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Application of RCM Principles to Identify Barriers in Design of Unmanned Engine Rooms for Oceangoing Merchant Vessels

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Preface

This Master's thesis is written at the Norwegian University of Science and Technology during the spring of 2016. I would like to thank my supervisor Professor Ingrid B. Utne for great guidance during the project. I would also like to thank Brage Mo and Ørnulf Jan Rødseth at Marintek for interesting discussions and for providing me with useful literature. I would also like to thank Solvang ASA for welcoming me to their office May 12th to answer questions and for providing me with data and useful information for my thesis. Especially I would like to thank Technical Superintendent Alexander Grødeland in Solvang for answering numerous questions and providing me with great support also after the meeting.

A handwritten signature in black ink, reading "Nikolai Havikbotn Jacobsen". The signature is written in a cursive style with a long, sweeping underline that extends to the right.

Nikolai Havikbotn Jacobsen
Trondheim, July 15th 2016

Summary

Research has shown that unmanned merchant vessels are possible, and researchers have claimed that larger autonomous vessels can be seen within 10 years. For oceangoing vessels, one of the biggest challenges is to get systems and machinery to work reliably for up to 4 weeks without maintenance. Therefore, a need to identify the systems that can be solely maintained in port, and those systems that will require redesign is present.

Reliability-Centered Maintenance (RCM) is a procedure that determines what must be done to ensure that any physical asset continuous to do whatever its users wants it to do in its present operating context. The procedure is a thorough process that identifies critical failures for an asset in its operating context, and determines whether maintenance tasks can reduce the risk to an acceptable level. If no maintenance tasks are found to be applicable and effective in the operating context, the process requires one-time changes, such as redesign, modification or change of the item's operating context. For an oceangoing merchant vessel that is to be used in a new operating context, where no maintenance will be possible for up to four weeks, the procedure can be used to identify the critical failures and whether the risk can be reduced by means of maintenance, or if one-time changes are necessary. In this thesis, those critical failures that cannot be managed effectively by maintenance has been defined as barriers.

This thesis establishes a step-by-step procedure for how to use RCM principles for identification of barriers. The procedure is considered to be a very useful tool for identifying and breaking barriers in design of unmanned engine rooms for merchant vessels. However, to effectively and successfully perform the procedure, a group consisting of an RCM facilitator well versed in RCM principles and experts with in-depth knowledge about the systems is strongly recommended.

The procedure is used in a case study to identify barriers in a fuel oil system that uses HFO, as this is the most common fuel used today on oceangoing merchant vessels. The analysis has been performed on the fuel system under normal seagoing conditions, and the functional failure analysed is "Supplies no fuel to the engine". As the RCM process only

focuses on the maintenance, other procedures the crew may have such as opening and closing of hand-operated valves falls outside of the scope.

Four barriers were identified in the analysis: plugging of the by-pass filter, plugging of the ME automatic backflush filter, plugging of the transfer pump filter and plugging of the flowmeter filter. These failure modes are identified as barriers because cleaning of the filters too often are required less than 4 weeks after the last cleaning. As the operating context states that maintenance cannot be performed at intervals less than 4 weeks, and the risk is considered to be unacceptable, the failures are considered to be barriers. The conclusion is therefore that one-time changes such as redesign, modification or change of operating context for the fuel system is necessary in order for an oceangoing merchant vessel to be able to sail without maintenance personnel with an acceptable risk. As the frequency of cleaning tasks are a direct function of the condition of the fuel, a one-time change that can be effective on all identified barriers is change of fuel. A comparison made with an FMECA analysis from a vessel running on diesel fuel indicate that this will have a significant effect.

Sammendrag

Forskning har vist at ubemannede handelsskip er mulig og forskere hevder at større autonome skip kan bli sett innen 10 år. For havgående skip så er et av de største utfordringene å få systemer og maskineri til å virke pålitelig i opptil 4 uker uten vedlikehold. Det er derfor et behov for å identifisere systemene det er mulig å vedlikeholde kun når skipet er i havn, og de systemene hvor designendringer er nødvendig.

Pålitelighetsbasert vedlikehold (RCM) er en prosedyre som bestemmer hva som må gjøres for å forsikre at en fysisk eiendel fortsetter å gjøre det den skal gjøre i sin operasjonelle kontekst. Prosedyren er en grundig prosess som identifiserer kritiske feil for eiendelen i dens operasjonskontekst og identifiserer hvorvidt vedlikeholdsoppgaver kan benyttes for å redusere risikoen til et akseptabelt nivå. Dersom ingen vedlikeholdsoppgaver er anvendelig og effektiv i operasjonskonteksten, så krever prosedyren engangsendringer slik som designendring, modifikasjon, eller endring av eiendelens operasjonskontekst. For et havgående skip som skal bli brukt i en ny operasjonskontekst, hvor vedlikehold ikke vil være mulig i perioder på opptil 4 uker, så kan prosedyren brukes til å identifisere de kritiske feilene og hvorvidt vedlikeholdsoppgaver kan redusere risikoen til et akseptabelt nivå, eller om engangsendringer er nødvendig. I denne oppgaven har de kritiske feil som ikke kan håndteres effektivt med vedlikehold blitt definert som barrierer.

Denne oppgaven etablerer en steg for steg prosedyre for hvordan man kan bruke RCM prinsipper for å identifisere barrierer. Prosedyren er vurdert til å være et veldig nyttig verktøy for å identifisere barrierer i design av ubemannede maskinrom for handelsskip. For å bruke prosedyren på en effektiv måte anbefales det sterkt at en gruppe bestående av en RCM gruppeleder godt trent i RCM prinsipper og eksperter med dybdekunnskaper om systemene etableres.

Prosedyren blir bruk i et case studie til å identifisere barrierer i et drivstoffsystemet som bruker tungolje, ettersom dette er det mest vanlige drivstoffer på havgående handelsskip. Analysen har blitt utført på skipet under normal transporttilstand og funksjonsfeilen som

har blitt analysert er «Leverer ikke drivstoff til motoren». Ettersom RCM prosessen kun fokuserer på vedlikehold, så har ikke andre arbeidsoppgaver som mannskapet kanskje har som å åpne og lukke manuelle ventiler blitt analysert.

Fire barrierer ble identifisert i analysen: tett by-pass filter, tett automatisk tilbakespylingsfilter, tett transferpumpefilter og tett gjennomstrømningsmålerfilter. Disse feilene er identifisert som barrierer på grunn av at filtrene alt for ofte har trengt rengjøring mindre enn 4 uker etter den forrige rengjøringen. Ettersom det ikke er mulig å gjøre vedlikehold med intervaller på mindre enn 4 uker og risikoen er vurdert til å være uakseptabel er disse vurdert til å være barrierer. Konklusjonen er derfor at engangsendringer slik som redesign, modifikasjon, eller endring av operasjonskonteksten for drivstoffsystemet er nødvendig for at havgående skip skal være i stand til å seile uten vedlikeholdsmannskap med en akseptabel risiko. Ettersom vedlikeholdsfrekvensen er en direkte funksjon av tilstanden på drivstoffet så kan endring av drivstoff være en effektiv løsning for alle barrierene som er identifisert. En sammenligning med en FMECA analyse utført på et skip som går på diesel drivstoff indikerer at denne endringen vil ha en betydelig effekt.

Table of contents

Preface	Error! Bookmark not defined.
Summary	III
Sammendrag	V
Table of contents	VII
List of Figures	IX
List of Tables	X
1 Introduction	1
1.1 Background	1
1.2 Objective	3
1.3 Scope and limitations	3
1.4 Structure of the report	4
2 Reliability-Centered Maintenance	5
2.1 Background (Why RCM)	5
2.2 Brief history – The evolution of RCM	6
2.3 Pros and cons of RCM in the maritime industry	8
2.3.1 Pros	8
2.3.2 Cons	9
3 Method - RCM step-by-step	11
3.1 Asset/system definition	12
3.1.1 Partitioning - System boundaries	12
3.1.2 Establishing objectives and prioritizing assets	15
3.1.3 Level of indenture	17
3.2 Operational context and functions	18
3.2.1 Operational context statement	18
3.2.2 Primary and secondary functions	19
3.2.3 Function statements	19
3.2.4 Performance standards	19
3.3 Functional failures	20
3.4 FMECA analysis	20
3.4.1 FMECA Worksheet	21
3.4.2 Failure modes	23
3.4.3 Failure effects	25
3.4.4 Failure consequence categories	26
3.4.5 Risk	29
3.5 Decision diagram approach	32
3.5.1 Failure management policies	33
3.5.2 Different layouts	34
3.5.3 Basic assumptions	36
3.5.4 Hierarchy of failure management policies	37
3.5.5 Failure management policy selection criteria	41
3.5.6 Definition of barrier	45
3.5.7 The selected decision diagram	46
3.5.8 How to handle uncertainty in the decision diagram	49
4 Case study: The fuel oil system	51
4.1 System selection and definition	51
4.1.1 Partitioning	51
4.1.2 Prioritizing and system selection	53
4.1.3 System break down and boundaries	56

4.2	<i>Operational context and functions</i>	59
4.2.1	Operational context	59
4.2.2	Functions	61
4.3	<i>Functional failures</i>	61
4.4	<i>FMECA analysis</i>	62
5	Results	65
5.1	<i>Pumps</i>	66
5.1.1	Transfer pump	66
5.1.2	Separator supply pump	67
5.1.3	Main engine supply pump	69
5.1.4	Main engine circulating pump	70
5.2	<i>Filters</i>	71
5.2.1	Transfer pump filter	71
5.2.2	Separator supply pump filter	72
5.2.3	Main engine supply pump filter	73
5.2.4	Main engine Flowmeter filter	74
5.2.5	Main engine automatic backflushing filter	76
5.2.6	By-pass filter	77
5.3	<i>Heaters</i>	78
5.3.1	Preheater before separator	78
5.3.2	Heater	79
5.4	<i>Separators</i>	80
5.5	<i>Settling and service tanks</i>	83
5.6	<i>Emergency shut off valves</i>	83
6	Discussion	85
6.1	<i>Results</i>	85
6.1.1	Assumptions	87
6.1.2	Total risk	88
6.1.3	Data	88
6.1.4	Limitations	88
6.1.5	Result in light of HFO as fuel	89
6.2	<i>Method</i>	89
7	Conclusion and recommendations	91
8	Further work	93
9	References	95

List of Figures

- Figure 3.1: SFI Group System..... 14
- Figure 3.2: FMECA worksheet. 22
- Figure 3.4: Risk matrix 30
- Figure 3.5: Definition of likelihood for risk matrix. 30
- Figure 3.6: Dominant failure patterns..... 42
- Figure 3.7: The P-F interval 43
- Figure 3.8: Decision diagram. 48
- Figure 4.1: SFI Group System..... 51
- Figure 4.2: Avg. number of tasks per ship per year for SFI m. groups 6, 7 and 8. 54
- Figure 4.3: Avg. maintenance frequency for top 16 groups in main groups 6, 7 and 8.... 55
- Figure 4.4: Avg. unplanned corr. maintenance freq. for groups in m. groups 6, 7 and 8.. 56
- Figure 4.5: Fuel oil system. 57
- Figure 4.6: Fuel oil transfer system..... 57
- Figure 4.7: Fuel oil purification plants. 58
- Figure 4.8: Fuel oil supply system..... 59
- Figure 4.9: FMECA part 1/2..... 63
- Figure 4.10: FMECA part 2/2..... 64
- Figure 5.1: Maintenance category distribution of HFO transfer pumps. 66
- Figure 5.2: Maintenance category distribution for separator supply pumps. 68
- Figure 5.3: Maintenance category distribution for main engine supply pumps..... 69
- Figure 5.4: Maintenance category distribution for main engine circulating pumps..... 70
- Figure 5.5: Cleaning task interval distribution for transfer pump filters..... 72
- Figure 5.6: Cleaning task interval distribution for separator supply pump filters..... 73
- Figure 5.7: Cleaning task interval distribution for ME supply pump filters..... 74
- Figure 5.8: Cleaning task interval distribution for ME flowmeter filter. 75
- Figure 5.9: Maintenance category distribution of ME auto back flushing filter..... 76
- Figure 5.10: Cleaning task interval distribution for ME auto filters..... 77
- Figure 5.11: Cleaning task interval distribution for by-pass filters..... 78
- Figure 5.12: Maintenance category distribution of main engine heaters..... 80
- Figure 5.13: Maintenance category distribution for separators. 81
- Figure 5.14: Cleaning task interval distribution for separators..... 83

List of Tables

Table 3.1: Characteristics of different levels of indenture.	17
Table 3.2: Failure modes at different levels of detail.	25
Table 4.1: Groups of main group 6.....	52
Table 4.2: Groups of main group 7.....	52
Table 4.3: Groups of main group 8.....	53
Table 4.4: Distribution of maintenance tasks of group 81.	55
Table 4.5: Required condition of HFO before any on-board cleaning.....	59
Table 4.6: Off-hire as function of failure location.	60
Table 4.7: Fuel system main and secondary functions.	61
Table 4.8: Functional failures of the fuel system.....	61
Table 5.1: Key statistics for transfer pump.	67
Table 5.2: Key statistics for separator supply pump.	69
Table 5.3: Key statistics for main engine supply pumps.....	70
Table 5.4: Key statistics for main engine circulating pumps.....	71
Table 5.5: Key statistics for transfer pump filter.	72
Table 5.6: Key statistics for separator supply pump filter.	73
Table 5.7: Key statistics for main engine supply pump filter.....	74
Table 5.8: Key statistics for main engine flowmeter filter.	75
Table 5.9: Key statistics for main engine auto back flushing filters.	77
Table 5.10: Key statistics for the by-pass filter.....	78
Table 5.11: Key statistics for the preheater.	79
Table 5.12: Key statistics for heaters.....	80
Table 5.13: Key statistics for separators.	82
Table 6.1: Risk of operating the vessel with today's maintenance.	85
Table 6.2: Ranked risk of components in the fuel system.	86

1 Introduction

1.1 Background

Over the past 150 years the crew size on oceangoing merchant vessels has been significantly reduced by the introduction of new technology and better maintenance management (Kretschmann et al., 2015). Still, the crew costs represent the second largest operating expense after the fuel cost for merchant vessels (Moore Stephens, 2014). At the same time it's been claimed that the recruiting of seamen in Europe has been tougher as the jobs are considered less attractive, while the transport volumes and the need for seamen increases at the same time (Dragland, 2014). This has led to an increased interest for unmanned vessels that have the potential of significant cost reductions. Royce claims that one captain located onshore can remotely control 10 vessels (Dragland, 2014). As the ships does not have crew on board, the ships can also be built without a costly and energy demanding accommodation area. Therefore, the ships can be built cheaper and lighter which makes it able to carry more cargo and be more environmental friendly. It has also been claimed that such ships will be safer as human error can be blamed for as much as 75 - 80 % of today's ship accidents (Dragland, 2014; Mokashi et al., 2002).

MUNIN, a collaborative research project co-funded by the European Commissions aimed to develop and verify a concept for an autonomous vessel. The conclusion in 2015 after nearly three years of research was that unmanned vessels are possible and that we probably will see larger autonomous vessels within 10 years (Marintek, 2016). In July 2015, Rolls-Royce confirmed in a press release that they will lead a similar project, AAWA, until the end of 2017. This is also a collaborative research project that will explore the economic, social, legal, regulatory and technological factors which need to be addressed to make autonomous ships a reality (Rolls-Royce, 2015). As part of this project, equipment for autonomous operation will be tested on a 65 meter long ferry. In less than a year after the project started, Mikael Makinen in Rolls-Royce stated that autonomous shipping is the future for the maritime industry. Actually he states that smart ships will revolutionize the design and operation of vessels the way smart phones has revolutionized the mobile phones, a statement that represents their optimism (Stensvold, 2016b).

In April 2016, the U.S. military christened a totally robotic trans-oceanic capable warship "Sea Hunter" (Stewart, 2016). This is a 40 meter long experimental self-driving warship

designed to hunt enemy submarines. The ship is designed to cruise for 2-3 months at a time without crew or anyone controlling it remotely. Experts say the vessel has the potential to not only revolutionise the military's maritime service, but also commercial shipping (Zolfagharifard, 2016). Actually, the program manager claimed that the full-size prototype could pave the way to developing crewless cargo vessels for the commercial shipping industry. Sea Hunter will undergo two years of testing, and within five years such ships might find place in the western Pacific according to the Deputy U.S. Defence Secretary, Robert Work (Stewart, 2016).

In Norway, The Norwegian Coastal Administration have suggested to use a specific fjord in Norway for testing of unmanned vessels, as a contribution to the National Transport Plan 2018-2029(Stensvold, 2016a). This was a result of meetings with the Norwegian maritime industry and the Norwegian University of Science and Technology (NTNU), and represents the current interest for unmanned vessels. Kongsberg Seatex have already started testing of equipment in collaboration with NTNU, Marine Robotics and the Norwegian Defence Research Establishment (Flaarønning, 2016). NTNU AMOS, Centre for Autonomous Marine Operations and Systems has an ongoing project called Autosea, which is a collaboration project with DNV GL, Kongsberg Maritime and Marine Robotics. This project aims to attain world-leading competence and knowledge in design and verification of methods and systems for sensor fusion and collision avoidance for autonomous surface vehicles (NTNU, 2016).

The interest and activity on the field indicate that more autonomous vessels can be seen in the near future and that totally unmanned merchant vessels may be more than a distant dream. However, there are many factors that need to be addressed before unmanned vessels can be realised such as the economic, social, legal, regulatory and of course the technological. Today the ships are required to have to have a minimum manning level called safe manning, that is sufficient to cover all relevant operations, tasks and functions required to safely operate the ship (IMO, 2000; Sjøfartsdirektoratet, 2016). However, to be able to carry out all the required maintenance on board, the vessels usually have more crew than the safe manning requirement (Solvang ASA, 2016). For oceangoing unmanned vessels, one of the biggest challenges is to get systems and machinery to function reliably without maintenance for periods up to four weeks (Stensvold, 2013). Consequently, there

is a need for identifying what systems in the engine room on today's oceangoing merchant vessels that can be maintained solely in the port, and those systems where new design is required.

RCM is a thorough process that determines what must be done to ensure that any physical asset continuous to do whatever its users wants it to do in its present operating context (Moubray, 1997). The process identifies critical failures in the assets operating context and then assesses whether maintenance tasks can reduce the risk to an acceptable level. If no maintenance tasks is found to be applicable and effective in the operating context for the critical failures, the process requires one-time changes, such as redesign, modification or change of the item's operating context. For an oceangoing merchant vessel that is to be used in a new operating context, where no maintenance will be possible for up to four weeks, the method can be used to identify the critical failures and whether the risk can be reduced by means of maintenance, or if one-time changes is necessary. In this thesis, those critical failures that cannot be managed effectively by maintenance has been defined as barriers.

1.2 Objective

This thesis aims to establish a procedure based on the RCM process that can be used to identify the barriers in design of unmanned engine rooms on oceangoing merchant vessels. In addition, the established procedure shall be used to identify barriers in the fuel system for an oceangoing merchant vessel.

1.3 Scope and limitations

Identification of barriers has been performed on a fuel system that uses HFO as fuel, as this is the most common fuel used today by oceangoing merchant vessels. The analysis has been performed on the system under normal seagoing conditions, and the functional failure analysed is "Supplies no fuel to the main engine". The RCM process only focuses on the maintenance, thus other procedures the crew may have such as opening and closing of hand-operated valves falls outside the scope.

1.4 Structure of the report

Chapter 2 describes the background for the RCM method and how the development has been since its introduction in the flight industry in 1978, along with some advantages and disadvantages with respect to the maritime industry. In Chapter 3, the methodology is developed to a step by step procedure. The case study is performed in 4, with the results presented in Chapter 5. Discussion and conclusion are provided in Chapter 6 and Chapter 7, respectively.

2 Reliability-Centered Maintenance

“Reliability-Centered Maintenance: a process used to determine what must be done to ensure that any physical asset continuous to do whatever its users want it to do in its present operating context. “ (Moubray, 1997, p. 7)

2.1 Background (Why RCM)

John Moubray(Moubray, 1997) describes the evolution of maintenance since the 1930s through three generations. The first generation covers the period up to World War II. In this period the industry was not very mechanized, the equipment was mostly simple and over-designed. This made it reliable and as a result, there was no need for systematic maintenance. In the second generation following World War II, the industry started to depend on numerous and more complex machines. As a result the idea that failures could and should be prevented led to the concept of preventive maintenance. At the time this consisted mainly of equipment overhauls at fixed intervals. This approach was based on the concept that mechanical parts have a “right age” where complete overhaul is necessary to ensure safety and operability.

Stanley Nowlan and Howard Heap, referred to as the true pioneers of RCM (Bloom, 2006), describes how the traditional RCM evolved from the airline industry (Nowlan & Heap, 1978). New performance requirements led to increasingly complex equipment with accordingly increasing maintenance costs. By the 1950s, the commercial airline fleet had grown to a point where ample data for study, and the cost of maintenance had become sufficiently high to warrant a search look at the actual result of existing practices. Studies, based on actuarial analysis of failure data suggested that this policy not only where expensive, but also ineffective in controlling failure rates. Unexpected, the reason was that for many items the likelihood of failure did not increase with an increasing operating age. At the same time the Federal Aviation Agency (FAA), which was responsible for regulating maintenance practices, was frustrated by experiences showing that it was not possible to control the failure rate of certain types of engines by any feasible changes in scheduled-overhaul policy. As a result, a task force was formed in 1960 to investigate the capabilities of scheduled maintenance. The work of this group led to the FAA/Industry Reliability Program that was issued in 1961. Two findings that were especially surprising were:

- Scheduled overhaul has little effect on the overall reliability of a complex item unless the item has a dominant failure mode.
- There are many items for which there is no effective form of scheduled maintenance

2.2 Brief history – The evolution of RCM

The development of RCM from the reliability programs performed in the early 1960s, and its impact on the maintenance programs in the aviation industry until the publication of Nowlan & Heap's "Reliability-Centered Maintenance", are best described by their own words (Nowlan & Heap, 1978):

"The next step was an attempt to organize what had been learned from the various reliability programs and develop a logical and generally applicable approach to the design of preventive-maintenance programs. A rudimentary decision-diagram technique was devised in 1965, and in June 1967 a paper on its use was presented at the AIAA Commercial Aircraft Design and Operations Meeting. Subsequent refinements of this technique were embodied in a handbook on maintenance evaluation and program development, drafted by the maintenance steering group formed to oversee development of the initial program for the new Boeing 747 airplane. This document, known as MSG-1, was used by special teams of industry and FAA personnel to develop the first scheduled-maintenance program based on the principles of reliability-centered maintenance. The Boeing 747 maintenance program has been successful.

Use of the decision-diagram technique led to further improvements, which were incorporated two years later in a second document, MSG-2: Airline/Manufacturer Maintenance Program Planning Document. MSG-2 was used to develop the scheduled-maintenance programs for the Lockheed 1011 and the Douglas DC-10 airplanes. These programs have also been successful. MSG-2 has also been applied to tactical military aircraft; the first applications were for aircraft such as the Lockheed S-3 and P-3 and the McDonnell F4J. A similar document prepared in Europe was the basis for the initial programs for such recent aircraft as the Airbus Industrie A-300 and the Concorde.

The objective of the techniques outlined in MSG-1 and MSG-2 was to develop a scheduled-maintenance program that assured the maximum safety and reliability of which the equipment was capable and also provided them at the lowest cost. As an example of the economic benefits achieved with this approach, under traditional maintenance policies the initial program for the Douglas DC-8 airplane required scheduled overhaul for 339 items, in contrast to seven such items in the DC-10 program. One of the items no longer subject to overhaul limits in the later programs was the turbine propulsion engine. Elimination of scheduled overhauls for engines not only led to major reductions in labor and materials costs, but also reduced the spare-engine inventory required to cover shop maintenance by more than 50 percent. Since engines for larger airplanes now cost more than \$1 million each, this is a respectable saving.

As another example, under the MSG-1 program for the Boeing 747 United Airlines expended only 66,000 manhours on major structural inspections before reaching a basic interval of 20,000 hours for the first heavy inspections of this airplane. Under traditional maintenance policies it took an expenditure of more than 4 million manhours to arrive at the same structural inspection interval for the smaller and less complex Douglas DC-8. Cost reductions of this magnitude are of obvious importance to any organization responsible for maintaining large fleets of complex equipment. More important:

- Such cost reductions are achieved with no decrease in reliability. On the contrary, a better understanding of the failure process in complex equipment has actually improved reliability by making it possible to direct preventive tasks at specific evidence of potential failures.*

Although the MSG-1 and MSG-2 documents revolutionized the procedures followed in developing maintenance programs for transport aircraft, their application to other types of equipment was limited by their brevity and specialized focus. In addition, the formulation of certain concepts was incomplete. For example, the decision logic began with an evaluation of proposed tasks, rather than an evaluation of the failure consequences that determine whether they are needed, and if so, their actual purpose. The problem of establishing task intervals was not addressed, the role of hidden-function failures was unclear, and the treatment of structural maintenance was inadequate. There was also no guidance on the

use of operating information to refine or modify the initial program after the equipment entered service or the information systems needed for effective management of the ongoing program. All these shortcomings, as well as the need to clarify many of the underlying principles, led to analytic procedures of broader scope and crystallization of the logical discipline now known as reliability-centered maintenance."

Following the success in the commercial aviation industry, the Office of the Secretary of Defense directed the military services to incorporate the practices into maintenance programs for military equipment in 1974. However, this effort was hampered by lack of explanatory material as the material originally was written for a small group of readers. To provide this explanatory material, the U.S. Department of Defense commissioned United Airlines to prepare a textbook that fully explains a logical discipline, based on tested and proven airline practices, which could be used to develop effective scheduled-maintenance programs for complex equipment. This is the textbook "Reliability-Centered Maintenance" by Nowlan and Heap. This textbook provided the basis for MSG-3 (1980), which today the industry standard used to develop and refine maintenance programs for all major types of civil aircraft (McLoughlin, 2006).

2.3 Pros and cons of RCM in the maritime industry

2.3.1 Pros

Experiences from not only the aircraft industry, but also within the military forces, the nuclear power industry, the offshore oil and gas industry, and many other industries has showed significant reductions in preventive maintenance costs, in addition to maintaining, or improving the availability of the systems (Rausand, 1998). In the shipping industry the maintenance is based on manufacturers recommendations and together with own experience with the equipment (Solvang ASA, 2016). However, many of the manufacturers get very little feedback from the users after the guarantee period. Thus, the recommendations from the manufacturers are not always based on real experience data. It has also been claimed that the manufacturers and suppliers tend to recommend a very conservative maintenance approach (Mokashi et al., 2002). In fear of guarantee or damage claims and lack of knowledge of the operating environment, they may suggest a maintenance program that can cope with the worst-case scenario. This will obviously lead

to over-maintenance, which is a waste of resources. It is therefore a great potential for cost savings by applying RCM in the development of maintenance programs in the marine industry.

2.3.2 Cons

The implementation of RCM to marine vessels can have some hurdles. Mokashi et al. (2002) addresses some of the issues which is discussed in the following paragraphs.

First of all the RCM analysis require reliability data of good quality to make the right decisions. The maritime industry it does not exist a large reliability databank as for example OREDA has for the offshore oil and gas industry. The failure data are also to a high degree dependent on the operating environment, and as ships operate in different and continuously changing environment, the data are less portable. For example, the seawater cooling system will experience an increased amount of microorganisms and fouling when operating in warmer waters (Wabakken, 2015). Additionally, the equipment may have different functions, operating conditions and redundancy from vessel to vessel. In the maritime industry, certain conditions like tightness, lubrication and cleanliness are also considered a constant source for concern. Therefore, the basic equipment condition cannot be taken for granted.

The research paper also mentions that that shipboard personnel are not trained in maintenance management or risk management techniques. As the personnel already are overburdened with tasks, a complex and long methodology as RCM may be a challenge. A consequence may be that the personnel does not understand the rationale behind the selected maintenance tasks, following a loss of motivation, which can affect the performance of the maintenance program.

Another concern is related to the implementation of RCM. In some industries and organisations, the suppliers are required to submit a FMEA of the equipment. This makes the implementation of RCM much easier. However, this is not the case in the maritime industry. The result of an RCM analysis may be maintenance tasks that deviate from the supplier's recommendations. A result of not following the supplier's recommendations in the guarantee period could remove the supplier from any obligations in case of a claim. This can obviously be a concern for the ship owner.

3 Method - RCM step-by-step

Since Nowlan and Heap's publication in 1978, their textbook has served as a basis for numerous attempts to refine and improve the method. This have led to a widespread use of the term "RCM" for new processes that not necessary have kept the key elements of the original process. Since many of these processes not only fail to achieve the goals of Nowlan and Heap, but also can be actively counterproductive, it has been a demand for a standard that sets out the criteria that any process must comply with in order to be called "RCM". SAE International issued in 1999 a standard to meet that demand, called "SAE JA1011: Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes". This standard was revised in 2009 where small changes were made to clarify the origin of RCM, update the terminology to reflect the current usage and to remove items that might have been considered biased to individual commercial processes. However, the overall technical process remained unchanged.

The criteria in SAE JA1011 are based on the RCM process established by Nowlan and Heap in 1978. In addition, three documents that closely followed the original process were used extensively as sources:

- US naval aviation's MIL-STD-2173(AS) – Reliability-Centered Maintenance Requirements of Naval Aircraft, Weapons Systems and Support Equipment, and its successor, U.S. Naval Air Systems Command Management Manual 00-25-403 – Guidelines for the Naval Aviation Reliability-Centered Maintenance Process
- NES 45 – Requirements for the Application of Reliability-Centered Maintenance Techniques to HM Ships, Royal Fleet Auxiliaries and other Naval Auxiliary Vessels (Restricted-Commercial)
- Reliability-Centered Maintenance (RCM2) by John Moubray.

The standard requires the following seven steps to be performed in sequence. However, the process assumes that the asset/system concerned already has been selected and defined. The reason given is that this process tends to be highly dependent on the type of asset/system and where, for what, and by whom it is being used. As a consequence SAE JA1011 doesn't provide any criteria for the process used for selecting and defining the assets/systems. However, SAE JA1012 provides some general guidance on the topic. Any

process shall ensure that all of the following steps are performed satisfactorily in the sequence presented (*SAE International, 2009, p. 7*):

1. Determine the operational context and the functions and associated desired standards of performance of the asset (operational context and functions).
2. Determine how an asset can fail to fulfill its functions (functional failures).
3. Determine the causes of each functional failure (failure modes).
4. Determine what happens when each failure occurs (failure effects).
5. Classify the consequences of failure (failure consequences).
6. Determine what should be performed to predict or prevent each failure (tasks and task intervals).
7. Determine if other failure management strategies may be more effective (one-time changes).

In addition, the standard sets requirements to what to include to perform each of the steps “satisfactory”. These requirements are discussed under section 3.2 – 3.5.

3.1 Asset/system definition

3.1.1 Partitioning - System boundaries

A ship consists of numerous systems, each with their own set of functions. To be able to identify all functions it may be necessary to break down the total functionality into more manageable blocks (Norsk elektroteknisk komite, 2009, p. 20). There are many ways of undertaking this process. Functional block diagrams are recommended as basis for FMECA (Norsk elektroteknisk komite, 2006; U.S. Department of Defence, 1980) and for RCM (Smith, 1993). Functional trees, a hierarchical breakdown structure of functions were proposed for functional analysis of complex systems by Rausand and Høyland (Rausand & Høyland, 2004, pp. 79-80). Rausand and Høyland states that it is often more obvious to use a physical breakdown of the system instead of a functional breakdown if an existing system is being analysed. As long as each function is performed by only one physical element these three will be similar.

SAE JA1012 (SAE International, 2011, p. 60) states that it is important to clearly define where the “system” to be analysed begins and where it ends. This is especially important

to consider when systems are partitioned to ensure that all items are included. For example, a group may be “Systems for machinery” which is partitioned to “Lube oil systems” and “Cooling systems” among others. These two systems are interfaced through a heat exchanger which it is important to make sure don’t “fall between the cracks”. Bloom (2006) states that this process of identifying boundaries and interfaces is one of the primary reasons for the failure of an RCM program to be implemented (Bloom, 2006, p. 77). The reason stated isn’t that the process is wrong, but that the process is very unwieldy and cumbersome and perhaps the most time-consuming and complicated aspect of the entire RCM process. Actually, he states that RCM doesn’t require the identification of system boundaries and interfaces. The method Bloom suggests, which is a primary aspect of his book, is to skip the process of partitioning and identifying boundaries and interfaces, and analyse all components one-by-one. This is a straightforward process that he claims will save substantial amounts of time. Bloom defines the component level as that level where a separate equipment identification number (equipment I.D.) is specified. This includes valves, pumps, switches, heat exchangers, circuit breakers etc., but not subassembly piece parts such as bearings, armature, stator, shaft, crank arm etc.

In 1956, Air Transport Association of America (ATA, 1956) published the standard “ATA Specification 100 - Specification for Manufacturers' Technical Data”. This standard contained among others a breakdown of the airplane into systems and subsystems, known as ATA 100 codes. Thus, Nowlan and Heap didn’t have to develop these system boundaries. Bloom claims that Nowlan and Heap started at the system level only as a matter of convenience, but that it was not a requirement (Bloom, 2006, p. 22). He also claims that it was the component’s functional failure and its effect on the aircraft (or plant) that was really important to them. However, it may be easier to identify the effects and associated consequences if such breakdown exists than to start directly at component level. Another advantage of using such functional breakdown is that not all components need to be analysed as it is possible to exclude less important systems from the analysis.

Fortunately, it exists a similar function-based group system for ships, namely the SFI Group System (Norges skipsforskningsinstitutt, 1973). An extract of the SFI group system is shown in Figure 3.1. The figure shows how the ship is grouped into main groups that is

further grouped into groups and sub-groups according to their function on board. Some ship owners register their maintenance data in systems that are based on the SFI group system, such as Star IPS. This makes the process of both prioritizing systems for RCM analysis, and the execution of the analysis a lot easier.

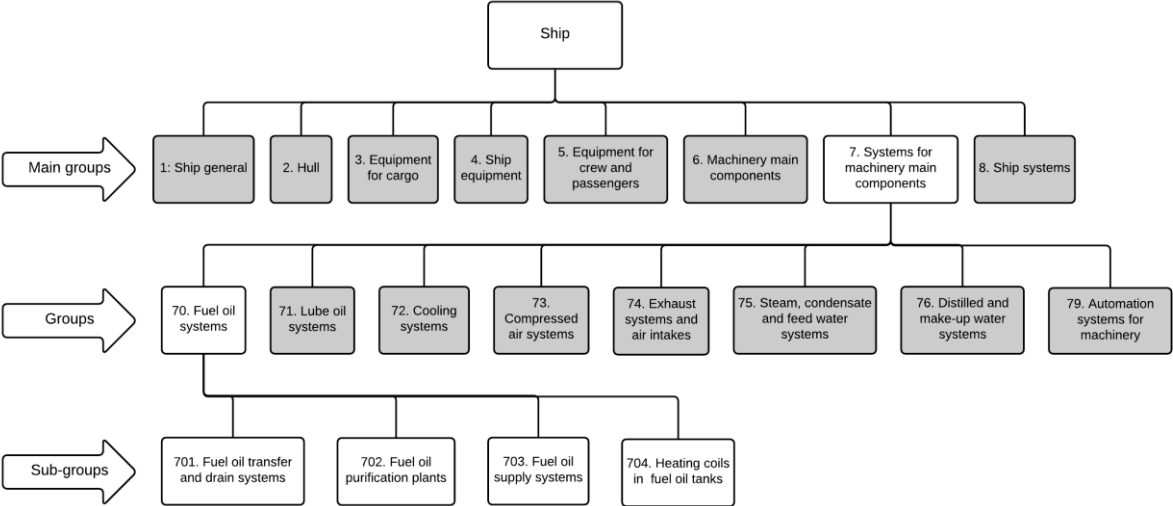


Figure 3.1: SFI Group System.

Since ships are equipped differently, the SFI group system is only broken down to three levels. However, once a group (or sub-group) is selected for analysis the sub-groups should be broken down further to a convenient level for analysis. According to Rausand and Høyland the systems should be broken down to maintainable items (Rausand & Høyland, 2004). Maintainable items are items that are able to perform at least one significant function as a stand-alone item (e.g. pumps, valves, etc.). This is a convenient level as there is no reason to analyse supporting equipment such as a valve actuator unless the valve has any significant failures. Subassemblies piece parts such as bearings, armature, stator, etc. does neither perform one significant stand-alone function alone, and so they only become important when identifying the causes of failure (Bloom, 2006, p. 79). The reason why these items are called “maintainable items” is that by the RCM approach all maintenance tasks are decided for these items such as repair, replacement, or testing of an item or part of the maintainable item. This choice of the lowest level in the hierarchy is supported by other sources as well (ABS, 2003; Bloom, 2006; Norsk elektroteknisk komite, 2009).

3.1.2 Establishing objectives and prioritizing assets

It is well known that applying RCM takes time and costs money. SAE JA1012 states that owners and users should set priorities among assets by using criteria that are appropriate to their organization. Selection and priority should be based on a wide range of criteria such as maintenance efficiency, dependability improvement and design/operation change (Norsk elektroteknisk komite, 2009, p. 16). Rausand & Høyland (Rausand & Høyland, 2004, p. 403) states one should start with the system that it's believed will benefit the most from the analysis. Their procedure then continues with describing operating context for each of the maintainable items in that system. Then they suggest to prioritize among the maintainable items by performing functional failure analysis (FFA). In the FFA, the functions and functional failures on system level is identified and ranked according to criticality. Once the critical functional failures are identified, potential critical maintainable items with respect to the functional failures identified are identified. These maintainable items are defined as functional significant items (FSI). For simple items the FSIs may be identified without any formal analysis, but for complex items a formal approach may be needed. In addition, items with high failure rates, high repair costs, low maintainability, long lead-time for spare parts, and items that require external maintenance personnel should be identified. These are denoted maintenance cost significant items (MCSI). Together the MCSIs and FSIs constitutes maintenance significant items (MSI). Their procedure then continues with a special FMECA analysis where required step 1-5 is performed for each of the MSIs, except for the operating context, which was described for all maintainable items before the MSI selection. It can be noted that Rausand and Høyland uses a different definition of failure mode, where failure mode is defined as functional failures of maintainable items. Therefore, their FMECA includes a column for failure cause, which corresponds to failure modes in the SAE standard.

MSG-3 also performs a MSI selection procedure to begin with, but it is somewhat different from Rausand and Høyland's procedure. The procedure starts by partitioning the aircraft into major functional areas (ATA systems and subsystems) until all on-aircraft replaceable components have been identified. Now, using a top-down approach a list of items is selected. These items are asked the following MSI selection questions(ATA, 2002, pp. 22-23):

1. Could failure be undetectable or not likely to be detected by the operating crew during normal duties?
2. Could failure affect safety (on ground or in flight), including safety/emergency systems or equipment?
3. Could failure have significant operational impact?
4. Could failure have significant economic impact?

For those items where at least one of the questions is answered by “yes”, the item is an MSI and an MSG-3 analysis is required. It should be considered to selecting a higher manageable level that includes this item as part of that higher-level system. While the MSIs are maintainable items in Rausand and Høyland’s procedure, the MSIs in the MSG-3 procedure are usually systems or a sub-systems, and in most cases, one level above the lowest level identified in the first step (replaceable components).

A significant difference between the two approaches is that Rausand and Høyland’s procedure starts with the system it’s believed that will benefit the most from the RCM analysis, while the MSG-3 procedure creates a list of MSIs where analysis is *required*. The former approach may be preferred if the goal is to make improvements to an existing maintenance program by prioritizing “low-hanging fruit”, but when the method is used to ensure that not only the maintenance program is effective, but also that the reliability and risk is acceptable for a new design or in a new operating context, all systems that may be critical with respect to risk should be considered, as in the MSG-3 procedure. However, recognising the limitations on time and resources available in this thesis, not all critical systems can be analysed. Therefore, a prioritising has been made among the systems in the engine room according to the amount of corrective maintenance that is performed on those systems. As the main change of operating the engine room unmanned is that all the maintenance has to be performed while the ship is in port, the system with most maintenance will be the system that is most affected by the new operating context.

The other main difference is that Rausand and Høyland RCM procedure is that the required RCM steps is performed on maintainable items, while the MSG-3 procedure strives to perform the required steps on the highest manageable level. The following subsection discusses this topic.

3.1.3 Level of indenture

One important decision that has to be made is what level the analysis shall be performed, i.e. the level where the 7 required steps shall be performed. According to SAE JA1012 there is no best level, but usually an optimum level (can vary within the hierarchy). This optimum depends on several factors such as whether a complete or a more limited analysis will be performed, if previous analyses they exists, complexity of the item etc. The consequence of choosing a too low level is difficultness in identifying functions and associated desired performance standards, harder to assess consequences readily and extra work. If too high level is chosen the result is too many failure modes per function, which increases the probability of overlooking failure modes. When applying RCM for the first time the tendency is to start at a too low level (UK Ministry of Defence, 2000, p. 8.2). The reason for this is a mistaken belief that a failure mode of a component only can be identified at the component level. Actually, failure modes can be identified from any level. For example, both the functional failure “unable to generate any power at all” and “unable to supply any fuel at all to the engine” may have the failure mode “fuel filter blocked by particulate build up”. As a consequence this standard provides a general rule to carry out the RCM analysis at one level higher than what first seems sensible (UK Ministry of Defence, 2000, p. 8.6). Table 3.1 summarizes what characterizes the choice of level of indenture.

Table 3.1: Characteristics of different levels of indenture.

Level	Characteristics
Too high	<ul style="list-style-type: none"> • Too many failure modes per function • Higher probability of overlooking failure modes
Optimum	<ul style="list-style-type: none"> • Functions identified in a form that is reasonably easy to comprehend • Manageable number of failure modes per function • Failure consequences assessed without difficulty
Too low	<ul style="list-style-type: none"> • Extra work • Difficult to identify functions and associated desired performance standards • Harder to assess consequences readily • More difficult to decide which components belong to which system. • Failure modes may be repeated several times. For example loss of electric power supply can cause many sub-systems to fail. • Control and protective devices may be more difficult to deal with. For example, a sensor in one sub-system may drive an actuator in another sub-system through a processor in a third sub-system. This causes the same function to be analysed three times in slightly different ways.

3.2 Operational context and functions

When determining an asset's functions, failure modes, failure effects, failure consequences, and appropriate failure management policy, it will not only depend on the asset, but also the exact circumstances under which it is to be used. Therefore, these circumstances need to be clearly defined in an operational context.

When the operational context is defined, the next step is to identify the asset's functions in its operational context. This step is important, as the main goal of the RCM process is to develop a set of failure management policies that preserve the functions of the asset. SAE JA1011 (2009) requires the following of an RCM process in this step:

1. The operational context of the asset shall be defined, recorded, and available.
2. All the primary and secondary functions of the asset/system shall be defined.
3. All function statements shall contain a verb, an object, and a performance standard (quantified in every case where this can be done).
4. Performance standards incorporated in function statements shall be the level of performance desired by the owner or user of the asset/system in its operational context (as opposed to the design capacity).

3.2.1 Operational context statement

"The operational context of the asset shall be defined, recorded, and available." (SAE International, 2009, p. 8)

The operational context for a physical asset typically contains a brief overall description of how it is to be used, where it is to be used, overall performance criteria (output, throughput, safety, environmental integrity, etc.), and so on. An example of an operational context statement of a diesel engine may be "The propulsion system consists of a *Manufacturer Diesel Type Model Number* low-speed diesel engine rated 16,860 kW Maximum Continuous Rating (MCR) at 91 RPM, coupled directly to a shaft supported by one intermediate bearing and two stern tube bearings, and driving a fixed pitched propeller" (ABS, 2003, p. 27).

3.2.2 Primary and secondary functions

“All the primary and secondary functions of the asset/system shall be identified” (SAE International, 2009, p. 8)

Functions which constitute the main reasons why a physical asset or system is acquired by its owner or user, is defined as primary functions (SAE International, 2011). In other words, the primary functions are those functions the asset is installed to fulfil. For example, the primary function of a diesel engine may be to provide at least 10,000 kW of power to the shaft.

In addition to the primary functions, the asset is often expected to perform other, often less obvious functions. This is functions that a physical asset or system has to fulfill apart from its primary function(s), such as those needed to fulfil regulatory requirements and those which concern issues such as protection, control, containment, comfort, appearance, energy efficiency and structural integrity (SAE International, 2011). These functions can still have serious consequences and it is therefore important to identify those as well.

3.2.3 Function statements

“All function statements shall contain a verb, an object, and a performance standard (quantified in every case where this can be done).” (SAE International, 2009, p. 8)

An example of this formulation for a pump can be “To pump (verb) water (objective) at not less than 500 litres per minute (performance standard)”. Protective functions usually acts when something goes wrong. Thus, the functional statements of protective functions usually contains the words “if” or “in the event of”. An example of a functional statement for a pressure safety valve may be “To be capable of relieving the pressure in the boiler if it exceeds 20 bar”.

3.2.4 Performance standards

“Performance standards incorporated in function statements shall be the level of performance desired by the owner or user of the asset/system in its operational context (as opposed to the design capacity).” (SAE International, 2009, p. 8)

Any asset deteriorates with time and will eventually reach an unacceptable performance unless the asset is maintained. As long as the performance of the asset is above the desired level of performance, the asset is in a functional state. It follows that the initial built-in capacity of the asset has no relevance in determining whether the asset is in a functioning or failed state. It is therefore important to clearly distinguish these concepts and only use the desired level of performance in the functional statement.

Although the built-in capacity of an asset is of no interest in the functional statements, it is important to have a sufficient margin for deterioration between the built-in capacity and the desired level of performance.

3.3 Functional failures

“All the failed states associated with each function shall be identified” (SAE International, 2009, p. 8)

These failed states, in which a physical asset or a system is unable to perform a specific function to a desired level of performance, are denoted functional failures. As explained in 3.2.2 the assets may have many functions. Consequently, the assets may also have many functional failures. The main objective of the RCM process is to determine the best maintenance plan, and all the steps in the process are performed to support this decision-making. Perhaps the most important factor to consider in this decision-making process is the consequences of the failure, as this is what maintenance is performed to prevent. As a consequence, total failure and partial failures should be distinguished as they nearly always have different consequences and failure modes. For example, the consequence of a pump that has deteriorated just below the desired performance level is probably lower than the consequence of not being able to pump at all. Note that the performance standards associated with some functions incorporate both upper and lower limits. Thus, the functional failure can be total failure, too low performance and too high performance.

3.4 FMECA analysis

The next three required steps in the RCM procedure consist of determining the causes of each functional failure (failure modes), determine what happens when each failure occurs (failure effects) and classify the consequences of failure (failure consequences). These

steps are normally effectively performed by a failure mode, effects and criticality analysis (FMECA).

3.4.1 FMECA Worksheet

The FMECA analysis is performed to obtain the information necessary for decision making in the decision diagram presented in 3.5. All necessary information is filled into a FMECA worksheet as illustrated in Figure 3.2. The information that is filled into the worksheet are discussed and described in the following subsections.

System: Fuel oil system
 Operating mode: Normal seagoing conditions at full speed
 Functional failure: Circulates no fuel through the engine

Date: 26.03.2016

Performed by: Nikolai H. Jacobsen

Failure mode	Effect	Redundancy provided?	Consequence category			Risk			Failure pattern	Remarks				
			Hidden/evident?	S	E	OH	RC	MTBM (months)			Likelihood category	Risk Index	Corrected RI	
H.F.O Transfer pump failure	Fuel cannot be transferred between HFO tanks or to HFO settling tanks, and filling of the settling tanks stops. Settling tanks + service tanks have in total a capacity for 96 hours of maximum fuel consumption. IMO transfer pump can be used if spectacle flange and hand operated flange is opened. Else, repair is necessary to restore function.	No*	Evident	1	1	2	1	1	4,9	2	4	4	B	* Three transfer pumps, but only one can transfer fuel to settling tank.

Figure 3.2: FMECA worksheet.

3.4.2 Failure modes

A failure mode is in SAE JA1011 (2009) defined as a single event, which causes a functional failure (state). A noun and a verb should describe the failure mode, as for example “filter plugged”. The description should be detailed enough to identify an appropriate failure management policy, hence, verbs such as “fails”, “malfunctions” and “breaks” should be used with care, as it gives little indication on what an appropriate failure management policy may be. For the same reason, the description of failure modes for items such as valves and switches should state whether it fails in open or closed position. The standard sets the following criteria to the identification of failure modes:

1. All failure modes reasonably likely to cause each functional failure shall be identified.
2. The method used to decide what constitutes a “reasonably likely” failure mode shall be acceptable to the owner or user of the asset.
3. Failure modes shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy. Failure modes should be addressed at the same level of detail that the asset or system will be maintained. Failure modes that can occur within a component of the asset or system that cannot or will not be addressed individually (because the component is the lowest level at which the system will be repaired and maintained) do not need to be enumerated. However, if the component will be disassembled to address specific internal failure modes, then those failure modes do need to be itemized.
4. List of failure modes shall include failure modes that have happened before, failure modes that are currently being prevented by existing maintenance programs and failure modes that have not yet happened but that are thought to be reasonably likely in the operational context.
5. Lists of failure modes should include any event or process that is likely to cause a functional failure (including deterioration, design defects and human error whether caused by operators or maintainers) unless these events are being sufficiently addressed by processes apart from RCM.

What is meant by “reasonably likely” is that people who are trained to use RCM, and that are knowledgeable about the asset in its operating context consider the probability that

the failure mode could occur is sufficiently high to warrant further analysis. Failure modes that are considered reasonable likely typically consist of failure modes that have happened before, failure modes that are currently being prevented by existing maintenance programs and failure modes that have not yet happened but that are thought to be reasonably likely in the operating context. As the organization that owns or uses of the asset will be accountable for the consequences of a functional failure, the organization must make the final decision in case of doubt or disagreement on whether a failure mode should be included or not.

The failure modes can be defined at almost any level of detail, and the appropriate level is different in different situations. To avoid wasting excessive time on the analysis it is important to restrict the level of causation to the same detail that the asset will be maintained. Table 3.2: Failure modes at different levels of detail. Table 3.2 shows how the number of failure modes for a pump set with the functional failure “unable to transfer any water at all” increases with the level of detail (Moubrey, 1997, pp. 66-68). It can be observed that the failure mode “pump fails” at level 1 has 21 failure modes at level 6. If the failure modes “motor fails”, “driveline fails”, “valve closed” and “power fails” also are analysed to this level, the number of failure modes at level 6 becomes 62. However, the level of causation where it is possible to identify an appropriate failure management policy will vary for different failure modes.

Table 3.2: Failure modes at different levels of detail.

Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	
Pump set fails	Pump fails	Impeller fails	Impeller comes adrift	Mounting nut undone	Nut not tightened correctly	
				Mounting nut worn away	Nut eroded/corroded away	
				Impeller nut cracked	Impeller nut overtightened	
				Impeller key sheared	Nut made of wrong material	
			Object smashes impeller	Part in system after maintenance	Assembly error	
				Foreign object enters system	Suction strainer not installed	
			Casing ruptured	Casing bolts come loose	Casing bolts undertightened	Assembly error
					Bolt loosened by vibration	
					Casing bolts corroded away	
					Bolts fail due to fatigue	
		Casing joint fails		Joint incorrectly fitted	Assembly error	
				Join fails due to fretting		
		Casing smashed	Casing smashed by vehicle	Operating error		
			Smashed by object from sky	Pump in vulnerable position		
		Pump seal fails	Normal wear and tear	Seal abraded		
			Pump runs dry			
			Seal misaligned	Assembly error		
			Seal faces dirty	Assembly error		
			Wrong seal fitted	Wrong seal supplied	Procurement error	
				Wrong seal specified	Storekeeping error	
			Damaged seal installed	Pump seal dropped in stores	Design error	
		Pump seal damaged in transit		Storekeeping error		
				Procurement error		
		Motor fails	*	*	*	*
		Driveline fails	*	*	*	*
		Valve closed	*	*	*	*
		Power fails	*	*	*	*

In this thesis, the method shall be used to identify barriers and not necessary design the optimal maintenance plan. From that point of view it is of more interest to know how often a component fails, than exactly what caused the failure, unless there is a dominant failure mode. If the analysis can point out components or systems as barriers, a deeper analysis of the causes and possible actions to break the barriers can be performed at a later stage. It can also be mentioned that describing failure modes on a higher lever not only increases the time spent on the analysis, but also requires more and more specific data to get accurate results. Therefore, one should also take into account the data available for analysis when describing the failure modes.

3.4.3 Failure effects

What happens when a failure mode occurs is denoted “failure effects”. The following criteria apply to the step of determining the failure effects (SAE International, 2009):

1. Failure effects shall describe what would happen assuming the failure mode and corresponding functional failure actually occurs.
2. Failure effects shall include all the information needed to support the evaluation of the consequences of the failure, such as:
 - a. What evidence (if any) that the failure has occurred (in the case of hidden functions, what would happen if a multiple failure occurred).
 - b. What it does (if anything) to kill or injure someone, or to have an adverse effect on the environment.
 - c. What it does (if anything) to have an adverse effect on production or operations.
 - d. What the physical damage (if any) is caused by the failure.
 - e. What (if anything) must be done to restore the function of the system after the failure.

To be conservative the failure effects should reflect the “typical worst case scenario”, but not the “extreme worst case”, as this would be excessively conservative (SAE International, 2011, p. 30). It can be noted that the RCM procedure distinguishes effects (what happens) from the consequences (how, and how much, the failure matters). The failure effect statement is the primary source of information used to assess the failure consequences, and should therefore contain enough information to be able to assess the consequences. An example of a failure effect statement for the failure mode “gearbox bearings seize” is “motor trips and alarm sounds in control room. 3 hours downtime to replace gearbox with spare. New bearings fitted in workshop”. Note that the failure effect statement should not contain phrases like “... has safety consequences” or “... affects the safety”, as the evaluation of consequences are left to the next stage in the process.

3.4.4 Failure consequence categories

Failure consequence categories are a classification of the failure effects of failure modes based on evidence of failure, impact on safety, the environment, operational capability, and costs. The following criteria apply to the process of classifying the consequences of failure(SAE International, 2009):

1. The consequences of every failure mode shall be formally categorized as follows:

- a. The consequence categorization process shall separate hidden failure modes from evident failure modes.
 - b. The consequence categorization process shall clearly distinguish events (failure modes and multiple failures) that have safety and/or environmental consequences from those that only have economic consequences (operational and non-operational consequences).
2. The assessment of failure consequences shall be carried out as if no specific task is currently being done to anticipate, prevent, or detect the failure.

A hidden failure is defined as a failure mode whose effects do not become evident to the operator(s) under normal circumstances if the failure mode occurs on its own (SAE International, 2009). The reason why this distinction is made is that these failure modes do not have direct effects if it occurs on its own, but may expose the organization to the risk of much more serious failure modes. One example may be a pressure safety valve with the primary function “to be capable of relieving the pressure in the boiler if it exceeds 20 bar”. If this valve is exposed to the failure mode “fail to open” there will be no immediate consequences, but the consequences of a failure causing increased pressure in the system will be increased. Note that the failure mode will be evident when the function is required, but will be classified as hidden because the failure mode does not become evident “on its own”. In such cases the consequence of the multiple failure (failure of protected device while protective system is in a failed state) would have to be considered. If the failure mode has an intolerable probability of killing or injuring a human being, the failure mode is said to have safety consequences. Another form of “safety” is environmental consequences. A failure mode has environmental consequences if there is an intolerable probability that it could breach a known environmental standard or regulation. The reason why these consequences should be distinguished from failure modes that only have economic consequences has to do with the selection of failure management tasks in the next stage. As described in 3.5.3 a valid RCM diagram approach deals with safety/environmental consequences before economic consequences, and assumes that if a failure management policy deals satisfactorily with a failure that has safety/environmental consequences, it also deal satisfactorily with the economic consequences. Thus, the economic consequences of a failure mode that has safety/environmental consequences will never be considered by this approach.

A topic that is not very well covered for all cases in the literature is how to handle redundancy. SAE JA1011 (2009) does not set any requirements to how redundancy should be dealt with. In SAE JA1012 (2011) the guide states that redundancy should be documented in the operating context statement. The guide further defines the protective functions as functions that avoid, eliminate, or minimize the consequences of the failure of some other function. These functions are among others equipment that take over from a function that has failed, as for example a stand-by component or redundant structural components. According to this definition a redundant component that acts as a stand-by unit has a protective function. A failure of this this component while it is in stand-by would be classified as a hidden failure, and according to the standard, the multiple failure – a hidden failure of the stand-by component followed by a failure of the active component would have to be considered. However, the scenario where the active component fails, followed by a failure of the stand-by component (now active) is not considered. In the discussion about hidden and evident failures, the guide discusses three scenarios of evident failures of protective functions: No failure, protected function fail where the protection carries out its intended function, and a scenario were the protective function fails before the protected function. It is stated that for the last scenario, the probability almost can be eliminated by shutting down the protected function, or by providing alternative protection until the protective function is restored. This may explain why the scenario of failure of the protected function (or component) followed by a failure of the protective function (or component) is not covered. However, in the operating context where repair may not be possible for several weeks, this scenario should be considered.

The reason why a distinction is made between hidden and evident failures is as described in 3.5.5 to evaluate whether the probability of a single failure (evident) or a multiple failure (hidden) is acceptable. Although the scenario where a failure of the active component is followed by a failure of the stand-by component (now active) will be considered as evident failures according to the definition, they should be considered in the same way as hidden failures, where the multiple failure are considered in the evaluation of the effectiveness of maintenance tasks. Therefore, a column are included in the FMECA to indicate redundancy. It should be noted this scenario is not a multiple failure according to the definition used in SAE JA1011 and JA 1012, where multiple failure

is defined as “An event that occurs if a protected function fails while its protective device or protective system is in a failed state”.

3.4.5 Risk

Risk is measured by multiplying probability by severity of a failure mode (SAE International, 2011). For a maintenance task to be considered effective, the risk must be reduced to a tolerable level. A common way of evaluating risk is by the use of a risk matrix where frequencies and consequences are grouped in rather broad classes. In the risk matrix the risk is lowest in the corner corresponding to low likelihood and low consequences, while the most risk is located in the opposite corner with high likelihood and high consequences. This characteristic divides the matrix in three regions: A region with tolerable risk, where no measures are required, a region with moderate risk that may be acceptable, and a region with intolerable risk and where measures are necessary. Often the frequency and consequence categories are set up on a logarithmic scale, so that the frequency/consequences of a class is 10 times higher than the preceding class (Rausand, 2011). When this is the case the risk can be evaluated by calculating the risk index (RI). The RI is defined as

$$R = C \cdot p$$

$$RI = \log R = \log C \cdot \log p$$

Where R is the risk, C is the consequences (severity) and p is the probability. An example of a 3x3 risk matrix is shown in Figure 3.3, and the definitions of likelihood classes are presented in Figure 3.4. The consequences and likelihood is divided into three levels with value from 1-3, where the risk index is shown for each combination. What is considered as tolerable risk may vary significantly from industry to industry and company to company, and therefore it doesn't exist a universal risk matrix. The risk matrix in Figure 3.3 is a slightly modification of a risk matrix provided by the shipping company Solvang ASA and should therefore provide a useful risk acceptance criteria for the analysis performed in this thesis.

Severity		Likelihood			
		Highly unlikely 1	Unlikely 2	Likely 3	
S	One or multiple fatal damages. Several victims with permanent damages or loss of body part	3	Moderate risk 4	Intolerable risk 5	Intolerable risk 6
E	Pollution reportable, major release. Limited effect on recipients				
C	Multiple damages on several areas (\$200,000 and above)				
OH	Time loss more than a week				
S	One ore multiple accident which imply time losses or permanent injuries	2	Moderate risk 3	Moderate risk 4	Intolerable risk 5
E	Pollution reportable, minor release. No long term effect on recipients				
C	Considerable damage on important areas or important equipment (\$20,000 - \$200,000)				
OH	Time loss up to 1 week				
S	Accident without loss of time or personal injuries	1	Tolerable risk 2	Moderate risk 3	Moderate risk 4
E	Negligible pollution				
C	Damage on equipment (< \$20,000)				
OH	Time loss up to 1 day				

Figure 3.3: Risk matrix

Likelihood	
1	Not likely to occur during the lifetime of the vessel
2	Several times during the lifetime of the vessel
3	Once per year per vessel or more often.

Figure 3.4: Definition of likelihood for risk matrix.

Since the risk matrix approach is easy to use and understand, the approach is widely used in many industries and has a long track record. However, the approach has some limitations that should be mentioned. First, the procedure look at one event at a time. This has its advantage in that it addresses the risk to specific failure modes, but it does not considers the total risk, which the risk decisions should be based on. Secondly, the matrices does not follow any standard terminology or layout, so it may be difficult to compare results, even between analyses performed in the same industry. The method is however suitable for relative ranking of risk and thus for pointing out the systems or components where risk reducing measures or a deeper analysis is needed. This makes the approach suitable for identification of barriers.

In Figure 3.2 it can be observed that the Mean Time Between Maintenance (MTBM) has been included in the risk part of the worksheet. The risk shall be calculated as the severity multiplied with the probability/likelihood of failure, and in the RCM procedure the selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure. Therefore, it would have been better to use list Mean Time To Failure (MTTF) defined as if no maintenance is performed to prevent the failure, and use this to select the likelihood class. However, due to lack of such data analysis in this analysis, the MTBM has been included instead and used as basis for selecting the likelihood class. For example, it may be assumed that filters that

is cleaned once per month will fail once per year or more frequently if no preventive cleaning is performed. Thus it can be noted that the MTBM does not represent a direct estimate on how often the item will fail, but is only a factor in determining the likelihood class.

In 3.4.4 it was explained why redundancy was included in the FMECA analysis. However, it was not discussed how the redundancy is accounted for in the analysis. Quantitative it is possible to calculate the probability of failure of a redundant system during a transit, but this requires knowledge about the failure distribution and the portion of common cause failures, or it has to be made assumptions of those. However, a method used by MARINTEK in an RCM analysis of a vessel with very similar definitions of likelihood and consequences, was to award redundancy by reducing the risk index by one value, which corresponds to reducing the likelihood of failure to 1/10 (Moen, 1995). This is a very simple and easy approach that can be well suited for identification of barriers, while a deeper more accurate quantitative analysis can be performed at a later stage of those items that exert most risk. This procedure has been adapted in the analysis performed in this thesis.

3.5 Decision diagram approach

The next step in the RCM procedure after the FMECA analysis is to manage the failure modes by selecting appropriate failure management policies. In this thesis, the main goal is not to develop an optimal maintenance program, but to identify systems or components that may not be possible to operate without crew on board with an acceptable risk. Therefore, the procedure used in this thesis is to first evaluate whether the current performed preventive maintenance is applicable and effective in the new operating context. This actually violates requirement 5.6.4 in SAE JA1011 that states “The selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure”. Consequently, the procedure used cannot be called RCM, and is the reason why the title is “Application of RCM principles to identify barriers ...”, and not “Application of RCM to identify barriers ...” The consequence of this violation is that although the current maintenance is considered applicable and effective, it may be other failure management policies that is more suited. However, as stated, the main goal is not to improve the current maintenance program or develop a new one, which RCM usually is performed for. In this thesis it would be a valuable result if the maintenance performed today is considered both applicable in the new operating context, as it can disprove that the failure mode represents a barrier. Thus, the consequences of this violation are considered acceptable for the purpose of this thesis.

SAE JA1012 describes two distinct approaches for selection of failure management policies: a rigorous approach and a decision diagram approach. The rigorous approach is more thorough and produces a fully cost-optimized failure management policy for each failure mode. This is achieved by first assessing all applicable failure management policies and then select the policy that deals most effectively with both the economic and the safety/environmental consequences. The decision diagram approach uses a diagram with a hierarchy of policies where the first policy that is considered to be applicable and effective is to be selected. This approach is popular because it is both quicker and cheaper to apply than the rigorous approach. For the same reason the decision diagram approach has been selected in this method.

3.5.1 Failure management policies

In total there are six types of failure management policies. Four are preventive maintenance tasks, each of which is applicable under a specific set of conditions(SAE International, 2009):

- **On-condition task:** A periodic or continuous task used to detect a potential failure. Potential failure is identified as an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring.
- **Scheduled discard task:** A scheduled task that entails replacing an item at or before a specified age limit regardless of its condition at the time.
- **Scheduled restoration task:** A scheduled task that restores the capability of an item at or before a specified interval (age limit), regardless of its condition at the time, to a level that provides an acceptable probability of survival to the end of another specified interval. Restoration for specific items may range from replacement of a single part to complete remanufacture (Nowlan & Heap, 1978)
- **Failure-finding task:** A scheduled task used to determine whether a specific hidden failure has occurred. A hidden failure has no direct consequences on its own, so a failure-finding task is actually considered as preventive as it prevents a possible multiple failure.

If no preventive maintenance is considered as applicable and effective, the remaining two options are:

- **One-time change:** Any action taken to change the physical configuration of an asset or system (redesign or modification), to change the method used by an operator or maintainer to perform a specific task, to change the operating context of the system, or to change the capability of an operator or maintainer (training).
- **Run-to failure:** A failure management policy that permits a specific failure mode to occur without any attempt to anticipate or prevent it.

3.5.2 Different layouts

In 1997 when John Moubray issued his textbook “Reliability-Centered Maintenance” (RCM2), four decision diagrams accounted for the majority of the RCM work done at the time: The diagram in Nowlan and Heap’s textbook, ATA’s MSG-3, US Mil-Std-2173 and RCM2 that is the subject in John Moubray’s textbook. Nowlan and Heap’s decision diagram is the version originally used by most RCM practitioner and is based on the decision diagram approach. The diagram can be divided into two levels where the first level determines the consequence categories, and the second level deals with the selection of failure management policy. Nowlan and Heap distinguishes between four consequence categories in level 1:

- i. Evident safety
- ii. Evident operational (economic)
- iii. Evident non-operational (economic)
- iv. Hidden-failure

Level 2 consists of a hierarchy of tasks that is prioritized as described in 3.5.4, but with some differences among the consequence categories. For failures with safety consequences a combination of tasks is also considered before redesign is required if no other preventive task is considered applicable and effective. For failures that have evident operational and evident non-operational consequences, “no scheduled maintenance” is an option if no preventive maintenance is considered applicable and effective. Hidden failures have the option of failure-finding tasks if no other preventive task is considered applicable and effective, but the policy “no scheduled maintenance” is never accepted for hidden failures.

MSG-3 was originally issued in 1980 (11th reversion issued in 2015) and is the version used by the civil aviation industry. The differences between MSG-3 and Nowlan and Heap’s diagram are:

- MSG-3 uses a the rigorous approach for failures that have safety consequences and the decision diagram approach for the other consequence categories, while Nowlan and Heap only uses the decision diagram approach.

- A question about lubrication is incorporated at the head of every task selection column. This was included to ensure that this important category of task was considered each time an item was analysed (ATA, 2002). However, regardless of the answer to this question, the next task selection question must be asked.
- MSG-3 separate the consequence category hidden-failure into hidden safety and hidden non-safety.
- MSG-3 prioritizes failure-finding tasks before other preventive tasks. According to SAE JA1012 (2011), RCM decision diagrams should always put the three categories of proactive tasks ahead of failure-finding in the task selection process. The rationale is that proactive maintenance is inherently more conservative (safer) since it prevents things from failing, rather than accepting that they will spend some time in a failed state.

U.S. Mil-Std-2173 (1986) uses the same approach as MSG-3 (Moubray, 1997). RCM2 is close related to Nowlan and Heap and can be considered to be a slightly modified version to improve clarity and user-friendliness, and to plug a small gap in the logic related to failure-finding tasks. The one major difference that warrants the change of name to RCM2 is the inclusion of a question related to environmental consequences, namely “Does the failure mode cause a loss of function or other damage which could breach any known environmental standard or regulation?” If the answer to this question is yes, the failure mode shall be treated as if the failure mode could hurt or kill someone (safety consequences). This was a result of the high and increasing priority which society places on the environment. In addition, two questions were added to close a small gap in the logic. Nowlan and Heap has failure-finding as a default action if no preventive action can be found, regardless whether the failure has safety consequences or not. Thus, RCM2 asks “Is a failure-finding task to detect the failure technically feasible and worth doing?” and “Could the multiple failure affect safety or the environment?” This enables the policy “No scheduled maintenance” to be selected in cases where the failure cannot affect the safety or the environment. The rest of the modifications consist of reformulations and substituted terms to improve clarity and user-friendliness.

It may be strange that MSG-3 doesn't consider environmental consequences in their decision diagram. However, this may be explained by that the environmental issues in relation to aircrafts are air pollution and noise pollution, both of which are controlled and minimized by design regulations rather than maintenance efforts (Ahmadi et al., 2010). In addition, there are tasks that are covered by national or international Advisory Circulars issued to control the level of pollution. However, for a vessel where failures can lead to significant pollution, the environmental consequences should be included in the analysis.

Another difference in consequence category that is often seen is in the way operational consequences are treated. Nowlan and Heap distinguishes between operational and non-operational consequences for evident failures. This is also done by MSG-3 and RCM2, while for example Defense Standard 02-45 NES 45) (UK Ministry of Defence, 2000) makes the distinction for hidden failures as well. Other standards such as NEK IEC 60300-3-11 (Norsk elektroteknisk komite, 2009) and NAVAIR 00-25-403 (NAVAIR, 2005) merges operational and non-operational consequences into economic consequences.. As operational consequences affect the revenue-earning capability of the organization they tend to be economic. In nearly all cases the costs of operational consequences are greater – often much greater – than the cost of repairing the failures (SAE International, 2011). It is therefore important to include these costs when assessing the cost-effectiveness of any failure management policy. However, the repair cost also needs to be included, so it seems like the question regarding operational consequences is asked to be reminded to include those costs and not only the repair costs. If this is the case it would be logic to either make the distinction for both hidden and evident failures as in Defence Standard 02-34 (NES 45), or to merge non-operational and operational consequences into economic consequences as in NEK IEC 60300-3-11 and NAVAIR 00-25-403. SAE JA1012 supports both of these approaches.

3.5.3 Basic assumptions

To comply with SAE JA1011, the decision diagram approach needs to be based on the assumption that safety/environmental consequences should be dealt with before economic consequences (SAE International, 2011). In addition it's assumed that if a failure management policy deals satisfactorily with a failure that has safety/environmental consequences, it will deal satisfactorily with the economic (operational

and non-operational) consequences of that failure. This assumption is valid in most cases, but there are exceptions. In practice this means that if a failure has a risk of safety/environmental consequences that is considered to be unacceptable, the user is compelled to find a failure management policy that reduces the risk of safety/environmental consequences to an acceptable level, without considering the economic consequences of the failure. This is a conservative approach that leads to a safe and environmental sound maintenance program, but some failure management policies may be more costly than they need to be.

Most diagrams are also based on the assumption that some failure management policies nearly always are more cost-effective than others, and that some are inherently more conservative than others. This leads to a hierarchy of failure management policies in which the users are encouraged to select the first failure management policy in the hierarchy that is considered to be applicable and effective.

3.5.4 Hierarchy of failure management policies

Nowlan and Heap (1978) states that the characteristics of the tasks themselves suggest a strong order of preference on the basis of their overall effectiveness as preventive measures. The order of task preference and the rationale is summarized below:

1. On-condition tasks

On-condition tasks have several advantages besides of being very effective in preventing the occurrence of failures. Not only does it avoid the premature removal of units that are still in satisfactory condition, but the cost of correcting potential failures is often far less than the cost of correcting functional failures, especially those that cause extensive secondary damage. Also, since the number of removals for potential failures only is slightly larger than the number that would result from functional failures, both the repair cost and the number of spare units necessary to support the repair process are kept to a minimum. Additionally, the cost of inspection is usually relatively low. SAE JA1012 states three additional benefits:

- They can nearly always be performed without moving the asset from its installed position and usually while it is in operation, so they seldom interfere with operations.
- They are usually easier to organize
- They identify specific potential failure conditions so corrective action can be clearly defined before work starts. This reduces the amount of repair work to be done, and enables it to be done more quickly.

2. Scheduled restoration tasks

When no on-condition task can be found to be applicable and effective, the next choice is scheduled restoration. For items that have a dominant failure mode (concentrated about an average), scheduled restoration of single parts or components leads to a significant reduction in the failure rate. Scheduled restoration may be cost-effective if the failures have major economic consequences. One great advantage compared to scheduled discard is that time-expired units can be reused. Hence, the material costs are lower than they would be if the entire unit had to be discarded. Scheduled restoration tasks do however have some disadvantages. Since the age-limit applies to all units of an item, many serviceable units will be removed before their useful lifetime. As the total number of removals consist of failed units plus scheduled removals, the workload will be substantially greater than on-condition tasks. Consequently, a large number of spare units are also needed. SAE JA1012 states two additional disadvantages:

- In nearly every case, they can only be done when items are stopped and (usually) sent to the workshop, so the tasks nearly always affect operations in some way.
- Restoration tasks involve shop work, so they generate much higher workload than on-condition tasks.

3. Scheduled discard tasks

The least desirable of the three directly preventive tasks is scheduled discard. Safe-life limits on simple components can however prevent critical failures caused by certain failure modes. Similarly, an economic-life limit can reduce the frequency of

functional failures that have major economic consequences. In such cases the average life realized by an item is much smaller than its potentially useful life, especially in the case of safe-life limits. This combined with the cost of new items makes these tasks costly. Other disadvantages are similar to scheduled discard tasks.

In SAE JA1012 scheduled restoration tasks and scheduled discard tasks are considered together. The reason is that they have much in common and that in reality it is often obvious which of the failure management policies that should be selected. However, sometimes both are applicable and the most cost-effective should be selected, which usually is scheduled restoration.

4. Failure-finding tasks

According to SAE JA1012, successful proactive maintenance prevents things from failing, whereas failure-finding accepts that they will spend some time – albeit not very much – in a failed state. This can be interpreted as the three direct preventive tasks are more conservative (safer) than failure-finding tasks. As a result, failure-finding should only be selected when none of the direct preventive tasks is considered applicable and effective.

5. Combination of tasks

It may be situations when no single task can reduce the risk of failure to an acceptable level. In such cases it may be possible that a combination of tasks (usually two different task categories) reduces the risk to an acceptable level. Obviously, a major disadvantage is that combination of tasks are inevitably more costly than single tasks. This may be the reason why SAE JA1012 only considers combination of tasks if the failure has safety/environmental consequences.

6. Run-to-Failure

For failures that have economic consequences the effectiveness criteria of maintenance policy is that they need to cost less than the run-to-failure policy. If no such policy is found it's quite obvious that run-to-failure should be considered.

However, according to SAE JA1011 and SAE JA1012, run-to-failure is not an option for failures that have safety or environmental consequences.

7. One-Time Changes

All RCM decision diagrams consider maintenance before one-time changes due to the following four reasons(SAE International, 2011):

- a. Most modifications take from six months to three years from conception to commissioning, depending on the cost and complexity of the new design. On the other hand, the maintenance person who is on duty today has to maintain the equipment as it exists today, not what should be there or what might be there some time in the future. So today's realities must be dealt with before tomorrow's design changes.
- b. Most organizations are faced with many more apparently desirable design improvement opportunities than are physically or economically feasible. By focusing on failure consequences, RCM does much to help us to develop a rational set of priorities for these projects, especially because it separates those that are essential from those that are merely desirable. Clearly, such priorities can only be established after the review has been completed.
- c. One-time changes are expensive. They involve the cost of developing the new idea (designing a new machine, drawing up a new operating procedure), the cost of turning an idea into reality (making a new part, buying a new machine, compiling a new training program) and the cost of implementing the change (installing the part, conducting the training program). Further indirect costs are incurred if equipment or people have to be taken out of service while the change is being implemented.
- d. There is a risk that the change will fail to eliminate or even alleviate the problem it is meant to solve. In some cases, it may even create more problems.

3.5.5 Failure management policy selection criteria

SAE JA1011 (2009) has four requirements to the selection of failure management policy, each of which is listed and explained below:

1. The failure management selection process shall take account of the fact that the conditional probability some failure modes will increase with age (or exposure to stress), that the conditional probability of others will not change with age, and the conditional probability of yet others will decrease with age.

The first requirement comes from the fact that not all failure rates are increasing and age-related as earlier assumed. United Airlines developed numerous failure rate curves for aircraft components and found out that these fell into the six basic patterns shown in Figure 3.5. Out of these six failure patterns, there are only failure pattern A, B and C where scheduled discard and scheduled restoration may be applicable and effective maintenance tasks. United Airlines' analysis showed that only 11 % of the items analysed fell into pattern A, B or C (Nowlan & Heap, 1978). Other research has shown results between 8-29%, thus conforming that the majority of the failures fell into failure patterns D, E and F (Norsk elektroteknisk komite, 2009). Generally, age-related failure patterns (A, B and C) apply to items that are very simple, or to complex items that suffer from a dominant failure mode. In practice, they are commonly associated with direct wear (most often where equipment comes into direct contact with the product), fatigue, corrosion, oxidation and evaporation (SAE International, 2011).

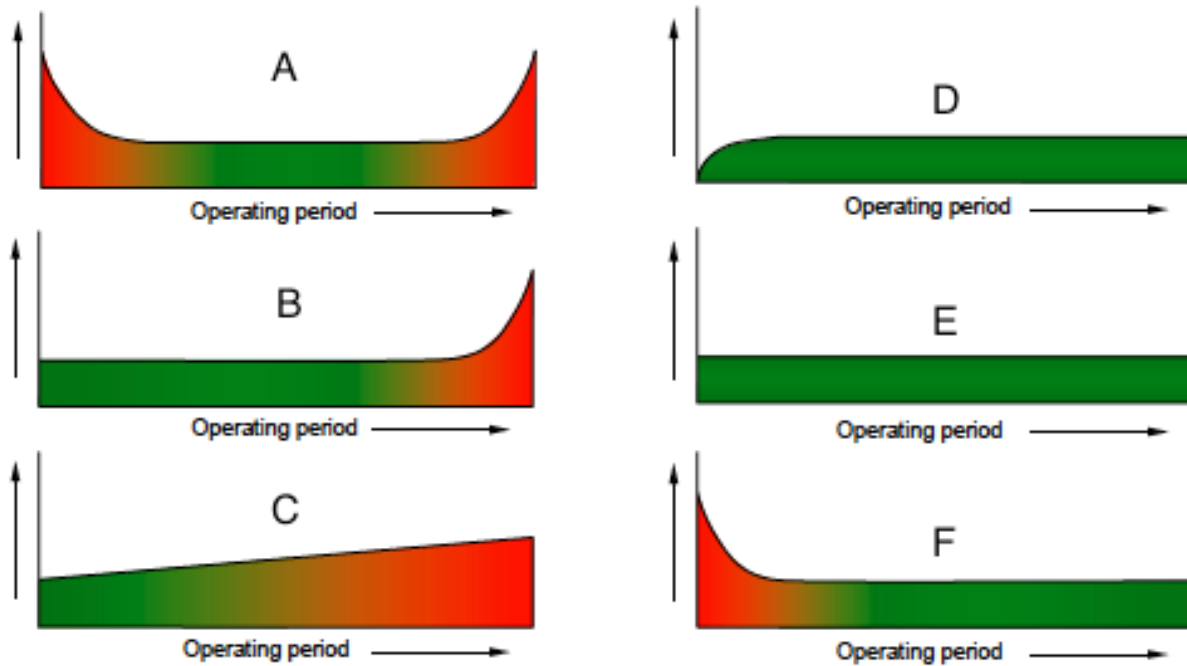


Figure 3.5: Dominant failure patterns.

2. All scheduled tasks shall be applicable and effective

All selected tasks have to be applicable and effective, meaning that they are technically feasible and worth doing. Whether or not a task is applicable depends on the technical characteristics of the policy and of the failure mode. The applicability criteria for each preventive task is:

On-Condition tasks

- There shall exist a clearly defined potential failure.
- There shall exist an identifiable P-F interval (or failure development period).
- The task interval shall be less than the shortest likely P-F interval.
- It shall be physically possible to do the task at intervals less than the P-F interval.
- The shortest time between the discovery of a potential failure and the occurrence of the functional failure (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.

Potential failure is defined as an identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring (SAE International, 2009).

Clearly, if on-condition shall be applicable it must be possible to detect a potential failure some time before the functional failure occurs. The interval between the potential failure and the point where a functional failure occurs is called the P-F interval. Figure 3.6 (UK Ministry of Defence, 2000) illustrates the relation between the condition, the potential failure and the point of functional failure as a function of operating units (may be calendar time, operating hours, number of activations etc.). To be sure that the on-condition task detects a potential failure condition before failure, it is necessary to perform the task at intervals less than the P-F interval. If the on-condition tasks are performed at intervals of the P-F interval, it may happen that one task is performed just before the potential failure becomes detectable, while the next task is performed just before failure, which would provide little time to avoid, eliminate or minimize the consequences of failure. Therefore, on-condition tasks shall always be performed at intervals less than the P-F interval. In most cases, it is sufficient to perform the task at intervals equal to half of the P-F interval (SAE International, 2009). In that case one may have an extra chance to detect the potential failure if the first on-condition task fail to identify the potential failure. It can be noted that for a ship that only will perform maintenance in port, the P-F interval will have to be two times the longest transit for on-condition task to be applicable.

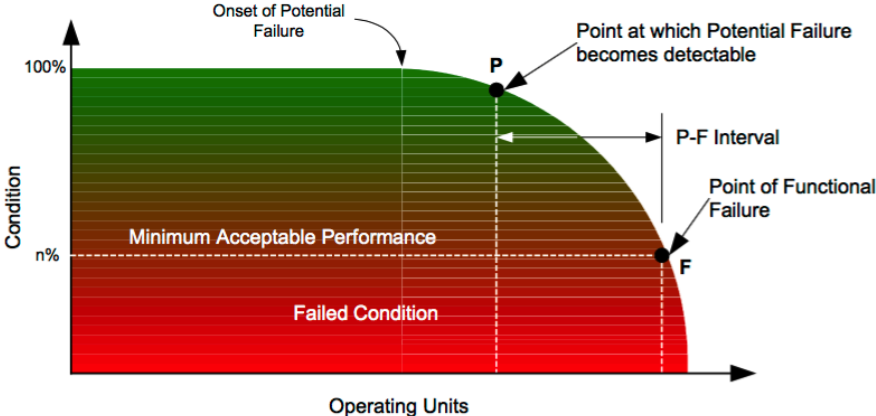


Figure 3.6: The P-F interval

Scheduled discard tasks

- There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.
- A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is acceptable to the owner or user of the asset.

Scheduled restoration tasks

- The same criteria as scheduled discard tasks plus
- The tasks shall restore the resistance to failure (condition) of the component to a level that is tolerable to the owner or user of the asset.

Failure-finding tasks

- The basis upon which the task interval is selected shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is acceptable to the owner or user of the asset.
- The task shall confirm that all components covered by the failure mode description are functional.
- The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.
- It shall be physically possible to do the task at the specified intervals.

Run-to-failure is the absence of performing any preventive tasks. This policy is only acceptable when the failure has economic consequences and is selected when the risk is acceptable without maintenance or no other preventive maintenance is effective.

The effectiveness criteria of the tasks and one-time changes depend on the consequence category as follows:

Evident safety and environmental consequences

The task shall reduce the probability of the failure mode to an acceptable level.

Evident economic consequences

Over a period of time, the task must cost less than the cost of the operational consequences (if any) plus the total cost of repair.

Hidden safety and environmental consequences

The task must reduce the risk of the hidden failure and mode to an extent which reduces the probability of the associated multiple failure to a level that is acceptable.

Hidden economic consequences

Over a period of time, the task must cost less than the cost of the operational consequences (if any) plus the total cost of repair of the associated multiple failure.

3. If two or more proposed failure management policies are applicable and effective, the rationale for selecting one over another shall be recorded.

This requirement is only of relevance when the rigorous approach is used, i.e. not relevant when the decision diagram is used where the first applicable and effective task is selected.

4. The selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.

As discussed in the introduction of 3.5, this requirement is of great importance if the goal is to refine a maintenance program or create a new one. This requirement is violated in this procedure since the selection procedure starts by checking whether today's maintenance is applicable and effective. However, if the answer is no, the search for other applicable and effective maintenance policies applies to this requirement. This will ensure that the best maintenance policy is selected.

3.5.6 Definition of barrier

In this thesis the objective is to identify barriers in design of unmanned engine rooms for merchant vessels, and hence not to develop a maintenance program as the normal objective of the RCM procedure. It is therefore necessary to define the term barrier so that these can be identified. In this thesis the following definition is used:

Barrier – *A failure mode that is considered as critical, but where no applicable and effective maintenance task has been identified.*

3.5.7 The selected decision diagram

There exist a large variety of RCM decision diagrams. Some are proprietary, while others are in the public domain. Several of those comply closely to the principles in SAE JA1012. As a result SAE JA1012 does not endorse any specific decision diagram. However, the standard illustrates the decision diagram with two examples that comply with the principles. The difference between these two diagrams is that one distinguishes between operational and non-operational consequences, while the other in a way merges these together into economic consequences. The latter has been used as basis and the final diagram is shown in Figure 3.7. However, one significant modification has been made by asking the question “Is the maintenance performed today applicable and effective?” The reason is stated in the introduction to 3.5.

The reason for selecting this diagram is based on the discussion in 3.5.2. RCM2 is seen as an improvement of the original diagram by Nowlan and Heap for two reasons. Firstly, RCM2 included a question about environmental consequences. This forces the environmental consequences to be assessed. Secondly, RCM2 asks if the multiple failure could affect safety/environment. This enables run-to-failure to be selected for hidden failures without safety/environmental consequences in cases where that is considered applicable. In comparison with MSG-3 there are two differences that has been considered. MSG-3 does not consider environmental consequences. This is ok in the aircraft industry since the environmental consequences related to aircrafts are controlled and minimized by design regulations and advisory circulars, but when ships are analysed the environmental consequences should be considered. The second difference is that MSG-3 asks if the multiple failure could affect safety right after asking if the failure is evident, while RCM2 asks at the foot of the hidden function column. The former makes a clear distinction in the diagram between the determination of consequence category at the top and the task evaluation at the bottom. This improves the readability. Regarding the consequence categories it has been decided to merge operational and non-operational consequences into economic consequences. The reason is that it greatly reduces the number of questions, keeps it simple and in the author’s opinion improves the readability. Lastly, the definition of barrier is included at the bottom

of the columns so that barriers are identified. It can be noted that run-to-failure is not a possible outcome of the diagram. The reason is that if the maintenance performed today is not considered applicable and effective, the risk will be too high, and run-to-failure would not be accepted.

Working from the top, the first questions in the decision diagram determines the consequence category of the failure mode under consideration. This is to determine which effectiveness criteria that apply, which can be seen at the bottom of each of the columns. The next step is to determine whether the performed maintenance today is applicable and effective. The applicability criteria can be seen to the left in the figure and depends on the type of task. If the maintenance performed today is not applicable and effective, the process continues by moving down the column and use the applicability and effectiveness criteria for each task until either an applicable and effective task is identified, or the failure mode is considered as a barrier.

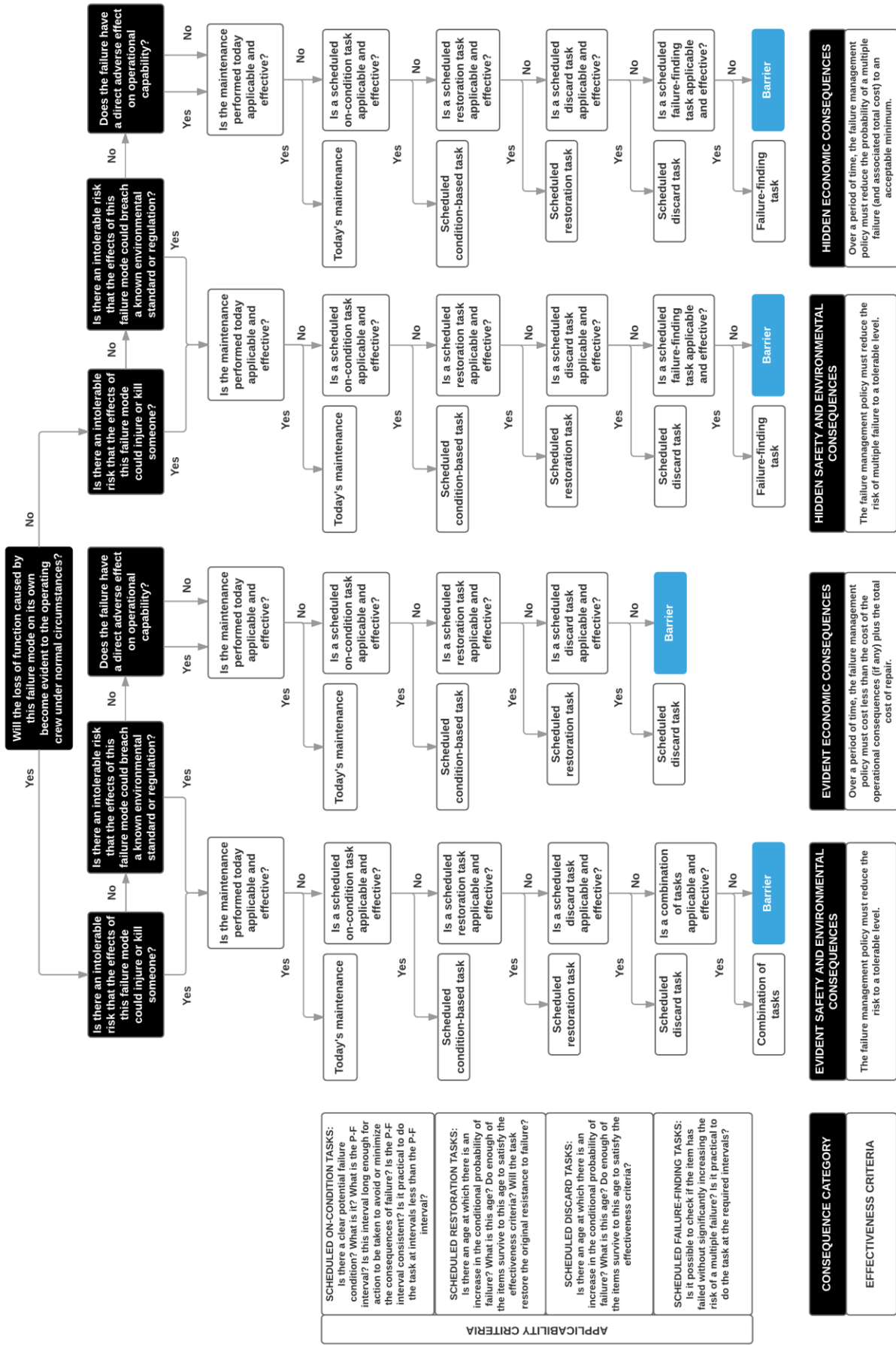


Figure 3.7: Decision diagram.

3.5.8 How to handle uncertainty in the decision diagram

In cases where there is a lack of operational data it may be difficult to provide clear-cut yes or no answers in the decision diagrams. In those cases there should exist a backup default strategy, which dictates the decision making under these circumstances.

Nowlan and Heap (1978) presented a default strategy with default answers to each of the questions in case of uncertainty. These answers are based on conservative answers to protect the equipment against serious consequences. As a result, some tasks are included in the initial maintenance program to protect against hazards that does not exist, while others are scheduled far too frequently. However, by the use of age-exploration studies, which begin as soon as the equipment goes into service, such excessive tasks (and cost) can be eliminated.

In evaluation of proposed tasks, Nowlan and Heap's default strategy suggest the answer "No" if there is uncertainty related to applicability and effectiveness, except for on-condition task where the answer is yes. As a result the initial maintenance program essentially consists of on-condition tasks, a few safe-life discard tasks, and failure-finding tasks for hidden-function items (as this is required for all hidden functions where no other policy is considered applicable and effective according to Nowlan and Heap's decision diagram), in addition to the usual servicing and lubrication tasks. Scheduled restoration or economic-life discard tasks rarely appear in an initial program with this default strategy, but may be added after their applicability and effectiveness can be evaluated.

MSG-3 (2002) states that "In the absence of adequate information to answer "YES" or "NO" to questions in the second level, default logic dictates a "NO" answer be given and the subsequent question be asked. As "NO" answers are generated the only choice available is the next question, which in most cases provides a more conservative, stringent and/or costly task". The second level refers to the evaluation of proposed tasks after the evaluation of consequence category (level 1). Thus, MSG-3 gives the opposite answer in case of uncertainty related to the applicability and effectiveness of on-condition tasks.

Although Nowlan and Heap (1978) consider the default strategy as necessary, not all publications agree with this methodology. SAE JA1012 states that "... Most decisions have

to be made in the absence of complete data. This can lead to a temptation to start relying excessively on “default logic”, in which decisions are made automatically if comprehensive data are not readily available. However the application of such logic can lead to incorrect decisions, especially in the assessment of consequences. In practice the view should be taken that, if the possible repercussions of too much uncertainty cannot be tolerated, then action should be taken to change the consequences of the failure mode – rather than rely upon “default” decisions.”

In this thesis the objective is to identify barriers in design of an unmanned engine room for a merchant vessel and not necessarily chose the optimum maintenance policies. Thus, it's reasonable to handle uncertainty related to consequence category by selecting the most conservative answer, and to answer no if there is uncertainty related to a maintenance task's applicability and effectively. The result of using this approach is that critical failures that cannot be properly managed with maintenance with certainty will be marked as barriers. As a consequence, barriers will not only consist of failures that requires redesign to be properly managed, but also failures where there is insufficient information to conclude. Thus, barriers represent all failures that cannot be operated unmanned with certainty of an acceptable risk.

4 Case study: The fuel oil system

The objective is to identify barriers in design of unmanned engine rooms for oceangoing merchant vessels. To get information about relevant systems on these vessels, contact was made with Solvang ASA, one of the world’s leading transporters of LPG and petrochemical gasses. Solvang has provided maintenance data, system drawings and answered numerous question regarding the systems analysed. The maintenance data provided, which plays a central part of the following analysis, consist of all registered maintenance tasks over a period of one year from 21 vessels and accounts for a total of more than 37,000 tasks for the main groups 6, 7 and 8 of the SFI Group System. The ships vary in age from 1-18 years, with an average age of approximately 8 years, and all vessels use HFO as fuel. Although there are many differences between oceangoing merchant vessels depending on the cargo they carry, they usually are propelled by a single low speed diesel engine that uses HFO as fuel, and thus most of the systems in the engine room are in principle very similar. It is therefore reasonable to assume that the result are representable also for other types of oceangoing merchant vessels.

4.1 System selection and definition

4.1.1 Partitioning

Following the arguments in 3.1.1, the SFI Group System’s partitioning of the ship is used in the analysis, which is illustrated in Figure 4.1.

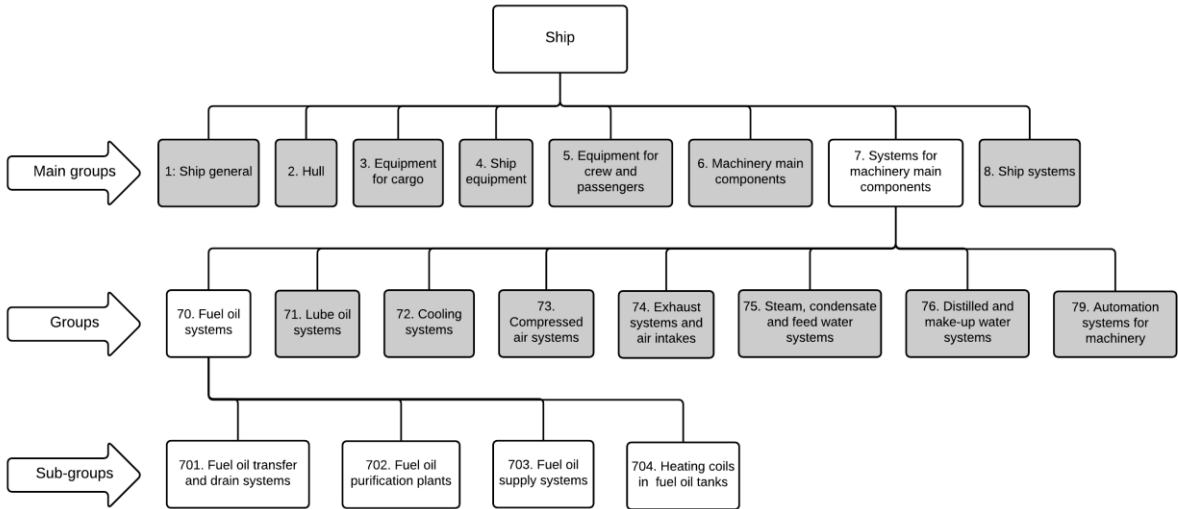


Figure 4.1: SFI Group System.

The groups that contains systems that are important for a functioning machinery are main group 6, 7 and 8. Main group 6 contains among others the main engine, auxiliary engines and boilers. Main group 7 contains systems that operates directly with the machinery, while main group 8 among others contain the electricity systems required to drive for example electrical engines that again drives pumps. The groups of main group 6, 7 and 8 are shown in Table 4.1, Table 4.2 and Table 4.3 (Norges skipsforskningsinstitutt, 1994). The relevant groups of the vessel under consideration is emphasized in bold.

Table 4.1: Groups of main group 6.

Main Group 6. Machinery Main Components
60. Diesel engines for propulsion
61. Steam machinery for propulsion
62. Other types of propulsion
63. Propellers, transmissions, foils
64. Boiler, steam & gas generators
65. Motor aggregates for main electric power production
66. Emergency generators
67. Nuclear reactor plants
69. Movable equipment

Table 4.2: Groups of main group 7.

Main Group 7. Systems for Machinery Main Components
70. Fuel systems
71. Lube oil systems
72. Cooling systems
73. Compressed air systems
74. Exhaust systems and air intakes
75. Steam, condensate and feed water systems
76. Distilled & make-up water systems
79. Automation systems for machinery

Table 4.3: Groups of main group 8.

Main Group 8. Ship Common Systems
80. Ballast & bilge systems, gutter pipes outside accomod.
81. Fire & lifeboat alarm, fire fighting & wash down systems
82. Air & sounding systems from tanks to deck
83. Special common hydraulic oil systems
84. Central heat transfer systems with chemical fluids/oil
85. Common electric & electronic systems
86. Electric power supply
87. Common electric distribution systems
88. Electric cable installation
89. Electric consumer systems

4.1.2 Prioritizing and system selection

Unmanned operation of the engine room during transit represents a significant change in the systems' operating context. To identify barriers it's convenient to start with the systems that is most affected by the new context. As most of the maintenance is performed while the ship is in transit, the systems that require most maintenance are probably the systems that is most affected by the new operating context. Although the risk associated with system failures also must be considered, it is convenient to start by ranking the systems according to their need for maintenance.

Figure 4.2 shows the average number of maintenance tasks per ship per year for main group 6, 7 and 8. The figure shows that most tasks are registered on main group 7 with an average of 629 registered maintenance tasks per year per vessel, but differences between the main groups are marginal.

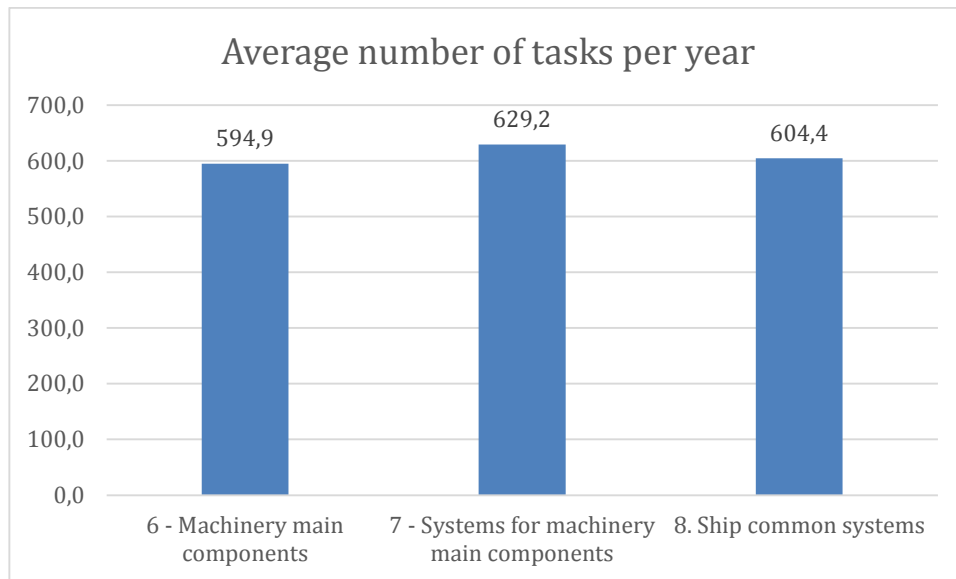


Figure 4.2: Avg. number of tasks per ship per year for SFI m. groups 6, 7 and 8.

Figure 4.3 shows how the maintenance is distributed if the tasks are sorted on groups. The figure shows that group 81 “Fire & lifeboat alarm, fire fighting & wash down systems” requires most maintenance with an average of 343 tasks per year, which corresponds to approximately 57 % of the tasks of main group 8. These tasks are distributed on the sub-groups shown in Table 4.4. From the table it can be observed that most of the maintenance in group 81, and thus of main group 8, is related to fire detection and fire fighting systems. 93 % of the maintenance registered on group 81 is registered as preventive and consist mainly of planned function testing. It is assumed that such function testing will be possible even though the engine room is unmanned, so that in case of any failures the crew will be aware of the loss of protection, which makes it possible to implement other measures until the function is restored.

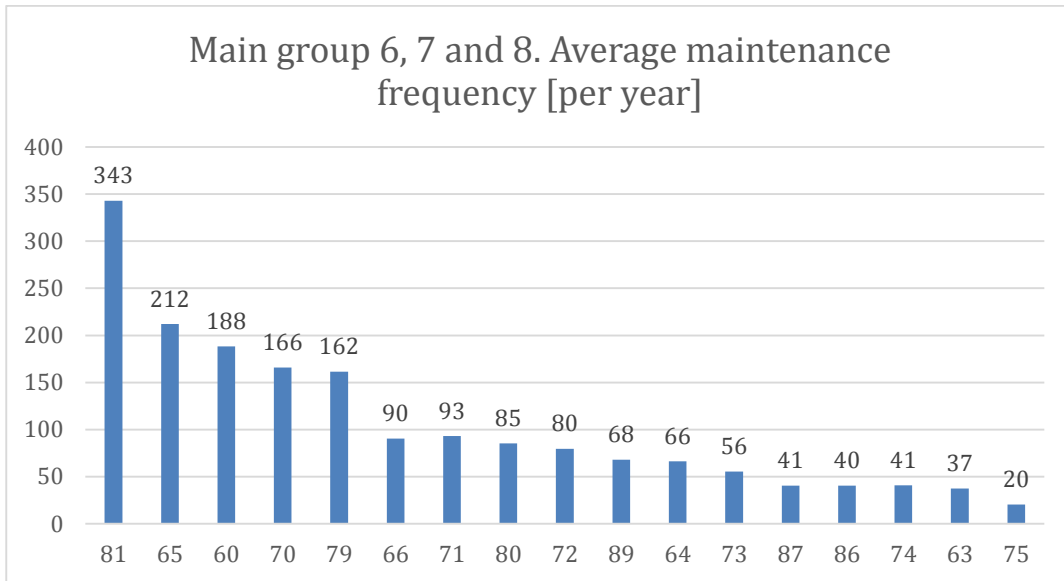


Figure 4.3: Avg. maintenance frequency for top 16 groups in main groups 6, 7 and 8.

Table 4.4: Distribution of maintenance tasks of group 81.

Sub-group	Group 81	%
811	Fire detection, fire & lifeboat alarm systems	20.4
812	Emergency shutdown system	8.5
813	Fire/wash down systems, emergency fire pumps, sprinkler system	59.3
815	Fire fighting systems w/gas (CO2, Halon, etc.)	4.9
816	Fire fighting systems w/foam	0.1
818	Fire fighting systems w/powder	6.7
81*	Unspecified	0.1
	Sum	100.0

As planned preventive maintenance, such as function testing, often are performed at intervals that are larger than the largest transits of the vessels, most of these can be performed while the ship is in port. If a ship is to be operated without the possibility to perform maintenance on board, the frequency of failures registered on the groups would be more relevant. Figure 4.4 shows how unplanned corrective maintenance is distributed on the groups. The figure shows that most unplanned corrective tasks are registered on group 65 and 60, which contain the auxiliary engines and the main engine, respectively. Since the engines are complex equipment that requires specialist knowledge to perform a good analysis, the fuel oil system, which is the group with third most unplanned corrective maintenance registered, has been selected for further analysis.

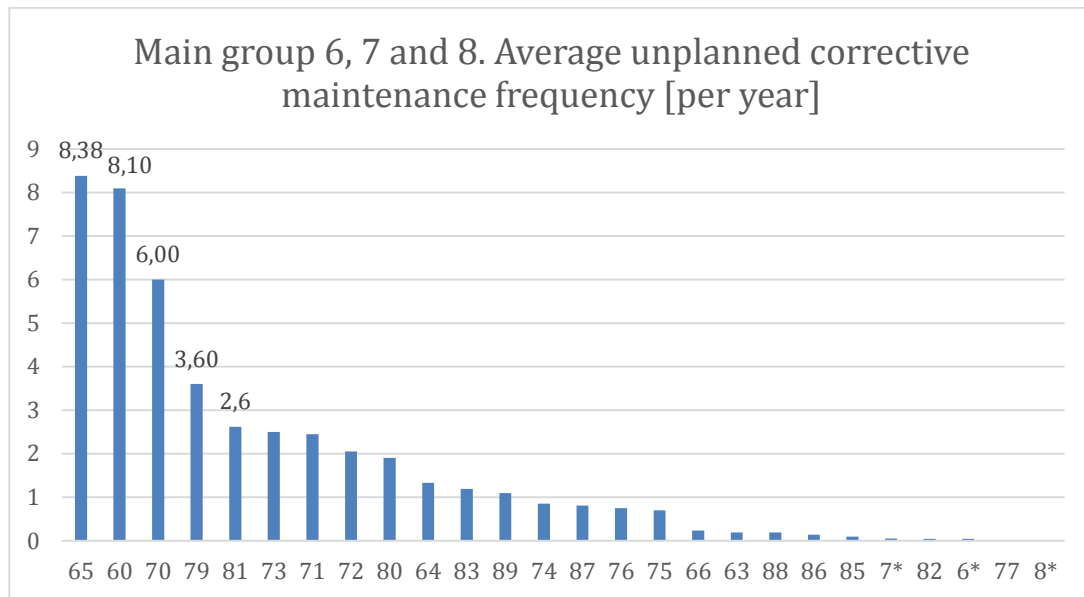


Figure 4.4: Avg. unplanned corr. maintenance freq. for groups in m. groups 6, 7 and 8.

4.1.3 System break down and boundaries

The fuel oil system (group 70) includes systems for distribution, treatment and supply of fuel to the main engine and auxiliary engines. The systems in the sub-groups include all associated system components such as: pumps with driving units, coolers, heaters, loose tanks for fuel oil, heating coils in fuel oil tanks, pipes, valves, local instruments and protection covers. It can be noted that only local instruments (thermometers, manometers, flowmeters, etc.) are included, while remote control, monitoring (alarm and safety), indicating and recording as well as other automation systems such as equipment for viscosity control come under group 79 “Automation systems for machinery”. It should also be noted that the bunker tanks come under main group 2 as the hull constitutes a part of the tank.

In the analysis performed, the scope has been limited to components between the bunker tank and the main engine. This means that only components between the service tanks and the main engine has been analysed, and the components between the service tanks and the auxiliary engines has been excluded. However, the supply system for the auxiliary engines have the same system configuration and it is reasonable to assume that the results for the main engine supply system will also apply for this system. The drain systems, pipes and valves has also been excluded from the analysis.

The fuel system used as case is based on a HFO fuel system from an oceangoing vessel where the propulsion power is provided by a single low speed diesel engine rated 9,350 kW. Figure 4.5 shows how the fuel oil system is broken down to four sub-groups according to their function. These groups are broken further down to maintainable items in Figure 4.6, Figure 4.7 and Figure 4.8 in reliability block diagrams to illustrate the scope and the redundancy.

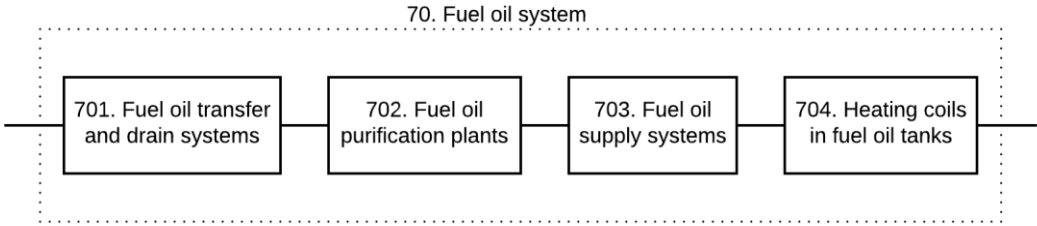


Figure 4.5: Fuel oil system.

Figure 4.6 shows a reliability block diagram of the fuel oil transfer system. HFO is loaded in four bunker tanks that are fitted with heating coils that heat the HFO to a viscosity that makes it pumpable. A single transfer pump fitted with suction strainer pumps the fuel from the storage tanks to two the two settling tanks, which is part of the fuel oil purification plants sub-group.

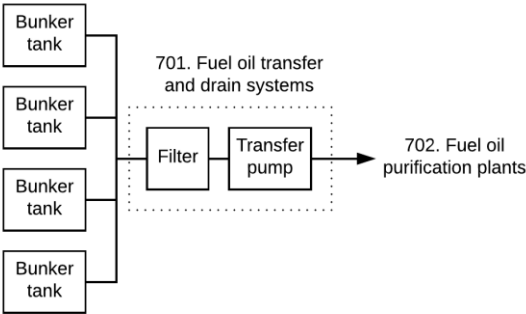


Figure 4.6: Fuel oil transfer system

From the transfer pumps, the fuel enters the settling tanks, which is part of sub-group 702, as illustrated in Figure 4.7. The purification process starts in the settling tanks where heavier liquids such as water and sludge sink to the bottom under the influence of gravity and are being drained off. The capacity of each of the settling tanks corresponds to 24 hours of operation at full load of all consumers (Babic, 2015, p. 553). From the settling tank the fuel is sucked through a filter and pumped into the separator via a preheater. The preheater heats the fuel up to a temperature of $98^{\circ}\text{C} \pm 2^{\circ}\text{C}$ (CIMAC, 2006, p. 21). The pre-

heating is of great importance as it greatly affects the efficiency of the separator. For example, if the fuel is fed with a temperature of 90°C, the capacity would have to be reduced with as much as 35 % to maintain the same efficiency of the separator. The separator uses centrifugal force to reduce the content of solids and water to a level that doesn't cause excessive wear or other related problems with the engine. The purified fuel then enters the service tanks, which is part of the fuel oil supply systems sub-group.

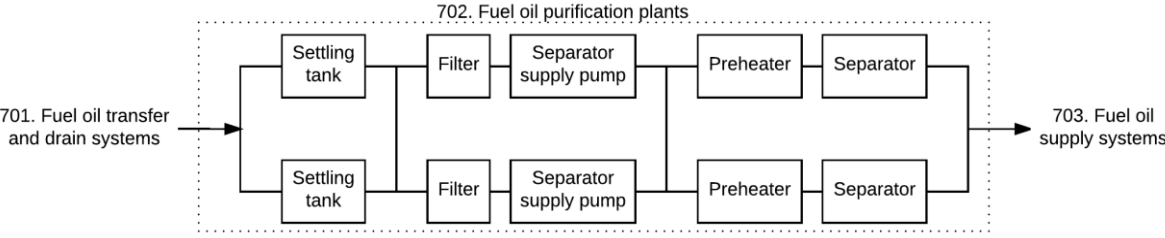


Figure 4.7: Fuel oil purification plants.

Figure 4.8 shows the fuel oil supply system. The purified fuel is stored in two service tanks, each with a capacity corresponding to 24 hours of operation at maximum fuel consumption. From the service tank the fuel oil is pumped by one of the redundant supply pumps and associated filter. Then the fuel passes through the flowmeter filter and the flowmeter. Then the fuel is pumped by one of the redundant circulating pumps that increases the pressure to 10 bars. This is to ensure a required pressure of 7-8 bars at the engine inlet. Then the fuel passes through one of the redundant heaters that ensures that the fuel has the correct viscosity of 10-15 cSt at the engine inlet. Right before the engine the fuel passes through a full flow filter. This filter is automatically cleaned with backflushing capabilities, and has a manually cleaned by-pass filter that normally is used when backflushing (cleaning) is being performed. The fuel then enters the engine (not part of the fuel system) where the electronically controlled pressure boosters, located on the Hydraulic Cylinder Unit (HCU) for each cylinder, injects the fuel. To ensure ample filling of the HCU, the circulating pumps provides more fuel than the engine consumes. The surplus fuel returns to the fuel system through a venting tank and enters the fuel system downstream of the flowmeter.

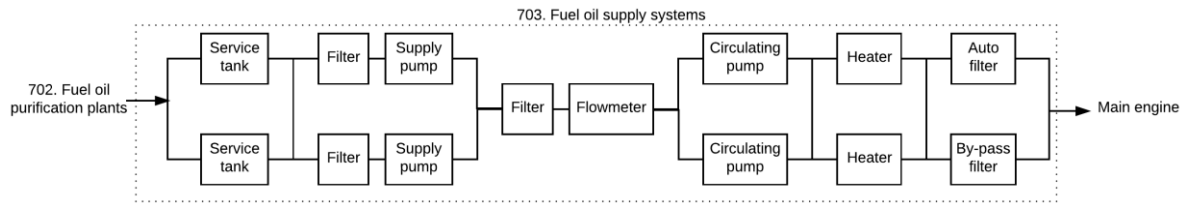


Figure 4.8: Fuel oil supply system.

4.2 Operational context and functions

A ship has several operating modes such as normal seagoing conditions, manoeuvring and cargo handling. In each of these operating modes the requirements of the fuel system, and hence the operating context, may differ. For the purpose of this analysis it has been selected to analyse the system in normal seagoing condition.

4.2.1 Operational context

The fuel oil system is located on an oceangoing merchant vessel that sails worldwide, and that is powered by a low speed MAN Diesel & Turbo 5S60ME-C engine rated 9,350 kW at maximum continuous rating. The fuel oil system shall be able to process fuel that comply with the manufacturers recommendations shown in Table 4.5 (Man B&W, 2014), and provide fuel to the engine with a nominal fineness of less than 35 μm , a viscosity of 10-15 cSt, a pressure of 7-8 bar at a rate of 5.9 m^3 per hour. The vessel is equipped with scrubbers to comply with emission regulations, and will thus solely use HFO as fuel.

Table 4.5: Required condition of HFO before any on-board cleaning.

Guiding specification (maximum values)		
Density at 15 °C	Kg/m ³	≤1.010*
Kinematic viscosity		
At 100 °C	cSt	≤ 55
At 50 °C	cSt	≤ 700
Flash point	°C	≥ 60
Pour point	°C	≤ 30
Carbon residue	% (m/m)	≤ 20
Ash	% (m/m)	≤ 0.15
Total sediment potential	% (m/m)	≤ 0.10
Water	% (v/v)	≤ 0.5
Sulphur	% (m/m)	≤ 4.5
Vanadium	mg/kg	≤ 450
Aluminium + Silicon	mg/kg	≤ 60
Equal to ISO 8217:2010 – RMK / CIMAC recommendation No. 21 – K700		
* Provided automatic clarifiers are installed m/m = mass , v/v = volume		

The vessel will not have crew on board during transits that can perform maintenance, thus all maintenance have to be performed while the ship is in port. The ship will be oceangoing and a typical oceangoing transit is estimated to be 2 weeks, which corresponds to a trans-pacific transit between USA and China at a speed of 16 knots. As the length of the transits may vary and maintenance personnel may not be available in every port, the system shall be able to operate without maintenance for up to 4 weeks. The typical worst case scenario is assumed to be a distance of 1 week from the next port at maximum fuel consumption. As the ship has settling tanks with a total capacity of 48 hours of operation at full load of all consumers, and the same for the service tanks, the off-hire consequences in case of failure depend on where the failure is located in the fuel system. For example, if the transfer pump fails, the ship will have fuel in the settling and service tank for 4 days of operation at full load of all consumers, while if the separators fails, the capacity will be reduced to 2 days. In such cases, the speed can be reduced to reduce the fuel consumption causing a delay. The most critical failure will be between the settling tank and the engine, where a total failure of the fuel system is immediate.

The relationship between the propulsion power and speed can be described by the following equation(Levander, 2012):

$$P = k \cdot V^3$$

Where P represents power, V the speed and k is a constant. If it's assumed that the fuel consumption follows the same relation, the delay caused by a reduction in speed can be calculated as shown in Table 4.6, assuming that all the available fuel is used. Obviously, a total failure between the service tank and the engine will stop the engine and the ship will not be able to reach shore without assistance/maintenance.

Table 4.6: Off-hire as function of failure location.

Failure location	V/V_{max}	Delay (days)	OH-category
Before settling tank	0.76	2.3	2
Settling tank – Service tank	0.53	6.0	2
Service tank – Engine	-	> 7	3

4.2.2 Functions

The functions of the fuel system identified are presented in Table 4.7. All functions are obviously related to supplying sufficient amount of fuel to the engine at the right condition.

Table 4.7: Fuel system main and secondary functions.

Type	Function
Primary function	To supply the engine with fuel oil at a rate of 5.9 m ³ /h at the engine inlet.
Secondary functions	To clean the fuel
	To heat the fuel to a viscosity of 10-15 cSt
	To contain the fuel

4.3 Functional failures

The functional failures of the fuel oil system are shown in Table 4.8. With reference to Rausand and Høyland's procedure described in 3.1.2, it may be beneficial to perform a FFA, either qualitative or quantitative, to avoid wasting time on insignificant functional failures. In this thesis, the time and resources available has been limited and therefore such prioritising of functional failures has been necessary, but it does not mean that the other functional failures are insignificant. In this analysis, the first functional failure "Supplies no fuel to the engine" has been selected. It should be noted that all failure modes that eventually causes stop in the supply of fuel to the engine must be included, and not only those that causes an immediate stop of the supply.

Table 4.8: Functional failures of the fuel system.

Function	Functional failure
To supply the engine with fuel oil at a rate of 5.9 m ³ /h at the engine inlet.	Supplies no fuel to the engine
	Supplies less than 5.9 m ³ /h
To clean the fuel	Fuel is not being cleaned at all.
	Fuel is less cleaned than required.
To heat the fuel to a viscosity of 10-15 cSt	Viscosity of the fuel at the engine inlet is above 15 cSt.
	Viscosity of the fuel at the engine inlet is below 10 cSt.
To contain the fuel	Fuel oil leak

4.4 FMECA analysis

The FMECA analysis performed for the functional failure “Supplies no fuel to the engine” is presented in Figure 4.9 and Figure 4.10. The analysis is performed according to the method described in 3.4. Sources of information has been piping and instrumentation drawings (P&ID), descriptions and maintenance data from Solvang, failure modes from ABS (2003) and failure patterns from ABS (ABS, 2004) and an FMECA analysis performed by Wabakken (2015).

System: Fuel oil system
 Operating mode: Normal seagoing conditions
 Functional failure: Supplies no fuel to the engine

Performed by: Nikolai H. Jacobsen,

Failure mode	Effect	Consequence category			Risk			Failure pattern	Remarks	
		Redundancy provided?	Hidden/evident?	S E OH RC	MTBM (months)	Likelihood category	Risk index			Corrected RI
H.F.O Transfer pump failure	Fuel cannot be transferred between HFO tanks or to HFO settling tanks, and filling of the settling tanks stops. Settling tanks + service tanks have in total a capacity for 96 hours of maximum fuel consumption. MDO transfer pump can be used if spectacle flange and hand operated flange is opened. Else, repair is necessary to restore function.	No*	Evident	1 1 2 1	4,9	2	4	4	B (Wear/fatigue)	* Three transfer pumps, but only one can transfer fuel to settling tank.
HFO Sep. Sup. pump failure	Fuel is not being purified and filling of the service tanks stops. The service tanks has a total capacity for 48 hours of maximum fuel consumption. It is two HFO separator supply pumps, where only one operates at a time. The other stand-by HFO separator supply pump can be started if flow is directed to it by hand operated valves.	Yes	Evident	1 1 2 1	3,7	2	4	3	B (Wear/fatigue)	
M/E Supply pump failure	Detected by low pressure alarm and flow indicator that sends signal to ECR. Fuel is not being supplied to the circulating loop. M/E will stop. It is two M/E supply pumps, where only one operates at a time. The standby M/E supply pump can be started if flow is directed to it by hand operated valves.	Yes	Evident	1 1 3 1	3,5	2	5	4	B (Wear/fatigue)	
Circulating pump failure	Circulation of fuel in the circulation loop and the M/E does not receive fuel and will stop. It is two M/E circulating pumps, where only one operates at a time. The standby M/E supply pump can be started if the flow is directed to it by hand operated valves.	Yes	Evident	1 1 3 1	3,2	2	5	4	B (Wear/fatigue)	
Filter trans. pump plugged	Fuel cannot be transferred between HFO tanks or to HFO settling tank. Settling tanks + service tanks have total capacity for 96 hours of maximum fuel consumption. Manual clean of filter is necessary.	No	Evident	1 1 2 1	1,3	3	5	5	B	
Filter H.F.O sep. Sup. Pump plugged (32 mesh)	Fuel is not being purified. The service tanks has a total capacity for 48 hours of maximum fuel consumption. It is two HFO separator supply pumps, where only one operates at a time. The HFO can be directed to the other stand-by HFO separator supply pump and associated filter if the flow is directed to it by hand operated valves.	Yes	Evident	1 1 2 1	1,4	3	5	4	B	
Filter M/E F.O. supply pump	Detected by low pressure alarm and flow indicator that sends signal to ECR. Fuel is not being supplied to the circulating loop. M/E will stop. It is two M/E supply pumps with associated filters where only one operates at a time. The F.O. can be directed to the other stand-by M/E F.O. supply pump and associated filter if the flow is directed to it by hand operated valves.	Yes	Evident	1 1 3 1	1,7	3	6	5	B	
Flowmeter filter plugged	Detected by flowmeter that sends signal to ECR. Fuel is not being supplied to the circulating loop and the M/E will stop.	No	Evident	1 1 3 1	1,1	3	6	6	B	
M/E F.O. Auto back flushing filter plugged	Detected by high differential pressure alarm. M/E will not receive fuel and will stop. Filter has auto back flushing to clean the filter and a manually cleaned by-pass filter.	Yes	Evident	1 1 3 1	1,5	3	6	5	B	It is only one ME auto filter, but fuel can by-pass the filter through the by-pass filter.
By-pass filter plugged	M/E will not receive fuel and will stop. The filter must be manually cleaned to restore the function.	Yes	Evident	1 1 3 1	1,0	3	6	5	B	Only one by-pass filter, but fuel can also pass through the ME auto filter.

Figure 4.9: FMECA part 1/2.

	1	1	2	1	6,0	2	4	3	B	It is two pre-heaters, one to each purifier. Change of pre-heater require change of purifier.
Pre-heater plugged										
M/E Heater plugged	1	1	3	1	6,0	2	5	4	B	
Separator failure	1	1	2	1	1,3	3	5	4	B	
Settling tank outlet plugged	1	1	2	1	24,0	2	4	3	N/A	
Service tank outlet plugged	1	1	3	1	24,0	2	5	4	N/A	Possible to run on M.D.O. and fuel directly from settling tank. Inspected every 24 months. Cleaned if necessary (AG)
Bunker tk. Emergency shut off valve closes prematurely	1	1	2	1	31,0	1	3	2	C	Redundant tanks, but not redundant emergency shut off valves.
Settling tk. Emergency shut off valve closes prematurely	1	1	2	1	31,0	1	3	2	C	Redundant tanks, but not redundant emergency shut off valves.
Service tk. Emergency shut off valve closes prematurely	1	1	3	1	31,0	1	4	3	C	Redundant tanks, but not redundant emergency shut off valves.

Figure 4.10: FMECA part 2/2.

5 Results

In accordance with the method described in Chapter 3, the analysis proceeds with assessing whether or not the preventive maintenance performed on the components today are applicable and effective in the new operating context. Maintenance task descriptions for the components have been used to determine the components' planned preventive maintenance and applicability. To assess the effectiveness, the Estimated Mean Time to Failure ($EMTTF_m$) defined as the mean time to failure when the planned preventive maintenance is performed, is calculated and used as a parameter in a risk assessment. The subscript is included to avoid confusion with Mean time to failure (MTTF), which is the mean time to failure if no maintenance is performed. The $EMTTF_m$ is calculated by the following formula

$$EMTTF_m = \frac{MTBM}{\% \text{ Corrective}}$$

Where *% Corrective* represents the share of maintenance that is corrective. The MTBM is calculated by sorting out maintenance tasks that is possible to address to specific pumps, and exclude data where tasks not are addressed to specific pumps, or where data may or may not belong to a certain pump. This selection process has been performed to get the best possible estimate from the data available. One consequence is that data from some vessels and pumps are excluded from the analysis.

The share of maintenance that is corrective is calculated somewhat different between some of the components. For pumps and components with several types of maintenance tasks registered, the share of corrective is calculated as the share of tasks that is registered as unplanned corrective and planned corrective. It may be that planned corrective maintenance is considered less critical than unplanned corrective and does not cause an immediate failure. However, as they are corrective maintenance they are performed after a failure, and to not get too optimistic values these are also included. The result may be that $EMTTF_m$ represents a conservative estimate.

For all filters, except for the ME auto filter, all tasks was registered as cleaning tasks. The planned preventive cleaning tasks for these components were performed at intervals of

at least 1 month. In the analysis it's assumed that cleaning tasks performed less than 4 weeks after the last cleaning task are corrective tasks. This is reasonable as it does not make sense to perform maintenance before unless it's needed. These tasks also represents tasks that wouldn't be possible in the defined operating context. Thus, the calculation of the share of maintenance that is corrective, is the share of cleaning tasks that is performed less than 4 weeks after the last cleaning task.

The applicability and $EMTTF_m$ calculations for each of the components are presented in the following sections. The risk assessment that considers the effectiveness of the maintenance tasks are presented and discussed in section 6.1.

5.1 Pumps

5.1.1 Transfer pump

Analysis of 165 maintenance tasks registered on transfer pumps from 19 vessels give the maintenance category distribution as shown Figure 5.1. As seen, 97% of the maintenance can be categorized as planned preventive maintenance, while planned corrective maintenance account for 3% of the tasks. It can be noted that no tasks has been registered as unplanned corrective work.

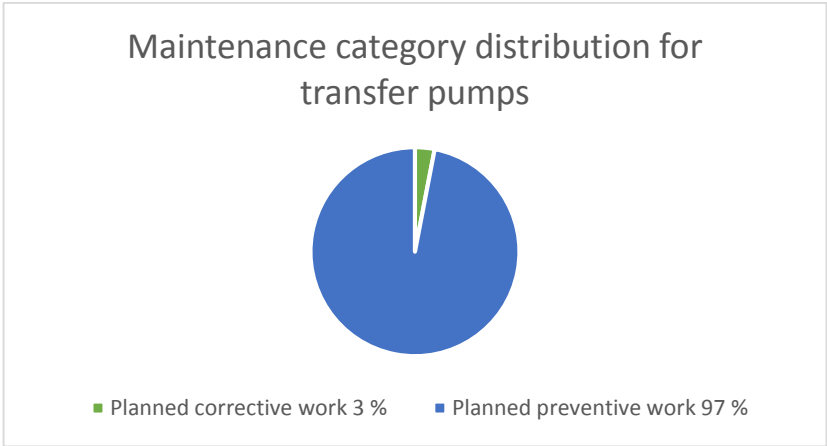


Figure 5.1: Maintenance category distribution of HFO transfer pumps.

The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on transfer pumps on one or more vessels:

- Performance test every 3rd month
- Running control every 4th month

- Performance tests every 6th month
- Maintenance/Survey every 24th month
- Survey by C/E every 5th year
- Other preventive tasks such as overhaul, inspection and megger testing.

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 77 of the tasks to 29 transfer specific transfer pumps. The results are presented in Table 5.1 and shows a MTBM of 4.9 months and an EMTTF_m of 13.5 years.

Table 5.1: Key statistics for transfer pump.

# of tasks	71	
# of components	29	
# tasks per year per component	2,4	
MTBM	4,9	Months
% Corrective	3 %	
EMTTF _m	13,5	Years

5.1.2 Separator supply pump

Analysis of 97 maintenance tasks registered on separator supply pumps from 17 vessels give the maintenance category distribution as shown in Figure 5.2. The figure shows that 90 % of the maintenance tasks can be categorized as planned preventive maintenance, 5 % as planned corrective maintenance and 5 % as unplanned corrective maintenance.

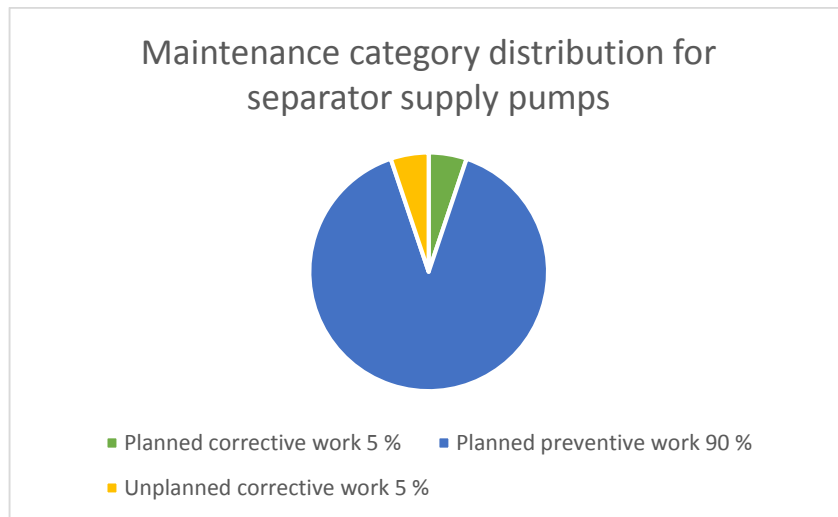


Figure 5.2: Maintenance category distribution for separator supply pumps.

The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on separator supply pumps on one or more vessels:

- Performance test every 3rd month
- Performance test every 6th month
- Condition control every 4th month
- Running control every 4th month
- Maintenance/Survey every 24th month
- Maintenance/Survey by C/E every 5 years
- Other preventive tasks such as overhaul, inspection and megger testing

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 91 of the tasks to 28 specific separator supply pumps. The results are presented in Table 5.2 and shows a MTBM of 3.7 months and an EMTTF_m of 3.0 years.

Table 5.2: Key statistics for separator supply pump.

# of tasks	91	
# components	28	
# tasks per year per component	3,3	
MTBM	3,7	Months
% Corrective	10 %	
EMTTF _m	3,0	Years

5.1.3 Main engine supply pump

Analysis of 103 maintenance tasks registered on main engine supply pumps from 18 vessels give the maintenance category distribution as shown in Figure 5.3. The figure shows that 92 % of the maintenance tasks can be categorized as planned preventive maintenance, 4 % as planned corrective and 4 % as unplanned corrective maintenance.

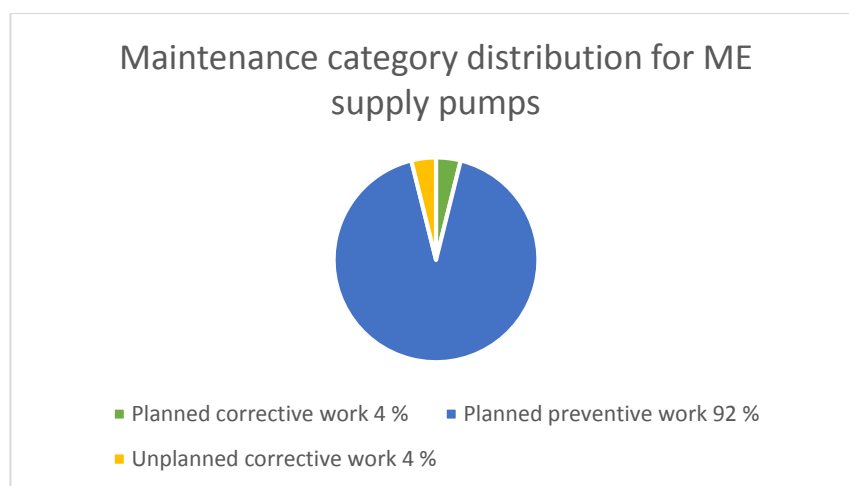


Figure 5.3: Maintenance category distribution for main engine supply pumps.

The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on main engine supply pumps on one or more vessels:

- Performance test every 3rd month
- Performance test every 6th month
- Condition control every 4th month
- Running control every 4th month
- Maintenance/Survey every 24th month
- Maintenance/Survey by C/E every 5 years
- Other preventive tasks such as overhaul, inspection and megger testing

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 99 of the tasks to 29 specific main engine supply pumps. The results are presented in Table 5.3 and shows a MTBM of 3.5 months and an EMTTF_m of 3.8 years.

Table 5.3: Key statistics for main engine supply pumps.

# of tasks	99	
# of components	29	
# of tasks per year per component	3,4	
MTBM	3,5	Months
% Corrective	8 %	
EMTTF _m	3,8	Years

5.1.4 Main engine circulating pump

Analysis of 113 maintenance tasks registered on of main engine circulating pumps from 18 vessels give the maintenance category distribution as shown in Figure 5.4. The figure shows that 88 % of the maintenance tasks can be categorized as planned preventive maintenance, 6 % as planned corrective and 6 % as unplanned corrective maintenance.

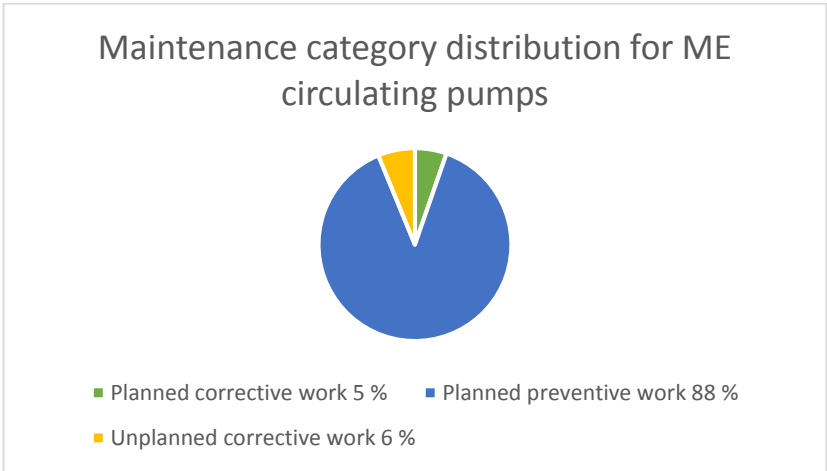


Figure 5.4: Maintenance category distribution for main engine circulating pumps.

The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on main engine circulating pumps on one or more vessels:

- Performance test every 3rd month

- Performance test every 6th month
- Condition control every 4th month
- Running control every 4th month
- Maintenance/Survey every 24th month
- Maintenance/Survey by C/E every 5 years
- Other preventive tasks such as overhaul, inspection and megger testing.

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 108 of the tasks to 29 specific main engine circulating pumps. The results are presented in Table 5.4 and shows a MTBM of 3.2 months and an EMTTF_m of 2.3 years.

Table 5.4: Key statistics for main engine circulating pumps.

# of tasks	108	
# components	29	
# tasks per year per component	3,7	
MTBM	3,2	Months
% Corrective	12 %	
EMTTF _m	2,3	Years

5.2 Filters

5.2.1 Transfer pump filter

Analysis of 219 tasks from 14 vessels showed that all tasks was registered as cleaning tasks. The maintenance task descriptions revealed that the only planned preventive maintenance performed on one or more vessels is monthly cleaning. No planned preventive maintenance is performed at intervals less than 4 weeks. Thus, the planned preventive maintenance performed on transfer pumps are applicable in the operating context.

It was possible to address 73 tasks to 8 specific filters. For these 8 transfer pump filters, the MTBM was calculated to be 1.3 months. Figure 5.5 shows the distribution of the time between cleaning of the same transfer pump filter. The distribution clearly shows that

most filters are cleaned in the 5th week after the last cleaning with 74 %. However, 11% of the tasks is performed in in less than 4 weeks after the last cleaning, which gives EMTTF_m of 1.0 years. A summary of key statistics the transfer pump filter is shown in Table 5.5.

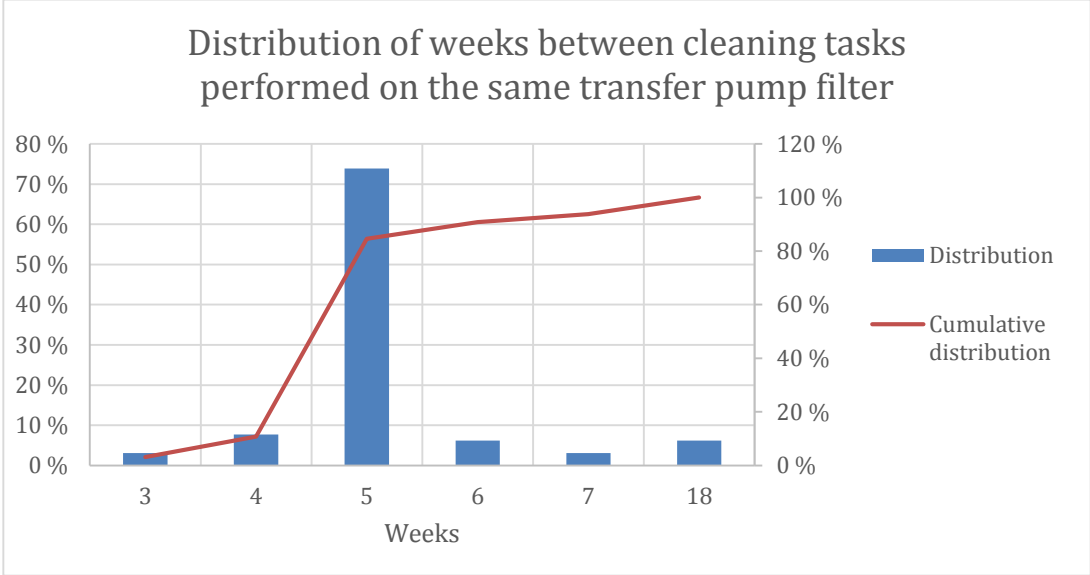


Figure 5.5: Cleaning task interval distribution for transfer pump filters.

Table 5.5: Key statistics for transfer pump filter.

# of tasks	73	
# of components	8	
# of tasks per year per component	9,1	
MTBM	1,3	Months
% Corrective - Performed < 4 weeks after last cleaning	11 %	
EMTTF _m	1,0	Years

5.2.2 Separator supply pump filter

Analysis of 83 tasks registered on 5 vessels showed that all tasks was registered as cleaning tasks. Two of the vessels clean both filters approximately once a month, two vessels clean both filters once every other month, and the last vessel clean one of the filters once every other month, while the other filter is cleaned every 3rd month. However, no planned preventive maintenance at intervals less than 4 weeks. Thus, the planned preventive maintenance performed on separator supply pump filters are applicable in the operating context.

It was possible to address 84 tasks to 10 specific separator supply pumps. For these 10 separator supply pump filters, the MTBM was calculated to be 1.4 months. Figure 5.6 shows the distribution of the time between cleaning tasks performed on the same separator supply pump filter. The figure clearly shows a peak in the 5th and 9th week. This can be explained by the maintenance performed at 1 and 2 months intervals. The figure also shows that 5 % of the cleaning tasks was performed less than 4 weeks the last cleaning task, which gives an EMTTF_m of 2.2 years. A summary of the key statistics of the separator supply pump filters are shown in Table 5.6.

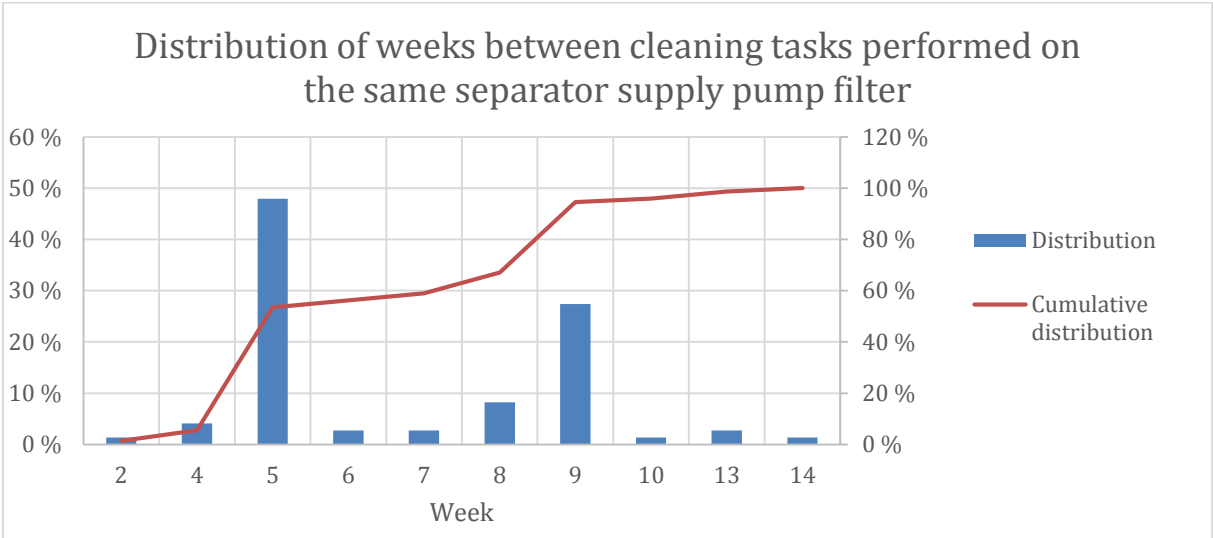


Figure 5.6: Cleaning task interval distribution for separator supply pump filters.

Table 5.6: Key statistics for separator supply pump filter.

# of tasks	83	
# of components	10	
# of tasks per year per component	8,3	
MTBM	1,4	Months
% Corrective - Performed < 4 weeks after last cleaning	5 %	
EMTTF _m	2,2	Years

5.2.3 Main engine supply pump filter

Analysis of 112 tasks registered on 9 vessels showed that all tasks was registered as cleaning tasks. The maintenance task descriptions revealed that planned preventive maintenance performed on main engine supply filters is monthly or 2nd monthly cleaning. No planned preventive maintenance is performed at intervals less than 4 weeks. Thus, the

planned preventive maintenance performed on ME supply pump filters are applicable in the operating context.

It was possible to address 57 cleaning tasks to 8 specific main engine supply pump filters. For those 8 filters, the MTBM was calculated to be 1.7 months. Figure 5.7 shows the distribution of weeks between filter cleaning performed on the same ME supply pump filter. It can be observed two distinct peaks at the 5th and 9th week, corresponding to approximately 1 and 2 months. This is caused by the planned preventive maintenance. 10 % of the filter cleanings are performed less than 4 weeks after the last filter cleaning, which gives an EMTTF_m of 1.4 years. A summary of the key statistics of the main engine supply pump filters are shown in Table 5.7.

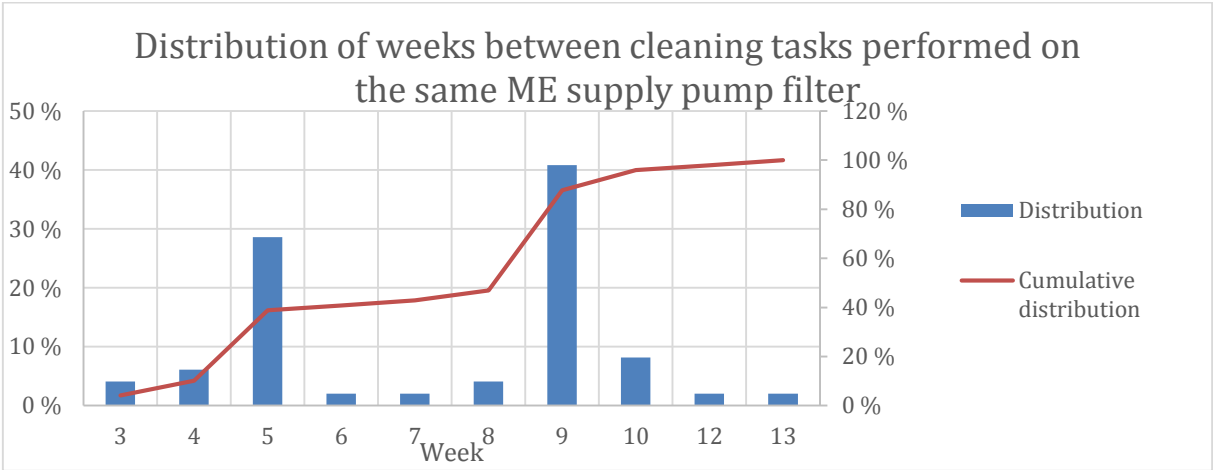


Figure 5.7: Cleaning task interval distribution for ME supply pump filters.

Table 5.7: Key statistics for main engine supply pump filter

# of tasks	57	
# of components	8	
# of tasks per year per component	7,1	
MTBM	1,7	Months
% Corrective - Performed < 4 weeks after last cleaning	10 %	
EMTTF _m	1,4	Years

5.2.4 Main engine Flowmeter filter

Analysis of 173 tasks registered on flowmeter filters revealed that the planned preventive maintenance performed on flowmeter filters are monthly cleaning. No planned preventive maintenance is performed at intervals less than 4 weeks. Thus, the planned

preventive maintenance performed on ME flowmeter filters are applicable in the operating context.

It was possible to address 136 of the cleaning tasks to 13 specific flowmeter filters. For those 13 filters the MTBM was calculated to be 1.1 months. Figure 5.8 shows the distribution of weeks between maintenance performed on the same flowmeter filter. It can be observed a clear peak in the 5th week with 63 % of the tasks performed in this week, and 82 % of the tasks are performed during the 5th and 6th week. This is caused by the planned preventive monthly cleaning tasks. It can also be observed that the 9 % of the filter cleanings are performed less than 4 weeks after the last cleaning, which gives an EMTTF_m of 1.1 years. A summary of the key statistics of the ME flowmeter filter is presented in Table 5.8.

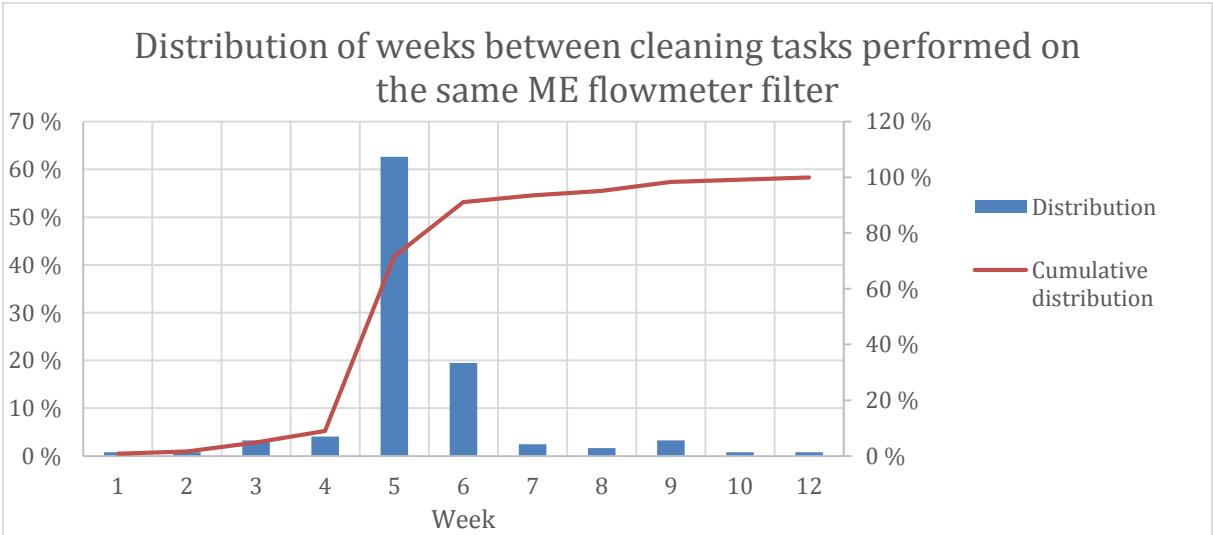


Figure 5.8: Cleaning task interval distribution for ME flowmeter filter.

Table 5.8: Key statistics for main engine flowmeter filter.

# of tasks	136	
# of components	13	
# of tasks per year per component	10,5	
MTBM	1,1	Months
% Corrective - Performed < 4 weeks after last cleaning	9 %	
EMTTF _m	1,1	Years

5.2.5 Main engine automatic backflushing filter

Analysis of maintenance data on the ME automatic back flushing filter from 18 vessels can be categorized as shown in Figure 5.9. As seen, 88 % of the maintenance can be categorized as planned preventive maintenance, 4 % as planned corrective maintenance and 8 % as unplanned corrective maintenance.

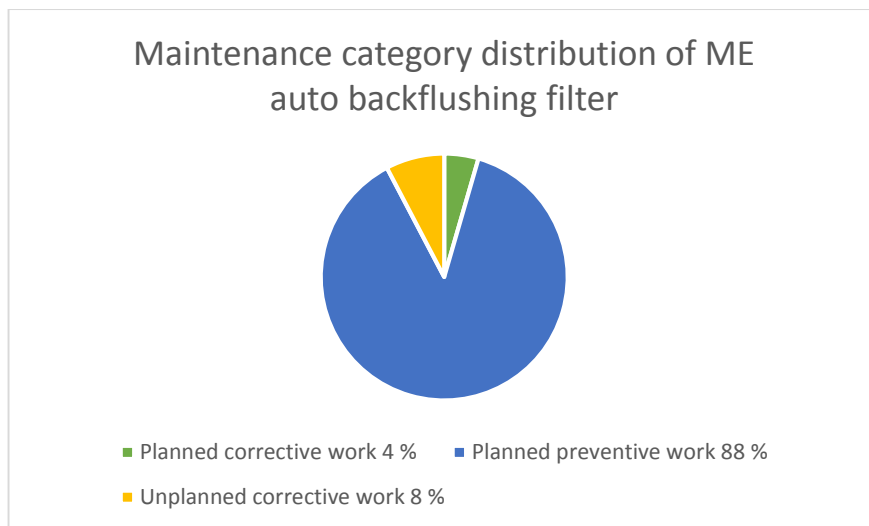


Figure 5.9: Maintenance category distribution of ME auto back flushing filter.

The maintenance data reveals that the following planned preventive maintenance tasks are performed on one or more vessels:

- Inspection every month
- Cleaning every 2nd month
- Cleaning every 3rd month
- Maintenance every 6th month
- Cleaning every 5000 flushes
- Other tasks such as overhauls and megger testing.

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 146 of the tasks to 18 specific main engine automatic backflushing filters. The results are presented in Table 5.9 and shows a MTBM of 1.5 months and an EMTTF_m of 1.0 years.

Table 5.9: Key statistics for main engine auto back flushing filters.

# of tasks	146	
# of components	18	
# of tasks per year per component	8,1	
MTBM	1,5	Months
% Corrective	12 %	
EMTTF _m	1,0	Years

47 % of the tasks, corresponding to once every 3.2 months were registered as cleaning tasks. Figure 5.10 shows the distribution of time between cleaning tasks performed on the same ME auto filter. It can be observed that 19 % of the cleaning tasks are performed less than 4 weeks after the last cleaning task. If it's assumed that these tasks are corrective, this means that even if the filter is to be preventive cleaned every month, corrective cleaning will be on average be needed once every 1.0 years.

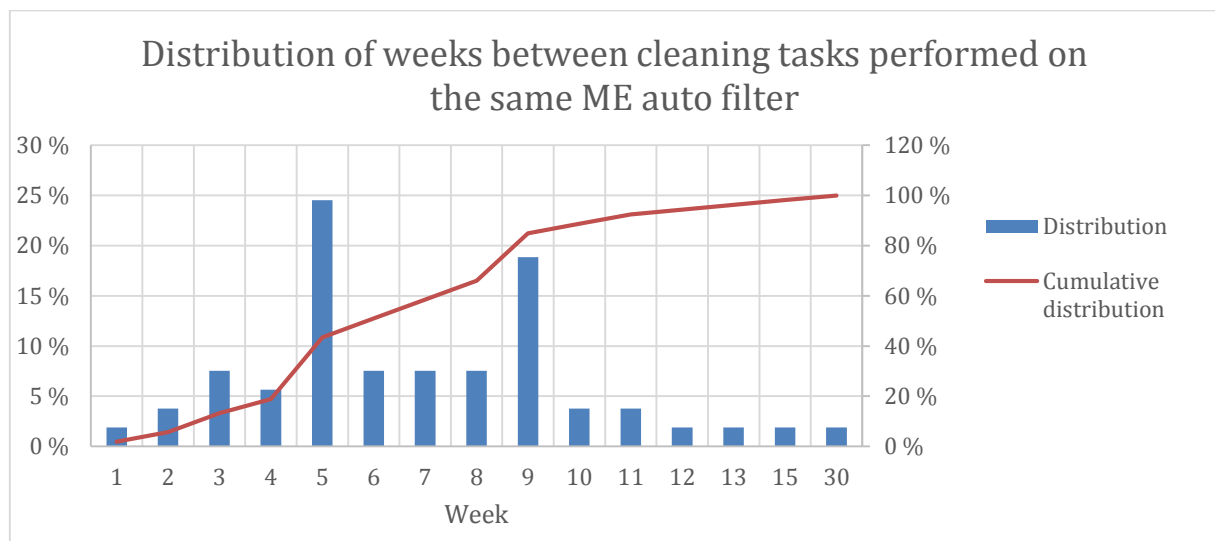


Figure 5.10: Cleaning task interval distribution for ME auto filters.

5.2.6 By-pass filter

Analysis of 51 tasks registered on by-pass filters revealed that the planned preventive maintenance performed on by-pass filters are monthly cleaning. No planned preventive maintenance is performed at intervals less than 4 weeks. Thus, the planned preventive maintenance performed on by-pass filters are applicable in the operating context.

It was possible to address 49 of the cleaning tasks on 4 specific by-pass filters. For those 4 filters the MTBM was calculated to be 1.0 months. Figure 5.11 shows the distribution of

weeks between maintenance performed on the same by-pass filter. It can be observed a clear peak in the 5th week with 56 % of the tasks performed in this week. This is caused by the planned preventive monthly cleaning tasks. It can also be observed that as much as 36 % of the filter cleanings are performed less than 4 weeks after the last cleaning, which gives an EMTTF_m becomes 0.2 years. A summary of the key statistics of the ME flowmeter filter is presented in Table 5.10.

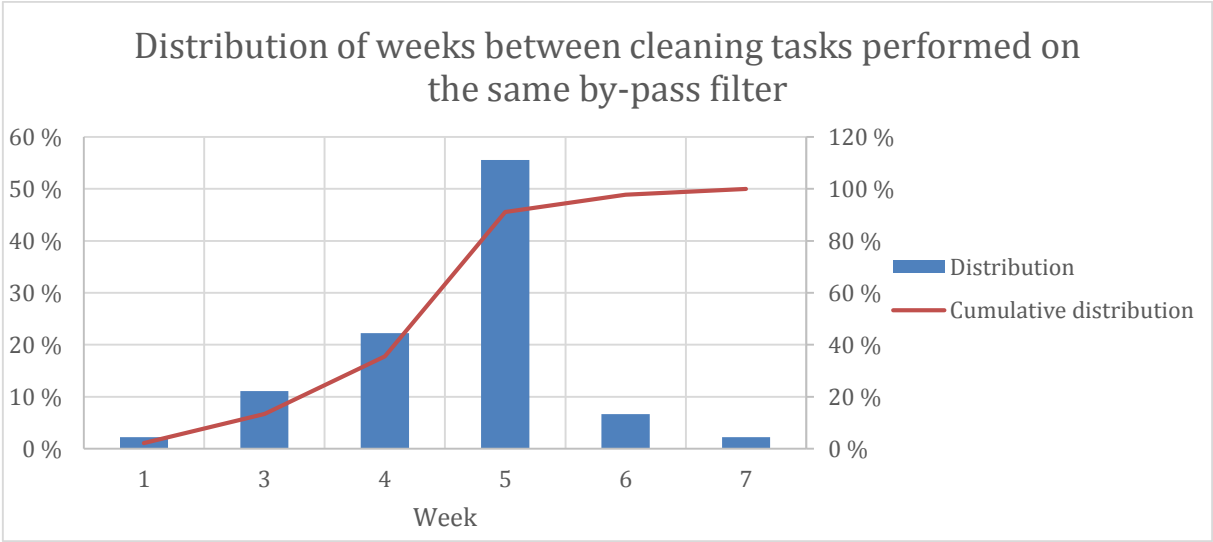


Figure 5.11: Cleaning task interval distribution for by-pass filters.

Table 5.10: Key statistics for the by-pass filter.

# of tasks	49	
# of components	4	
# of tasks per year per component	12,3	
MTBM	1,0	Months
% Corrective - Performed < 4 weeks after last cleaning	36 %	
EMTTF _m	0,2	Years

5.3 Heaters

For the heaters the EMTTF_m is calculated as for the pumps.

5.3.1 Preheater before separator

All of the 35 analyzed tasks registered on 13 vessels were registered as planned preventive maintenance. The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on the preheaters one or more vessels:

- Condition control every 6th month
- Inspection/maintenance every year
- Maintenance/survey every 24th month
- Maintenance/survey by C/E every 5th year

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 20 of the tasks on 10 specific pre-heaters. The results are presented in Table 5.11 and shows a MTBM of 6 months. As no corrective tasks has been registered it is not possible to estimate the EMTTF_m, but it's assumed that the EMTTF_m will be the same as for the heater, i.e. 21 years (see 5.3.2).

Table 5.11: Key statistics for the preheater.

# of tasks	20	
# of components	10	
# of tasks per year per component	2,0	
MTBM	6,0	Months
% Corrective - Performed < 4 weeks after last cleaning	0 %	
EMTTF _m	21,0	Years

5.3.2 Heater

Analysis of 42 maintenance tasks registered on heaters from 18 vessels give the maintenance category distribution as shown in Figure 5.12. The figure shows that 98 % of the maintenance tasks can be categorized as planned preventive maintenance and 2 % as planned corrective maintenance.

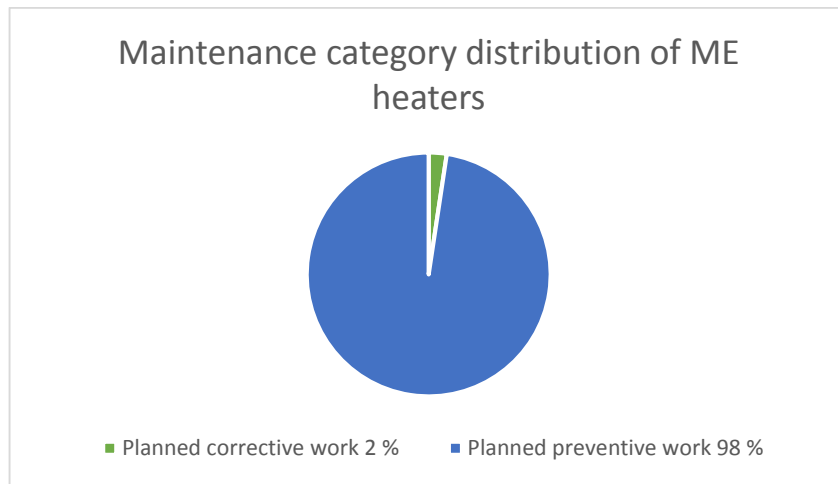


Figure 5.12: Maintenance category distribution of main engine heaters.

The maintenance task description reveals that the following planned preventive maintenance tasks are performed on the heaters on one or more vessels:

- Condition control every 6th month
- Inspection/maintenance every year
- Maintenance/survey every 24th month
- Maintenance/survey by C/E every 5th year

None of the planned preventive tasks are performed at intervals less than 4 weeks and are thus considered as applicable in the operating context.

It was possible to address 20 of the tasks to 10 specific heaters. The results are presented in Table 5.11 and shows a MTBM of 6 months and an EMTTF_m of 21 years.

Table 5.12: Key statistics for heaters.

# of tasks	20	
# of components	10	
# of tasks per year per component	2,0	
MTBM	6,0	Months
% Corrective - Performed < 4 weeks after last cleaning	2 %	
EMTTF _m	21,0	Years

5.4 Separators

Analysis of 310 maintenance tasks registered on separators from 19 vessels give the maintenance category distribution as shown in Figure 5.1. The figure shows that 78 % of

the maintenance tasks can be categorized as planned preventive maintenance, 8 % as planned corrective maintenance and 13 % as unplanned corrective maintenance.

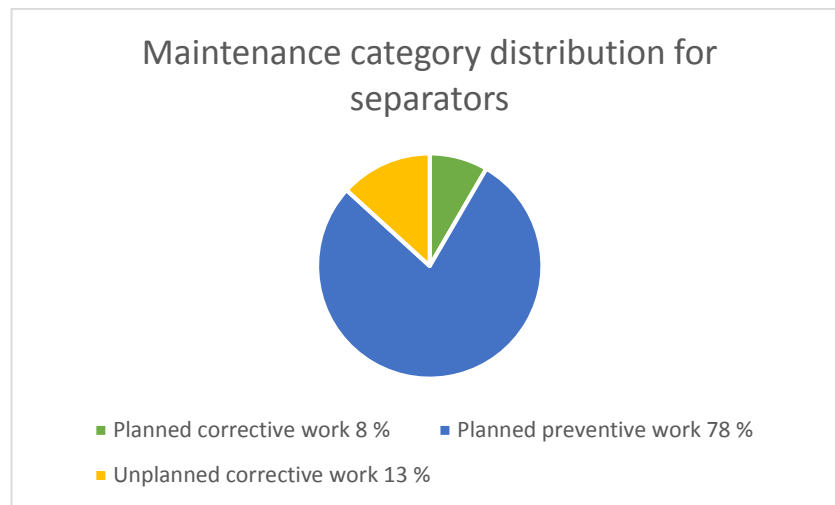


Figure 5.13: Maintenance category distribution for separators.

The maintenance task descriptions reveals that the following planned preventive maintenance tasks are performed on separators on one or more of vessels:

- Alarm test every week
- Condition monitoring every month
- Alarm test every 3rd month
- Cleaning of the bowl every 2000 hours
- Overhauls every 8000 hours
- Condition control every 4th month
- Other tasks such as inspection, megger testing etc. not registered more than once per year per separator.

The only preventive tasks performed at intervals less than 4 weeks are the weekly alarm test. However, these tasks are only performed on one of 19 vessels. Thus, as the planned preventive maintenance is applicable in the operating context for 18 of 19, it's assumed that the planned preventive maintenance is applicable in the operating context.

It was possible to address 341 tasks to 38 specific separators. The result is presented in Table 5.13 and shows a MTBM of 1.3 months and an EMTTF_m of 0.5 years.

Table 5.13: Key statistics for separators.

# of tasks	341	
# of components	38	
# of tasks per year per component	9,0	
MTBM	1,3	Months
% Corrective	22 %	
EMTTF _m	0,5	Years

An evaluation of the consistency of the planned preventive maintenance showed that all were consistent except for the cleaning tasks. For example, one of the vessels had 6 and 7 tasks registered as “Cleaning of bowl – 2000 Hours” registered on its two separators during a period of one year. Figure 5.14 shows the distribution of time between cleaning performed on the same separator, based on 106 tasks that could be addressed to specific separators. While it could be expected to see a peak that represents the 2000 hour cleaning, the figure clearly shows how inconsistent the cleaning are performed on separators. Even more interesting is it that 32 % of the cleaning tasks, which accounts for 14 % of all tasks, corresponding to once every 9.5 months, the separators are cleaned less than 4 weeks after the last cleaning. If it’s assumed that cleaning tasks performed less than 4 weeks after the last cleaning is corrective, which is reasonable if the planned cleaning is every 2000 hours, one can expect the separator to fail once every 9.5 months even if the separators is to be cleaned every month. By even further analysis of the maintenance data it was found that 3 vessels had registered 4 cleaning tasks on their two separators (cleaning tasks on each separator) within 4 weeks, which indicates that one can expect to lose the separator function several times in a the lifetime of the vessel in the operating context defined.

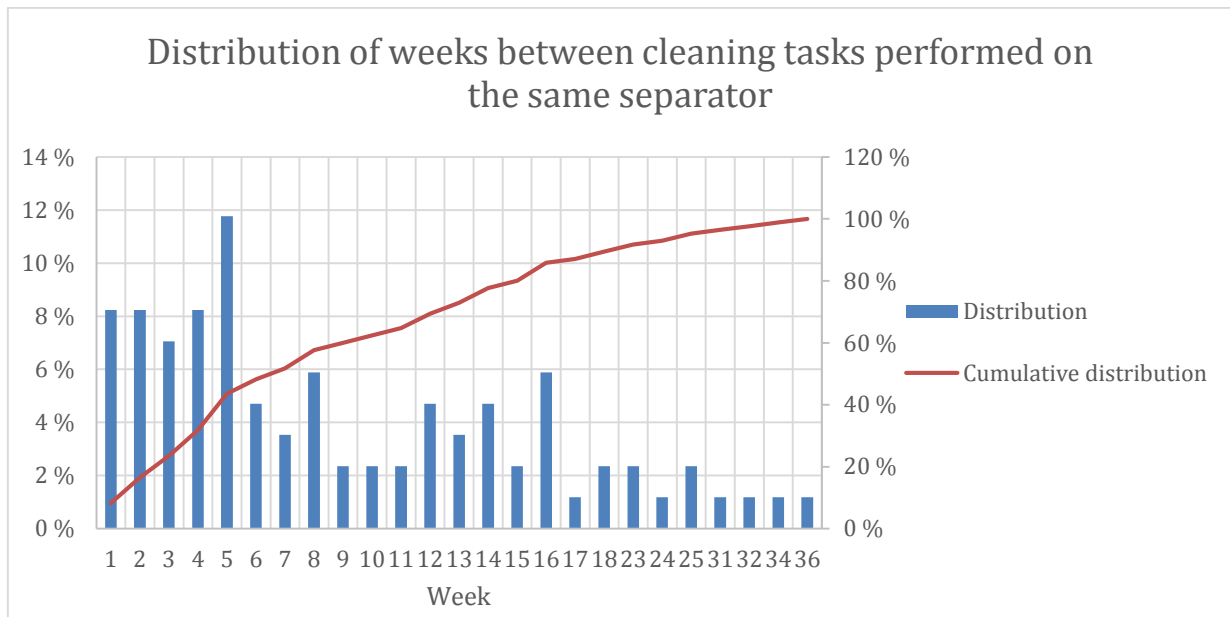


Figure 5.14: Cleaning task interval distribution for separators.

5.5 Settling and service tanks

According to Solvang, the tanks are inspected once every 24 months, and cleaned when needed. The preventive maintenance is thus applicable in the operating context. It has not been registered any corrective maintenance on the settling or service tanks. As both tanks (settling or service) have to be plugged to stop the fuel supply within one transit, it's assumed that the maintenance also is effective. Thus, the failure modes "Settling tank outlet plugged" and "Service tank outlet plugged" have not been assessed any further.

5.6 Emergency shut off valves

In the FMECA, the risk associated with premature closing of emergency shut off valves during transit was considered acceptable. Thus, these valves are not assessed any further. However, it can be noted that these valves would be of more importance when analyzing the functional failure "Fuel oil leak".

6 Discussion

6.1 Results

The analysis of today's maintenance plan showed that no planned preventive maintenance is performed at intervals less than 4 weeks. Thus, all planned preventive maintenance performed today on the analyzed components are applicable in the operating context defined.

The effectiveness of the planned preventive maintenance varies. Some of the equipment has no registered corrective maintenance, while the percentage of corrective maintenance of other components is up to 36 %. For preventive maintenance tasks to be considered effective, the risk must be reduced to an acceptable level. The risk is evaluated by the same method described in 3.4.5 and the result is presented in Table 6.1. In Table 6.2, the components are ranked according to their risk. The tables shows that 4 components have an unacceptable risk: the by-pass filter, the ME automatic backflush filter, the transfer pump filter and the flowmeter filter. Additionally, there are 5 components that have moderate risk, which means that the risk may be acceptable: the separator, the ME supply pump filter, the ME circulating pump, the ME supply pump and the transfer pump. 4 of the components analyzed are considered as acceptable, meaning that the preventive maintenance performed today is sufficient.

Table 6.1: Risk of operating the vessel with today's maintenance.

Failure mode	Redundancy	MTBM (months)	% Corr.	EMTTF _m (years)	Consequence	Likelihood	Corrected RI
Transfer pump failure	No	4,9	3	13,5	OH2	2	4
Separator supply pump failure	Yes	3,7	10	3,0	OH2	2	3
ME supply pump failure	Yes	3,5	8	3,8	OH3	2	4
ME circulating pump failure	Yes	3,2	12	2,3	OH3	2	4
Plugged transfer pump filter	No	1,3	11	1,0	OH2	3	5
Plugged separator supply pump filter	Yes	1,4	5	2,2	OH2	2	3
Plugged ME supply pump filter	Yes	1,7	10	1,4	OH3	2	4
Plugged flowmeter filter	No	1,1	9	1,1	OH3	2	5
Plugged ME automatic backflush filter	Yes	1,5	12	1,0	OH3	3	5
Plugged by-pass filter	Yes	1,0	36	0,2	OH3	3	5
Plugged preheater	Yes	6,0	0	21	OH2	1	2
Plugged heater	Yes	6,0	2	21	OH3	1	3
Plugged separator	Yes	1,3	22	0,5	OH2	3	4

Table 6.2: Ranked risk of components in the fuel system.

Failure mode	Corrected RI
Plugged by-pass filter	5
Plugged ME automatic backflush filter	5
Plugged Transfer pump filter	5
Plugged Flowmeter filter	5
Plugged Separator	4
Plugged ME supply pump filter	4
ME circulating pump failure	4
ME supply pump failure	4
Transfer pump failure	4
Plugged separator supply pump filter	3
Separator supply pump failure	3
Plugged heater	3
Plugged Preheater	2

The planned preventive maintenance performed on the four components with unacceptable risk are considered not effective in the defined operating context. For all of these components, except the ME automatic backflush filter, all maintenance tasks was registered as cleaning tasks. Since cleaning tasks performed less than 4 weeks after the last cleaning tasks represents a deterioration of the filter's condition within 4 weeks, no other maintenance strategy can reduce the risk. For condition monitoring the P-F interval would be too short for action to be taken before the failure occurs, and would thus not be applicable. Scheduled restoration and discard tasks would not be applicable, as not enough of the filters survive the minimum maintenance interval in the context of 4 weeks. For the automatic backflush filter not all tasks were registered as cleaning tasks, but the analysis showed that cleaning had to be performed less than 4 weeks after the last cleaning approximately once per year, which qualifies for the highest likelihood category in the risk calculation. As for the other filters, no other maintenance strategy can reduce this risk. Therefore, according to the results of this analysis, the by-pass filter, ME automatic backflush filter, transfer pump filter and the flowmeter filter represents barriers.

Five of the components were considered to have moderate risk, and may be acceptable. The analysis of the cleaning tasks on the separator showed that 32 % of the cleaning tasks are performed less than 4 weeks after the last cleaning task. This means that even if the

cleaning task interval was reduced from once every 2000 hours to once per month, a corrective cleaning would be expected once every 9.5 months and thus not be effective. As for the filters, no other maintenance strategy can reduce this risk. It was also observed that 3 of the 18 vessels have had 4 cleaning tasks (2 on each separator) within 4 weeks, which confirms the risk. Risk reduction is not possible for the ME supply pump filter for the same reasons as for the filters discussed in the previous paragraph. For the pumps with moderate risk, a risk reduction may be possible by other maintenance tasks, but no effective tasks or change of intervals have been identified.

6.1.1 Assumptions

Two assumptions have been central in the assessment of $EMTTF_m$. First, it has been assumed that all cleaning tasks performed less than four weeks after the last cleaning task are corrective and represents total failure. This assumption is based on the rationale that cleaning of filter more often than planned is a waste of time unless the maintenance is needed. It may be that cleaning sometimes is performed earlier to make time for other maintenance tasks, from a planning perspective, or that the condition would be sufficient to avoid delays until the next planned cleaning task. Thus, the calculated $EMTTF_m$ will be conservative.

The other assumption is the assumption that all corrective tasks on pumps causes total failure. This may be a very conservative assumption. Failures that for example are identified by the 6 months performance tests, are not total failures, but partial failures. Therefore, the calculation of $EMTTF_m$ will be conservative.

Although these assumptions causes a conservative value of $EMTTF_m$, the corrected risk index is not expected to change significantly from these assumptions. The reason is that the likelihood classes are relatively broad. For the corrected risk index of plugged transfer pump filter and plugged automatic auto backflush filter, the risk index may in reality be reduced by one level since the $EMTTF_m$ value is on the limit between likelihood category 3 and 2, but for plugged flowmeter filter for example, the $EMTTF_m$ must be increase by a factor of approximately 20 before a risk reduction is possible. The risk must also be considered in a total risk perspective, where even the failure modes with moderate risk may be considered to be barriers.

6.1.2 Total risk

As discussed in 3.4.5, one of the disadvantages of using a risk matrix for risk assessment is that individual failure modes are assessed one by one, rather than in accumulation, which the risk decision should be based on. Therefore, the results should be interpreted in the perspective of the total risk that all failure modes exert on the vessel, its crew and the owner/company. From that perspective, also the failure modes that is considered to have moderate risk may be considered as barriers.

6.1.3 Data

The data used in the analysis consists of real operational maintenance data from 20 vessels, spanning from 1-18 years old and an average age of approximately 8 years. Thus it is not only a lot of registered maintenance task to analyze which improves the quality, but also data from components with different age. This ensures that not only new or old components are analyzed, which may provide a better risk picture in light of the lifetime of the vessel. However, not all maintenance tasks are registered in an unambiguous way and it's not always possible to identify the component that has been maintained. To ensure that the dataset analyzed are as complete as possible a lot of effort has been put into sorting of data and evaluate the completeness of the data. As a result the amount of data varies significantly from component to component, but the result presented should be of good quality.

6.1.4 Limitations

It is important to realize the limitations of the analysis. Only one functional failure has been analyzed, and therefore the failure modes that not are considered as barriers for this functional failure, may be considered to be barriers if other functional failures are analyzed. The analysis is only performed for the operating mode "Normal seagoing conditions", which means that other failure modes may be identified as barriers for the same functional failure in another operating modes, such as during maneuvering. It should also be noted that valves have not been considered in this analysis. Today, a large amount of the valves of the fuel system are hand-operated, and unless these valves are automated, most of the redundancy in the fuel system will not be present. So the result in the analysis depends on automation of the valves. There may also be other manual interactions with the fuel system that will have to be analyzed further to ensure that all functions are available without crew in the engine room. It should also be noted as

mentioned in 4.1.3 that the part of the fuel system between the service tank and the auxiliary engines was not analyzed. As this part is almost identical with the part between the service tank and the main engine, the $EMTTF_m$ values of components in this part can be assumed to be the same as for the components between the service tank and the main engine. The consequences will however differ and more analysis will be required to determine the risk.

6.1.5 Result in light of HFO as fuel

One of the questions that is of great interest is whether HFO can be used as fuel on ship that sails without maintenance crew onboard. To answer that question one can observe from the results that it's the lack of ability to perform cleaning tasks in the new operating context that causes the barriers. These tasks are a direct consequence of the condition of the fuel, i.e. the HFO.

To illustrate the effect of the fuel choice, a comparison has been made with an FMECA analysis performed on a fuel system of a cable laying vessel that has been retrofitted from operating on HFO to solely diesel fuel (Wabakken, 2015). In that analysis a fuel filter blockage is expected to occur once every 6 months when no preventive maintenance is performed. Blockage of the purifier from contaminated oil was expected to occur after 10 years if no preventive maintenance was performed. This is strong contrast with the result from this analysis where 32 % of the cleaning tasks was performed less than 4 weeks after the last cleaning task, even when the planned preventive cleaning is performed once every 2000 hours. Although, the analysis wasn't performed by a chief engineer or someone that works close with the equipment, which probably would have given the best estimate, it was performed by a group consisting of an RCM facilitator, one vessel manager, two fleet managers and a master student and gives an indication of the extra need for cleaning when operating on HFO.

6.2 Method

The procedure developed and used which is based on RCM has many benefits. The procedure is thorough so that all critical failures are identified if applied correctly. In contrast with RCM procedures that apply with the SAE1011 standard, the procedure

investigates whether today's maintenance is applicable and effective before considering other maintenance tasks. This is a step that makes it possible to exploit registered maintenance that is more available than zero-based data. Therefore, new maintenance tasks are not considered before it's confirmed that the maintenance performed today isn't applicable and effective, which saves time. The consequence is that the result of the procedure isn't an optimal maintenance program, but that is neither the objective when applying the procedure. The procedure also investigates the potential for risk reduction by means of maintenance before often more expensive alternatives such as redesign.

The procedure also have some disadvantages that should be mentioned. In the literature there exist a large variety of procedures that is referred to as RCM procedures. Many of these are streamlined RCM processes that claims to achieve the same result with less time and fewer steps(Regan, 2012). Choosing such processes are strongly advised against (Bloom, 2006; Regan, 2012). Additionally, there exists a lot of contradictory advises on for example what level the analysis should be performed at, and what should be included in the steps. To make the confusion absolute, there are also different definitions of for example failure mode among different sources. Another disadvantage is that the procedure needs in-depth knowledge about the systems, the context the systems are being used in, in addition to knowledge about the failure characteristics and failure data. This makes it difficult to perform the procedure alone. Actually, it is stated that "One of the least effective ways to apply RCM is to ask a single individual to apply the process on his or her own"(Moubray, 1997, p. 286). This statement is also supported by other literature(Bloom, 2006; Regan, 2012).

To summarize, the procedure developed can be a useful tool for identifying and breaking barriers in design of unmanned engine rooms for merchant vessels. The process complies with the requirements for RCM processes stated in the SAE JA1011 standard, except for one requirement, where the consequences are well understood and discussed. However, it is strongly recommended that the procedure is performed by a team that has the necessary knowledge. In this team, it should preferably also be an RCM facilitator that is well versed in RCM principles to avoid confusion and to ensure an effective process.

7 Conclusion and recommendations

A case study was performed to identify barriers in a fuel system that uses HFO, as this is the most common fuel type used today by oceangoing merchant vessels. The analysis has been performed on the system under normal seagoing conditions, and the functional failure analysed is “Supplies no fuel to the engine”. The analysis identified four barriers with an unacceptable risk: plugging of the by-pass filter, plugging of the ME automatic backflush filter, plugging of the transfer pump filter and plugging of the flowmeter filter. It follows from the procedure that one-time changes such as redesign, modification or change of operating context for the fuel system is necessary in order for an oceangoing merchant vessel to be able to sail without maintenance personnel with an acceptable risk. These one-time changes must reduce the need for manual cleaning of filters and separators. As the frequency of cleaning tasks are a direct function of the condition of the fuel, a one-time change that can be effective on all identified barriers is change of fuel. A comparison made with an FMECA analysis from a vessel running on diesel fuel indicate that this will have a significant effect.

A procedure based on RCM has been established to identify barriers in design of unmanned engine rooms for oceangoing merchant vessels. The procedure is considered to be a very useful tool for identifying and breaking barriers in design of unmanned engine rooms for merchant vessels. However, to effectively and successfully perform the procedure, a group consisting of an RCM facilitator well versed in RCM principles and experts with in-depth knowledge about the systems is strongly recommended.

8 Further work

Considering the result of the case study performed on the fuel system in this study, it will be of great interest to study how the filters' and separators' need for cleaning can be reduced to see if the preferred HFO can be used as fuel on oceangoing merchant vessels without maintenance crew. If this is possible without changing the fuel, it would be interesting to also perform the procedure on other functional failures.

The case study performed in this analysis focuses only on the fuel system. For an oceangoing merchant vessel to be able to sail without maintenance crew on board, it is necessary to identify barriers for all systems with critical functions during transit. It would therefore be of great interest to also perform the analysis on other systems as well. In this thesis, group 65 (auxiliary engines) and group 65 (main engine) were identified as the groups with most unplanned corrective maintenance. It would therefore be of great interest to perform the procedure on these systems to identify whether these engines represents barriers.

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