reasons. As discussed in section 2.2, several shipping companies rely on manufacturers recommendations when constructing their maintenance program. This means that the sense of ownership and maintenance control of essential systems may not be in the hands of the ones that operate them on a daily basis. Shipping companies may then lose valuable competence during a system's operational lifetime. For instance, an operator that regularly performs maintenance actions outlined by a manufacturer's manual has likely gained useful knowledge about the equipment. This may be information about how, when and why different functional failures happen, or generally indications about the condition of the equipment. If such information was processed and properly put into a data collection system, optimizing the maintenance activities would become easier. Additionally, the developed maintenance competence would be kept in the shipping company. Overall, this may lead to savings during the operational lifetime of a vessel, as the equipment is more reliable and downtime is less likely.

3.6.2 Negative aspects of RCM

Utilising RCM is a wise choice once used in the correct way and for the appropriate context. However, it is necessary to highlight the existing drawbacks related to the process. Although RCM caused great results in the aviation industry, applying it rigorously to ships could have some hurdles. Mokashi et al. (2002) address a few disadvantages, as discussed in the following paragraphs.

The personnel working on board the vessels represent one of the challenges. Typically, during a shift shipboard crew are overloaded with tasks and areas of responsibility related to operation and maintenance. The crew often come from different backgrounds not necessarily with much specialised training, particularly in a theoretical manner. Maintenance methodologies that contain extensive amounts of information may be perceived as complex and inapplicable. The working teams are frequently changing, which makes it challenging to ensure that essential information is communicated effectively at all times. Additionally, the personnel are seldom trained in risk assessment techniques and maintenance management. A result could be that the personnel have an ambiguous view of why the required maintenance tasks are necessary. Consequently, a lack of motivation to perform the activities correctly may grow.

The maritime environment is a challenging setting from an RCM point of view, especially compared to onshore facilities. Operating in the ocean creates a much more unstable framework, not making it possible to draw the same conclusions as one can do onshore (Bouwer Utne and Rasmussen, 2012). For instance, equipment conditions like tightness, lubrication and cleanliness, can often be taken for granted in other industries. Conversely, these are constantly a source for concern in a maritime environment. Furthermore, data collection of various types of equipment is much more portable in land-based industries as the surrounding milieu is not constantly changing. Additionally, there is no easy access to a failure databank due to commercial sensitivity reasons. Some industries require the equipment suppliers to deliver proper failure mode analyses, which greatly help implementing RCM. Yet, this is not a common trend in ship operations (Wang et al., 2010).

How portable the RCM results are from ship to ship may also be an issue. As each item analysis is done for specific operational contexts, the extent of transferable information may be limited if used for a similar item on another ship. Operating at sea also makes the ships isolated from repair and spares. This means that if critical equipment functions fail, the location of the ship greatly affects repair time. Hence, a failure mode analysis should consider this when looking at the consequences.

The common approach RCM has on redundancy is not well suited for ships. Typically, equipment with redundancy is assigned to corrective maintenance, i.e. letting it run to failure (Mokashi et al., 2002). However, due to space restrictions ships cannot allow multiple redundancies, which may be more typical in other industries. On a ship, critical systems might only have single redundancies, meaning that run to failure solutions could be disastrous.

3.7 Gathering information; meetings and workshops

As clarified throughout the chapter, RCM is the method applied further in the thesis. To illustrate how the RCM approach may suit a maritime context, it is used to analyse a part of the machinery system connected to one of WSM's operating vessels. The analysis largely follows the RCM perspective of Moubray (1997). Results are presented in chapter 5, which aim to reflect the procedure presented in previous sections of this chapter. Certain parts of the results have been achieved through meetings with MainTech AS and WSM. Additionally, an FMEA performed for the vessel's propulsion system has been utilized to establish suitable functional failures. As for the arranged meetings, four occasions have been used to gather information for the thesis:

- 30th of January 2015, WSM office at Lysaker
  Agenda: Start-up meeting to outline general objectives of the thesis and decide upon which vessel from WSM's fleet to analyse
  Present (apart from author): Engineer (MainTech AS) and two Fleet Managers (WSM)
- 7th of April, MainTech AS office in Trondheim
  Agenda: Discuss and decide which technical system from the vessel that is suited to study further in the RCM analysis. Exchange instrument diagrams of auxiliary systems.
  Present (apart from author): Vessel Manager/Superintendent (WSM)
- 27th of April 2015, WSM office at Lysaker
  Agenda: RCM workshop. Establish FMECA information related to the vessel's propulsion system for further accomplishment of the RCM analysis
  Present (apart from author): Engineer (MainTech AS), Vessel Manager (WSM) and two Fleet Managers (WSM)
- 5th of May 2015, Borg Harbour, Fredrikstad
  Agenda: Visit vessel at the quay, meet crew and be presented to the technical systems on board.
  Present (apart from author): Vessel Manager (WSM) and relevant vessel crew, such electrician, chief engineer and engineer officer

Out of these occasions, the meeting of greatest importance for the analysis was the RCM workshop.

3.7.1 RCM workshop

FMECA worksheets are a vital part of the RCM analysis, containing fundamental data that essentially constructs the final maintenance strategy. In chapter 5, the analysis' resulting worksheets are presented. Information given in these worksheets were chiefly gathered during a workshop 27th of April 2015, at WSM's office in Oslo. The agenda of the workshop was to discuss the engines and thrusters connected to a specific vessel, in accordance with the RCM methodology. The workshop was possible to accomplish due to collaboration between MainTech AS and WSM. Apart from the author, people present were:

RCM Facilitator and Engineer at MainTech AS
Vessel Manager at WSM (in charge of the ship under consideration)
Two Fleet Managers at WSM

As most content of the FMECA worksheets was outlined by the author in advance, the first part of the workshop discussed the reliability of proposed data. Specifically, this concerned suggestions towards functional failures, failure modes and failure effects. For the remaining time, WSM provided the analysis expert opinions related to the residual content of the FMECA. This was particularly connected to MTBF data, failure patterns and consequence effects. Throughout the workshop, WSM's own consequence parameters and risk matrix was utilized. Each failure mode at the lowest level was considered. Due to lack of time, only the auxiliary systems connected to one engine received sufficient amounts of data to perform a suitable RCM analysis. Henceforth, the maintenance strategy was outlined for this engine with additional focus on its auxiliary systems. A proper description of the vessel, its propulsion system with the relevant engine and connected auxiliary systems are thoroughly described in the next chapter.

3.7.2 Failure Modes and Effects Analysis (FMEA) from 2010

In 2010, an FMEA was performed for the vessel that is analysed further in the thesis. The scope of the work was to reveal any single point failure of the equipment that could result in failure of station keeping during operation. The analysis showed that the worst-case scenario was failure of a bow thruster. This is during an operational situation, i.e. typically when the vessel is in dynamic positioning (DP) mode. There are strict requirements towards how much power the vessel needs to contain its position, and losing one forward thruster leads to difficulties with controlling the ship’s bow part . The executed FMEA lacked of proper functional descriptions and did not contain precise explanations towards possible failure modes. Functional failures were commented, as well as partly their effects. Yet, the FMEA was performed due to requirements for DP vessels (DNV GL, 2014), and was not meant to establish a maintenance program. Henceforth, the only results utilized from the FMEA were the functional failures suggested for the engines.

Before presenting the results from the executed analysis, the succeeding chapter provides proper system descriptions of the vessel and equipment examined by the RCM procedure.

4 System description

4.1 Vessel, machinery and propulsion characteristics

The RCM process is performed for an engine of a vessel within WSM's fleet. The vessel has operated in more than thirty years and is fitted with a dynamic positioning (DP) system, a large inventory of spare parts and various operating equipment. It operates worldwide, which includes locations that may be both remote and with harsh weather conditions. The vessel must comply with regulations from its classification society, DNV GL. A central classification notation connected to the vessel is its status as DYNPOS-AUTR. This notation is granted to vessels that utilize a DP system. More specifically, there are different groups of which DP vessels can be classified within. Generally, the degree of availability, robustness and redundancy of the DP system decides which classification notation the vessel receives. DYNPOS-AUTR refers to a dynamic positioning system with redundancy in technical design and with an independent joystick system back up (DNV GL, 2014). Furthermore, it is required that loss of position should not occur in the event of a single failure. A single failure refers to any active equipment and various static components, defined by failure modes under the description of DYNPOS-AUTR (DNV GL, 2015). To comply with the DP requirements, the ship has been retrofitted more than once, and is generally equipped with redundant systems.

4.1.1 Propulsion and machinery

A part of the vessel's machinery system has been analysed with the RCM methodology. It is a vessel of both conventional and diesel electric propulsion solutions. The ship is equipped with five thrusters, all connected to their own separate engine. The ship is reliant on station keeping during operation, hence fitted with DP systems. As a result, the machinery equipment is arranged to comply with regulations and guidelines of DYNPOS-AUTR. A regulatory example is outlined by DNV (2011), stating that the vessel's position must be maintained without disruption from any single failure. Here, full stop of thrusters and subsequent start-up of available thrusters is not considered as an acceptable disruption. All thrusters are needed during operation, thus logically requiring a reliable system with a high level of redundancy to avoid downtime.

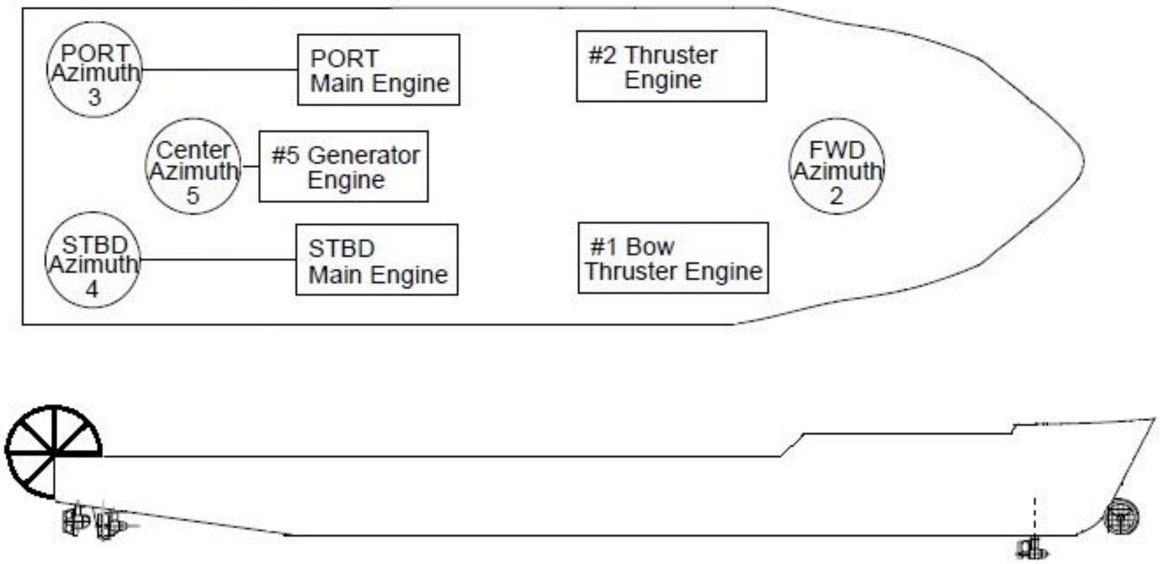


Figure 12. Sketch of the cable laying vessel and its arrangement of propulsion equipment.

Figure 12 illustrates the main parts of the vessel's propulsion system. There are five thrusters and each one have its own dedicated source of power. In the aft of the vessel, the main propulsion equipment is placed. This is where the main engine room is located, containing two main engines and four auxiliary diesel generators.

Two thrusters are installed in the forward part of the ship. There is a tunnel thruster (TT) in the bow, referred to as thruster 1. It is supported by its own diesel electric power source, including an electric motor, supplied by an alternator. The alternator converts mechanical energy from the connected diesel engine into electrical energy. The engine that drives thruster 1, is the main component from the machinery system taken further in the analysis. Figure 13 and Table 3 show the engine and its characteristics.

Table 3. Characteristics of the tunnel thruster engine.

Engine type	2-stroke Duetz MVM BA 16M 816C
Power output	1140 kW
Speed (revolutions per minute)	1800 rpm
Alternator type	Stamford MSC 734B 440V 1640A
Connected thruster	Brunvoll propeller, SPA – VP –1300

Figure 13. Picture of the vessel's tunnel thruster engine.

Overall, the vessel has relatively dependent machinery and propulsion equipment. A failure of one engine or thruster should not necessarily affect the failure of others since they are separated into independent systems. However, losing the power from only one thruster is considered as an unacceptable situation during DP operation. This is due to the station keeping capabilities and DP requirements of the ship. At exceptionally favourable weather conditions, the vessel may be capable of holding its position with one reduced thruster. Nevertheless, this cannot be taken as very liable since such circumstances would be a state of coincidence and pure luck. In transit, the circumstances are different, mainly depending on the aft propulsion thrust.

The redundancy of the propulsion equipment indicates that a failure of more than one thruster and/or engine should be unlikely. However, it is important to remember that the propulsion and machinery equipment is depending on other structures, i.e. requiring reliable systems on all levels. The auxiliary systems are essential for the prosperity of the thrusters and engines. Arrangements of special concern connected to the tunnel thruster are the fuel system, water-cooling systems and lubrication oil system. Automation and compressed air systems are additional auxiliary systems that would be natural to include. However, these are disregarded in the RCM analysis due to lack of available data and system descriptions. System descriptions of auxiliary systems relevant for the analysis are presented in the following section.

4.2 Auxiliary systems

4.2.1 Water cooling systems

Sea and freshwater are used as cooling medium for several important components connected to the engines and thrusters.

The primary mission of seawater is to circulate through heat exchangers that in turn cool fresh water, lubrication oil and charge air. The cooling system in the forward part of the ship is displayed in Figure 14, being in accordance with the vessel's arrangement drawings. Icon descriptions are given in appendix C. Sea chests allow seawater to enter the cooling system through sea suctions equipped with filters and isolation valves. The water flows through pipelines fitted with gate valves, non-return valves and filters. Thermometers and manometers measure temperature and pressure, ensuring that the performance standard of the water is fulfilled. Seawater pumps are installed to ensure correct speed and pressure for the circulating water. To avoid undesirable sediments and contain the cooling effect of seawater, there are limits at which rate the desired temperature of the circulating seawater rises. A reasonable upper limit for the temperature is 50°C (White, 2008). When the seawater reaches its upper temperature limit, it is discharged back into the ocean. The system illustration on page 60 shows that the seawater circuit cools charge air, lubrication oil, freshwater, gear oil, steering and pitch control.

Essential components of the engine are cooled by the freshwater cooling system. This typically includes cylinders, bearings, casings and pistons. Seawater is not an appropriate option to use directly as corrosion and fouling would become a problem. After removing heat from the engine parts, the freshwater is in turn cooled by the seawater cooling circuit. The temperature must be kept within a specific interval. If the water is too cold, it may cause thermal shocking that can lead to component failure. On the other hand, too hot water will not remove any heat and is likely to cause excessive wear on the apparatuses. A suitable temperature interval for the freshwater is between 60 – 90°C (Sandbakken, 2010). The freshwater receives chemical dosing to keep it slightly alkaline, which will prevent corrosion and scale formation.

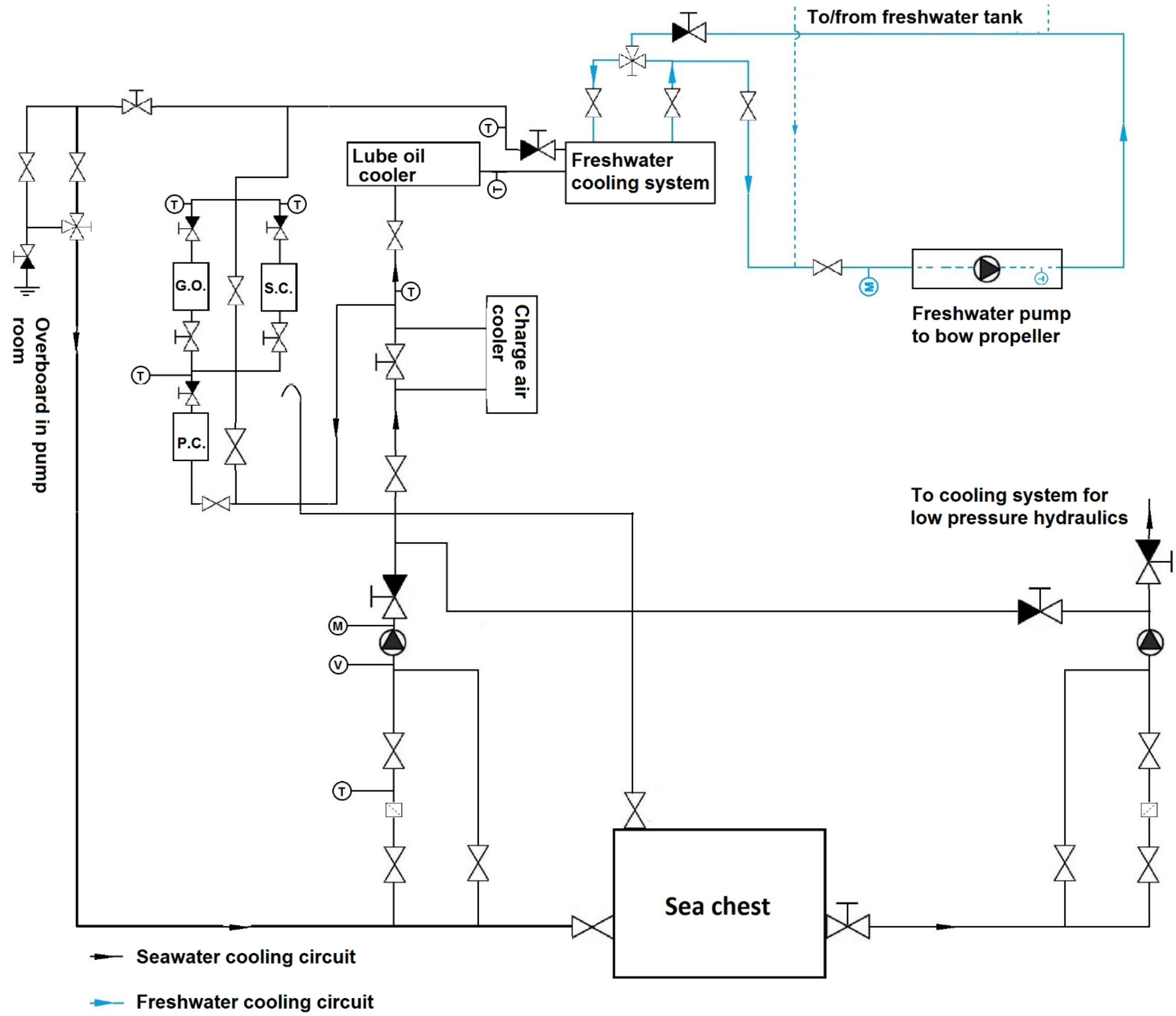


Figure 14. Sea and freshwater cooling circuit in the bow part of the vessel.

4.2.2 Lubrication oil system

Lubrication oil has mainly two functions, lubricating gliding surfaces and cooling various components, e.g. bearings and pistons. The oil is pumped from a draining tank, regularly placed underneath the engine. It is cooled by the seawater cooling system, filtered and supplied to the engine at appropriate pressure. Cascades of lubrication oil is poured onto the moving parts of the engine and then drained through the bottom into the draining tank.

The lubrication oil is important to avoid friction and extensive wear of the engine’s components. It is vital that the oil is clean, otherwise it may quickly loose its lubricating and cooling effect. Thus, the filters are central components for this system. The filters ensure that the lubrication oil contains a minimum of sediments and contaminants. Regularly cleaning the filters for deposits are necessary to avoid clogging of the system. However, one of the manometers would detect this, due to the resulting pressure drop in the circuit. Cooling from the seawater system is also of high importance since the viscosity of the oil decreases as the temperature rises. Lower viscosity means that the lubrication oil loses its initial lubrication effect and becomes too thin. By analysing sliding surfaces, Yuan et al. (2004) clearly showed that elevated lube oil temperatures increased the probability of both adhesive, and corrosion wear. Since a reduced lubrication effect greatly influences a rotating machinery containing multiple sliding surfaces, this system has to be reliable and operative whenever the connected engine is running.

The ship under consideration has a lubrication system in the bow as seen in the system illustration below. Applied icons are described in appendix C. There are two lubrication oil pumps for each thruster, both electrically driven. If the power supply to the operating pump should fail, a different switchboard will drive the standby pump. Thus, the latter pump should start automatically without interruption to the thruster. To equalize wear and prevent deterioration of the pump’s shaft seals, the on board crew switch between using the two of them. This provides analogous operating hours and ensures that the pumps are tested regularly. The system is equipped with manometers and thermometers, respectively checking that the lube oil’s pressure and temperature is kept within its performance standards. After the oil has lubricated the engine parts, a three-way valve checks its temperature. Based on the temperature values the valve passes the oil either towards the cooler or back into the circuit within the engine.

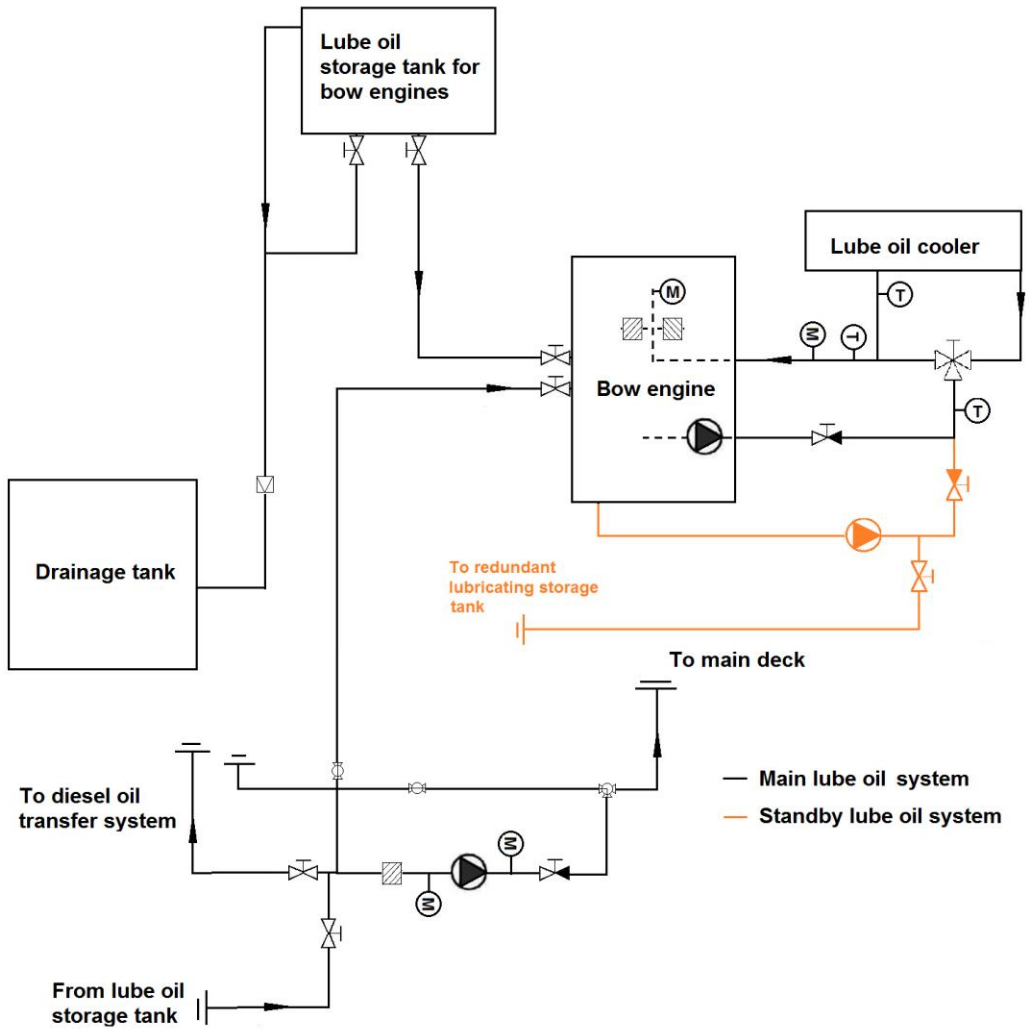


Figure 15. Lubrication oil system in the bow part of the vessel.

4.2.3 Fuel oil system

The vessel has been retrofit from operating on heavy fuel oil to utilize solely diesel fuel. The fuel oil system provides the engine with diesel fuel for the combustion process. A simplified system drawing is given in Figure 16. The main settling and service tanks are placed in the aft part of the vessel. Fuel oil is supplied from settling tanks, via purifiers to the service tanks. To enter the forward fuel system, the diesel oil flows via two transfer pumps passing the oil to the bow part from one of the aft starboard service tanks. The tank system is redundant, thus if one tank shuts down, another can take over to supply the forward engines. As with the lubrication oil, it is of significance that the oil is clean. Henceforth, the purifiers located in the aft part of the ship ensure that contamination by foreign objects and water is kept at a minimum.

Purified fuel oil flows to the forward diesel service tank where it is separated into two circuits, one flowing to the tunnel thruster engine and one to the retractable thruster engine located further in the same engine room. The forward service tank has a local sight glass, drain cock, level switch and a quick closing valve (QCV) on the outlet lines. The sight glass makes it possible for the operators to check the oil level of the service tank visually. If there is a humid environment inside the service tank, water is drained from it through drain cocks. The QCV fitted on each branch line from the tank is a safety measure in case of an emergency in the engine room, e.g. in the event of a fire. The two QCV's are grouped together such that a single activation will close both valves, shutting off all fuel supply to the forward thruster engines.

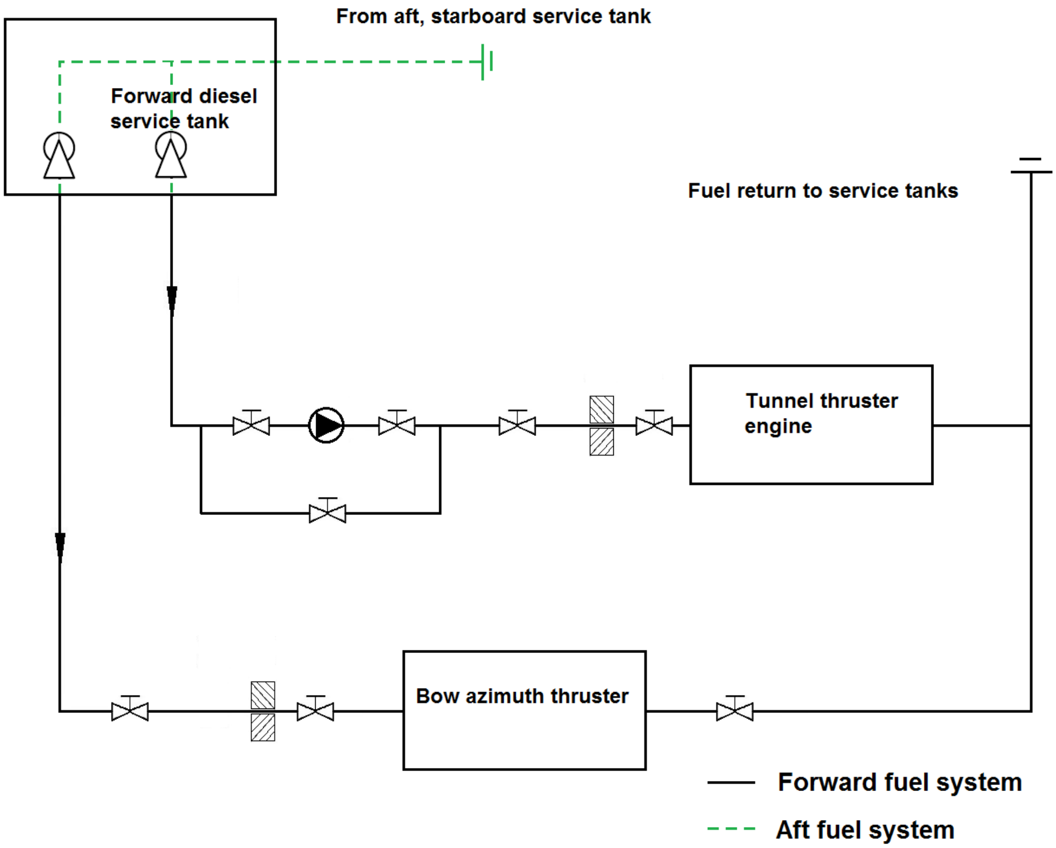


Figure 16. System illustration of the vessel's forward fuel oil system.

As a description the main system and its subsystems have been established, it is possible to perform an analysis of the equipment, following the stages described in chapter 3. To exemplify how the RCM procedure may be used for a machinery system, it has been performed for the tunnel thruster engine and its auxiliary systems, supposing that the vessel is in a DP situation. I.e. being a state at which the TT engine's function is vital. A maintenance program for the engine is the main result after the process. In addition, improved equipment knowledge and better reliability of the system is evident advantages of the procedure.

5 Results; RCM for tunnel thruster engine

5.1 Functions

The tunnel thruster's functions are evaluated in DP operating mode. During station keeping, the tunnel thruster is essential for manoeuvring the bow part of the vessel. It was installed to ensure that the vessel could keep its position at locations with challenging environmental conditions. Figure 17 displays the location of the TT engine. More extensive engine characteristics are presented in section 4.1.

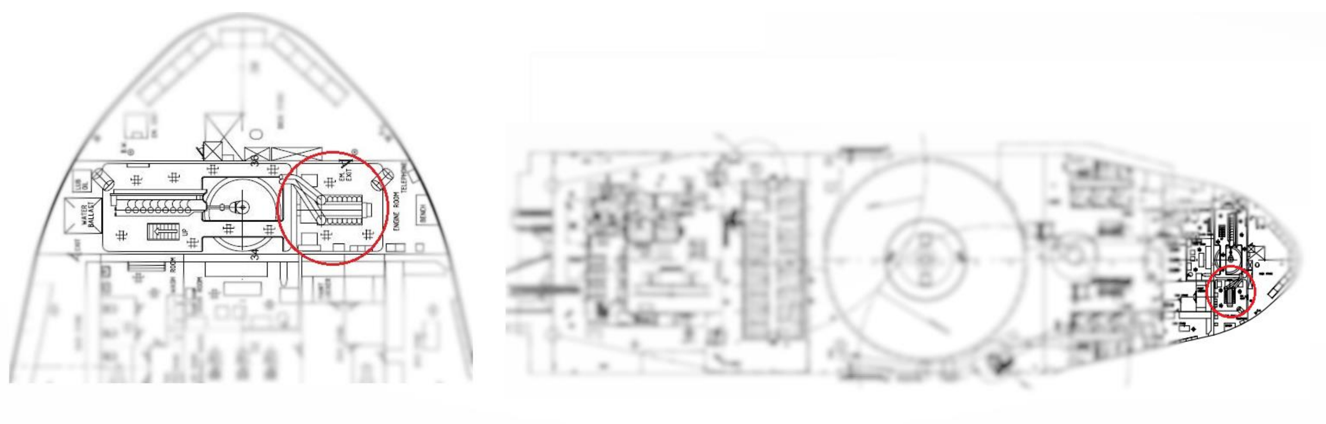


Figure 17. Excerpt from general arrangement, showing TT engine in the forward engine room.

5.1.1 Functional statement

The tunnel thruster (TT) engine generates 1140 kW of power. The power is transmitted through an alternator at 1800 rpm that in turn drives an electric motor. The electric motor drives the TT with a power of 960 kW at 892 rpm to station keep or manoeuvre the forward part of the ship.

5.1.2 Operating context

The TT engine is analysed under an operating condition, i.e. considered to be in DP state. The engine is located in the forward engine room, driving the TT via an alternator and electric motor. In the same engine room is the other bow engine, which is connected to azimuth thruster no. 2.

The TT propulsion system is fitted with equipment that has to handle humidity and constant vibrations from the ship and/or running engines. A main problem is therefore wear and tear on several components, as well as corrosion. Small leakages from diverse components occur regularly in the engine room, most likely due to old equipment and constant vibrations. However, due daily checks and several pressure and temperature detectors, bilge systems and high/low level alarms it has previously been detected in time (Chief engineer, May 2015). An annual DP trial report from 2014 showed that the TT engine's operating hours were 11210 hours, which is about 10 % of the noted value for the main engines (Anonymous external company, 2014). As the TT was installed later than the main engines and only runs in DP and manoeuvring situations, its operating hours are quite logical. The vessel operates on a global level. As a result, some of the auxiliary systems are affected when the vessel changes locations. In particular, the seawater cooling systems may experience an increased amount of microorganisms and fouling when operating in warmer waters.

The engine is generally equipped with several redundant solutions. The system illustrations listed in section 4.2 shows that the auxiliary systems have parallel branch lines fitted with redundant pumps and valves, which step in if the primary branch fails. The vessel has available spare parts that are essential if subsystems would fail, for instance pumps, valves and filters.

5.1.3 Primary and secondary functions, performance standards

The TT engine's primary function, secondary functions and performance standards are illustrated in Table 4.

Table 4. Primary function, secondary functions and performance standards for the TT engine.

<table>
<tr><th colspan="4">Duetz diesel engine</th></tr>
<tr><td>Primary function</td><td colspan="3">The engine generates power that is transmitted via an alternator</td></tr>
<tr><td>Secondary functions</td><td>Operate with appropriate temperature</td><td>Run with low friction between rotating parts</td><td>Run with effective fuel consumption</td></tr>
<tr><td>Performance standards</td><td>Generate 1140 kW</td><td colspan="2">Operate at 1800 rpm</td></tr>
</table>

5.1.4 Functional hierarchy

The functional hierarchy of the vessel's machinery and propulsion system is shown in Figure 18. The hierarchical placement of the TT engine and its auxiliary systems are marked in red.

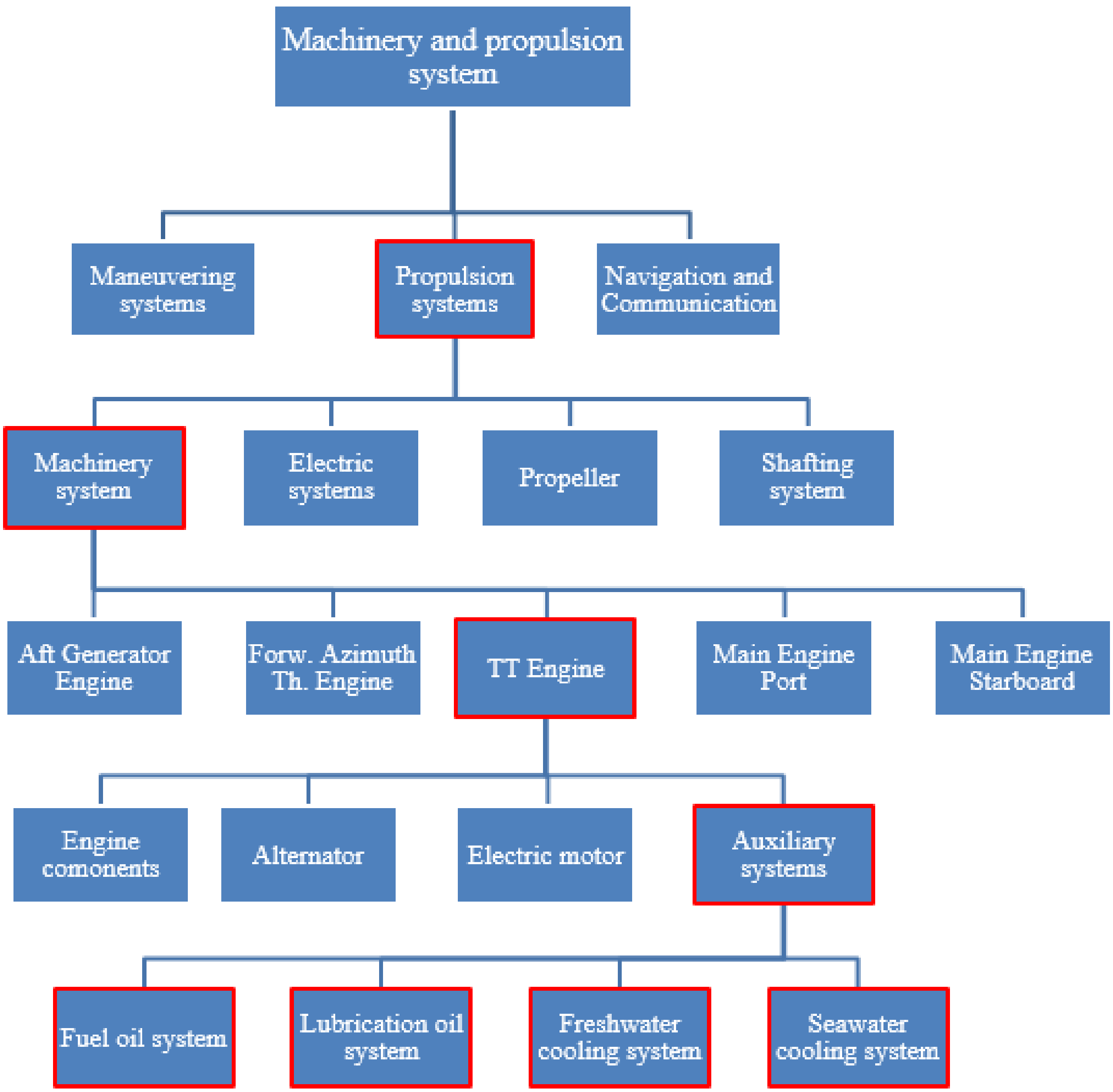


Figure 18. Functional hierarchy of the TT engine in its operational context.

5.2 Functional failures

Functional failures for the TT engine may occur if the engine fails in fulfilling its primary and/or secondary functions. Mainly four functional failures are considered as relevant for the TT engine:

1. Engine stops during operation (no major failure of engine component)
2. Engine runs at lower speed/effect than required during operation
3. Engine runs at higher speed/effect than required during operation
4. Engine stops due to major failure of a component part

The first functional failure is categorised in such way that it does not include a major failure of an engine component, which is covered by the fourth functional failure. This is done to distinguish between the two main failure modes that could cause the engine to stop, i.e. a failure of auxiliary systems or failure of an engine component part. These two functional failures demonstrate failure of the engine’s primary function. If the engine stops it cannot deliver power to the alternator and in turn, the electric motor connected to the TT will stop. When the vessel is in a critical state during DP operations, this is a highly unwanted consequence.

The second and third functional failures are connected to erroneous speed of the engine. These failures do not necessarily represent failure of the engine’s primary function, but can be connected to failure of secondary functions. For instance, incorrect speed of the engine does not provide effective fuel consumption, friction between moving engine parts may increase and the engine temperature may change in either directions.

The first functional failure, the engine stopping during operation is analysed further, presented in the succeeding sections. In a thorough RCM process, the three remaining functional failures should be included to preserve all required functions of the TT engine correctly.

5.3 FMECA

FMECA for the TT engine is structured in worksheets that include a diversity of parameters. Failure modes are listed, covering the different reasons for why the TT engine might stop, as well as effects considered as probable. The failure modes are divided into three levels of detail. This is done for establishing an appropriate database of what the independent causes for each failure mode might be. The level of detail concerning the failure modes enables identification of the appropriate maintenance tactics to apply.

Rasmussen (2003) and White (2008) suggests several failure modes especially connected to corrosion and erosion of pumps and pipelines that are utilized in the FMECA worksheets. Kim et al. (1996) discusses failure modes related to general material fatigue for components exposed to a flowing medium and/or continuous vibrations. These suggestions are also taken into consideration in the FMECA. In addition, system descriptions from Norwegian Shipowners' Association (1999) has contributed to clarify that essential equipment parts for each auxiliary system is included in the FMECA. Remaining failure modes were discussed and set at the RCM workshop described in section 3.7.1.

An intention behind the constructed worksheets is to concentrate on every listed failure mode, analysing the features of each one. This is done by evaluating failure patterns corresponding to those illustrated in Figure 10, propose an approximate mean time between failure (MTBF) as well as judge if the failure mode is hidden or evident. The MTBF is the proposed time at which failure happens if no maintenance activities are performed. Furthermore, the criticality of each failure mode is assessed in accordance with the consequence parameters defined in Table 2, section 3.4.3. For each consequence parameter the failure mode receives a number between 1-5. Combining this value with the MTBF, here utilized as the frequency, gives the risk index. Finally, the gathered information is applied in the decision tree process, as outlined in section 3.5.2. The suitable maintenance tasks are listed as the last point, even though this formally is a part of the maintenance task analysis. Thus, the resulting maintenance tasks are properly presented in chapter 5.4.

Table 5 shows the first part of the FMECA worksheet. The engine stopping during operation is highlighted, as this functional failure will be analysed further. Remaining functional failures are also listed, with an initial level of probable failure modes. Disregarding component failure, the first level of failure modes that cause the TT engine to stop are failure of the engine's auxiliary systems. This includes failure of either the seawater cooling system, freshwater cooling system, lubrication oil system or fuel oil system.

Table 5. Excerpt of FMECA for TT engine, including first level of failure modes.

Tunnel Thruster Diesel Engine		
Function	**Functional failure**	**Failure mode** **Level 1**
1. Duetz type MVM BA 16M 816C, a 2 stroke engine. The engine generates 1140kW of power at 1800rpm. 2. Drives the tunnel thruster, a Brunvoll propeller type	**1. Engine stops during operation (no major failure of engine component).**	**1. Seawater cooling system failure**
		2. Freshwater cooling system failure
		3. Lubrication oil system failure
		4. Fuel oil system failure
	2. Engine runs at lower speed/effect than required during operation	1. Fuel starvation
		2. Calibration failure
		3. Governor failure
		4. Software/hardware failure - control system
	3. Engine runs at higher speed than required during operation	1. Too much fuel oil
		2. Governor failure
		3. Software/hardware failure - control system
	4. Unforeseen catastrophic failure of a component part.	1. Engine bearings failure
		2. Crankshaft seizure
		3. Cylinder or piston failure

Appendices D1-D4 contain the created FMECA worksheets for the engine's auxiliary systems. Each worksheet is an extended version from the first level of failure modes that are highlighted in Table 5. In other words, each worksheet evaluates failure of the sea- and freshwater cooling systems, lubrication oil system and fuel oil system. The values listed under each consequence category equals the consequence value plus the frequency value, i.e. resulting in a risk index for each of the consequence parameters. The risk indexes listed in the second column from the right shows the highest value from the indexes given under each consequence parameter.

5.3.1 Failure of seawater cooling system

Failure of the seawater cooling system will eventually lead to an engine shutdown. As explained in section 4.2.1 is the seawater essential for cooling freshwater, lubrication oil and thruster control systems such as the pitch and steering. It is therefore mainly subsequent effects of having seawater cooling system failure that lead to the engine stopping. This may include reduced cooling from the freshwater leading to overheating of the engine or that reduced effect from other subsystems leads to excessive wear of the engine, such as reduced lubrication effect from the lube oil system. An illustration of the failure modes at different causation levels connected to the seawater cooling system is displayed in Figure 19.

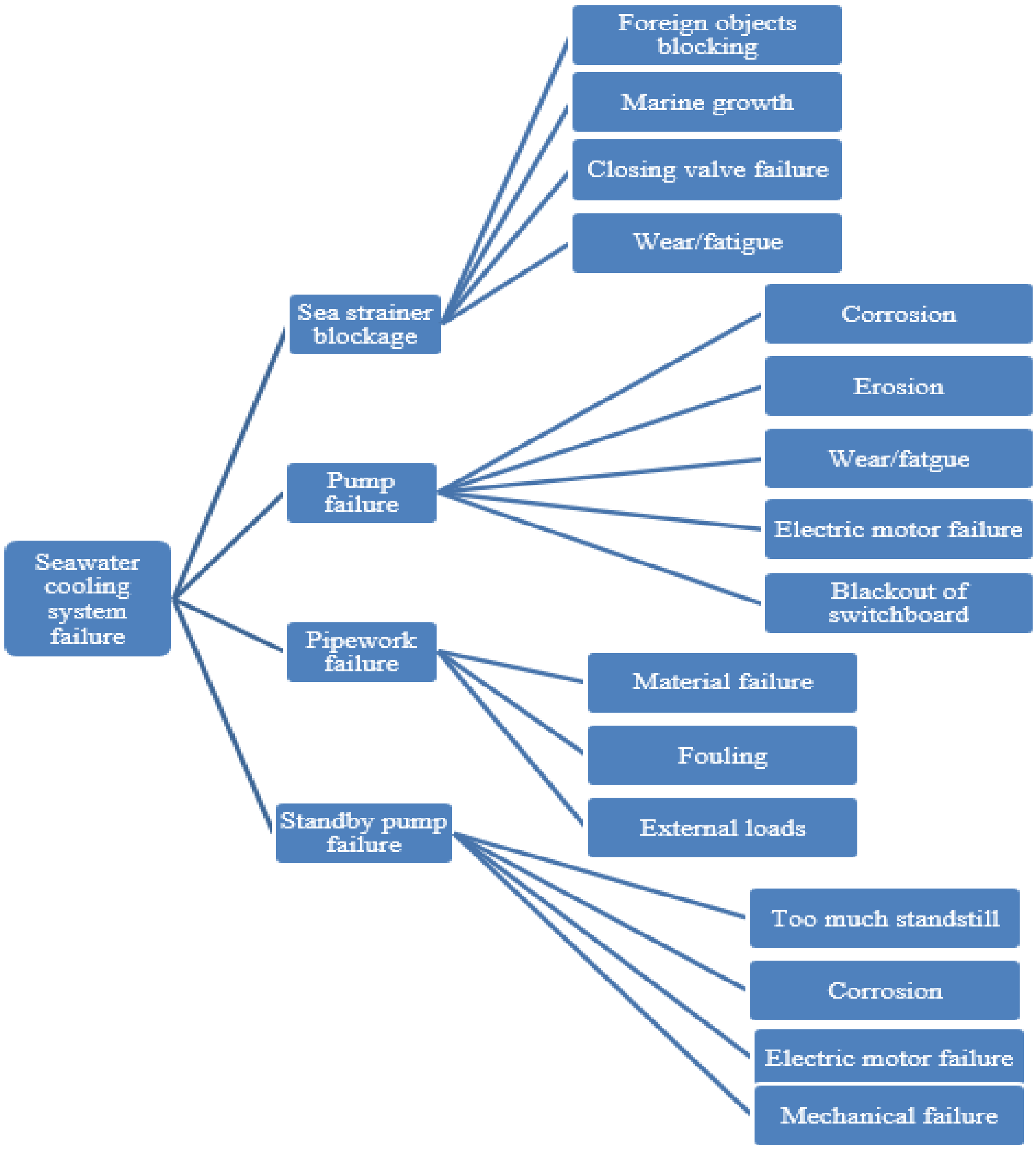


Figure 19. Failure modes connected to seawater cooling system failure.

Appendix D1 contain the entire FMECA worksheet connected to the seawater cooling system. Figure 19 illustrates that sea strainer blockage, single pump failure, pipeline failure or standby pump failure are failure modes at the second level. At the next level, established failure modes are corrosion, erosion and general wear or fatigue damage. If the sea strainer is blocked, the effects may be complete or partly stop of the seawater flow. In addition, larger objects can get into the system and create material damage or block the pipelines and pumps. Estimated effects following failure of the seawater pump are problems with the circulation of water and in worst case, completely stop of the water flow. Pump failure can happen if it is damaged, loses power from supporting switchboards or the electric motor fails. Effects connected to system pipework failure are pressure drop for the circulating water and reduced amount of water circulating. This also poses a risk towards a leakage of seawater in the engine room. However, the vessel has installed bilge alarms and manometers solely committed to detect leakages. The standby pump is a redundant solution, aiming to step in if the initial seawater pump fails. Yet, most standby pumps on board the vessel are utilized regularly to avoid mechanical damage due to lack of rotation and standstill operation.

Appendix D1 presents MTBF values that range between one year to ten years and more. The lowest values are typical for failure modes connected to the sea strainer, where sudden blockages and fouling may happen due to a marine environment. Next, electrical and mechanical failure modes receive MTBF numbers around 5 years. The remaining majority of failure modes occur in larger intervals, i.e. more than ten years between each failure.

The failure patterns are mostly of type B, meaning that the likelihood of the failure mode is age related. This includes failure modes that evolve after a certain time has passed, and then develops quickly. The table shows that this pattern is typically given to wear, corrosion, erosion and fouling occurrences. Failure pattern C is also utilized. This indicates a steady increase in the failure mode probability, but no distinct wear-out zone. Failure pattern E and D are not age related and are instead connected to failure modes that may occur at a more random point in time. These are listed for failure modes connected to electrical failure or sudden blockage of external objects in the sea strainer.

The risk indexes for each failure mode are generally low. Only closing valve failure and blackout of sub switchboards get a high score, both due to higher values for the cost consequence parameter. These failure modes are placed in the risk matrix on page 81. The remaining failure modes are not illustrated in the risk matrix as they all receive the lowest possible risk index.

5.3.2 Failure of freshwater cooling system

Appendix D2 contains FMECA results related to failure of the freshwater cooling system. From illustrations and descriptions in section 4.2.1, it is evident that this system is less complex than the seawater cooling system. This is reflected in the reduced number of possible failure modes listed for the freshwater system. The circuit of freshwater is shorter and in direct contact with the engine component. One might therefore say that compared to the seawater cooling system, a failure of the freshwater cooling has more of an immediate effect of the engine performance. If the cooling should fail completely, the engine gets overheated and shuts down.

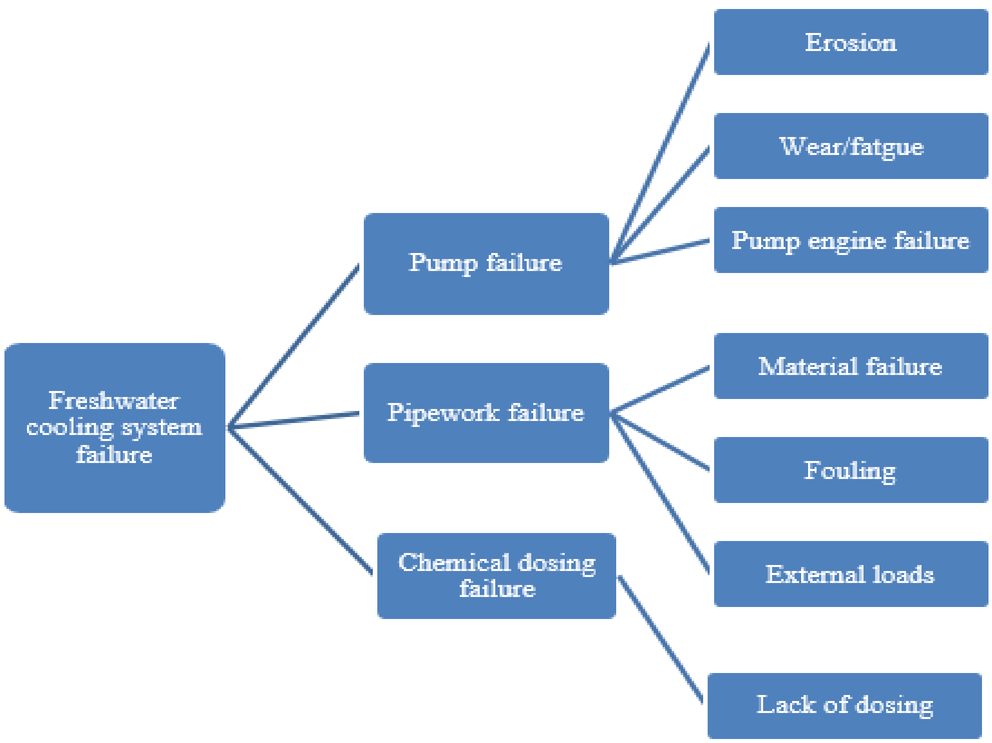


Figure 20. Failure modes connected to freshwater cooling system failure.

Figure 20 illustrates that failure of the freshwater cooling system may be caused by single pump failure, system pipework failure or chemical dosing failure. A standby pump system is not installed, hence the absence of such a failure mode. The freshwater pump may fail due to the same reasons as the seawater pump. Yet, it does not include corrosion, since the flowing medium is freshwater. System pipework failure has corresponding failure modes as those for seawater pipework, including material failure, fouling and external loads due to ship/engine vibrations. As there is a smaller amount of freshwater circulating, the effect of a leakage mainly poses a risk towards engine shutdown more than flooding the engine room. The freshwater receives chemical dosing to avoid corrosion and scale formation in the system. As listed, lack of dosing may lead to a diversity of corrosive attacks, cavitation and leakages.

The FMECA table in appendix D2 demonstrate that the failure patterns are mainly of type B, in particular failure modes connected to material failures and fouling. Failure pattern C is mentioned for vibration loads causing pipework failure. Failure of the pump engine and lack of dosing receives failure pattern D and E, which is not age related. This is mainly because the pump engine failure is often connected to relatively random electrical cuts, and lack of dosing is often due to unforeseen human error.

The only failure modes that are considered as hidden are connected to pump failure, either because of wear damage of pump or pump engine failure. Most of the risk indexes are low, but the failure mode considering lack of dosing receives slightly higher values, this because the freshwater is in direct contact with the engine. Consequently, lack of chemical dosing may also harm the engine's component parts and not only the cooling system. As the operating context is considered to be during station keeping, repairing the damages may be costly, time-consuming and lead to delay in operation. This is reflected in the risk index values for off-hire, costs and reputation.

5.3.3 Failure of lubrication oil system

If the lubrication oil system was to fail, it could lead to great friction damages to the engine. As the TT engine has several sliding and rotating parts, the lubrication oil plays a vital role to reduce the abrasion load on the engine components.

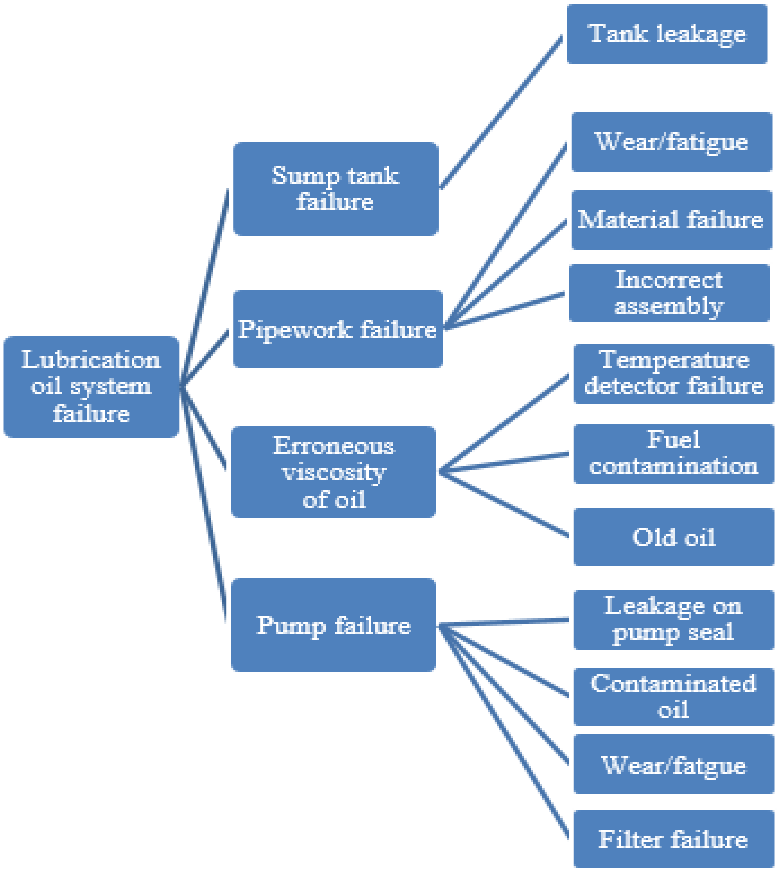


Figure 21. Failure modes connected to lubrication oil system failure

Appendix D3 contains the FMECA worksheet connected to failure of the lubrication oil system. Figure 21 shows that failure modes connected to this system are failure of attached pump, pipework failure, erroneous viscosity of lube oil and sump tank failure. Failure modes connected to pump failure differs somewhat from the water cooling pumps. The circulating oil may be contaminated and contain constituents that create more wear on other system parts, such as the pump. Filter failure and contaminated oil could cause a breakdown of the pump, leading to reduced lubricating effect and possibly an engine stop.

Failure modes for system pipework failure correspond to those presented in the previous worksheets, though incorrect assembly procedure is added as a potential cause. Such errors may happen during inspections or maintenance activities. When assembling work is done incorrectly, it may lead to stress loads in the pipes that increases the chance of cracks and fatigue damage. Another failure mode is erroneous viscosity of lube oil, which generally is most vital if the temperature of the oil gets too high. As a result, the oil becomes too thin and loses its lubricating effect. This may lead to excessive component wear, causing engine breakdown. Viscosity inaccuracies can be caused by temperature detector failure, fuel contamination or old oil. Contamination from fuel is often caused by a leaking fuel valve. Sump tank failure could lead to system failure as the tank is the main supply source for lubrication oil. The failure might happen due to a tank leakage; given that the tank's low-level alarm also fails.

Once more, the listed failure patterns in appendix D3 are dominated by category B. It is typically linked to failure modes with problems such as contaminated oil, material failure and assembly error. C is also an age-related pattern that is listed, hereby connected to wear damage on the attached lube pump. Pattern E is set for failures of the temperature detector and sump tank, indicating that these failure modes happen at a random basis. In this case setting a value for MTBF is challenging. However, with expert opinions from WSM it was decided that these failure modes are rare, hence given MTBF values of ten years or more for both failure modes.

Failure modes connected to the lubrication oil's purity are considered as hidden, i.e. filter failure, old and contaminated oil that damage the pump and contribute to erroneous viscosity. The remaining failure modes are evaluated as evident. Furthermore, the risk indexes connected to the hidden failure modes obtain higher values, generally due to their relatively short MTBF interval. The lubrication oil is in contact with several engine parts and is dependent on being cleaned regularly. As a result, it is constantly vulnerable towards contamination, explaining why the MTBF interval is shorter. Dealing with contaminated lube oil could become costly, hence the higher values for this consequence parameter. Sump tank failure is not likely to occur frequently, but may have greater consequences towards off-hire and costs.

5.3.4 Failure of fuel oil system

A fuel oil system failure directly affects the engine as it loses its provision of fuel, leading to problems with the combustion process. A leakage of fuel in the engine room is also hazardous considering the risk of fire. The complete FMECA table connected to failure of the fuel oil system is given in appendix D4.

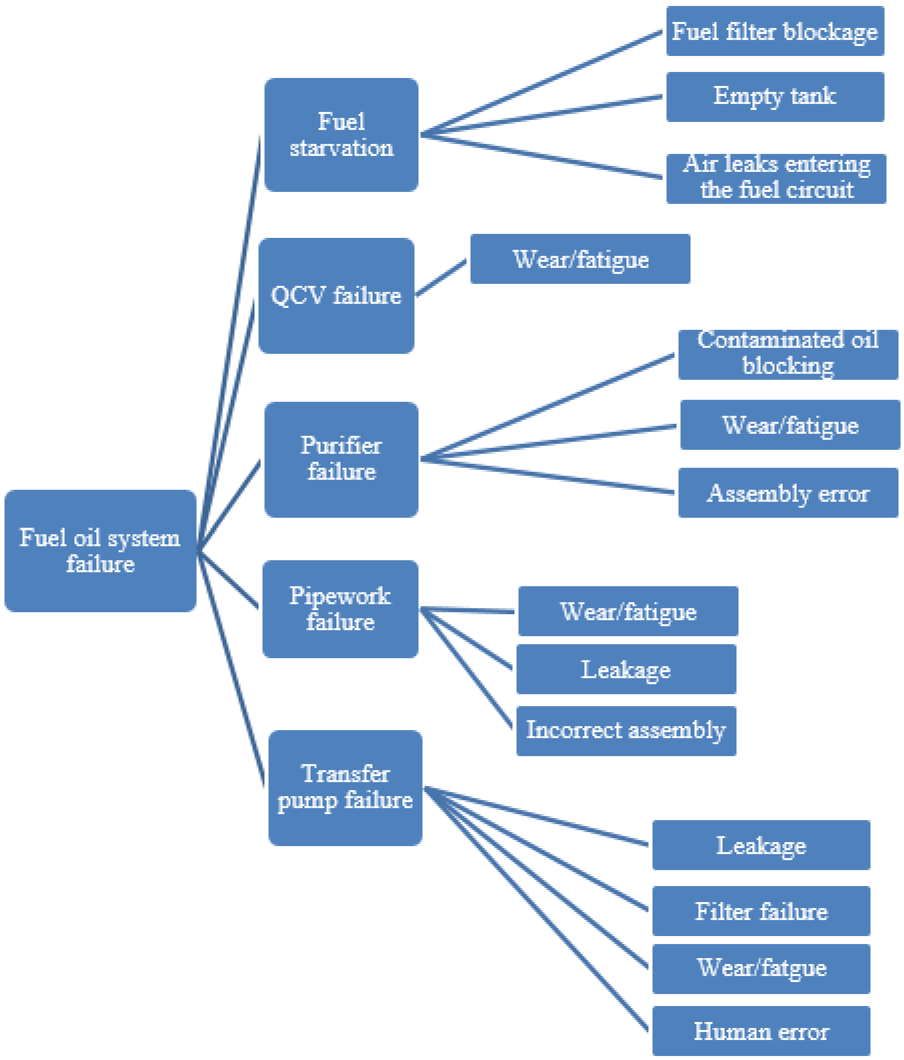


Figure 22. Failure modes connected to lubrication oil system failure.

Figure 22 shows that the system may fail due to fuel starvation or failure of the purifier, pipework, transfer pump or QCV. Fuel starvation can happen by fuel filter blockage, empty tank or air leaks in the fuel circuit. The fuel filter and service tank are both fitted with alarm equipment that helps prevent functional failure. The equipment includes an indicator showing the pressure drop through the filter and for the service tank; a sight glass physically showing the fuel level of the tank and a low-level alarm. I.e. these must also fail for obtaining full effect of a fuel starvation. Air leaks may lead to irregular combustion and varying RPM of the engine, eventually causing the engine to stop.

When the purifier fails, water and unwanted particles are not separated from the fuel. If so, the fuel is typically circulated back to the settling tanks and not supplied to the engines due to its low quality. In this case, as the fuel purifiers are in the aft of the vessel, the fuel would not be transferred to the forward engine room at all. Purifier failure may be a result of blockage, general wear damage or assembly error. The latter may also cause leakage of either water or fuel from the purifier.

Pipework failure may occur due to the same reasons as for the lubrication system. It is listed that the risk of fire in the event of pipeline leakage is small as the circulation pressure of the fuel is relatively low, approximately 2-3 bar. Additionally, the engine room is equipped with bilge alarms that should detect a potential leakage or flooding.

Transfer pump failure is generally critical, as the forward service tank that supplies the two forward engines would not receive any fuel. However, as the system is redundant, both pumps have to fail to attain full effect of this failure mode. The transfer pump may fail due to a leakage, filter failure, fatigue or human error. By filter failure, the pumps may partly work. Yet, it would be more time-consuming and the transferred amount of fuel would be reduced. Human error is listed as a potential failure mode because the transfer pumps work manually. An essential component is the QCV connected to the fuel circuit. If this malfunctions, the fuel will enter the engine in spite of it being unwanted. The valve is therefore tested regularly, as a malfunction poses a risk especially in the event of a fire.

The failure modes presented in appendix D4 have failure patterns of type B, C and E. Failures connected to wear and fatigue, filter damage, assembly errors and leakages are of sort B. Pattern C is only set to QCV malfunctioning, indicating a steady increase in the probability of failure occurring. Type E is connected to human error, empty service tank, contaminated oil blockage and air leaks in the fuel circuit. Blockage of the purifier due to contaminated oil and mechanical failure of the QCV is listed as hidden failures. The MTBF values vary between five months to more than ten years. The risk indexes obtain higher values for failure modes with MTBFs less than two years. This can be observed for fuel filter blockage and wear of the purifier. Assembly error and wear connected to the purifier obtain higher values on all consequence parameters. This is connected to the potential high cost and time-consumption caused by failure of the purifier. Additionally, it can lead to consequences within the reputation category if operation is delayed. Filter failure related to the transfer pump also has higher risk values due to similar reasons. Empty tank receives slightly higher risk index for off-hire. This is mainly because the failure mode might lead to downtime, especially if the tank is empty due to external damage.

5.3.5 Risk matrix

The risk matrix below shows the failure modes that obtained highest risk indexes in the FMECA worksheets. Notations for each failure mode corresponds to those that was utilized in the FMECA, whereas SW, FW, LO and FO denotes seawater cooling, freshwater cooling, lubrication oil and fuel oil, respectively. I.e. SW: a.3 refers to closing valve failure in the seawater cooling system. The majority of the remaining failure modes obtained low risk indexes, not illustrated in the risk matrix for simplicity reasons.

		1	2	3	4	5
	Consequences → Frequency ↓	**Negligible**	**Minor**	**Moderate**	**Significant**	**Severe**
5	**Very high (daily/weekly)**					
4	**High (once a month)**					
3	**Medium (twice a year)**					
2	**Low (less than every year)**			LO: c.3 FO: b.2 FO: b.3	LO: a.2 LO: a.4 LO: c.2	
1	**None (less than every 2 years)**				FW: c.1	SW: a.3 SW: b.4

Figure 23. 5x5 risk matrix illustrating the failure modes with highest risk indexes.

5.4 Establishing activities in the maintenance program

The last column of the FMECA worksheets presented in the previous section show proposed maintenance activities connected to each failure mode. By utilizing the decision tree given in chapter 3.5.2 it was possible to establish suitable maintenance activities for each failure mode. As a result, the maintenance actions are a combination of corrective and preventive means. The distribution of maintenance tasks is displayed below.

Many failure modes receive the maintenance sort ‘run to failure’. Specifically, this allows the failure mode to take place. I.e. maintenance actions to restore the component to its initial state are only executed after the failure mode has occurred. In general, hidden failure modes do not fit for this sort of maintenance. This is because such failures are likely to be detected at a delayed time, and by then potentially have caused extensive damage. It is therefore logical that the decision tree process resulted in no hidden failure modes receiving ‘run to failure’ maintenance tasks. A majority of the remaining maintenance actions are categorised as condition monitoring. Just a few failure modes are connected to functional testing, periodic overhaul/replacement and restoration.

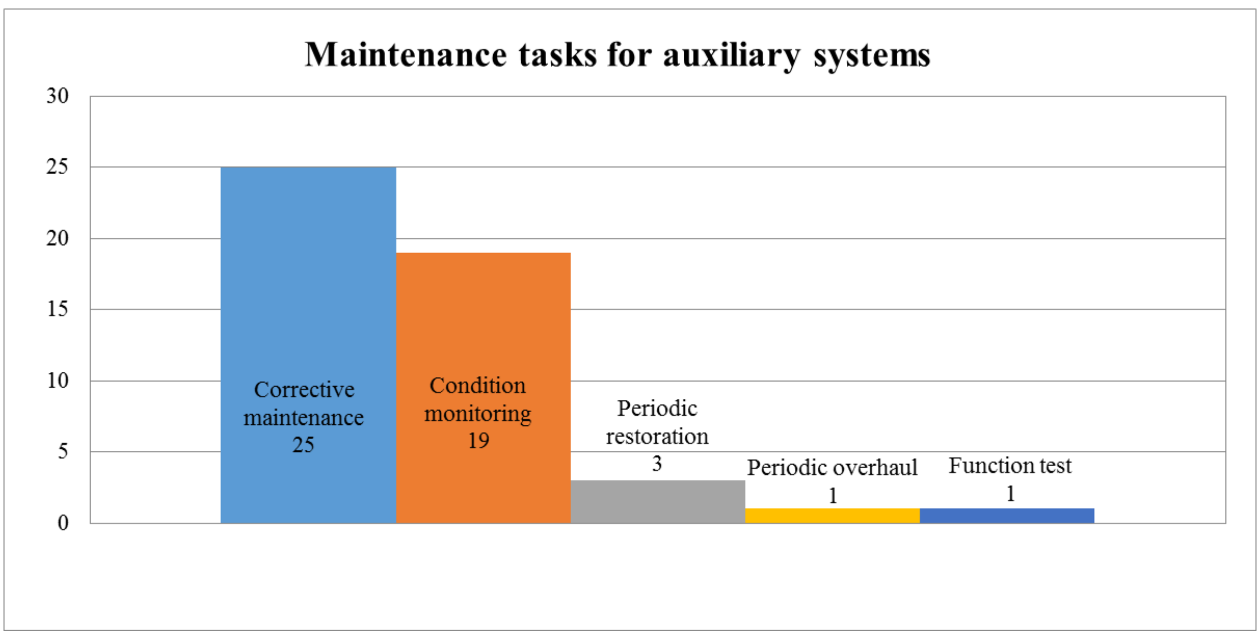


Figure 24. Chart showing the distribution of activities in the maintenance program.

Run to failure maintenance tasks is mainly dependent on spare part management. This is apparent since the decision of applying these actions in the first place, is based on the idea that it is safe and economically efficient to let the item fail instead of using preventive means. In other words, spare parts must be available to replace the component or its parts when it fails. The remainder of maintenance tasks are considered as preventive. Applying this sort of maintenance necessitates more planning concerning how and when the activities should be executed.

Table 6 to Table 9 show the proposed maintenance strategy meant for the auxiliary systems covered by the FMECA. Failure modes are referred to using the notation from the FMECA worksheets in the previous sections. The tables list maintenance tasks, a description of the procedure and the time intervals by which the maintenance should be executed. In addition, failure patterns and risk indexes from the worksheets presented in the previous section is included to better perceive the correspondence between these parameters and the maintenance that was chosen.

Table 6. Maintenance tasks description for the seawater cooling system.

Maintenance tasks for seawater cooling system					
Failure mode	**Maintenance task**	**Maintenance task description**	**Maintenance interval**	**FP**	**RI**
a.1	Run to failure	When pump delivery pressure is falling and/or temp. is rising check strainer for blockage, clean the strainer from objects.	-	E	2
a.2	Run to failure	Remove the marine growth physically or with chemicals.	-	E	2
a.3	Overhaul/replace	Change valve with a new one	Every 5th year	C	6
a.4	Condition monitoring	Perform water flow measurements, a performance standard must be established when strainer is clean. Deviating flow (less) indicates blocked strainer.	Every 5th year	B	2
b.1	Periodic restoration	Open pump, visually check for corroded elements in the pump, and renew elements if corrosion has occurred.	Every 5th year	B	2
b.2	Run to failure	Change pump/eroded pump parts.	-	B	2
b.3	Condition monitoring	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters, avg. output from each filter measured successively.	Every 5th year	B	2
b.4	Run to failure	Repair from chief electrician	-	E	6
b.5	Condition monitoring	Vibration measurements, frequency analysis - Fast Fourier Transformation of data.	Every year	D	2
c.1	Run to failure	Change pipework, repair holes that leak seawater	-	B	2
c.2	Run to failure	Remove fouling with marine growth chemicals.	-	B	2
c.3	Run to failure	Repair damaged pipework, consider pipework dampers	-	C	2
d.1	Run to failure	Change pump parts that is damaged due to a static load	-	B	2
d.2	Periodic restoration	Open pump, visually check for corroded elements in the pump, and renew elements if corrosion has occurred.	Every 5th year	B	2
d.3	Condition monitoring	Vibration measurements, frequency analysis - Fast Fourier Transformation of data.	Every year	D	2
d.4	Condition monitoring	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters , avg. output from each filter measured successively.	Every year	B	2

Table 7. Maintenance tasks description for the freshwater cooling system.

Maintenance tasks for freshwater cooling system					
Failure mode	**Maintenance task**	**Maintenance task description**	**Maintenance interval**	**FP**	**RI**
a.1	Run to failure	Change pump/eroded pump parts.	-	B	2
a.2	Condition monitoring	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters , avg. output from each filter measured successively.	Every year	B	2
a.3	Condition monitoring	Vibration measurements, frequency analysis - fast fourier transformation of data.	Every year	D	2
b.1	Run to failure	Change pipework, repair holes that leak freshwater	-	B	2
b.2	Run to failure	Remove fouling with marine growth chemicals.	-	B	2
b.3	Run to failure	Repair damaged pipework, consider pipework dampers	-	C	2
c.1	Condition monitoring	Perform freshwater sampling	Every 3rd month	E	5

Table 8. Maintenance tasks for lubrication oil system.

Maintenance tasks for lubrication oil system					
Failure mode	**Maintenance task**	**Maintenance task description**	**Maintenance interval**	**FP**	**RI**
a.1	Run to failure	Change pump seal when leak is detected	-	B	2
a.2	Condition monitoring	Mesh obscuration particle counter Oil passes through each mesh and particles bigger than the pores are stuck in the mesh. Sensors measure the pressure change.	Every month	B	6
a.3	Periodic restoration	Repair damaged seals and bearings, change damaged impellers	Every 2nd year	C	2
a.4	Condition monitoring	Mechanical indicator showing the pressure drop through the filter	Every month	B	6
b.1	Run to failure	Change pipework, repair holes that leak lubrication oil	-	B	2
b.2	Run to failure	Change pipework, repair holes that leak lubrication oil	-	B	2
b.3	Run to failure	Repair damaged pipework, consider updating/evaluating training and work procedures	-	B	2
c.1	Run to failure	Change temperature detector	-	E	3
c.2	Condition monitoring	Mesh obscuration particle counter -Oil passes through each mesh and particles bigger than the pores are stuck in the mesh. Sensors measure the pressure change.	Every month	B	6
c.3	Condition monitoring	Direct reading ferrography – quantitatively measure the concentration of ferrous particles by subjecting an oil sample to a strong magnetic field.	Every 2nd month	B	5
d.1	Run to failure	Change low level alarm and repair hole in the tank	-	E	4

Table 9. Maintenance tasks for fuel oil system.

Maintenance tasks for fuel oil system					
Failure mode	**Maintenance task**	**Maintenance task description**	**Maintenance interval**	**FP**	**RI**
a.1	Condition monitoring	Mechanical indicator showing the pressure drop through the filter - pressure drop indicates clogging of filter.	Every 2nd month	B	3
a.2	Run to failure	Repair leakage of tank, change low level alarm, clean sight glass	-	E	3
a.3	Run to failure	Perform valve inspection and check if they are properly closed	-	E	2
a.4	Run to failure	Evaluate training and procedures for fuel oil transfer, consider automatic pumps that are triggered by low level signal from forward day tank	-	E	2
b.1	Condition monitoring	Detectors measuring amount of water, flow and back pressure (already installed, due to requirements from class	Every day	E	2
b.2	Condition monitoring	Detectors measuring amount of water, flow and back pressure (already installed, due to requirements from class	Every day	B	5
b.3	Condition monitoring	Detectors measuring amount of water, flow and back pressure (already installed, due to requirements from class	Every day	E	5
c.1	Run to failure	Change pipework, repair holes that leak fuel oil	-	B	2
c.2	Run to failure	Change pipework, repair holes that leak fuel oil	-	B	2
c.3	Run to failure	Perform valve inspection, inspect crossings, change damaged parts	-	B	2
d.1	Run to failure	Change pump, repair/close holes in pump	-	B	2
d.2	Condition monitoring	Mechanical indicator showing the pressure drop through the filter	Every 6th months	B	4
d.3	Condition monitoring	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters avg. output from each filter measured successively.	Every year	B	2
e.1	Condition monitoring	Mechanical indicator showing the pressure drop passing the valve, pressure drop may indicate wear	Every 5th year	C	2
e.2	Functional testing	Test if the QCV works by closing and opening it regularly	Every year	C	2

The maintenance tasks for each auxiliary system are roughly explained in the tables to obtain a clear understanding of how the failure modes can be treated. The maintenance procedures particularly connected to CM are inspired by techniques outlined by Moubray (1997), Rasmussen (2003) and Chimples et al. (1979). The proposed CM techniques aim to handle and prevent each relevant failure mode from occurring in a best possible manner. Procedures in the maintenance plan can easily be updated if it turns out that a different maintenance approach is a better alternative.

The interval at which CM is planned uses data from the FMECA, setting the execution time for CM to be shorter than the MTBF for the relevant failure mode. This is done to enable discovering the failure mode before it occurs. Additionally, the created CM intervals are thought to detect larger deviations from the system's initial condition. The concept is illustrated on Figure 25. CM carried out at a later point along the P-F curve makes it easier identify specific symptoms of failure. Monitoring at an earlier time creates smaller deviations, making it necessary to have sensitive monitoring techniques. Yet, performing CM closer to the point at which failure occurs gives a smaller P-F interval. This gives the operators less time to react if a potential failure is detected.

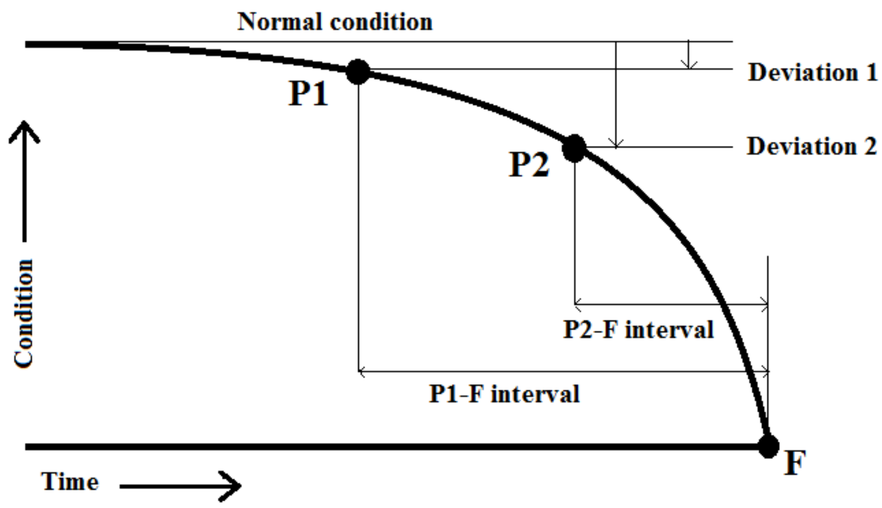


Figure 25. P-F intervals and deviations from normal conditions in accordance with Moubray (1997).

Despite the disadvantages and risk in waiting longer between the CM actions, it is considered to suit this particular system. This is because the TT engine is not considered as the most vital machinery part to loose, and there exist spare parts to replace most of the equipment. Pushing the interval for CM is therefore more cost efficient because you achieve extended time intervals of maintenance actions and since it is possible to utilize monitoring equipment that measure more coarse data. Yet, one of the advantages of the maintenance plan is its dynamic composition. This means that the maintenance interval not only can, but also should be updated throughout a system's lifetime.

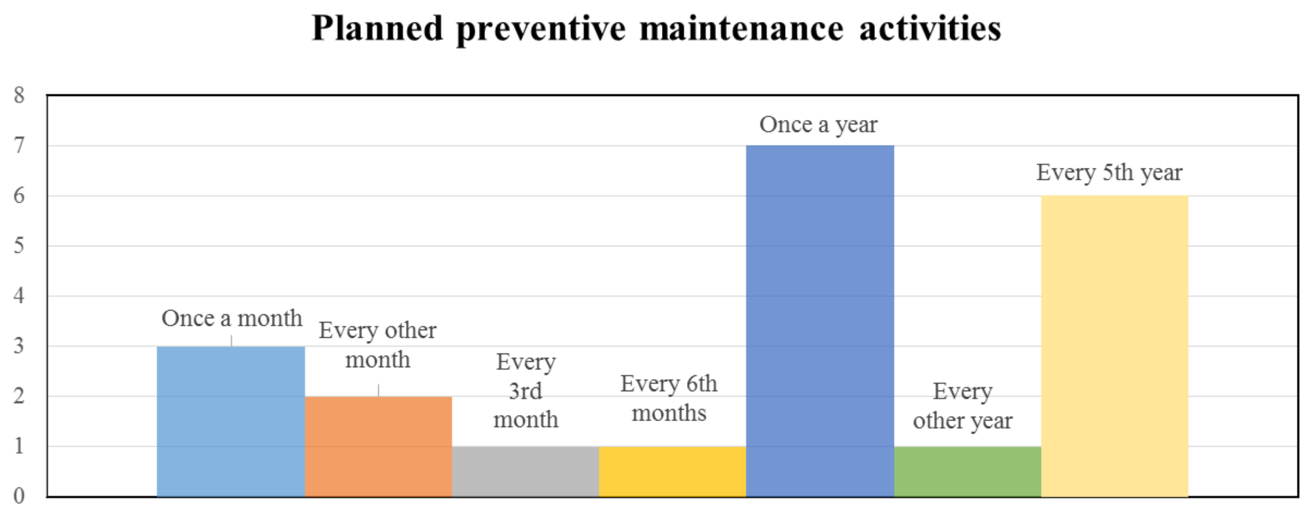


Figure 26. Chart of planned preventive maintenance.

Results from the maintenance plan can be presented in several different ways. It may also be used to analyse the maintenance program and the equipment further. For instance, Figure 26 displays the amount of planned preventive maintenance activities in relation with their time interval. This makes it simple for the maintenance management to understand the activity amount as well as how often preventive maintenance tasks are executed. A natural continuation could be to look at the time it takes for performing the maintenance tasks, as well as evaluating which tasks that can be done while the ship is in transit to avoid downtime connected to the maintenance.

Additionally, performing a cost-benefit analysis would be suitable to estimate whether the maintenance program is cost efficient. Due to lack of input data, it was not possible to complete such analysis for the proposed maintenance program. Yet, Glesnes (2015) has provided a case study from Karsten Moholt, demonstrating how maintenance costs and possible savings could be calculated by comparing a traditional maintenance program to a new one. The specific case study focuses primarily on the benefits of implementing condition monitoring for thrusters. Moreover, the case study evaluates how maintenance costs can be reduced by extending the maintenance interval if applicable, as discussed in section 2.2 and supported by Knödlseder (2015). The calculations are presented in appendix G. There might be inaccuracies in the performed calculations, as the numbers are only approximate. On the other hand, it demonstrates appropriate steps to do a cost evaluation. By exchanging the input data with relevant maintenance cost data from WSM, it would be possible to perform a similar analysis for the TT engine and its auxiliary systems.

A continuation to make the maintenance program more efficient is to outline and systemize which maintenance tasks that can be performed simultaneously. In appendices E1-E3, worksheets for a maintenance package plan is outlined. These worksheets include a more thorough explanation of each preventive maintenance task procedure, specification of tasks categorised within the same maintenance package, which packages or tasks that can be performed at the same time, as well as suggested crew and equipment to include in the process. Additionally, a complexity level is proposed to indicate how demanding the procedure might be.

Documentation given in appendices E1-E3 makes the plan more compact. In addition, it should be utilized as an explaining appliance, ensuring that each maintenance package is properly understood. Outlining a maintenance program might often be completed by personnel that do not execute the maintenance. Therefore, it is of great importance to present the maintenance program in a logical manner, making it easy to interpret for all personnel involved in the execution process. I.e. the program is outlined to also enhance planning and execution, being other elements in the overall maintenance strategy, as discussed in section 2.1.

Additionally, it is essential to facilitate good communication and exchange of experience between the planning and execution personnel. In a maritime context, this classically holds for the relationship between the people working on- and offshore. Typically, the onshore personnel in the maintenance management are responsible of outlining and planning the maintenance and crew on board the vessel execute the planned maintenance tasks. In this context, the maintenance package plan in appendices E1-E3 are thought of as documentation for the maintenance management onshore, responsible of the planning. A manner of simplifying the results from these worksheets towards the on board crew is illustrated in the package plan below.

Figure 27. Schedule for executing maintenance packages.

Figure 27 presents a schedule that can be utilized on board the vessel. It clarifies in a comprehensible manner when the maintenance packages should be executed, in addition to illustrating which ones that can be done simultaneously. The schedule is drawn for a period of five years. As time goes by, the plan should be updated if the maintenance tasks or time intervals needs to be adjusted. To complete such changes, input related to the initial plan should be available. Ideally, such information is best given by personnel that utilize the maintenance plan, i.e. the on board crew.

Tailoring the maintenance task documents for the on board crew may facilitate better exchange of information related to the condition of the equipment and status of the maintenance plan. Additionally, it can help increase the crew's motivation and understanding of the planned activities. This can be obtained by using the setup and results from the RCM procedure. Wang et al. (2010) supports this by stating that the full benefit of utilizing RCM is only achieved by including the ship-staff, contributing with their competence and experience of the equipment.

Appendices F1-F3 contain a proposed layout of maintenance report documents. These are meant for the on board crew in charge of accomplishing the maintenance packages. The documents utilize the established knowledge from the RCM process to enhance the understanding of why the maintenance tasks are performed and what the potential hazards of not doing the planned procedures could be. Table 10 shows an excerpt of the on board maintenance sheet connected to maintenance package 1. The complete sheet is presented in appendix F1.

Table 10. Excerpt of maintenance task sheet for on board crew.

Maintenance task sheet, for on board crew					
Maintenance task	**Activity executed to (failure mode):**	**Because (effect):**	**Possible consequence:**	**Report/Feedback**	**Interval**
1.1 CM on attached pump, lubricating oil system	Prevent contaminated lube oil	You get an increase of the wear on the engine's rotating parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Once a month
1.2 CM on attached pump, lubricating oil system	Prevent filter failure in lubricating oil system	You get dirty oil that increase the wear on the engine's rotating parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Once a month

The maintenance tasks are categorised by using the same notations as presented in the maintenance package sheets in appendices E1-E3. Failure modes established in the previous stages of the RCM process are presented to show what the specific maintenance tasks should prevent. The following column explains the possible effects to provide awareness of the reasons for why maintenance is done. The next column describes potential consequences to give an impression of what the outcomes might be if the task is not executed. A report/feedback column is included to suggest aspects and parameters that the maintenance crew should record to keep the maintenance program updated.

Overall, it is clear that the RCM procedure has created a basis for a maintenance program that includes a long-term plan of maintenance activity, which again can and should be updated by relevant personnel.

6 Discussion

6.1 Evaluation of the RCM procedure in a maritime context

The results have showed that studying engine stop due to failure of an auxiliary system created an analysis that mainly concerned the subsystems in the last stages of the RCM procedure. I.e. the TT engine and its main components were not examined much further in the analysis. Other functional failures could have been studied during the RCM workshop, such as too high/low engine speed or engine component failure. As a result, the analysed equipment would have become completely different. Yet, the RCM procedure that has been demonstrated for the auxiliary systems is just as applicable for the remaining functional failures. That is, the structure of the presented analysis has created a framework that could be used as a guideline for additional equipment. This feature of the RCM practice is clearly advantageous. It facilitates an extension of the analysis to include all engines of the vessel, which would be appropriate in a complete RCM analysis. These results could then be transferred to similar vessels of WSM's fleet.

This corresponds well to the indicated adaptability of the method, discussed in section 3.6. However, section 3.6 also highlights that in a maritime context it is important to remember that a change in operational context can influence the maintenance program largely. Logically, this would be important to consider for WSM as well, especially if the practice were to be used on another operating vessel or system on board.

It took one workday to cover merely one functional failure connected to a single engine, i.e. referring to the RCM workshop. Consequently, it is evident that it would require a great deal of resources to analyse the remaining failures of the engine, and even more if other engines were included. Rausand (1998) avoids taking an extensive amount of equipment through all stages of the RCM process by suggesting to include a critical item selection before the FMECA. Another alternative approach to reduce the use of time and resources is discussed by Mokashi et al. (2002). This is to use Pareto's 80-20 principle. Roughly, the method consists of analysing all failures that have occurred during a fixed period with somewhat steady operating conditions. Twenty percent of the failures leading to eighty percent of the overall operating risk are picked out and analysed further. Out of these failures, twenty percent of the systems causing eighty percent of the failures are then selected for a proper RCM analysis. The authors Mokashi et al. (2002) claim that using this principle leads to concentrating limiting resources on the most troublesome failures in an efficient manner. In other words, it may be an appropriate tactic to make the RCM analysis less extensive.

An underlying effect has shown to become increasingly transparent after working systematically through the RCM procedure. This is how the process makes people recognise the actual function and importance of specific systems and its connected equipment. Even though it requires both time and resources, working through the RCM practice methodically in cooperation with relevant personnel, suits the maintenance strategy demonstrated in section 2.1. The process facilitates a clear shift towards emphasizing the reason for why specific maintenance tasks are performed. This is a contrast to simply accepting the maintenance tasks as the manufacturer outlines them. Overall, this can be connected to the value of double-loop learning.

Argyris and Schön (1996) comprehensively discuss the theories related to single and double loop learning in an organisation. Single-loop learning is the most common learning style, when a management modifies its strategy or action based on results from its previous actions. On the other hand, double-loop learning goes further and modifies the theory that underlies the action. In the thesis' context, single-loop learning is typically related to the traditional approach towards managing maintenance in the maritime sector. However, by utilizing the RCM practice it is clear that underlying reasons for planning and executing the maintenance tasks would become evident. Furthermore, double-loop learning allows the maintenance management to act proactively in a much more efficient manner, instead of passively utilizing preventive means without actually knowing if it suits the equipment.

6.1.1 Evaluation of FMECA worksheets

Overall, the FMECA worksheets contain most of the analysis data related to the equipment. The worksheets systematically show how components within each auxiliary system may lead to engine stop. It has created a top-down perception of how a functional failure may occur by different levels of failure modes. When studying effects and consequences, each failure mode has been addressed and not only the functional failure. I.e. for the seawater cooling system, each failure mode at the lower level is analysed instead of simply looking at the subsequent events of failure by the cooling system. This makes the FMECA structure more complete. Yet, as discussed in section 3.1.2, it requires a lot of time and the results may be perceived as slightly overwhelmingly considering the amounts of information.

The presented results have established maintenance tasks that consistently aim to handle the sources of a potential failure, which is the best way of proactively avoid the failure from occurring in the first place. Scheduling maintenance by only looking at the functional failures increases the possibility of planning inappropriate maintenance tasks. Specifically, this may result in maintenance that either is unfit for the considered equipment, measure useless parameters or overlook important indications of the condition of the equipment. E.g. establishing maintenance tasks for detecting corrosion in the seawater pump (failure mode) is a much more consistent action, compared to outlining maintenance tasks to prevent failure of the TT engine (functional failure) as a whole.

Yet, the FMECA results contain a slightly unexpected outcome related to the detail level of the failure modes. As discussed in section 3.7, evaluating consequences and risk indexes for each failure mode was accomplished during an RCM workshop. Consequently, by using WSM's expert opinion, the values should reflect the risk levels connected to each failure mode in a best possible manner. However, most risk indexes for each consequence parameter generally obtained low values. This is despite the experts' joint opinion concerning the severity of losing function of the TT engine or an auxiliary system. I.e. there was no doubt that such loss could be very critical, not only towards stopping the engine, but also due to large maintenance costs, downtime and negative publicity. Obviously, in a process where expert opinions are being outed, there is always a chance of someone's personal opinions somewhat erroneously affecting the results. Yet, this is meant to be avoided in the RCM process by forming a mixed group of participants, e.g. experts from different backgrounds and relevant personnel. Hence, it is of relevance to discuss if there are features of the FMECA structure that have led to possible low risk values.

Firstly, a direct cause for the low risk indexes could be the outlined frequencies utilized to evaluate the criticality. When the frequency with the lowest criticality number corresponds to 'less than two years' it is very likely that a lot of failure modes falls under this category. It is not necessarily straightforward to evaluate how well the risk index results correspond to the real risk level for each analysed auxiliary system. However, it is reasonable to assume that the FMECA risk results could have slightly low values. Analysing the failure modes at lower levels provided detailed results for each mode. At this point, the attention shifted from looking at each auxiliary system in an overall manner to focusing more on its separate components. As a result, it may seem like the risk evaluation lacked in revealing the overall danger and consequence severity if the superior system actually should fail. For instance, FMECA results for fuel oil system failure obtained very few failure modes with high risk indexes. Still, if the overall fuel oil system were to fail, it would clearly have a large impact on costs, off-hire and potentially the environment. In other words, the detail level seems to have drawn the attention away from the overall risk level connected to the engine and auxiliary systems. As a result, the maintenance program may encourage executing quite a noticeable amount of corrective maintenance. This is unexpected, as the actual trend is more connected to preventive measures recommended from manufacturers.

6.1.2 Evaluation of constructed maintenance program

One of the goals connected to the resulting maintenance program has been to ease the communication between personnel involved in both planning and execution. As seen in appendices F1-F3, there are report/feedback columns suggesting aspects and parameters that the maintenance crew should record. This information is important to optimize, as it can help modify the maintenance program to better match the real status of the equipment. For instance, if the engineer officer executes periodic restoration every other year without detecting any indications of wear or fatigue, perhaps the maintenance interval could be changed to every 3rd year instead.

However, to contain an efficient maintenance program the maintenance management should consider what the appropriate amount of feedback is. This is to avoid a situation where the vessel's maintenance crew consider the feedback procedures as repetitive and unnecessary. In general, the feedback should reflect the knowledge and competence of the maintenance crew, which should continuously help restoring an updated maintenance plan.

The presented documents for the maintenance crew on board utilize the results from the RCM analysis in a very advantageous manner, helping to achieve an overall maintenance strategy that obtains continuous improvement. Yet, this requires good communication between the planning and executing staff. Additionally, the management must continuously encourage and support their maintenance team through their maintenance work. This creates a motivated maintenance crew that is likely to work towards the common objectives of the superior organisation.

Overall, the maintenance program obtained by the RCM procedure could help WSM in achieving their maintenance objectives, given in section 2.3.2. Specifically, this is because the process permits a proper upkeep of the ship's equipment, by timely and safe execution of maintenance activities. One of the main goals of RCM is to effectively concentrate resources on those tasks that gain system reliability. By this, the resulting maintenance program should also facilitate another stated objective, i.e. reducing repair costs and downtime.

WSM's last maintenance objective states to use preventive maintenance routines systemically to attain extended machinery life. One might say that this objective has only been partly fulfilled, since the RCM practice does not necessarily promote preventive maintenance tasks, e.g. as seen on Figure 24, page 83. However, preventive means is not necessarily connected to extending the lifetime of equipment. This is supported by the risk of erroneous maintenance, which was one of the listed failure modes in the FMECA worksheets. In some cases, by which the RCM practice analyses properly, corrective means may be more appropriate. If this appears to be unreasonable, the RCM structure contains information that justifies the choice. Then again, the maintenance program can be easily updated if preventive means seems to be more suitable after all.

The results and maintenance program did not contain explicit estimations of how the RCM procedure could have an improved effect towards a vessel's operational availability, costs, safety and reputation. However, it is fair to state that the results show strong indications that the procedure has great potential to achieve this. Improved operational availability would be an obtained result due to the main goals connected to RCM, as discussed in section 3.1. This also holds for improving the safety level of the vessel. Altogether, a vessel that is safe, reliable and has a high level of availability would also have few problems with its reputation. In a competitive setting, this can be very profitable, as the vessel's reputation might be decisive for assigning operational contracts.

In the long run, by implementing the resulting maintenance program operational costs is very likely to be reduced. Specifically, the economic winnings would be a decrease in repair costs, less off-hire, less costs of maintenance and unforeseen spare parts. Additionally, by using RCM, WSM could obtain class notations from DNV GL or Lloyds, discussed in section 2.2. As a result, there would be less interference with the equipment and the class surveys would become much more efficient. I.e. this provides an opportunity to avoid extensive inspections every five years that are both costly and time-consuming. However, this clearly requires that WSM is consistent in implementing RCM as a 'living system'. That is, keeping the maintenance program abreast, or as Wang et al. (2010) explains it; updating the maintenance program with any newly identified failure modes, as well as recording the effectiveness of the recommended maintenance actions.

6.2 Limitations

Despite achieving several beneficial results from the RCM process, some factors limit the analysis and results. Firstly, the initial idea was to include more systems and equipment in the examination. This includes the remaining functional failures of the TT engine, and additional engines. Looking at the functional failure – TT engine stopping, created an FMECA where the auxiliary systems were emphasized. The TT engine stopping due to component failure was considered as a separate functional failure, and was not analysed any further. Thus, the engine and its components were more or less excluded in the main analysis. Including one additional functional failure would at least have provided results that directly involved the engine more.

Covering additional engines would form results involving a diversity of equipment. The systems that have been studied are properly covered, but do not facilitate an overall evaluation of the reliability and risk connected to the vessel's machinery systems as a whole. A more extensive analysis would have made this easier. In addition, it would better reveal which equipment that is critical to keep the machinery and propulsion systems function as desirable. However, it became evident during the RCM workshop that due to limited time and resources, not all equipment could be thoroughly studied. The resulting examination is therefore somewhat narrow. Then again, due to the objectives of the thesis, illustrating each step of the RCM procedure was considered more important than covering an extensive amount of equipment. As mentioned in the previous chapter, the results demonstrate a framework that could be employed if the analysis was developed further.

Considering the FMECA, some assumptions should be commented. For instance, the effect and consequence evaluation of failure modes poorly covers probability aspects. Even though this part of the analysis should reflect realistic events following a failure, the probability of it actually occurring might almost be insignificant in some cases. The redundancy level of the equipment has an effect on this issue. Yet, redundancy is not properly assessed in the RCM procedure and its effect on the system's reliability is only slightly covered in the analysis. The procedure may therefore trigger 'worst case scenario' conclusions, despite the fact that such scenarios might be very unlikely. Evaluating the frequency of each failure mode should prevent this to some extent, resulting in low risk indexes in such cases. Yet, here the outlined intervals for frequencies were slightly peculiar, especially related to the lowest frequency level ‘less than every 2 years’. This also makes it uncertain if the choice of calculating risk indexes by adding the frequency and consequence was correct for this particular analysis. This because the frequency categories from WSM were not logarithmic, which is an assumption the risk index calculation is based upon (Rausand, 2011).

Ideally, a comparison of the constructed maintenance program and WSM’s maintenance approach for the equipment should have been completed; covering WSM’s planned and/or performed maintenance activities for the analysed equipment. This would make it easier to perform trend analyses as ABS (2003) suggests, evaluating equipment downtime, equipment parameters and whether the outlined maintenance program is being properly followed. For instance, the time it takes for executing the various activities in the maintenance program have not been considered, including what the mean down time (MDT) connected to the maintenance work might be. This is essential to assess, because actions corresponding to high values of MDT would have a negative effect, creating both downtime costs and reduced operational availability. A comparison would also provide information helping to reveal whether the suggested maintenance program is realistic, if some of the maintenance can be done while the ship is in transit, if changes on WSM’s routines should be done, if the new program could lead to achieving beneficial factors for WSM etc. However, it was not possible to obtain this information from WSM. In retrospect, analysing a system having such information available would likely have been a better choice than studying the TT engine.

Finalising the examination by performing a cost-benefit analysis such as Glesnes (2015) presented, would also have strengthened the results. A suitable tactic could be to evaluate the costs of WSM’s former maintenance program with the one suggested. If so, parameters to consider would have been planned costs for executing different maintenance actions. That is, including costs of spare parts, maintenance equipment, personnel and potential downtime due to the maintenance work. Additionally, downtime costs during operation due to broken equipment should be included. Establishing data connected to these parameters for both the old and new program facilitates an evaluation of whether the new maintenance program is economically beneficial. Additionally, the savings for obtaining alternative class notations as those discussed in section 2.2 should also be implemented in the cost-benefit equation.

7 Conclusion

The goal of this thesis has been to construct a maintenance program by applying the RCM procedure on machinery equipment for a vessel operated by WSM. In order to achieve this, the work of the thesis has focused on analysing a tunnel thruster engine and its connected auxiliary systems by the RCM perspective of Moubray (1997). By covering each necessary step of the RCM procedure, it was possible to outline a program for executing maintenance tasks for the lubrication oil system, fuel system as well as the sea- and freshwater cooling system. The main input employed to justify the different choices of maintenance tasks has been FMECA worksheets, which is an essential stage of the RCM process. The FMECA has utilized WSM's own consequence and frequency parameters, in addition to their risk matrix. The FMECA has received information directly from WSM, which was a key part in constructing the worksheets.

As a last step, maintenance tasks associated with each failure mode has been established in cooperation with WSM through a decision tree process. No equipment connected to the evaluated failure modes turned out as highly critical. Yet, some failure modes are classified within the medium risk area of the defined risk matrix and should not be neglected. The suggested maintenance program contains a diversity of maintenance tasks, and not all are preventive means. This is demonstrated for failure modes that receive the maintenance task category 'run to failure'. Typically, this turned out to be relevant for equipment with failure modes that were not critical, easily detected and/or inexpensive to renew. Including corrective means in the maintenance program illustrates that the RCM procedure does not necessarily conclude with preventive maintenance as the best solution for all equipment types. This is a consequence of how the method focuses on establishing economically efficient maintenance activities that facilitating system reliability.

The structure of the analysis can be utilized generically for similar equipment, but in a modified version since the operational context must be taken into consideration. The accomplished maintenance program suits as an essential element in a maintenance strategy corresponding to the one presented in section 2.1, aiming for continuous improvement. Additionally, the program enables improvement of other elements in the maintenance strategy loop, such as planning, execution and feedback/reporting.

The thesis has shown that RCM is applicable for analysing diverse equipment in a maritime context. The outcome is a maintenance program that is based on a detailed structure, systematically showing why the different maintenance tasks are chosen. Despite a lack of proper calculations, once the RCM practice has been utilized to examine operational equipment, a company such as WSM is likely to achieve several benefits. This includes:

- Enhanced safety, operational availability and equipment reliability
- Competitive advantages when the vessel obtains a record of high operability and little downtime
- Costs are reduced due to a maintenance program that leads to efficient maintenance tasks tailored for the equipment, less operational downtime, less unforeseen corrective maintenance and better control of spare parts
- Employing the RCM method on machinery or propulsion parts can make the equipment relevant for an alternative class notation, enabling less extensive and more flexible class surveys
- Utilizing the employees' experience and competence to develop and update the maintenance program facilitates a motivated maintenance crew that work towards the common objectives as the company

However, executing an RCM analysis has proved to be a comprehensive process, requiring an extensive amount of time and resources. The author considers this as the main drawback of the method and is likely to make it less tempting to employ RCM. It takes time before the benefits of the procedure becomes evident and gets to validate its positive effects. Hence, it is fair to assume that maritime companies might hesitate to apply the procedure when it becomes clear how detailed the analysis actually is. I.e., a danger is that initial investments may overshadow the perception of RCM's positive long-term effects.

Hence, the RCM procedure is considered to fit equipment that is critical towards safety and/or operation. This is to avoid analyses becoming too extensive, spending unnecessary time to study systems uncritical for operational reliability or safety level. Yet, at an initial stage, it may be difficult to decide which equipment is critical. Therefore, all relevant experience and historical data should be utilized in such decision processes or consider the approaches by Rausand (2011) or Mokashi et al. (2002). This would aid in legitimating the choice of equipment fitted for further analysis as well as reduce the chance of disregarding essential components.

Overall, in a time where the maritime industry continuously looks for tactics to reduce operational costs, optimizing the maintenance program could provide significant results. It is therefore clear that if found applicable and utilized appropriately, the RCM practice could help in obtaining such results.

8 Recommendations and further work

8.1 Recommendations and comments to WSM

Constructing a maintenance strategy, which by the RCM practice creates a structure for continuous improvement, would be ambitious and appropriate long-term tactic for WSM. Several fallouts from the RCM analysis may be considered as useful for WSM. Central parts are:

- The RCM practice creates learning and makes relevant maintenance personnel utilize their expertise in an analytical manner. This will facilitate better fulfilment of each work process in the maintenance strategy loop from chapter 2.1.
- It is time-consuming to create an initial RCM analysis including FMECA worksheets, risk matrices, consequence parameters etc. Once a structure is outlined, such as the one proposed, it is easier and likely less time-consuming to perform the same analysis on other systems
- The resulting maintenance program is consistent and can be easily updated by operational feedback from the PMC and the on board crew
- The maintenance program facilitates proper spare part planning. Failure modes connected to ‘run to failure’ maintenance tasks necessitates available spare parts, creating clear input that can be applied directly for such planning
- Utilizing the resulting maintenance program enables further reliability studies, maintenance trend analyses, metrics and analyses to improve the maintenance plan even more
- If WSM wish to obtain a class notation for their machinery system similar to those discussed in section 2.2, the class society would require documents describing why CM and other preventive maintenance actions have been chosen for the equipment (Knödlseder, 2015). This is exactly what the RCM results can provide
- The resulting maintenance program has created a documental framework that helps WSM in meeting requirements from IMO (2002). Additionally, the structure enhances the process of other elements in the maintenance strategy loop, specifically related to planning and execution

Furthermore, recommendations for WSM's further work are:

- Compare the proposed maintenance program to their existing one
- RCM could be utilized in a design phase, for instance an initial RCM analysis for critical equipment could be demanded when receiving new-builds
- Request more RCM analyses from manufacturers or some documentation describing why the recommended maintenance program is outlined the way it is
- Perform an evaluation of the existing risk matrix, including consequence parameters and frequency intervals
- Evaluate which equipment that is suited for an RCM analysis and prioritise equipment that is critical towards safety and/or operation

8.2 Further work

To improve the analysis the following is recommended:

- Extending the RCM analysis to include all relevant functional failures connected to a system, at least for one engine. If the analysis becomes too extensive, Pareto's 80-20 principle may be utilized (Mokashi et al., 2002)
- Examine and calculate the potentials for reducing operational costs as a result of implementing a maintenance program constructed by the RCM practice
- It would provide greater knowledge if the obtained maintenance program could be compared to one that is being applied currently
- An interesting development would be to perform an RCM analysis earlier in a vessel's lifecycle, particularly in the design phase
- Evaluate probability and statistical data in a larger extent when studying the failure modes
- Utilize the maintenance program to execute additional analyses, such spare part planning, optimizing maintenance intervals, trend analyses etc.
- Study how to effectively and safely choose critical equipment fit for an RCM analysis at an early stage, with minimum risk of overseeing vital functional failures and failure modes

9 References

ABS 2003. Guide for survey based on reliability-centered maintenance Houston, TX, USA.

ALGELIN, G. B. 2010. *A survey of maritime management systems and utilisation of maintenance strategies.* Master of Science, CHALMERS UNIVERSITY OF TECHNOLOGY.

ALHOULI, Y. M., LING, D. & KIRKHAM, R. 2011. Development of Ship Maintenance Performance Measurement Framework to Assess the Decision Making Process to Optimise in Ship Maintenance Planning. The University of Manchester, Manchester, UK.

ALIREZA, A., PETER, S. & UDAY, K. 2010. On aircraft scheduled maintenance program development. *Journal of Quality in Maintenance Engineering,* 16**,** 229-255.

ANONYMOUS EXTERNAL COMPANY 2014. *Annual DP trial*

ARGYRIS, C. & SCHÖN, D. A. 1996. *Organizational learning II : theory, method, and practice,* Reading, Mass, Addison-Wesley.

BAI, Y. 2003. Chapter 34 - Risk Centered Maintenance. *In:* BAI, Y. (ed.) *Marine Structural Design.* Oxford: Elsevier Science.

BOUWER UTNE, I. & RASMUSSEN, M. 2012. Introduction to Operation Management of Ships and Offshore Oil and Gas Installations. Department of Marine Technology, NTNU.

CHIEF ENGINEER. May 2015. *RE: Personal communication.*

CHIMPLES, C., TSIPOURAS, C., SOCIETY OF NAVAL, A. & MARINE, E. 1979. *Advanced condition monitoring and control techniques for marine applications*.

DAI, L. 2013. *Reliability centered maintenance (RCM),* Lecture Notes: TMR 4260 Safe operation and maintenance, Norwegian University of Science and Technology.

DE BOER, R., SCHUTTEN, J. M. J. & ZIJM, W. H. M. 1997. A Decision Support System for Ship Maintenance Capacity Planning. *CIRP Annals - Manufacturing Technology,* 46**,** 391-396.

DHILLON, B. S. 1999. *Reliability-Centered Maintenance-Chapter 9*.

DNV 2008. Guidance for Condition Monitoring.

DNV 2011. *Dynamic Positioning Systems,* Rules for Classification of Ships - Part 6 Chapter 7, Det Norske Veritas AS.

DNV GL 2014. Dynamic Positioning Systems. *SPECIAL EQUIPMENT AND SYSTEMS – ADDITIONAL CLASS.* Det Norske Veritas AS.

DNV GL 2015. Class notations. *GENERAL REGULATIONS.* DET NORSKE VERITAS AS.

GLESNES, T. 4th of June 2015. *RE: Personal communication, Comments on economic benefits when condition monitoring ships and offshore structures.*

IMO 2002. *International safety management code: ISM code : and revised guidelines on implementation of the ISM code by administrations,* 2002 ed., 2nd ed., London, International Maritime Organization.

KIM, T. W., SINGH, B., SUNG, T. Y., PARK, T. Y. & LEE, Y. H. 1996. Failure Mode, Effect and Criticality Analysis (FMECA) on Mechanical Subsystems of Diesel Generator at NPP. Korea Atomic Energy Research Institute.

KNÖDLSEDER, T. 2015. *Class Systematics Machinery - The Way to Condition Monitoring,* Company Presentation, DNV GL

LINTON, E. M. 2011. Coast Guard Reliability&Centered Maintenance. *Naval Engineers Journal,* 123**,** 25-30.

LLOYD'S REGISTER 2013. Machinery Planned Maintenance and Condition Monitoring.

MOKASHI, A. J., WANG, J. & VERMAR, A. K. 2002. A study of reliability-centred maintenance in maritime operations. *Marine Policy,* 26**,** 325-335.

MOUBRAY, J. 1997. *Reliability-centered maintenance,* New York, Industrial Press.

MURTHY, D. N. P. & KOBBACY, K. 2008. Complex system maintenance handbook. London: Springer.

NORDEN, C., HRIBERNIK, K., GHRAIRI, Z., THOBEN, K.-D. & FUGGINI, C. 2013. New Approaches to Through-life Asset Management in the Maritime Industry. *Procedia CIRP,* 11**,** 219-224.

NORSOK STANDARD Z-008 2011. Risk based maintenance and consequence classification, rev 2. Norwegian Technology Centre: Standards Norway

NORWEGIAN PETROLEUM DIRECTORATE 1998. Basisstudie vedlikeholdsstyring.

NORWEGIAN SHIPOWNERS' ASSOCIATION 1999. *Superintendent's Manual: Technical Part, Main Group 7 & 8*

RASMUSSEN, M. 2003. *Driftsteknikk grunnkurs: tema: vedlikeholdsstrategi og -styring, feilmekanismer, inspeksjons- og tilstandskontrollmetodikk,* Trondheim, Marinteknisk senter, Institutt for marin teknikk.

RAUSAND, M. 1998. Reliability centered maintenance. *Reliability Engineering and System Safety,* 60**,** 121-132.

RAUSAND, M. 2011. *Risk assessment - Theory, Methods and Applications*, John Wiley & Sons, Inc. .

SAE INTERNATIONAL 1999. SAEJA1011; Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. Warrendale, USA.

SAE INTERNATIONAL 2002. SAEJA1012; A Guide to the Reliability-Centered Maintenance (RCM) Standard. Warrendale, USA.

SANDBAKKEN, E. C. 2010. Marine Machinery Systems - Tools and Architecture. Norges teknisk-naturvitenskapelige universitet, Fakultet for ingeniørvitenskap og teknologi, Institutt for marin teknikk.

SELVIK, J. T. & AVEN, T. 2011. A framework for reliability and risk centered maintenance. *Reliability Engineering & System Safety,* 96**,** 324-331.

SIDDIQUI, A. W. & BEN-DAYA, M. 2009. *Reliability centered maintenance*.

STANDARD NORGE 2010. NS-EN 13306. *Maintenance - Maintenance Terminology.*

THOMAS, P. 2013. The risk of using risk matrices. Stavanger: P. Thomas.

TURAN, O., LAZAKIS, I., INCECIK, S. & JUDAH, A. 2011. Investigating the reliability and criticality of the maintenance characteristics of a diving support vessel.

UTNE, I. B., RASMUSSEN, M. & NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET INSTITUTT FOR MARIN, T. 2012. *TMR 4310 : marine technology 4 - reliability, availability, maintenance and safety (RAMS) in design and operation of marine systems,* Trondheim, Department of Marine Technology, NTNU.

VINNEM, J. E. 2014. *Offshore risk assessment : principles, modelling and applications of QRA studies : Vol. 2,* London, Springer.

WANG, J., PILLAY, A. & MOKASHI, A. 2010. Application of reliability centred maintenance in ship operations. *Safety and Reliability of Industrial Products, Systems and Structures.* CRC Press.

WHEELER, P. 2007. Reliability-centered maintenance.(MAINTENANCE: Align facilities engineering objectives with business goals to improve results and eliminate wasted time and money)(Interview). *Buildings,* 101**,** 38.

WHITE, M. F. 2008. *TMR4310 : marine technology 4 - machinery,* Trondheim, Fakultet for ingeniørvitenskap og teknologi, Norges teknisk-naturvitenskapelige universitet, Institutt for marin teknikk.

WILHELMSEN SHIP MANAGEMENT 2013. *Ship and Equipment Maintenance* Internal paper, Wilhelmsen Ship Management.

WILHELMSEN SHIP MANAGEMENT. n.d.-a. *About Wilhelmsen Ship Management* [Online]. Available: http://www.wilhelmsen.com/services/maritime/companies/barbership/AboutBarber/Pages/AboutBarber.aspx [Accessed 24 Mar 2015].

WILHELMSEN SHIP MANAGEMENT. n.d.-b. *Vision & Mission* [Online]. Available: http://www.wilhelmsen.com/services/maritime/companies/barbership/AboutBarber/Pages/VisionValues.aspx [Accessed 24 Mar 2015].

XANTIC 2001. SFI® Group System – Product Description.

XIAO, N., HUANG, H.-Z., LI, Y., HE, L. & JIN, T. 2011. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Engineering Failure Analysis,* 18**,** 1162-1170.

YUAN, C. Q., PENG, Z., ZHOU, X. C. & YAN, X. P. 2004. Effects of temperature on sliding wear process under contaminated lubricant test conditions. *Wear,* 257**,** 812-822.

Appendix A. Problem description

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2015

For Stud.Techn. Iselin Wabakken

Application of RCM to Construct a Maintenance Program for a Maritime Vessel

Bruk av RCM til å utforme et vedlikeholdsprogram for et maritimt fartøy

Background: Wilhelmsen Ship Management (WSM) is a main provider of third party ship management services worldwide. An essential element within the areas of responsibility to the company is planning and executing maintenance work. By creating an applicable maintenance program including maintenance intervals and written procedures for maintaining and handling relevant components, the results could provide systems that are more reliable with less downtime.

Yet, traditional maintenance programs connected to a ship's technical systems are often a result of recommendations from manufacturers and classification societies. Class approval of machinery and propulsion components are commonly based on inspection and condition monitoring performed after specific operating hours.

Knowing that the manufacturer has obligations in case of claims, shipping companies typically follows the recommended practices in terms of inspections and operating hours without further questions. Yet, using a more analytical approach would facilitate a reduction in unnecessary maintenance work and a maintenance plan better tailored to its context.

MainTech AS has extensive experience from a variety of industries in facilitation of operation, maintenance and inspection. A maintenance method that the company has utilized to achieve successful maintenance programs is reliability centred maintenance (RCM).

The method should help construct a maintenance program that prioritises maintenance needs and concentrate resources on those tasks that promote system reliability. Consequently, RCM is considered an applicable approach as an alternative to traditional maritime maintenance.

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

Objective: The thesis should study the application of RCM for constructing a maintenance program in a maritime context. The purpose is to evaluate whether the RCM process could have an improved effect towards a ship's operational availability, safety, costs and/or reputation.

By this, the thesis should address the following:

1. Discuss the importance of maintenance and maintenance programs
2. Study the traditional maintenance practice common in the shipping industry, relevant rules/regulations and WSM's own requirements and procedures
3. Describe the RCM method, including positive and negative aspects
4. Perform an RCM analysis for parts of a machinery system on one of WSM's vessels
5. Based on results from the analysis, establish an appropriate maintenance program that suits the analysed equipment
6. Evaluate whether the maintenance program can obtain beneficial results for WSM
7. Discuss how the RCM analysis and resulting maintenance program may inspire to create a strategy which is continuously striving for improvement
8. Suggest recommendations for WSM based on the performed analysis and maintenance program
9. Conclusions, further work

All necessary input data is assumed to be provided by WSM and MainTech AS.

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent.

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

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

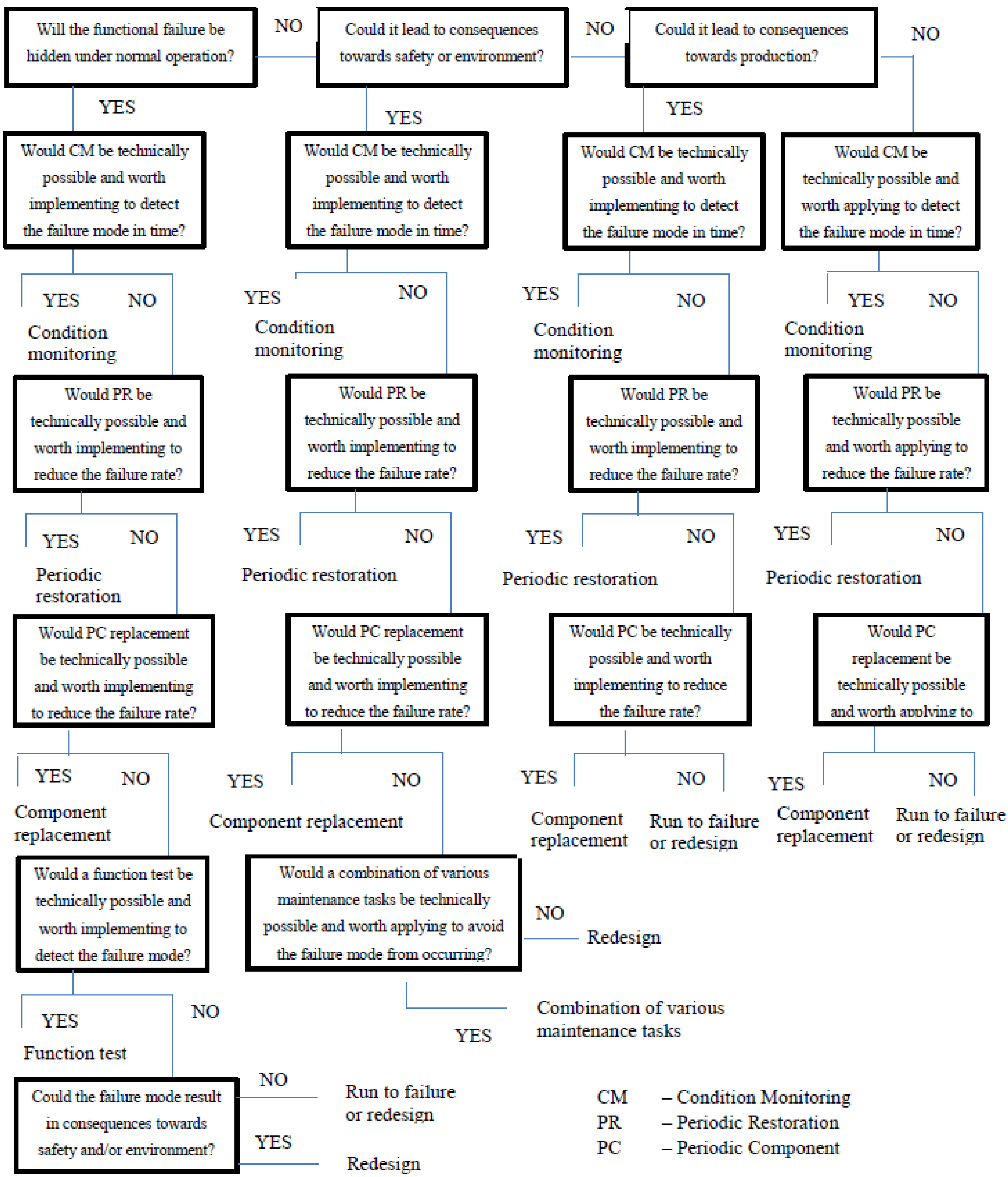
NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

The thesis is to be handed in electronically. Also, a .pdf-version of the final thesis is to be submitted to the supervisor by email.

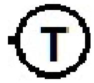
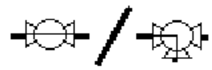
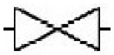
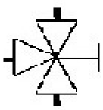
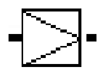
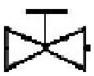
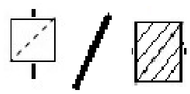
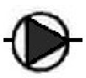
Starting date:	**15th January 2015**
Deadline:	**10th June 2015**
Supervisor:	**Ingrid Bouwer Utne**
Co. Supervisor:	**Sverre Wattum (MainTech AS)**
WSM contact person:	**Hans Petter Grønlund**
WSM contact person:	**Yngve Beite**

Ingrid Bouwer Utne
Supervisor

Appendix B. Decision tree applied in the RCM analysis



Appendix C. List of icons for system illustrations in section 4.2

G.O.	Gear oil cooler		Manometer
S.C.	Steering cooler		Thermometer
P.C.	Pitch cooler		Cocks
	Gate valve		QCV
	Non-return valve		Pipe loop
	Three-way valve		Sight glass
	Shut-off valve		Filter
	Pump		

Appendix D1. FMECA table; failure of seawater cooling system

Failure mode, level 1: Seawater cooling system failure

Failure mode Level 2	Failure mode Level 3	Effect	FP	MTBF	Hidden/ Evident	Consequences* H	E	OH	C	R	RI	Maintenance task
a. Sea strainer blockage	1. Plankton/schools of small fish/foreign objects blocking	No cooling effect, temp. increase of engine, shutdown of engine. Location and season dependent.	E	1 year	Evident	2	2	2	2	2	**2**	Run to failure
	2. Marine growth	No cooling effect, temp. increase of engine, engine shutdown. Location and season dependent.	E	1 year	Evident	2	2	2	2	2	**2**	Run to failure
	3. Closing valve failure	Not possible to isolate strainer, can't open nor close it, can't clean strainer, blockage of sea strainer, engine shutdown.	C	>10 years	Evident	2	2	2	6	2	**6**	Overhaul/replace regularly
	4. Wear/Fatigue	Strainer housing failure, larger objects block pipelines , more corrosion. Engine shutdown.	B	>10 years	Evident	2	2	2	2	2	**2**	Condition monitoring
b. Attached pump failure	1. Corrosion	Hole in the pump, leakage. Seawater not circulating at correct pressure.	B	10 years	Evident	2	2	2	2	2	**2**	Periodic restauration
	2. Erosion	Hole in the pump, leakage. Seawater not circulating at correct pressure.	B	>10 years	Evident	2	2	2	2	2	**2**	Run to failure
	3. Wear/Fatigue	Pump not kept sealed, wear on rings, impeller wear, overpressure on delivery side	B	3-5 year	Hidden	2	2	2	2	2	**2**	Condition monitoring
	4. Black out of sub switchboard E and F	Complete stop of the pump, cooling effect stopped, engine stops, if E stops, F takes over	E	>10 years	Evident	2	2	2	6	3	**6**	Run to failure
	5. Failure of electric motor	Pump stops, increased temp of engine, engine stops	D	3-5 year	Evident	2	2	2	2	2	**2**	Condition monitoring
c. Pipework failure	1. Material failure (erosion, corrosion)	Leakage, slow flooding, bilge alarms detects water ingress and before the hole gets too big	B	>10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Fouling	Pipeline blockage	B	>10 years	Evident	2	2	2	2	2	**2**	Run to failure
	3. External loads, e.g. vibrations	Will get wear and tear on the pipeline, abrasive wear, gets hole in the pipeline	C	5-7 year	Evident	2	2	2	2	2	**2**	Run to failure
d. Standby pump failure	1. Lack of rotation due to standby operation	Damage on bearings, small vibration loads on same spot, may function, failure	B	>10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Corrosion	Hole in the pump, leakage, the pump gets eaten up	B	10 years	Evident	2	2	2	2	2	**2**	Periodic restauration
	3. Electric motor failure	Pump stops, increased temp of engine, engine stops	D	3-5 year	Hidden	2	2	2	2	2	**2**	Condition monitoring
	4. Mechanical failure	Pump not kept sealed, wear on rings, impeller wear, overpressure on delivery side	B	3-5 year	Hidden	2	2	2	2	2	**2**	Condition monitoring

*FP = Failure Pattern, MTBF= Mean time between failure, H = Human, E = Environment, OH = Off-Hire, C = Costs, R = Reputation, RI = Risk Index

Appendix D2. FMECA table; failure of freshwater cooling system

Failure mode, level 1: Freshwater cooling system failure												
						Consequences*						
Failure mode Level 2	**Failure mode Level 3**	**Effect**	**FP**	**MTBF**	**Hidden/ Evident**	**H**	**E**	**OH**	**C**	**R**	**RI**	**Maintenance task**
a. Single pump failure	1. Erosion	Hole in the pump, leakage, the pump gets eaten up. Freshwater not circulating at correct pressure.	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Wear/Fatigue	May get slippery mechanical seal, pump not kept sealed, wear on rings, impeller wear, overpressure on delivery side	B	3-5 year	Hidden	2	2	2	2	2	**2**	Condition monitoring
	3. Pump engine failure	Pump stops, increased temp of engine, engine stops	D	3-5 year	Hidden	2	2	2	2	2	**2**	Condition monitoring
b. System pipe work failure	1. Material failure (due to erosion)	Leakage, slow flooding, bilge alarms detects it if there's a lot of water ingress and therefore before the hole gets too big	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Fouling	Pipeline blockage	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	3. External loads, e.g. vibrations	Will get wear and tear on the pipeline, abrasive wear, gets hole in the pipeline	C	5-7 year	Evident	2	2	2	2	2	**2**	Run to failure
c. Chemical dosing failure	1. Lack of dosing	Gets corrosion because of increased temperature, oxygen corrosion, acidic corrosion, cavitation, leakage, breakdowns	E	1 year	Evident	2	2	5	3	4	**5**	Condition monitoring

**FP = Failure Pattern, MTBF= Mean time between failure, H = Human, E = Environment, OH = Off-Hire, C = Costs, R = Reputation, RI = Risk Index

Appendix D3. FMECA table; failure of lubrication oil system

Failure mode, level 1: Lubrication oil system failure

						Consequences*						
Failure mode Level 2	**Failure mode** Level 3	**Effect**	**FP**	**MTBF**	**Hidden/Evident**	**H**	**E**	**OH**	**C**	**R**	**RI**	**Maintenance task**
a. Attached pump failure	1. Leakage on pump seal	Leakage of lube oil, dirt on pump seal, reduced pressure of circulating lubrication oil, wear on engine parts	B	5 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Contaminated oil	Increased wear on rotating parts, foreign particles reduce the lubrication effect, increased friction loads	B	6 months	Hidden	4	4	4	6	4	**6**	Condition monitoring
	3. Wear/fatigue/tear	Lube oil not circulating at correct pressure, more wear on rotating engine parts, component failure	C	5-7 years	Evident	2	2	2	2	2	**2**	Periodic restauration
	4. Filter failure	Increased wear on rotating parts, foreign particles reduce the lubrication effect, increased friction loads	B	6 months	Hidden	4	4	4	6	4	**6**	Condition monitoring
b. System pipe work failure	1. Material failure (due to erosion)	Leakage, slow flooding , manometers detects the pressure drop before the hole gets too big, reduced lubrication	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Wear/fatigue	Leakage, slow flooding - will take time before it is critical, reduced lubrication of engine parts	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	3. Incorrect assembly procedure	Fatigue of pipelines, pipeline cracks	B	7 year	Evident	2	2	2	2	2	**2**	Run to failure
c. Erroneous viscosity of lube oil	1. Temperature detector failure	Lube oil temp gets too high, bigger problem than too low, the oil gets thinner and loses its lubricating effect, more wear on rotating components	E	10 years|	Evident	2	2	2	3	2	**3**	Run to failure
	2. Fuel contamination	More wear on rotating parts, pipeline leakage, fuel valve leakage	B	6 months	Hidden	4	4	4	6	4	**6**	Condition monitoring
	3. Old oil	Base number too low, foreign objects gets into the oil, wear and tear	B	6 months	Hidden	4	4	4	5	4	**5**	Condition montioring
d. Sump tank failure	1. Tank leakage (given that low level alarm malfunctions)	Lube oil will leak, no lube oil to engine, engine will stop due to too high friction between component parts	E	> 10 years	Evident	2	2	4	3	2	**4**	Run to failure

F*FP= Failure Pattern, MTBF= Mean time between failure, H = Human, E = Environment, OH = Off-Hire, C = Costs, R = Reputation, RI = Risk Index

Appendix D4. FMECA table; failure of fuel oil system

Failure mode, level 1: Fuel oil system failure													
						Consequences							
Failure mode **Level 2**	**Failure mode** **Level 3**	**Effect**	**FP**	**MTBF**	**Hidden/ Evident**	**H**	**E**	**OH**	**C**	**R**	**RI**	**Maint. task**
a. Fuel starvation	1. Fuel filter blockage	Engine stops, cannot receive fuel, the engine needs more fuel and will stop if it doesn't, filter indicator showing pressure drop must fail also	B	6 months	Evident	3	3	3	3	3	**3**	Condition monitoring
	2. Empty tank	Engine stops, cannot receive fuel, the engine needs more fuel and will stop if it doesn't, the sight glass of the tank plus low level alarm must fail first	E	2 years	Evident	2	2	3	2	2	**3**	Run to failure
	3. Air leaks entering the fuel circuit	Unstable flow, air pockets in the fuel that enters the engine, the engine will get varying RPM, by large amounts the engine will stop	E	5-10 years	Evident	2	2	2	2	2	**2**	Run to failure
b. Purifier failure	1. Blockage from contaminated oil	The purifier do not separate the fuel, water and particles gets in the fuel. The fuel will circulate back to settling tank. Depends on the fuel quality.	E	10 years	Hidden	2	2	2	2	2	**2**	Condition monitoring
	2. Wear/fatigue	Breakdown of O-rings, brake blocks, bearings, Purifier stops. Contaminants are not removed from the fuel. The fuel will circulate back to settling tank.	B	5 months	Evident	4	4	5	4	4	**5**	Condition monitoring
	3. Human error, assembly error	Incorrect tightening, teflon rings and o-rings not placed properly or damaged in assembly action, water leakage, fuel oil leaks out internally	E	1,5 years	Evident	4	4	5	5	4	**5**	Condition monitoring
c. Pipework failure	1. Leakage	Bilge alarms will detect the leaking fuel, alarm will go off. Not high risk for fire. Engine receives less fuel	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Wear/fatigue (due to vibrations)	Leakage, slow flooding - will take time before critical. Engine receives less fuel.	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	3. Incorrect assembly procedure	Material fatigue, pipeline crack, increased stress loads on pipelines, leakage, engine gets less fuel.	B	7 years	Evident	2	2	2	2	2	**2**	Run to failure
d. Transfer pump failure	1. Leakage	Not high risk for fire. The pressure of fuel oil leak is not severe (2-3 bar). No fuel to engine, engine stops.	B	> 10 years	Evident	2	2	2	2	2	**2**	Run to failure
	2. Filter failure	Will take longer time to transfer the fuel, less fuel goes through the pump. Less fuel to the engine.	B	2 years	Evident	4	4	4	4	4	**4**	Condition monitoring
	3. Wear/fatigue	May get slippery mechanical seal, pump not sealed, wear on rings, impeller wear, overpressure on delivery side	B	7 years	Evident	2	2	2	2	2	**2**	Condition monitoring
	4. Human error	Pumps work manually, empty tank, no fuel circulating from the aft to the forward day tank, engine stops	E	2 years	Evident	2	2	2	2	2	**2**	Run to failure
e. QCV malfunction	1. Wear/fatigue of pipes	Fuel enters engine even if it is unwanted, cont. fuel flow, critical in the event of pipework failure, fire in engine	C	10 years	Evident	2	2	2	2	2	**2**	Condition monitoring
	2. Mechanical failure	Fuel enters engine even if it is unwanted, cont. fuel flow, critical in the event of pipework failure, fire in engine	C	10 years	Hidden	2	2	2	2	2	**2**	Condition monitoring

Appendix E1. Maintenance packages 1-4

Maintenance packages

MP no.	AMP no.	Interval	Maint. task	Maintenance description	Personnel	Equipment	CL
1	-	Once a month	1. CM on attached pump, lubrication oil system	Mesh obscuration particle counter - three high-precision micron screens with known number of pores. Oil passes through each mesh and particles bigger than the pores are stuck in the mesh. Sensors measure the pressure change which is converted to reflect the number of particles larger than the screen size.	Engineer officers to execute CM Chief officer/ skilled engineer officer to analyse CM data	Mesh obscuration particle counter instrument	M
			2. CM on attached pump, lubrication oil system	Utilizing mechanical indicator showing the pressure drop through the filter	Engineer officers to execute and analyse CM	Mechanical indicator	L
			3. CM of oil, lubrication oil system	Mesh obscuration particle counter - three high-precision micron screens with known number of pores. Oil passes through each mesh and particles bigger than the pores are stuck in the mesh. Sensors measure the pressure change which is converted to reflect the number of particles larger than the screen size.	Engineer officers to execute CM Chief officer or skilled engineer officer to analyse CM data	Mesh obscuration particle counter instrument	M
2	1	Every other month	1. CM of oil, lubrication oil system	Direct reading ferrography - quantitavely measure the concentration of ferrous particles by subjecting an oil sample to a strong magnetic field. Only reads ferrographic particles.	Engineer officers to execute CM Chief officer or skilled engineer officer to analyse CM data	Direct reading ferrography instrument	L
			2. CM of oil through filter, fuel oil system	Perform oil pressure measurements, before the oil passes the filter and when exiting the filter. A performance standard must be established for when the filter is clean. Deviating pressure (less) indicates blocked filter.	Engineer officers to execute and analyse CM	Mechanical indicator	L
3	1	Every 3rd month	1. CM of cooling medium, freshwater cooling system	Execute freshwater sample, measure the alkalinity level, chlorine and nitrite level	Engineer officers to execute and analyse CM	Freshwater treatment instrument	L
4	1, 2, 3	Every 6th months	1. CM of transfer pump, fuel oil system	Utilizing mechanical indicator showing the pressure drop through the filter	Engineer officers to execute and analyse CM	Mechanical indicator	L

MP no. = Maintenance Package number, AMP = Additional maintenance packages to perform simultaneously, CL = Complexity Level (L= Low, M= Medium, H = High)

Appendix E2. Maintenance package 5

Maintenance packages

MP no.	AMP no.	Interval	Maint. task	Maintenance description	Personnel	Equipment	CL
5	1, 2, 3, 4	Every year	1. CM of electric motor connected to attached pump, seawater cooling system	Vibration measurements, frequency analysis - fast fourier transformation of data by host computer or data collector itself. A baseline spectrum of frequencies in excellent condition is compared to the measured spectrum. Any increase over the baseline of more than one standard deviation can indicate a potential problem.	Engineer officers to execute CM Chief officer or skilled engineer officer to analyse CM data	Vibration Analyzer	M
			2. CM of electric motor connected to standby pump, seawater cooling system	Vibration measurements, frequency analysis - fast fourier transformation of data by host computer or data collector itself. A baseline spectrum of frequencies in excellent condition is compared to the measured spectrum. Any increase over the baseline of more than one standard deviation can indicate a potential problem.	Engineer officers to execute CM Chief officer or skilled engineer officer to analyse CM data	Vibration Analyzer	M
			3. CM of standby pump parts, seawater cooling system	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters divide frequency spectrum into a series of bands of interest, then plotted logarithmically. Avg. output from each filter measured and values displayed by a meter or plotted on a recorder.	Engineer officers to execute and analyse CM	Octave band filters + transducer + vibration meter	L
			4. CM of pump parts, freshwater cooling system	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters divide frequency spectrum into a series of bands of interest, then plotted logarithmically. Avg. output from each filter measured and values displayed by a meter or plotted on a recorder.	Engineer officers to execute and analyse CM	Octave band filters + transducer + vibration meter	L
			5. CM of electric pump motor, freshwater cooling system	Vibration measurements, frequency analysis - fast fourier transformation of data by host computer or data collector itself. A baseline spectrum of frequencies in excellent condition is compared to the measured spectrum. Any increase over the baseline of more than one standard deviation can indicate a potential problem.	Engineer officers to execute CM Chief officer or skilled engineer officer to analyse CM data	Vibration Analyzer	M
			6. CM of transfer pump, fuel oil system	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters divide frequency spectrum into a series of bands of interest, then plotted logarithmically. Avg. output from each filter measured and values displayed by a meter or plotted on a recorder.	Engineer officers to execute and analyse CM	Octave band filters + transducer + vibration meter	L
			7. Functional tests for QCV, fuel oil system	Primarly test if the QCV works by closing and opening it regularly, also visually check if there are other damages/wear on valve	Engineer officers to execute and analyse CM	No extra equipment required	L

MP no. = Maintenance Package number, AMP = Additional maintenance packages to perform simultaneously, CL = Complexity Level (L= Low, M= Medium, H = High)

Appendix E3. Maintenance package 6-8

Maintenance packages

MP no.	AMP no.	Interval	Maint. task	Maintenance description	Personnel	Equipment	CL
6	5.7	Every 2nd year	1. Periodic restoration on attached pump, oil lubrication system	Repair damaged seals and bearings, change damaged impellers	Engineer officers to execute maintenance, chief officer to supervise	Spare pump parts e.g. seals and bearings,, general maintenance equipment	L
7	-	Every 5th year	1. Overhaul/replace closing valve near sea strainer, seawater cooling system	Change valve with a new one	Engineer officers to execute maintenance, chief officer to supervise	New valve	L
			2. Periodic restoration of attached pump, seawater cooling system	Open pump, visually check for corroded elements in the pump, renew elements if corrosion has occurred.	Engineer officers to execute maintenance, chief officer to supervise	Spare pump parts e.g. seals and bearings,, general maintenance equipment	L
			3. Periodic restoration of standby pump, seawater cooling system	Open pump, visually check for corroded elements in the pump, renew elements if corrosion has occurred.	Engineer officers to execute maintenance, chief officer to supervise	Spare pump parts e.g. seals and bearings,, general maintenance equipment	L
8	1, 2, 3, 4, 5.1, 5.2, 5.3, 5.4, 5.5, 5.6	Every 5th year	1. CM sea strainer, seawater cooling system	Perform water flow measurements, a performance standard must be established when strainer is clean. Deviating flow (less) indicates blocked strainer.	Engineer officers to execute and analyse CM	Flowmeter	L
			2. CM of attached pump, seawater cooling system	Vibration measurements on bearings, casing: octave band analysis - contiguous and fractional octave filters divide frequency spectrum into a series of bands of interest, then plotted logarithmically. Avg. output from each filter measured and values displayed by a meter or plotted on a recorder.	Engineer officers to execute and analyse CM	Octave band filters + transducer + vibration meter	L
			3. CM of QCV, fuel oil system	Mechanical indicator showing the pressure drop passing the valve, pressure drop may indicate wear	Engineer officers to execute and analyse CM	Mechanical indicator	L

MP no. = Maintenance Package number, AMP = Additional maintenance packages to perform simultaneously, CL = Complexity Level (L= Low, M= Medium H = High)

Appendix F1. Sheet for vessel crew; maintenance packages 1-4

Maintenance task sheet, for on board crew

Maintenance task	**Activity executed to (failure mode):**	**Because (effect):**	**Possible consequence:**	**Report/Feedback**	**Interval**
1.1 CM on attached pump, lubrication oil system	Prevent contaminated lube oil	You get an increase of the wear on the engine's rotating parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Once a month
1.2 CM on attached pump, lubrication oil system	Prevent filter failure in lubrication oil system	You get dirty oil that increase the wear on the engine's rotating parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Once a month
1.3 CM of oil, lubrication oil system	Prevent contaminated lube oil with erroneous viscosity	You get pipeline leakage, fuel valve leakage, an increase of the wear on the engine's rotating parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, indications of lube oil system wear, should the maintenance interval be changed?	Once a month
2.1 CM of oil, lubrication oil system	Prevent achieving old oil from circulating in the system	You get a base number which is too low, foreign objects gets into the lube oil, wear and tear occur on lube oil system parts	Breakdown of TT engine, large maintenance/ repair costs	Small deviations, challenges with the maint. tasks, indications of lube oil system wear, should the maintenance interval be changed?	Every other month
2.2 CM of oil through filter, fuel oil system	Prevent fuel filter blockage and check that the filter indicator works (shows pressure drop if filter is blocked)	Fuel starvation leads to the engine not receiving fuel	TT engine stops	Small deviations, challenges with the maint. tasks, check filter indicato, should the maintenance interval be changed?	Every other month
3.1 CM of cooling medium, freshwater cooling system	Prevent chemical dosing failure	You get corrosion due to increased temperature, acidic or oxygen corrosion, cavitation, leakage in system pipelines/parts	Lack of proper cooling of subsystems (lube oil, freshwater) dependent on cooling from seawater, wear on engine/engine gets too hot and stops	Small deviations, challenges with the maint. tasks, any indications of wear/damage on pipelines/parts, should the maintenance interval be changed?	Every 3rd month
4.1 CM of transfer pump, fuel oil system	Prevent filter failure in the fuel oil transfer pump	The fuel will take longer to transfer , less fuel goes through the transfer pump	Fuel starvation that leads to the engine not receiving fuel, TT engine may stop	Small deviations, challenges with the maint. tasks, check filter indicator, indications of wear/damage on fuel pipelines/parts, should the maintenance interval be changed?	Every 6th months

Appendix F2. Sheet for vessel crew; maintenance package 5

Maintenance task sheet, for on board crew

Maintenance task	Activity executed to (failure mode):	Because (effect):	Possible consequence:	Report/Feedback	Interval
5.1 CM of electric motor connected to attached pump, seawater cooling	Prevent failure of electric motor to seawater cooling pump	The seawater attached pump stops	Increased temperature of the engine, engine stops because it is too hot	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear or on electric motor, should the maintenance interval be changed?	Every year
5.2 CM of electric motor connected to standby pump, seawater cooling	Prevent failure of electric motor to standby seawater cooling pump	The seawater standby pump does not work	Increased temperature of the engine, engine stops because it is too hot	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear or on electric motor, should the maintenance interval be changed?	Every year
5.3 CM of standby pump parts, seawater cooling system	Prevent mechanical failure of standby pump	You get slippering of mechanical seal creating difficulties in keeping the pump sealed wear on O-rings, impeller wear, gets over pressure on delivery side of pump	Breakdown of standby pump, seawater cooling failure, increased temp of engine and cooling subsystems	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every year
5.4 CM of pump parts, freshwater cooling system	Prevent wear/fatigue of freshwater pump	You get slippering of mechanical seal creating difficulties in keeping the pump sealed wear on O-rings, impeller wear, gets over pressure on delivery side of pump	Directly increase of engine temperature, engine stops	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every year
5.5 CM of electric pump motor, freshwater cooling system	Prevent failure of electric pump motor in freshwater system	Freshwater pump stops	Directly increase of engine temperature, engine stops	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear or on electric motor, should the maintenance interval be changed?	Every year
5.6 CM of transfer pump, fuel oil system	Prevent wear/fatigue of transfer pump	Transfer pump breakdown	Fuel starvation that leads to the engine not receiving fuel, TT engine may stop	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every year
5.7 Functional tests for QCV, fuel oil system	Prevent mechanical failure of QCV due to stand still position for too long	QCV may fail to close, fuel will enter the engine even though it is unwanted, fuel will continue to flow. If it fails to open it may lead to fuel starvation.	If other failures has happened e.g. pipework failure, fuel may leak, fire in engine. Or engine stops due to fuel starvation.	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of wear on valve, should the maintenance interval be changed?	Every year

Appendix F3. Sheet for vessel crew; maintenance packages 6-8

Maintenance task sheet, for on board crew

Maintenance task	**Activity executed to (failure mode):**	**Because (effect):**	**Possible consequence:**	**Report/Feedback**	**Interval**
6.1 Periodic restoration on attached pump, oil lubrication system	Prevent wear/fatigue/tear of attached pump in lube oil system	You get lube oil not circulating at correct pressure, more wear on rotating engine parts	Breakdown of TT engine	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every 2nd year
7.1 Overhaul/ replace closing valve near sea strainer, seawater cooling system	Prevent closing valve failure in seawater cooling system	It may become impossible to isolate strainer, can't open nor close the valve, can't clean strainer	Sea strainer may be blocked, failure of seawater cooling system leading to failure of cooling subsystems, engine stops	Small deviations, challenges with the maint. tasks, detected pipeline or valve damage, condition of valve when replaced, should the maintenance interval be changed?	Every fifth year
7.2 Periodic restoration of attached pump, seawater cooling system	Prevent corrosion damage on seawater pump	You can get holes in the pump, a leakage, the pump gets eaten up, the pump may fail to pump seawater	Increased temperature of the engine, engine wear due to less lubricating effect from lube oil, engine stops because it is too hot	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every fifth year
7.3 Periodic restoration of standby pump, seawater cooling system	Prevent corrosion damage on standby seawater pump	You can get holes in the pump, a leakage, the pump gets eaten up, the pump may fail to pump seawater	Increased temperature of the engine, engine wear due to less lubricating effect from lube oil, engine stops because it is too hot	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every fifth year
8.1 CM sea strainer, seawater cooling system	Prevent wear/fatigue of the sea strainer	Larger objects may enter the pipelines which again can lead to blockage and more wear on the seawater system parts	No cooling effect, temperature increase of engine, may lead to shutdown of engine	Small deviations, challenges with the maint. tasks, detected pipeline or valve damage, strainer condition when maintained, should the maintenance interval be changed?	Every fifth year
8.2 CM of attached pump, seawater cooling system	Prevent wear/fatigue of attached seawater pump	You get slippering of mechanical seal creating difficulties in keeping the pump sealed wear on O-rings, impeller wear, gets over pressure on delivery side of pump	Failure of seawater pump, seawater cooling system may fail leading to failure of cooling subsystems, engine stops	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of pump wear, should the maintenance interval be changed?	Every fifth year
8.3 CM of QCV, fuel oil system	Prevent wear/fatigue on QCV in fuel oil system	QCV may fail to close, fuel will enter the engine even though it is unwanted, fuel will continue to flow. If it fails to open it may lead to fuel starvation.	If other failures has happened e.g. pipework failure, fuel may leak, fire in engine. Or engine stops due to fuel starvation.	Small deviations, challenges with the maint. tasks, detected pump damage/ indications of other type of wear on valve, should the maintenance interval be changed?	Every fifth year

Appendix G. Case study from Karsten Moholt.

Rig company «X» has implemented a condition based maintenance (CBM) program for the thruster units on 22 drill ships and semi-submersibles.

Approximately 140 thruster units.

Costs by regular maintenance program

PM maintenance cost for 1 thruster:

- Cost for overhaul = 1060000 USD (every 5 year, pr. unit)
- Estimated PM pr. year = 25000 USD (filters / oil / inspections)
- Total maintenance cost pr. year over a five year period = 237000 USD

Thruster maintenance cost pr. rig (8 thrusters)

- 237000 x 8 thrusters = 1896000. pr. year / 9,5 mill. USD 5 year. (MTBF)

Dry dock cost for maintenance of 8 thrusters:
Day rate = 400.000, - USD x 20 days = 8 mill. USD.
5 year maintenance budget for 8 thrusters = 9,5 mill. + 8 mill. = 17,5 mill. USD

Maintenance budget for 22 rigs with 8 thrusters:

- 1 rig = 1896000 USD pr. year x 22 rigs = 41,7 mill. USD (Pr. year)
- 41,7 mill. USD x 5 år = 208 mill. USD (MTBF)

Dry Dock for 22 platforms in 20 days = 176 mill. USD (MDT)

PM budget 22 rigs over 5 years = 384 mill. USD (MTBF + MTD)

PM budget pr year = 76,8 mill. USD (MTBF + MTD / 5 year)

After the first five years, condition monitoring (CM) resulted in only nine thrusters having deviations, i.e. indicating that the thrusters were operating desirably related to its performance standards. However, preventive maintenance was scheduled and performed.

By utilizing CM the maintenance interval could be extended from every fifth year to every seven and a half year instead. The results were:

<u>Maintenance cost for 1 thruster – 7,5 year interval:</u>

Cost for overhaul = 1060000. (pr. thruster)

PM & CM program = 30000 USD

<u>Yearly maintenance cost pr thruster is;</u>

1060000 / 7,5 year + 30000 = 171300, -

Savings: 65700 USD - pr. thruster pr. year.

<u>Maintenance cost per rig:</u>

- 171300 x 8 thrusters = 1,37 mill per year
- For maintenance interval 7,5 years = 6,85 mill USD. (Every fifth year = 10,2 mill)
- **<u>Cost savings = 1.89 mill USD – 1.37 mill USD = 526000 USD pr. rig</u>**
- **<u>Cost savings for 22 rigs = 11.5 mill. USD</u>**