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Evaluation of Vibration Monitoring of HFO Purifiers in the Klaveness Fleet

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Preface

This master's thesis is submitted for the degree of Master of Science in Marine Technology at the Norwegian University of Science and Technology (NTNU) and corresponds to 30 credits. The thesis has been written in its entirety by Odin Dypdalen Kjærvik for Klaveness Operation during the spring of 2019. The author was supervised by Prof. Ingrid Bouwer Utne, Department of Marine Technology, whom I gratefully acknowledge the assistance of. I am extremely thankful to her for sharing her expertise and for providing valuable guidance and encouragement to the very end.

I would also like to thank Christian Bjanger Skjelbred in Klaveness for all the time and effort that he has put into the guidance of this thesis. His passionate participation and input has been unvaluable and is highly appreciated.

A thank you is also due to Vidar André Johannessen in Karsten Moholt for a clarifying and valuable discussion about vibration monitoring towards the end of writing the thesis.

Finally, I would like to thank all of those who have supported, encouraged and given me valuable advice throughout the entire period of writing this thesis. No one mentioned - no one forgotten.

Odin Dypdalen Kjærvik

Trondheim,
June 18, 2019

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Summary

Over the years, the maintenance discipline has been under constant development. It has evolved from being a corrective process, performed after functional failure, to be more preventive, where components and systems are overhauled or replaced based on a giving time-schedule, assuming that they have a defined lifetime. However, such lifetime estimates often come with a high degree of uncertainty, resulting in scheduled maintenance being performed too late or too early, causing functional failures or high costs from unnecessary replacements.

To reduce the uncertainty associated with time-based schedules, predictive approaches based on evaluation of asset condition have appeared. Such maintenance strategies can help to maximise asset lifetime and further reduce downtime and maintenance costs. The perhaps most common is condition monitoring (CM), which is a significant component of predictive maintenance (PdM), often referred to as condition-based maintenance (CBM). These developments can be traced back to the air transportation industry in the 1960s (Knutsen et al., 2014).

In 2018, Klaveness conducted a CBM pilot project on two of their combination carriers, where offline and manual vibration monitoring equipment was installed on a considerable amount of equipment, mostly compressors, pumps and engines. The pilot was initiated to help build knowledge and better understand the benefits and limitations of CBM, as Klaveness does not have significant experience within this area from before. They hope that this can help them move towards a more predictive maintenance regime in the future.

After the pilot was conducted, Klaveness decided to reduce the number of equipment to be monitored when implementing vibration monitoring equipment on vessels throughout their fleet. Among the equipment removed from the scope was the heavy fuel oil (HFO) purifiers. The purpose of the purifiers is to remove liquid and solid contaminants from the heavy fuel oil before being used in the main engine. Failing to treat the fuel oil properly will result in decreased combustion efficiency and possibly cause severe damage to the engine. Even though the purifiers have redundancy, it has a history of incidents that could have been prevented.

The objective of this thesis is to assess whether it would be beneficial for Klaveness to equip HFO purifiers with vibration monitoring equipment onboard their ships in a fleet-wide installation. The thesis answers the following two research questions:

1. What are the failure modes with the highest probabilities of occurrence and severity of consequences, and how can these be detected?
2. What kind of information can be extracted from the incident reports regarding HFO purifiers in the Klaveness fleet, and could any of these incidents have been detected by vibration monitoring?

A failure mode, effect and criticality (FMECA) analysis was performed along with an analysis of incident reports on HFO purifiers in the Klaveness fleet to answer these questions. As a part of the FMECA, the likelihood of occurrence of failures on the subsystem and sub-component level was estimated based on the analysed incident reports. Further, a qualitative assessment of whether the incidents could have been discovered by vibration monitoring (VM) was conducted based on available literature on the topic, the author's knowledge and discussions with Karsten Moholt, a company working with lifetime extension of rotating equipment through, amongst others, condition monitoring and analysis.

The results from the FMECA and incident report analysis show that the most critical failures with respect to the severity of consequences concerning safety, downtime and costs, are those related to leakages in the system or failure of electronic equipment such as controllers and sensors. VM cannot detect these failures. However, those failures that could potentially have been detected by VM constitute more than half of the failures analysed. These are failures mainly related to the power transmission subsystem and the electrical motor. Even though these failures are not as critical as those that cannot be detected by VM, they may still result in downtime of up to two months and costs in the range between 20,000-200,000 USD.

Before a final decision is made, a life-cycle cost (LCC) analysis should be carried out to determine whether this is a cost-effective method to prevent failures on the HFO purifiers.

Sammendrag

Vedlikehold som fagfelt har til enhver tid vært under konstant utvikling. Det har utviklet seg fra å være en korrektiv prosess utført etter at utstyr har sluttet å fungere slik det skal, til å bli mer forebyggende, hvor utstyr og systemer blir reparert eller erstattet basert med faste mellomrom, forutsatt at de har en bestemt levetid. Slike antagelser er ofte usikre, noe som ofte medfører at vedlikehold utføres for sjeldent eller for ofte. Dette vil kunne resultere i hyppigere utstyrsfeil eller høye kostnader som følge av unødvendige utskiftninger.

For å redusere usikkerheten knyttet til kalenderbaserte vedlikeholdsplaner, har det med årene blitt utviklet prediktive vedlikeholdsstrategier som baserer seg på en vurdering av utstyrets tilstand. Slike strategier kan bidra til å maksimere utstyrets levetid, samt redusere nedetid og vedlikeholdskostnader. Den kanskje mest av kjente av disse strategiene er tilstandsmonitorering, som er en viktig del av det som kalles prediktivt vedlikehold. Utviklingen i retning prediktivt vedlikehold kan spores tilbake til luftfartsindustrien på 1960-tallet (Knutsen et al., 2014).

I 2018 gjennomførte det norske shippingselskapet Klaveness et pilotprosjekt som omhandlet tilstandsbasert vedlikehold på to av deres skip. Som en del av prosjektet ble offline og manuelt vibrasjonsutstyr installert på en betydelig mengde utstyr, hovedsakelig på kompressorer, pumper og motorer. Klaveness iverksatte dette prosjektet for å tilegne seg kunnskap om fordelene og begrensningene med tilstandsbasert vedlikehold, da de ikke har betydelig erfaring innen området fra før. De håper at dette kan hjelpe dem med å bevege seg i retning av et mer tilstandsbasert vedlikeholdsregime i fremtiden.

Etter at piloten ble gjennomført bestemte Klaveness seg for å redusere mengden utstyr som skal overvåkes når vibrasjonsmonitoreringsutstyr rulles ut i flåten. Blant utstyret som er besluttet fjernet finner man drivstoffseparatorene. Formålet med disse separatorene er å fjerne uønsket væske og partikler fra drivstoffet før det brukes i hovedmaskineriet ombord. Dersom drivstoffet ikke blir tilstrekkelig renset vil det kunne medføre redusert forbrenningseffekt og potensielt skade hovedmaskineriet ombord på skipet. Selv om drivstoffseparatorene er et redundant system, viser feilhistorikken at flere av hendelsene potensielt kunne vært avverget.

Målet med denne oppgaven er å vurdere om det vil være en korrekt avgjørelse av Klaveness å ut-

styre drivstoffseparatorene med vibrasjonsmonitoreringsutstyr ombord i flåten sin. Oppgaven svarer på følgende spørsmål:

1. Hvilke feil forekommer med størst sannsynlighet og hvilke feil har de alvorligste konsekvensene? Hvordan kan disse avdekkes?
2. Hvilken informasjon finner man i hendelsesrapportene som omhandler drivstoffseparatorene, og kunne noen av disse hendelsene vært oppdaget ved hjelp av vibrasjonsmonitoreringsutstyr?

For å kunne svare på disse spørsmålene ble det gjennomført en feilmode, effekt og kritikalitetsanalyse (FMECA), samt gjort en analyse av hendelsesrapportene på drivstoffseparatorene i Klaveness-flåten. Som en del av FMECAen ble sannsynligheten for utstyrssvikt estimert basert på de analysert rapportene. Videre ble det foretatt en kvalitativ vurdering om hvorvidt de ulike hendelsene kunne vært oppdaget dersom man hadde brukt vibrasjonsmonitoreringsutstyr. Denne vurderingen baserte seg på tilgjengelig litteratur og studier vedrørende vibrasjonsmonitorering, samt forfatterens egen kjennskap til temaet og diskusjoner med Karsten Moholt, et selskap som blant annet driver med overvåkning og analyse av maskineri.

Resultatene fra FMECAen og analysen av hendelsesrapportene viser at de meste kritiske feilene med hensyn til alvorlighetsgraden og konsekvenser for sikkerhet, nedetid og kostnader, er de som er relatert til lekkasjer i systemet eller feil på elektronisk utstyr som kontrollere og sensorer. Disse feilene kan ikke avdekkes ved hjelp av vibrasjonsmonitorering. De feilene som kunne vært avdekket av vibrasjonsmonitorering, derimot, utgjør mer enn halvparten av feilene som ble analysert. Dette er i hovedsak feil tilknyttet elektromotoren, selve separatoren, og kraftoverføringssystemet mellom disse. Selv om disse feilene ikke er like alvorlige som eventuelle lekkasjer, kan de likevel medføre nedetid på opptil to måneder og kostnader mellom 20.000-200.000 USD.

Før en endelig beslutning fattes bør en livssyklusanalyse med fokus på kostnader utføres for å avgjøre om vibrasjonsmonitorering er en kostnadseffektiv metode for å forhindre feil på drivstoffseparatorene.

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Acronyms

CBM Condition-Based Maintenance.

CM Condition Monitoring.

FMECA Failure Modes, Effect and Criticality Analysis.

HFO Heavy Fuel Oil.

LCC Life-Cycle Costs.

MTBF Mean Time Between Failure.

MTTF Mean Time To Failure.

MTTR Mean Time To Repair.

PdM Predictive Maintenance.

PM Preventive Maintenance.

RCM Reliability Centered Maintenance.

SSC Structure, System and Component.

USD United States dollar.

VM Vibration Monitoring.

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Chapter 1

Introduction

1.1 Background

Ships and other marine platforms are complex and capital-intensive systems designed for being in service for many years. Most ships are in service for 25-30 years before reduced efficiency, increased wear, costly operations and reparations make it unprofitable for the owner (Henriksen, 2015). While ships are in service, their availability and operational readiness are highly crucial to the supply chain, due to costs associated with downtime and knock-on effects on the entire transportation system.

Experiences with analyzing life-cycle costs (LCC) suggest that a large share of a system's projected costs are assigned maintenance and support activities to keep the system operational and available throughout its planned service life. Such maintenance and support costs often account for up to 70-75% of the system's LCC (Blanchard et al., 1995; Dhillon, 1989). Since maintenance can account for a substantial amount of the LCC of a ship, an increased focus on the maintenance system is likely to reduce total life-cycle maintenance costs and durations, prevent long out-of-service times and possible injuries to maintenance personnel and the environment.

Over the years, maintenance has evolved from being something performed after a functional failure to a preventive activity, assuming that a component has a defined lifetime. Here, components and systems are overhauled, or replaced, based on a schedule. However, such lifetime estimates often come with a high degree of uncertainty. As a result, the scheduled maintenance is often performed too late or too early, causing functional failures or high costs from unnecessary replacements. Additionally, when disassembling components for inspection, there is also a risk of introducing faults, causing a failure shortly after (Knutsen et al., 2014).

To reduce the uncertainty associated with time-based schedules, predictive approaches based on evaluation of asset condition have appeared. These developments can be traced back to the 1960s when discovering that a considerable amount of failures in complex aircraft were random, and not age-related as previously believed. Thus, regular inspections and condition monitoring using sensors were implemented to determine whether any failures were imminent. These discoveries have, amongst others, led to the development of Reliability Centered Maintenance (RCM), a maintenance framework using condition monitoring (CM) as a means to cost-effectively increase safety and availability (Knutsen et al., 2014).

The reason for implementing condition monitoring is ”to increase the overall safety level in order to reduce the risk of loss of life and property, while also minimizing the costs associated with maintenance of the component or system being monitored” (Knutsen et al., 2014). To achieve this, one can increase the reliability of the monitored component or system or reduce the consequences of failures. The reliability can be improved by closely monitoring potential failure mechanisms and avoiding these through operational measures and maintenance, in the short- and long-term, respectively.

Norwegian shipping company Klaveness is a leading service provider to the global dry bulk industry, operating close to 135 vessels and carrying about 65 million tonnes of cargo annually. Also, Klaveness has a unique concept for combination carriers. On two of their ships, they have installed a large amount of offline and manual vibration monitoring equipment. Klaveness want this to take them from Preventive Maintenance (PM) to Condition-Based Maintenance (CBM) and predictive maintenance.

The ships are now conducting monthly measurements, and they are receiving quarterly reports from their supplier IKM Instrutek with information on system condition, in addition to advice and guidance on recommended measures. On their most recently built ships, they will also send ashore operating parameters from the automation systems that report pressures, temperatures, RPM and load, amongst others, from most components on board. These parameters are also available on the vessels in the pilot project, however, only locally onboard.

When installing online monitoring equipment in the entire fleet, Klaveness plan to reduce the number of equipment being monitored to ensure that it adds value. One of the systems considered for online monitoring is the heavy fuel oil (HFO) purifiers. The purpose of this system is to remove undesirable liquid and solid contaminants from the HFO to prevent decreased fuel oil efficiency and damage to the main engine. The HFO purifier system is a system with redundancy, but also with a history of incidents that could have been prevented. Because of the importance of proper fuel treatment and the incident history of the HFO purifiers, the thesis will focus on condition monitoring of the HFO purifiers.

1.2 Objective

The objective of this thesis is to assess whether it would be beneficial for Klaveness to equip HFO purifiers with vibration monitoring equipment onboard their ships in a fleet-wide installation. This question arose after Klaveness conducted a condition monitoring pilot onboard two of their ships. Even though this is a redundant system, it has a history of incidents that could have been prevented.

The thesis will, in a qualitative manner, attempt to answer the following research questions:

1. What are the failure modes with the highest probabilities of occurrence and severity of consequences, and how can these be detected?
2. What kind of information can be extracted from the incident reports regarding HFO purifiers in the Klaveness fleet, and could any of these incidents have been detected by vibration monitoring?

The outcome of this thesis will aid Klaveness in the decision-making process regarding whether to equip the HFO purifiers in their fleet with vibration monitoring equipment. The results may also help Klaveness in optimizing the maintenance of these purifiers, primarily with regard to overall maintenance strategy.

1.3 Scope and Limitations

The scope in this task is twofold, but the two parts are still closely related. The first part is to exemplify the practice of FMECA by analysing an HFO purifier system used onboard several ships in the Klaveness fleet, while the second part consists of analysing incident reports related to the same HFO purifiers in the fleet. The two parts are carried out in parallel as the incident reports provide important and valuable input for the FMECA.

Therefore, the overall scope is to highlight the most critical parts of the HFO purifier system concerning the probability of occurrence and severity of consequences and provide Klaveness with information regarding the amount and type of incidents that could potentially have been revealed by vibration monitoring.

Due to time limitations, no further analyses of the most critical failures highlighted in the FMECA are conducted. Furthermore, the FMECA is conducted in a semi-qualitative manner. Both the likelihood of failures and the severity of consequences are given scores based on the risk matrix seen in Appendix C. The likelihood of failure is estimated based on analysis of the provided incident reports, while the severity of consequences are a result of Klaveness' own experiences with the equipment and discussions between Klaveness and the author.

Additionally, the FMECA and incident analysis is performed by the author alone. As the author's first-hand experience with the analysed system is somewhat limited, it must be expected that the outcome of the analyses may contain minor errors. However, the FMECA analysis has been reviewed by Klaveness throughout the process, and the author has discussed the probability that the occurred incidents could have been detected by vibration monitoring with Karsten Moholt, a company with expertise in maintenance and monitoring of rotating machinery and equipment. This ensures that the final results of the thesis should be at an acceptable level.

1.4 Thesis Structure

The work of this thesis has essentially been carried out as follows: literature review, description of the condition monitoring pilot conducted in Klaveness, explanation of the methods used, and finally a presentation and discussion of the obtained results. The thesis is structured in the following way:

- **Chapter 2 - Literature:** First, the literature review explains the history of maintenance, followed by the status of maintenance in shipping today and in the future. Then, CBM is explained, with a focus on vibration monitoring (VM). Further, centrifugal purifiers in fuel oil treatment systems are presented. This includes a description of fuel oil treatment systems in general, a more detailed description of the function and design of HFO purifiers and their most common failure modes and causes, followed by previous studies and analyses on such systems. Finally, the method of FMECA and incident investigation is presented.
- **Chapter 3 - Condition Monitoring Pilot in Klaveness:** Here, the condition monitoring pilot conducted on two ships in the Klaveness fleet is presented. First, the background for the pilot and Klaveness' maintenance ambitions are explained, followed by a description of the benefits of condition monitoring. Further, the key takeaways from the pilot are summarised, followed by a comparison between offline and online condition monitoring. Finally, Klaveness' proposal for which equipment should be monitored in a fleet-wide installation is given.
- **Chapter 4 - Method:** This chapter explains how the analyses in this thesis were carried out. An explanation of the FMECA methodology is presented, followed by an explanation of how the incident reports were analysed.
- **Chapter 5 - Results:** Following the structure of the previous chapter, the results of the FMECA is presented first, followed by the results from the incident report analysis.
- **Chapter 6 - Discussion:** This chapter first discusses the data available for the FMECA and incident report analysis. Then, the FMECA and its results are discussed, followed by a review of the results from the incident report analysis. Finally, the actual incident reports are discussed. This includes their structure, content and recommended changes to improve the reports.
- **Chapter 7 - Conclusions:** As the penultimate part of this thesis, the conclusions is presented.
- **Chapter 8 - Further Work and Recommendations:** Finally, any recommendations and further work that should be considered before a final decision is taken is given.

Chapter 2

Literature

This chapter provides background information on the topic of maintenance, the system to be analysed, and analysis methods used. It also serve as a more thorough introduction to the thesis itself. First, the history of maintenance is described in brief. Then, the status and future of maintenance and condition monitoring in shipping are reviewed. Next, an introduction to CBM is given, and vibration monitoring is described in more detail. After that, the design and function of centrifugal separators in fuel oil treatment systems is explained. Finally, the method of FMECA, as well as a brief introduction to incident investigation, is presented.

2.1 Maintenance

2.1.1 History

Over the years, the maintenance discipline has been under constant development. It has evolved from being a corrective process, performed after functional failure, to be more preventive, where components and systems are overhauled or replaced based on a given time-schedule, assuming that they have a defined lifetime, see Figure 2.1. However, such lifetime estimates often come with a high degree of uncertainty. To reduce the uncertainty associated with time-based schedules, predictive approaches based on evaluation of asset condition have appeared. The perhaps most common is condition monitoring (CM), which is a significant component of predictive maintenance (PdM), also known as, and often used interchangeably with, condition-based maintenance (CBM). These developments can be traced back to the air transportation industry in the 1960s (Knutsen et al., 2014).

Moubray, 1997, one of the pioneers of RCM, say that the evolution of maintenance since the 1930s can be traced through three generations. The first generation takes place in the period up to the Second World War. In this period, industries were not particularly mechanised, but instead dependent on manual labour. As a result, equipment downtime and prevention of failures was thus not devoted much attention. Additionally, more complicated maintenance strategies than corrective maintenance was not deemed

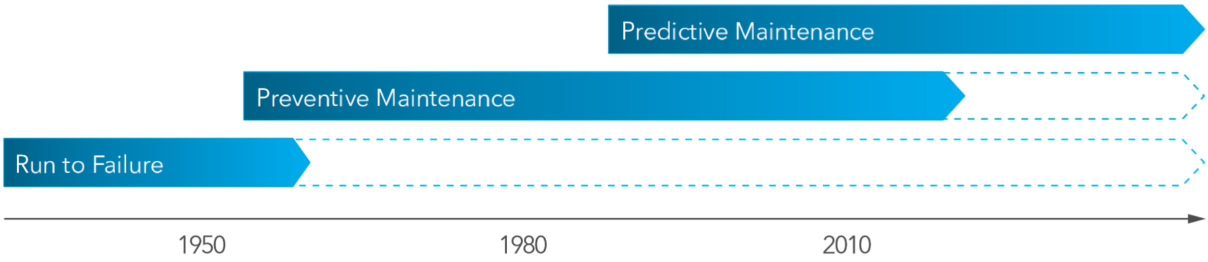


Figure 2.1: Evolution of maintenance practices. From Knutsen et al. (2014).

necessary as most types of equipment were simple and over-designed constructions, hence making it reliable and easy to repair.

During the Second World War, the demand for goods grew while the supply of human resources to the industry decreased, resulting in increased mechanisation. It was invested more and more capital in complex machines, and production downtime started to gain more attention. The desire to reduce downtime and maintenance costs, but also maximise asset lifetime, led to the concepts of preventive maintenance (PM) and maintenance planning. Moubray considers this the second generation of maintenance.

The evolution from the second to the third generation of maintenance started to gather momentum from the mid-seventies, and is a result of new expectations, research and techniques:

- New expectations: Reducing downtime has become even more critical as many industries move towards just-in-time systems. Reliability and availability have also become more important as a result of increased automation and mechanisation, society's view on safety and the environment, and the introduction of associated regulations. Also, as the cost of owning, operating and maintaining physical assets are increasing, businesses are forced to become more cost-effective in an increasingly competitive world.
- New research: When analysing equipment failures on board aircraft, Nowlan and Heap discovered that most failures, 89%, were not age-related but random, meaning that a preventive maintenance program does not address them. Similar numbers have been shown for marine vessels. The relative number of random failures was found to be 77% and 71% in the MSP study (1982) by the US Navy and the SUBMEPP study on US Navy submarines, respectively. These failures have to be detected before they occur, i.e. one has to implement a predictive maintenance strategy.
- New techniques: New maintenance concepts and techniques have been developed based on the expectations of maintenance and the research conducted. These include, amongst others, decision support tools like hazard and operability studies, FMECA, new techniques such as condition monitoring, and a much greater emphasis on maintainability and reliability already in the design phase.

Even though this third generation of maintenance started to gather momentum already some 40-50 years ago, few companies seem to have taken the final step into it. However, several companies are operating between the second and third generation. Bellias, 2017, state that CBM is the most widely accepted current method. The significant development within computer and sensor technology is making CBM possible and profitable for an increasing number of companies. However, CBM solutions are data intensive and require that condition monitoring processes are established, which is why it is not prevalent in industries today, though this is starting to change as it is becoming increasingly more common. Furthermore, Bellias believes that prescriptive maintenance is the future. Like predictive maintenance, it utilizes advanced analytics, but differ in the way that it does ”not only make recommendations but also act on recommendations.”

2.1.2 Status in Shipping

Through the International Safety Management (ISM) Code, the International Maritime Organization (IMO) provide an international standard for the safe management and operation of ships and pollution. This standard applies to all commercial vessels greater than 500 gross tonnes (GT). About maintenance, ISM states that ”The Company should establish procedures to ensure that the ship is maintained in conformity with the provisions of the relevant rules and regulations and with any additional requirements which may be established by the Company”. Thus, the shipping companies are required to perform inspections at regular and appropriate intervals, report any nonconformities, take appropriate corrective action and record these (International Maritime Organization, 2010). It is up to each company to decide which maintenance strategy to opt for as long as they can show that they comply with the standard. Class societies offer recommendations on maintenance, and DNV GL, for instance, declares that ”Every ship shall have implemented a maintenance system” and that ”maintenance [...] shall be in accordance with applicable recognised standards in the industry or in accordance with procedures recommended by the manufacturer” (DNV GL, 2019a).

DNV GL (Knutsen et al., 2014), state that ”maintenance in shipping generally follows a preventive or scheduled maintenance system, often called Planned Maintenance System (PMS)”. Many ship owners and operators tend to follow the guidelines regarding maintenance as given by the manufacturer and class (Mokashi et al., 2002). By doing so, the company do not have to spend resources on developing maintenance schedules. Additionally, for the warranty to be valid, many suppliers require that their guidelines are followed. Even though the strategy is both simple to follow and implement, it is rarely the most optimal for the ship operator. Many equipment manufacturers and suppliers do not have sufficient or satisfactorily knowledge about the operating context of the equipment and working environment where it will be used, often leading to maintenance requirements that should be able to manage worst-case scenarios. This is often likely to result in over-maintenance, thus wasting valuable resources for the shipowner and operator (Linton, 2011; Mokashi et al., 2002; Tam et al., 2006). Linton (2011) demonstrates this through laboratory tests conducted on an outboard engine on a ship in the US Coast Guard. The results showed that the recommended maintenance requirements from the manufacturer were excessive. Never-

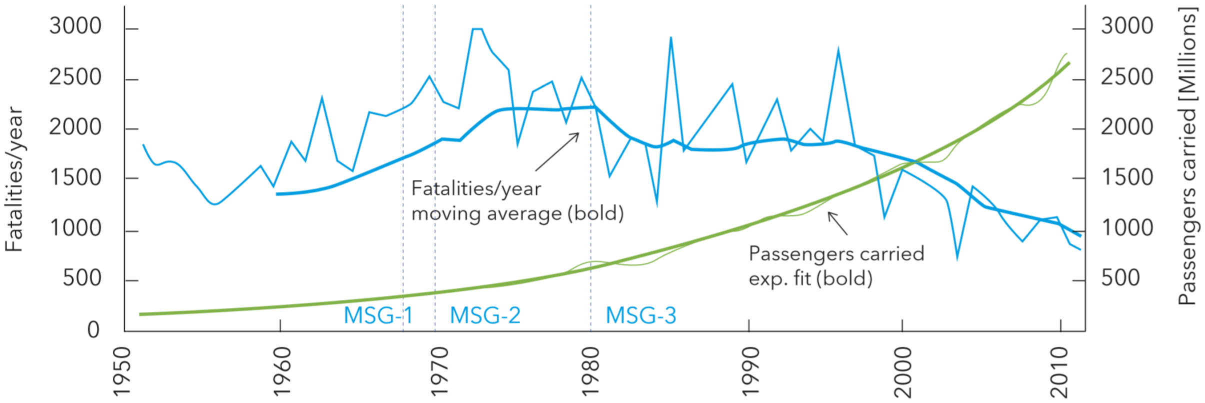


Figure 2.2: Fatalities per year in passenger aircraft (left axis), and passenger carried (right axis). From Knutsen et al. (2014).

theless, the manufacturer was unwilling to extend the maintenance intervals. One of the reasons might be the fear of liability claims.

Only having to meet a minimum standard to comply with rules and regulations has, according to Shorten (2012), lead to an industry that is ”lead by compliance” and ”does not normally seek to exceed the minimum standard”. This puts most shipping companies in the second generation of maintenance, as described by Moubray (1997). In his paper, Shorten (2012) presents numbers showing that only 17% of classed ships operate with an approved PMS, and only 12% of these use CM, meaning that only 2% have a CM scheme in place, despite the many benefits of implementing such schemes. DNV GL list several benefits of moving towards a condition-based maintenance approach: diagnostics, prognostics and risk tools, increased safety, reliability and industry transparency, reduced number and frequency of inspections and repairs, improved spare parts exchange and logistics, reduced costs related to maintenance and downtime and to preserve asset value, and improved design (Knutsen et al., 2014).

The introduction of CBM has had a positive effect on aircraft safety. The discoveries of Nowlan and Heap (1978), indicating that most failures are not age-related but random, shifted the maintenance paradigm towards on-condition maintenance. MSG-1 (Maintenance steering group 1) was introduced in 1968, followed by MSG-2 in 1970 and MSG-3 in 1980. The implementation of the maintenance strategies developed here shows that passenger safety improved greatly approximately 5-10 years after the documents were published, as depicted in Figure 2.2. The number of fatalities per year peaked between 1970 and 1980 and has steadily decreased since then. At the same time, the number of passengers carried per year has more than tripled, and seem to increase exponentially. The same numbers are not to be found in the shipping industry as of today, see Figure 2.3. Here, it seems like the number of ship years has increased linearly, while the number of fatalities per year has remained constant. The increase in fatalities per year, and the number of ship years flattening out might indicate that the safety of, in this case, passenger ships have become worse lately. The fact that the development of maintenance strategies and procedures has been slower compared to the aviation industry could be a contributing cause (Knutsen et al., 2014).

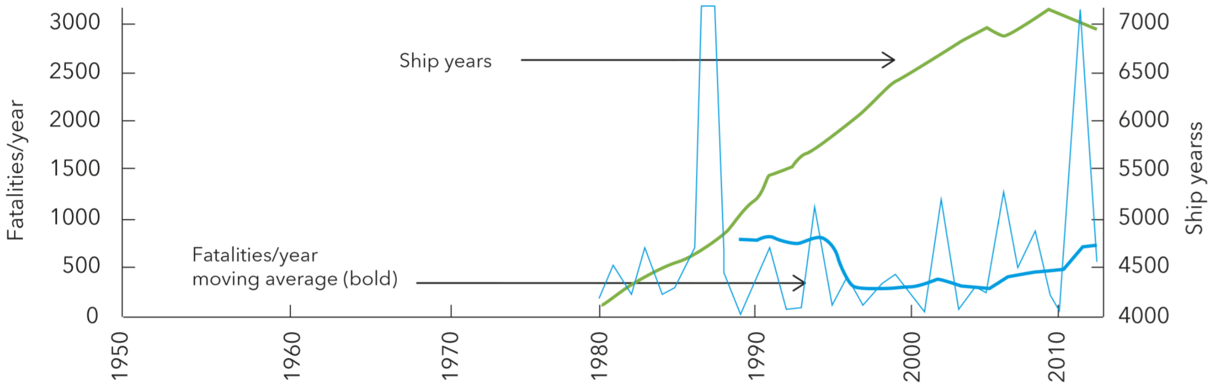


Figure 2.3: Fatalities per year in passenger ships (left axis), and ship-years (right axis). From Knutsen et al. (2014).

DNV GL (Knutsen et al., 2014) discusses several reasons why the implementation of predictive maintenance approaches in shipping have not been at the same rate as in the aviation industry:

- Knowledge: It requires extensive knowledge about ship functions, systems and components. This knowledge can only be achieved by having a considerable focus on asset maintainability throughout the entire design phase. Furthermore, the increasing complexity of systems requires an increased focus on the effects of interacting and interdependent components.
- Software and standards: Appropriate software and new standards are necessary to control these new complex and interconnected systems and hence the vast amount of data generated.
- Failure and measurement data: A comprehensive database of reliable failure and measurement data is a prerequisite for applying statistical analysis methods for diagnostics and prognostics, and the quality of the condition monitoring relies heavily on this. This prerequisite is especially a problem for smaller and medium-sized ship owners, who might not be able to obtain the required amount of data.
- Data transfer: The capability of effectively sharing real-time condition monitoring data from ship to shore for analysis has been a major barrier. Several initiatives have been launched over the last five years. Inmarsat, a leader in global mobile satellite communications, has launched four data transfer satellites since 2013, and a fifth targeted for launch in 2019, as a part of their Global Xpress service. Another one is Telenor's Thor 7 satellite, providing broadband communications for maritime customers in Europe and the northern areas such as the North Sea, Norwegian Sea, Red Sea and Baltic Sea (Inmarsat, 2019; Knutsen et al., 2014).

Even though predictive maintenance has not come as far as in the aviation industry, yet, there is rapid development and massive interest in the area. DNV GL has offered condition-based monitoring surveys for several years and has recently announced that all DNV GL classed vessels now have the possibility of remote surveys for some inspections - ”another big step forward in using the power of digitalization and increased connectivity to deliver smarter and more efficient services” (DNV GL, 2019b).

2.1.3 Maintenance in the Future

When considering the development of maintenance, and especially condition monitoring, the aviation experienced from 1970 to 2000, it is far from unlikely that the shipping industry might experience a similar accelerated development in the years to come. In their position paper about condition monitoring in the maritime industry, DNV GL says that shipping may even have caught up with aviation regarding maintenance technologies by 2030. Together with the emerging wind turbine industry, shipping may even be a part of those ”pushing forward the science of condition monitoring and maintenance”. In order for the shipping industry to shift from today’s scheduled maintenance approach to condition-based maintenance, the development of, amongst others, smart sensors, i.e. sensors with integrated pre-processing capabilities, connectivity between ship and shore, databases and information management systems is essential (DNV GL, 2017).

2.1.3.1 Trends and Technologies Transforming Vessel Maintenance

As technology progresses, new techniques are continually emerging that can help improve maintenance in the shipping industry. For the shipping companies, it is vital to keep up with these trends and developments and not fall behind in an increasingly competitive market. In the shipping and logistics industry, ”grow or go” is the new norm according to WNS, and it is essential for companies to continuously identify opportunities to ”optimize revenues, reduce costs, improve profitability and enhance customer experience” WNS (2019a,b). Some of the trends and technologies that are believed to transform vessel maintenance are listed below and explained briefly.

Sensors: Sensor technologies are already well developed and widely used, but they are becoming increasingly more intelligent. Smart sensors, i.e. sensors with integrated pre-processing capabilities, are one of those technologies that have the potential to make maintenance more manageable, less expensive and invasive. Energy harvesting devices are also emerging, thus removing the need for cabling and batteries to power the wireless sensors. Sensors that are resilient to high temperatures and pressures are also appearing, allowing for monitoring in, e.g. engine cylinder walls, turbine blades or other abrasive locations. Another recent focus has been on how sensors can be combined to form a ”reconfigurable and collaborative network”, thus optimizing their output (Knutsen et al., 2014). Besides, by introducing artificial intelligence and machine learning, sensors can provide an even more detailed insight into ship operations and immediately alert the crew if any components need maintenance.

Increased Connectivity: IT-based technologies and solutions are playing an increasingly more important role in ship maintenance. As aforementioned, vast amounts of data will be collected and sent ashore for further data processing, and a fast broadband connection between ship and shore is essential to maximize the potential of these new solutions and technologies. The advantage of sending the data to shore is that experts and more computationally intensive analyses can be used to advice on operational measures or corrective actions that need to be taken, thus also improving the competence of the crew onboard. The lesser need for the physical presence of experts will also help reduce costs. The development of ”structures and methods for the collection, transmission, and handling of this new ’big data’” is therefore essential for the shipping industry to migrate to real-time, risk-based maintenance (Knutsen et al., 2014).

Virtual Engineering and Augmented Reality: Support services from remote control centres can be further enhanced by utilizing virtual engineering and augmented reality (AR) technologies. With this technology, the crew can interact with technical experts onshore and receive real-time advice and technical support through mobile devices and specially made goggles. As a result, a crew member or engineer does not have to be an expert in one discipline, but can rather be reasonably proficient across a range of disciplines instead. These support services are highly relevant when operations are becoming increasingly more autonomous, with less crew on board (Wingrove, 2018).

Artificial Intelligence and Machine Learning: With increased global connectivity and the advent of the Internet of Things (IoT) technology, shipping companies are gathering vast amounts of data every day, including fuel consumption, performance, weather and numerous of other variables. The big question is how to utilize these amounts of data. Machine learning (ML) algorithms are the building blocks of artificial intelligence (AI), that can prove to be important in the transition to predictive maintenance. AI is capable of crunching numbers and detects anomalies at a much higher level than us humans. Even though AI can provide beneficial results already today, humans will still play an essential role in finding the causes of the detected anomalies, according to Wärtsila (Lipsith, 2019). Among the obstacle to the uptake of AI, Texas-based AI company SparkCognition mentions the ”lack of connectivity on many ships, [...] the actual lack of sensors installed on ship equipment” and the fact that ”AI must be ’explainable’ rather than a ’black box’”, i.e. it has to show its workings and how it reaches conclusions (Lipsith, 2019).

Digital Twins: One can define a digital twin as ”a digital replica of a living or non-living physical entity. By bridging the physical and the virtual world, data is transmitted seamlessly allowing the virtual entity to exist simultaneously with the physical entity” (El Saddik, 2018). Such digital models allow for complex simulations of the ship and its systems, or even the entire ship itself. That way, anything in the model can be tested before taking any risk. Also, by feeding live data into the digital twin, one can potentially predict, and optimize, the performance and health of the vessel. In addition to operations simulation and troubleshooting, digital twins can also aid in product improvement in the design phase, as well as training of the crew and classification in the operational phase. Challenges with digital twins and predictive maintenance are related to the difficulty of precisely modelling the physical twin’s properties and any equipment changes made later on, as well as detailed information and data about equipment failure modes (Shiklo, 2018).

2.1.3.2 Stages of implementation

Considering the challenges mentioned above associated with a CBM approach, the transition towards a real-time, risk-based maintenance regime will most likely be a step-wise process. Depending on the level of ”commitment and corporal cultural changes” and will to invest in research, development and necessary infrastructure, the benefits of implementing advanced condition monitoring systems will also happen in stages. In their position paper (Knutsen et al., 2014), DNV GL list three possible stages of implementation for ship-owners wanting to shift from today’s scheduled maintenance approach to condition-based maintenance:

1. Identify the most critical failure modes of ship system and equip the relevant components with applicable sensors. The gathered data is to be analysed by onboard computers, determining whether a component should continue to operate, be inspected, overhauled, or discarded.

2. Determine the remaining useful life (RUL), and thus what kind of maintenance that should be performed and when, of components by combining statistical information about failures, physical degradation models and continuously measured parameters. This is also called prognostics. The benefit here is that the reliability of the monitored ship systems can be estimated real-time, improving availability and further reducing maintenance costs compared to the previous stages.

3. At this stage, condition-based maintenance will determine the correct amount and timing of maintenance for specific monitored components. Increased knowledge and experience with systems and failure development improves the accuracy of diagnostics and prognostics, thus providing more accurate RUL estimates. However, this requires considering asset maintainability throughout the entire design phase. At the design stage, it is also necessary to develop models of ships systems that can be used in future operations and be a part of a company’s decision support and information management system.

2.1.3.3 A Possible Future

Further in their paper, DNV GL describes a possible future for the maintenance of shipping and how it may develop until 2025, see Figure 2.4. Back in 2014, DNV GL predicted that systems to monitor onboard conditions would become more mainstream in the next decade, and that data collection from machinery would be performed on advanced ships by 2020 (e.g. offshore vessels). As of 2019, more and more shipping companies are installing condition monitoring equipment, even on vessels that can be considered less advanced, such as container vessels (Instrument, 2016).

Considering autonomy, DNV GL predicted that a prototype of a fully autonomous ship might appear as early as 2015, and that we will see fully autonomous ships by 2025. There are several such projects today, such as the container ship Yara Birkeland and DNV GL’s ReVolt. Also, the world’s first fully autonomous ferry was successfully demonstrated by Rolls-Royce and Finferries in late 2018. Furthermore, they believe that autonomous operation capabilities will become increasingly more standard on several

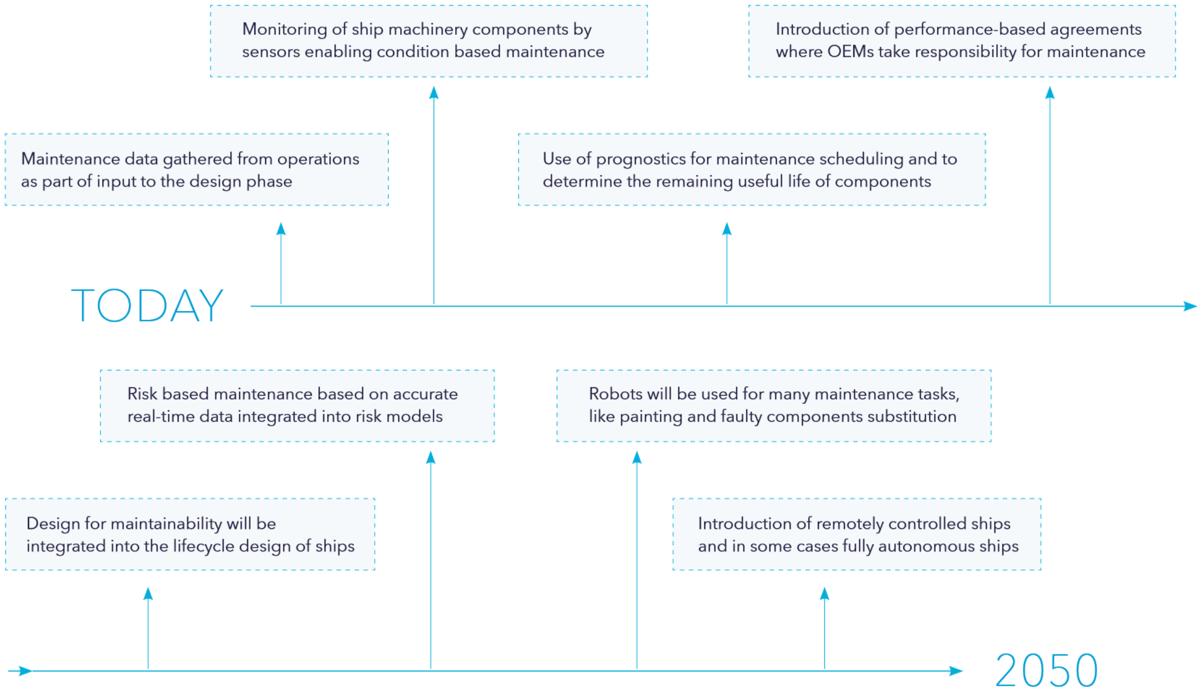


Figure 2.4: A possible future for maintenance onboard ships. From Knutsen et al. (2014).

types of ships by 2035. Combined with the development of automated systems in ports for loading and unloading of cargo, some shipping segments, e.g. container transportation may become fully automated by 2050 (DNV GL, 2014).

Among the other developments that might be expected in the future, DNV GL mentions ”collaborative software tools to enable seamless coordination between various stakeholders, onboard robots, modular designs, autonomous decision support systems, and tools for virtual operations, such as virtual surveys, virtual guidance from land-based operators” as enablers for ”safer, smarter and greener” maintenance procedures (DNV GL, 2014).

2.2 Condition-Based Maintenance

Condition-based maintenance, also known as and used interchangeably with predictive maintenance, was first introduced in 1975 to ”maximise the effectiveness of PM decision making” (Ahmad and Kamaruddin, 2012). It is the most modern and aspiring maintenance technique, there exist vast amounts of literature on the topic, and research in the area is rapidly growing (Jardine et al., 2006). According to Jardine et al. (2006), CBM can be defined as ”a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring”, consisting of three main steps: data acquisition, data processing and decision-making. Unlike previous maintenance techniques, the lifetime of an asset is measured by monitoring different parameters that can say something about its operating condition. Such parameters can, for instance, be vibration, lubricating oil, temperature or noise. The main reason for adopting such a maintenance strategy is that 99% of machinery failures are preceded by some sign indicating an impending failure (Bloch and Geitner, 1997). CBM can, therefore, help to maximise asset lifetime and further reduce downtime and maintenance costs.

Condition monitoring is the ”heart of CBM”, comprising data acquisition, processing and analysis (Campos, 2009). CM can be carried out in two ways: online or offline. These terms are often used interchangeably with continuous and periodic condition monitoring. There exist different definitions for these expressions in the literature. From now, it will be distinguished between online and offline condition monitoring. For this thesis, online condition monitoring is defined as continuous and automatic monitoring based on permanently installed measurement devices, such as vibration sensors. Thus, offline condition monitoring is defined as periodic monitoring carried out with given time intervals by the use of portable measurement devices, e.g. handheld vibration meters, where the data is downloaded and analysed at a later time (Carnero, 2005).

Several condition monitoring techniques exist, some more suitable for a certain type of equipment than others. Some of these are oil-analysis, lubricant monitoring, sound or acoustic monitoring, performance monitoring, temperature or electrical monitoring. Physical condition monitoring is also a widely used technique in many maintenance programs, focusing on the identification of physical changes of the equipment, such as cracks and corrosion. The most popular technique, however, is vibration monitoring, especially for rotating equipment (Ahmad and Kamaruddin, 2012; Barszcz, 2019; Higgs et al., 2004).

2.2.1 Vibration Monitoring

Braun et al. (1986) consider vibration analysis to be one of the two main techniques, along with lubricant analysis, for obtaining information about the internal conditions of machines, especially for rotating equipment (Hameed et al., 2009). It can, for instance, detect unbalanced rotating machinery, misalignment, damaged gear teeth, belt drive defects and damaged bearings (Lazakis et al., 2016). It is by far the most used method for condition monitoring, constituting about 58% of the total CM market (Barszcz, 2019; MarketsandMarkets Research Private Ltd., 2018).

No matter how good the condition of a machine, it generates vibrations. These vibrations can be linked to periodic events in the operation of a machine, such as rotating shafts and meshing gear teeth, or for instance fluid flow, as in for example pumps. When machine vibration increases, it is usually due to wear or deterioration or changes made to the machine or structure. A proper functioning machine has a specific vibration signature, thus allowing for fault detection by identifying changes in that signature, linking those to potential failure modes.

The recorded vibration data is compared to characteristics of vibration of ”various types of trouble” (Bloch and Geitner, 1997). Bloch and Geitner (1997) state that frequency is the key to this comparison. The frequency comparison is based on the running or rotating speed(s) of the machine or machine parts. When comparing the vibration data to the so-called baseline spectrum, i.e. vibration levels when the machine is functioning correctly, the key is to compare frequencies. The displayed frequency determines the type of fault or the source of the vibration. Different types of faults are associated with some multiple

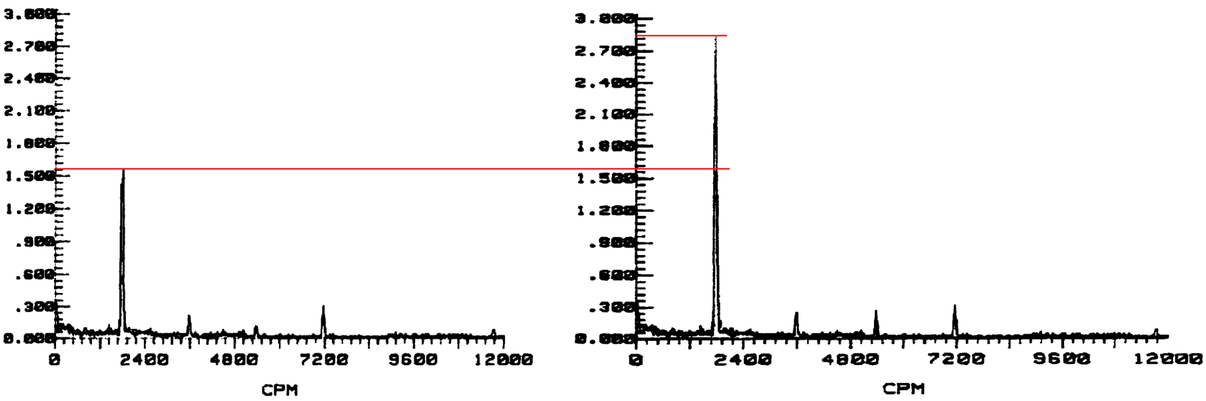


Figure 2.5: Baseline spectrum of a pump (left) and the vibration spectrum of the same pump three months later (right). From (Bloch and Geitner, 1997).

of the RPM (or running speed) of the machine. For instance, if there is an increase in amplitude at 1x running speed (i.e. the RPM of the machine) compared to the baseline spectrum, the most likely cause is an imbalance. The vibration frequency of unbalance is 1x running speed 90% of the time. If there is an increased amplitude at 2x running speed instead, there is a high chance, 60%, that misalignment is the cause (Bloch and Geitner, 1997).

Furthermore, the amplitude of the frequency determines the severity of the fault. Also, the larger the amplitude is, the closer the sensor is to the source of the fault. How to interpret the collected vibration data is shown in an example below:

Example: The vibration spectrum to the left in Figure 2.5 shows the initial vibrations of a pump, with an amplitude of magnitude 1.5 at the running speed of the pump (1x CPM, or cycles per minute). After three months, the amplitude at 1x running speed had increased significantly, to approximately 2.83, thus calling for action. As mentioned above, this indicates an unbalance in the pump. After dismantling the pump, it was discovered that a foreign object found its way through the pump and damaged the impeller blades. This changed the centre of mass and led to an unbalance. Small harmonics can also be seen at 3600 CPM (2x running speed), 5400 CPM (3x running speed) and 7200 CPM (4x running speed). These are small and were considered insignificant in this case (Bloch and Geitner, 1997).

Vibration monitoring has several advantages compared to other monitoring and analysis methods. As it reacts immediately to any change, it can be used for both online (permanent) and offline (intermittent) monitoring, as opposite to oil analysis which may take several days from sampling to the analysis is completed. Some online oil analysis systems do exist, however. The method of vibration monitoring is also more likely to pinpoint the faulty components. For example, while many bearings are made of the same metal with the same chemical composition, only the defective one will experience increased vibration (Braun et al., 1986). According to Braun et al. (1986), the most important advantage of vibration monitoring, however, is the possibility of applying multiple signal processing techniques to the vibration signals. Hence, even weak indications of faults, or developing faults, can be extracted from the signals.

Several companies have successfully used vibration analysis on rotating equipment to uncover developing machine problems, thus saving substantial amounts of money. In their paper, through different case studies, Orhan et al. (2006) investigated how vibration monitoring can be used to diagnose ball and cylindrical roller element bearing defects. In one of the case studies, a large centrifugal pump was monitored. Vibration monitoring revealed the development of ball bearing looseness, thus preventing possible damage and production loss. Renwick and Babson (1985) also describe several successful applications of vibration monitoring. One of the case studies involved ”the detection of a bearing fault in a large [...] gear reducer” in a mill. Vibration data was collected and analyzed bimonthly. The analysis suggested a bearing failure, which was confirmed upon disassembly of the reducer case, once again proving vibration monitoring to be both timely and cost-effective. Here, the cost of downtime for the mill was $2000/h, while a replacement would have cost $200 000 with a 14-month delivery time (Renwick and Babson, 1985). Another early application of vibration monitoring can be seen in (Brown, 1985). Through weekly checks conducted with a hand-held vibration meter, complemented by monthly machine-condition analysis, numerous faults were detected in rotating machinery at a nuclear power station.

2.2.1.1 Online vs Offline Monitoring

Critical machines are often continuously monitored so that they quickly can be shut down in case of the detection of a potentially disastrous failure. Even though this most likely will disrupt operation and production, the consequences of a disastrous failure are likely to result in damages causing even longer and more expensive shutdowns (Randall, 2011). In his book, Randall (2011) presents some of the most important advantages and disadvantages of online and offline condition monitoring. The advantages are:

- Sudden changes are quickly noticed, thus offering the most significant potential for maximising up-time and protecting essential and costly equipment. However, ever-decreasing sensor costs might also justify surveillance of non-critical assets.
- It is the best protection for sudden, unpredictable failures.
- Frees up working hours that can be used on, e.g. other maintenance tasks or to improve the quality of equipment.

The disadvantages of online condition monitoring, however, are:

- The cost of purchasing, installing and configuring online monitoring equipment is very high compared to offline monitoring. Therefore, it has historically been applied to critical equipment. However, ever-decreasing sensor costs might also justify surveillance of non-critical assets. Based on their own experiences, Klaveness say that the cost of online monitoring is between three to six times the price of offline monitoring. This does, however, depend on the number of components to be monitored, the number of ships, as well as any discounts one might manage to negotiate from the supplier.

- The reaction must be quick to shut down the equipment in time. Thus, online monitoring is normally based on simple parameters, e.g. overall RMS or peak vibration level. Such simple parameters do not give notice of impending failures long beforehand. This notice could be just a few hours or days, as compared to more advanced diagnostic techniques, which could give warnings weeks, or even months, in advance.

Even though online monitoring is used, it is still possible to analyse the vibration signals more thoroughly; however, not continuously. Hence, intermittent and online monitoring can be carried out in parallel. This also allows for intermittent monitoring to be carried out even more frequently, typically on a daily or weekly basis instead of once per month, or even more seldom.

For the vast majority of equipment and machines, especially those with redundancy, it might be challenging to justify the installation of online monitoring systems from a financial point of view. However, Randall state that ”the major economic benefit from condition monitoring is the potential to predict incipient failure weeks or months in advance, to be able to plan maintenance to give the minimum disruption of production, acquire replacement parts, and so on”. Hence, it might not necessarily be that important to do online monitoring. The intervals must, however, be shorter than the time required for maintenance and production planning. The advantages of offline, or intermittent, condition monitoring are:

- Substantially lower cost of monitoring equipment. Requires smaller initial expenditures (Barszcz, 2019).
- The potential to obtain warning of impending failures long before they occur through detailed signal analysis.

The disadvantages of offline condition monitoring are:

- Sudden failures causing rapid breakdowns may be missed. For equipment where unpredictable failures are likely to happen, this technique is inappropriate.
- It is not necessarily easy to decide how often measurements should be taken. One has to weigh the benefits of increased lead time to failure, the time between when a fault condition is detected and has failed, against the cost of monitoring more frequently.
- Require more labour cost in the long run, as it is manual work (Barszcz, 2019). The offline system has to be transported, measurements need to be conducted, and data has to be transferred and analyzed (Barszcz, 2019).

To sum up, online monitoring has typically been used to shut down equipment and machines if sudden changes that might lead to catastrophic failures are detected. Therefore, it has usually been used on critical and expensive assets. It is, however, based on monitoring ”simple parameters that react quickly to change”, which does not give alerts long in advance. Offline, intermittent, monitoring is used on a more significant number of machines compared to online monitoring. Here, data is gathered manually and then analyzed with advanced diagnostic techniques. It is widely used on assets where financial loss, caused by downtime and production loss, is ”the prime economic factor rather than the cost of machines themselves”.

It should be emphasized that sensor technology, diagnostic techniques and other areas within condition monitoring are improving every day. Sensors are becoming smaller, cheaper and better, and signal analysis are revealing impending failures earlier and more accurate than before, mainly thanks to developments in areas such as machine learning and big data. The main differences between online and offline condition monitoring are still the same as earlier, but the most considerable advantages and disadvantages between the two have possibly diminished over the years.

2.3 Centrifugal Purifiers in Fuel Oil Treatment Systems

This section provides an introduction to fuel oil systems, the basic principles and working of centrifugal separators on ships, as well as a more detailed description of the HFO separator (operated as a purifier) under review in this thesis; the Alfa Laval P 615 High-Speed Separator. This description includes both design and function.

2.3.1 Fuel Oil Treatment Systems

Heavy fuel oil is a by-product of crude oil refining. It is widely available and inexpensive compared to other fuel alternatives. However, it may contain different undesirable liquid and solid contaminants, such as water, dust, rust, sand and solid particles known as catalytic fines. If such contaminants are not removed before it enters the engine, it leads to a decrease in fuel oil efficiency, corrosion of internal parts and abrasive damage to engine cylinders during the combustion process. A typical fuel oil treatment system consists of the following stages (Babicz, 2008):

1. *Settling tank*. Fuel is received and delivered to settling tanks via fuel oil transfer pumps. These tanks are used for pre-treatment of fuel oil using gravity. The denser water and solids settle on the bottom where it can be drained off. A fuel oil treatment system often consists of two settling tanks. The fuel is heated to 50-60°C to speed up the process.

2. *Heater*. The fuel is drawn out by a purifier inlet pump and delivered to a thermostatically controlled heater. The temperature is raised to about 80°C before being transferred to a centrifugal purifier.

3. *Centrifugal separator*. Cleans the fuel oil by utilizing centrifugal force. In a purifier, the fuel oil is cleaned from water and solid particles, with water being discharged continuously from a separate outlet. In a clarifier, the fuel oil, which now contains little to no water, is being cleaned for finer and lighter particles that were not removed by the purifier. The separator can be operated either as a purifier or as a clarifier. Classification rules require that the fuel oil treatment system should comprise at least two separators, i.e. it has to be redundant (MARINTEK, 2016).

4. *Service tank*. When the fuel oil has gone through purification and clarification, it is pumped to a service tank, ready to be used by the engine.

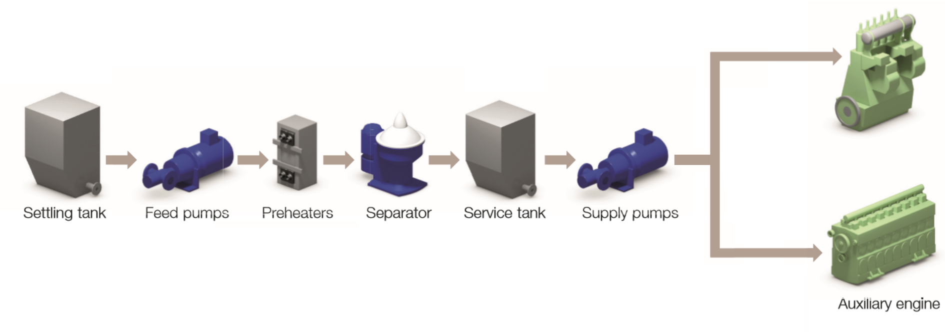


Figure 2.6: Flowchart of a generic fuel oil treatment system. Adapted from (Alfa Laval, 2018b).

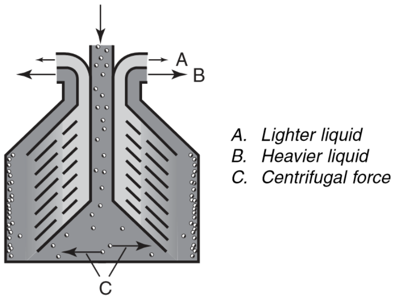


Figure 2.7: Cross section view of a centrifugal separator with gravity discs. From (Alfa Laval, 2018b).

An illustration of a generic fuel oil treatment system is depicted in Figure 2.6. A piping and instrumentation diagram (P&ID) of the fuel oil treatment system onboard one of the CABU (Caustic Soda and Bulk Carrier) combination carriers in the Klaveness fleet can be found in Appendix A.

2.3.2 Basic Principles of Separation

The purpose of separation is to remove solid particles in a liquid or separate liquids with different densities while simultaneously removing any solid particles present. This separation can be achieved either by gravity, e.g. in settling tanks, or by centrifugal separation. The latter is described here.

2.3.2.1 Centrifugal Separation

Since centrifugal force can be thousands of times greater than gravity, centrifugal separation is far more effective than separation by gravity alone. Thus, what may take several hours by gravity in a tank may be achieved within a few seconds by the centrifugal force in a separator bowl, a rapidly rotating bowl. Figure 2.7 depicts the cross section of a centrifugal separator. The efficiency of a centrifugal separator is affected by the fuel oil viscosity, temperature and throughput.

2.3.3 Design and Function

In this section, the Alfa Laval P 615 High-Speed Separator is described in more detail, based on its manual (Alfa Laval, 2018a). This separator is the one installed on Klaveness' CLEANBU ships, and not

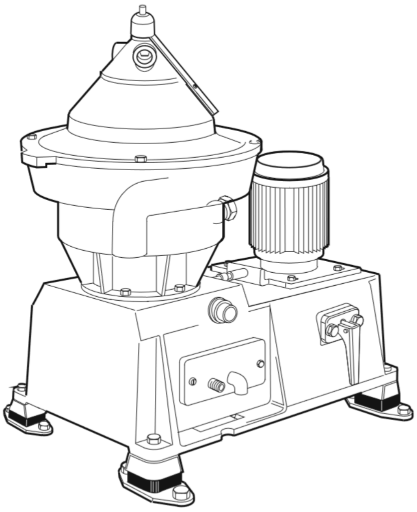


Figure 2.8: 3D model of the Alfa Laval P 615 separator. From (Alfa Laval, 2018a).

on the CABU combination carriers which were involved in the pilot project. However, this does not have any effect on the obtained results and their validity.

2.3.3.1 Application

The separator, Figure 2.8, is a high-speed centrifugal separator designed for cleaning mineral oils from water and solid particles (sludge). The cleaned oil is discharged continuously, while the sludge is discharged at intervals, ranging from 2 to 60 minutes. It is capable of handling HFO with viscosity 30-600 cSt/50°C. It can be operated as either a purifier or a clarifier. When operated as a purifier, the separated water is discharged continuously. When operated as a clarifier, i.e. there are only small amounts of water present in the fuel oil, the water is discharged together with the sludge.

2.3.3.2 Design

The separator comprises a frame consisting of three parts: the frame lower part, the intermediate part and the top part with a frame hood. The rotating separator bowl (C) is driven by an electric motor (A) via a flat-belt power transmission (D) and bowl spindle (B). See Figure 2.9. To prevent overload, the motor drive is equipped with a friction coupling.

The bowl is of the manual type, i.e. with gravity discs, and hydraulically operated at sludge discharges. The hollow bowl spindle features an impeller that pumps closing water from an integrated tank (E) to the operating system for sludge discharge.

In Figure 2.9, all main inlets and outlets, with corresponding connection numbers, are shown. These are given in chapter 7, Technical Reference, in (Alfa Laval, 2018a). The basic size drawing of the separator can also be found here.

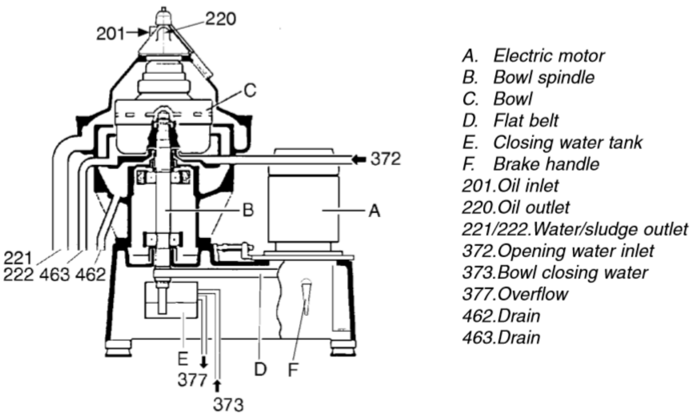


Figure 2.9: Cross section view of the P 615 separator. From (Alfa Laval, 2018a).

2.3.3.3 Outline of Function

The actual separation of the fuel oil takes place in the rotating bowl. The oil enters the bowl through the inlet (201). The clean oil is discharged from the separator through the outlet (220) via a paring chamber. Impurities heavier than the fuel oil accumulate in the sludge space at the bowl periphery. The sludge is removed automatically at fixed intervals.

2.3.3.4 Separating Function

Liquid flow As mentioned above, the untreated fuel oil enters the separator bowl through the inlet pipe (201). The oil is led towards the periphery of the bowl by the distributor (T), see Figure 2.10. When it reaches the slots of the distributor, it will rise through channels formed by the stack of discs (G) and be distributed uniformly into the disc stack.

The oil is continuously separated as it flows towards the centre of the bowl. From here, it rises upwards into the paring chamber, before being pumped by the paring disc (F), and finally leaving the bowl through the outlet (220).

Because of differences in density, sludge and water move towards the periphery of the bowl. During purification, separated water rises along the outside of the disc stack, moves from the top disc (I) channels and over the gravity disc (K), before being discharged through the common sludge and water outlet (221). Heavier impurities accumulate in the sludge space at bowl periphery, where it is discharged through the sludge ports (L) at fixed intervals.

Water seal in purification A water seal must be provided in the bowl to ensure that oil does not flow out to the separated water outlet. This seal is achieved by filling the bowl with water through the water inlet (206) before the oil feed supplying the unseparated fuel oil is turned on. When the oil feed is turned on, the oil forces the water towards the periphery of the bowl, creating an interface (X) between the water and the oil, see Figure 2.11. The position of this interface depends on the size of the gravity disc (K).

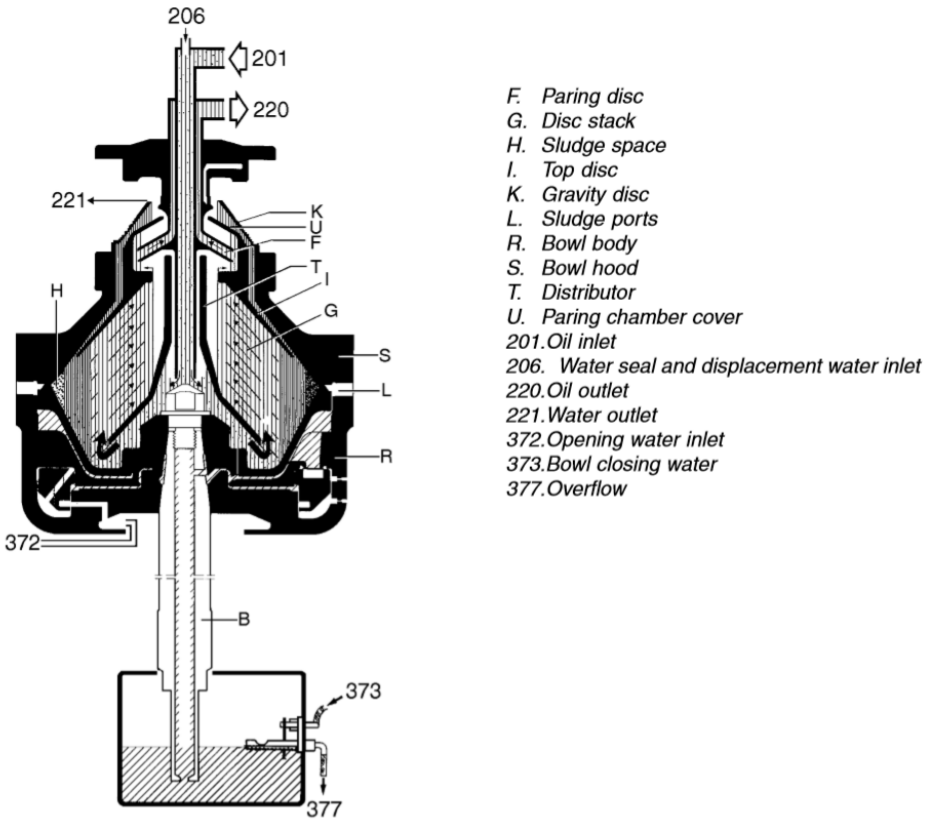


Figure 2.10: Cross section view of the P 615 separator showing the liquid flow. From (Alfa Laval, 2018a).

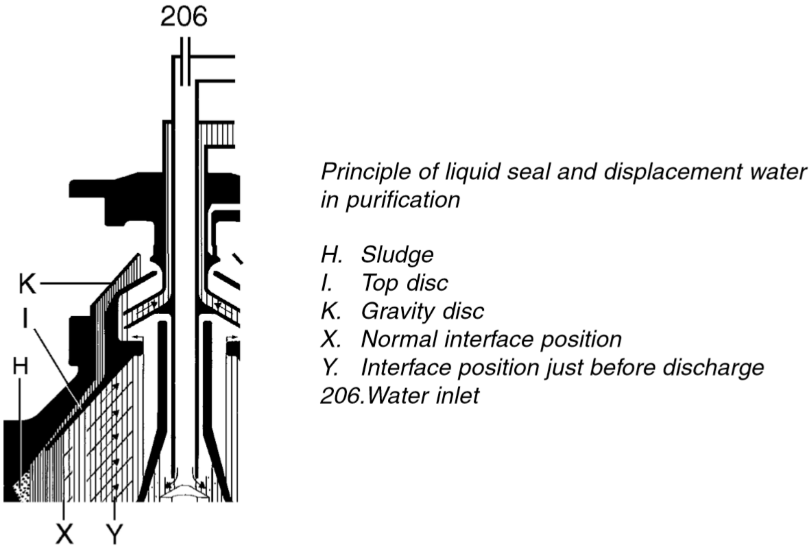


Figure 2.11: Close-up of separator cross section view. From (Alfa Laval, 2018a).

A larger gravity disc will move the interface outwards, towards the bowl periphery, while a smaller disc will move it inwards, closer to the centre of the bowl. The correct size of the is selected from a gravity disc nomogram.

Displacement of oil When discharging sludge, displacement water must be fed to the bowl to avoid losing oil. Before discharging the sludge, the oil feed is turned off, and displacement water is supplied through the water inlet (206). The increased volume of water in the bowl results in the water and oil interface being moved inwards from (X) to (Y). Then, when discharging the sludge, only sludge and water will be discharged. A new water seal is established immediately, and the oil feed is turned on again.

2.3.4 Most Common Failure Modes and Causes

There exist a large number of potential failure modes and causes for the different components in the purifier. This section aims to highlight the most common ones. This might be helpful when studying extensive FMECA's, especially if few or none of the failure modes stand out in terms of probability of occurrence or severity of consequences. The separator bowl is not included here due to the lack of literature and information available on failure modes in such bowls.

2.3.4.1 Power Transmission

Belt Drive: A belt drive consists of a belt and pulleys or sheaves, and is a simple and economical way of transmitting rotary motion from one shaft to another. According to Naval Surface Warfare Center (2012), the most common failure mode of belts is a broken belt caused by improper operating tension. Too little tension result in slippage, while too much tension results in excessive stress on both belts, bearings and shafts (Naval Surface Warfare Center, 2012). As stated by Gates Corporation (2014), improper drive maintenance, followed by improper belt or pulley installation, are the most common sources of problems with belt drives. See Figure 2.12 for a more detailed description of the most common belt drive failure causes.

Friction coupling: Couplings are used to transmit power, i.e. torque, from one shaft to another. Friction couplings are used to, for instance, protect motors against overloads. Proper maintenance and equipment handling is perhaps the most crucial factor affecting coupling lifetime. Failure rate data from Versicherungs-AG (1978), show that operational faults, i.e. mishandling, maintenance and repair faults, account for 63% of the number of damage cases of mechanical couplings. Also, 75% of all gear-coupling failures are caused by improper or insufficient lubrication (Bloch and Geitner, 1997).

Spindle: A spindle is a short shaft. See Section 2.3.4.5.

2.3.4.2 Electrical Motor

An electrical motor comprises several parts, such as bearings and shafts (see Section 2.3.4.5), windings, brushes and gears. The reliability of a motor, therefore, depends on the reliability of each part. According to Naval Surface Warfare Center (2012), the reliability of electrical motors is "usually associated with bearing life and the life of the windings before they require rewinding". The most common bearing failure modes and causes are described further in Section 2.3.4.5.

There are several studies on the distribution of failures in electrical motors. Thorsen and Dalva (1994) presents a survey of faults on induction motors (1637 failures) in the offshore oil industry, petrochemical industry, gas terminals and oil refineries. This survey is also known as the 1995 IEEE survey. The result shows that bearing faults account for more than half, 51%, of the failures, see Figure 2.14. These could be due to, e.g. insufficient lubrication, wrong lubricant, shaft overload, misalignment, vibration, or overheating. A similar failure distribution can be seen from the 1985 IEEE survey as well (O'Donnell, 1985; Bell et al., 1985; O'Donnell et al., 1987).

2.3.4.3 Inlet and Outlet

Fluid systems are connected using fluid conductors: pipes, tubing and hoses. The HFO purifier consists of both rigid inlet and outlet pipes and flexible hoses. Their most common failure modes and causes are described below. It should, however, be noted that there are many factors to consider when assessing the reliability of fluid connector systems, such as the operating environment and usage and maintenance variables, amongst others (Naval Surface Warfare Center, 2012).

Pipes: As with most fluid conductor systems, failures usually occur at or within interconnection points, e.g. fittings and flanges. These are "sensitive to installation and maintenance procedures and the inclusion

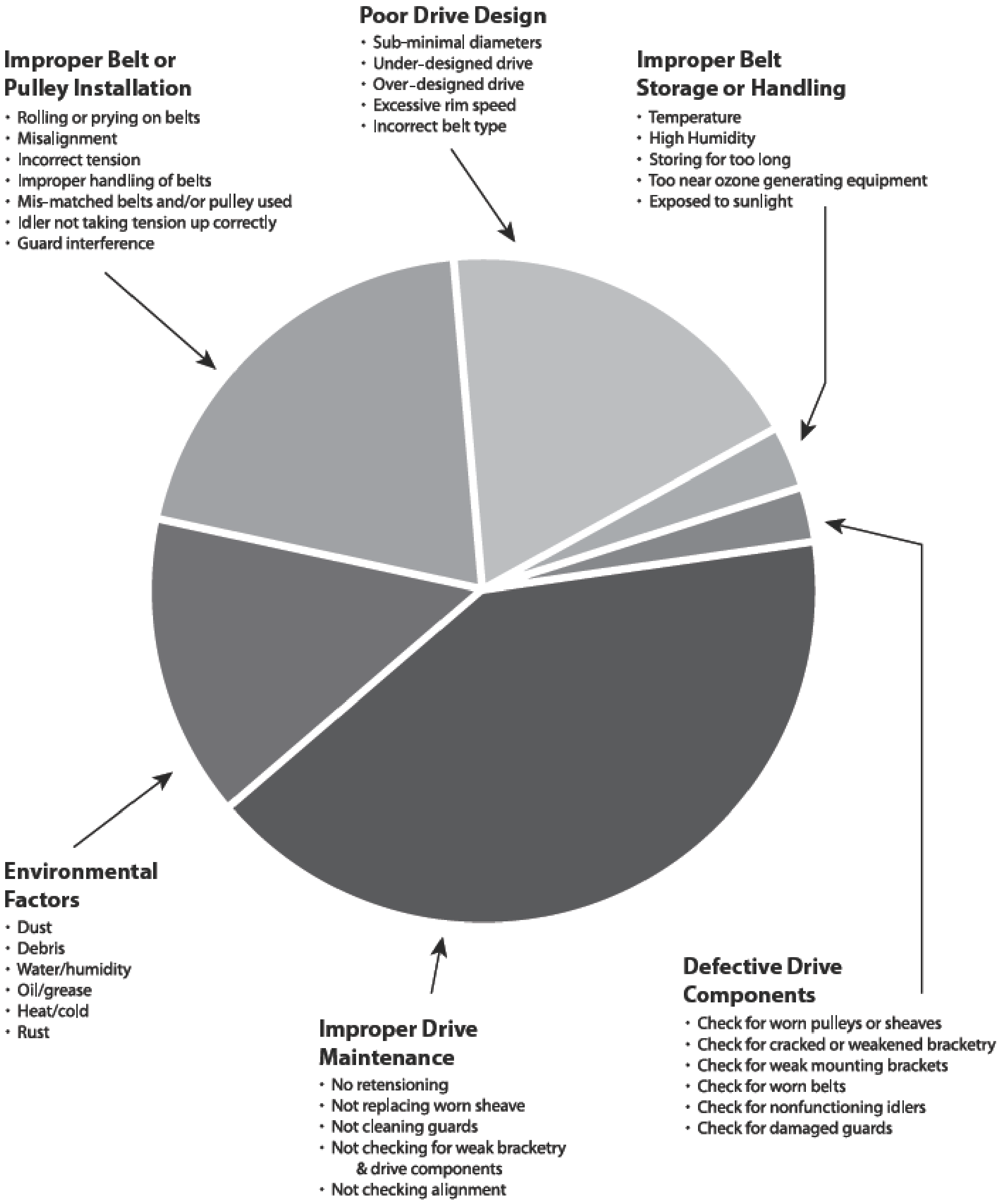


Figure 2.12: Sources of drive problems. From (Gates Corporation, 2014).

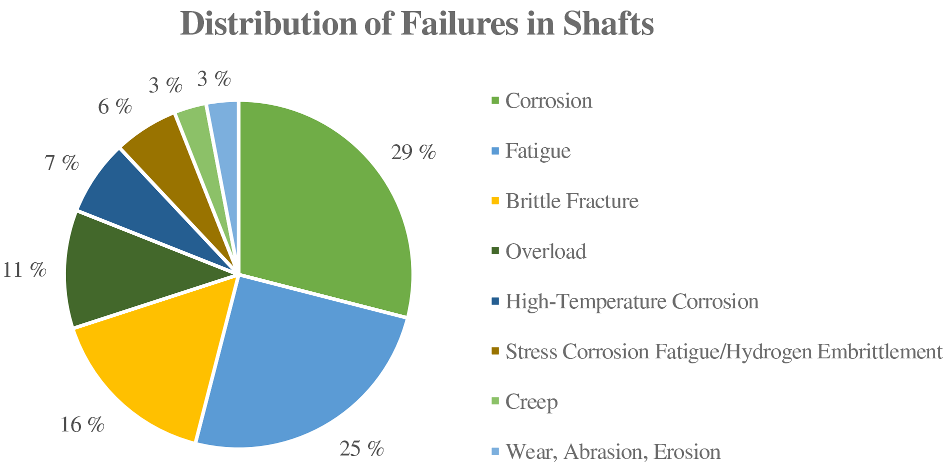


Figure 2.13: Distribution of failures in shafts. Adapted from (Sachs, 1993).

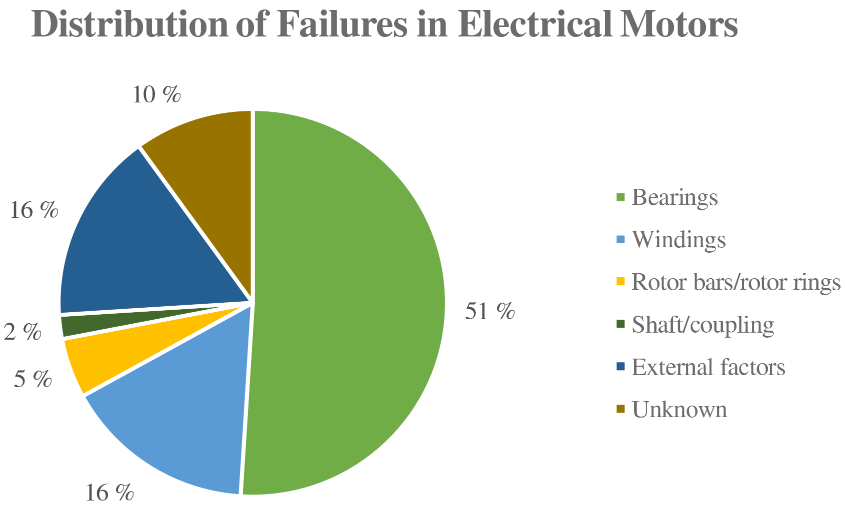


Figure 2.14: Distribution of failures in electrical motors. Adapted from (Thorsen and Dalva, 1994).

of seals" (Naval Surface Warfare Center, 2012). Connectors can be damaged due to, e.g. corrosion, improper torque on fitting (damaging the pipe threads), and failure of gaskets or seals.

Hoses: There are several reasons to why flexible hoses may fail. Naval Surface Warfare Center (2012) list the following as the most common causes of failure: violation of the minimum bend radius, operating the fluid system above maximum temperature, exposure to temperature extremes and frequent and extreme pressure fluctuations, thus accelerating the ageing and fatigue of the hose. Excessive bending and twisting of the hose will also drastically reduce its service life.

Solenoid valves: Dutch valve specialist Tameson state, based on their own experience, that the top failure modes of solenoid valves are: leaks caused by dirt particles, valve not shutting off or leaking due to damaged seals, or valve not opening and/or closing correctly as a result of inadequate power supply, wrong flow direction, too high pressure or burnt out coil. The most prominent cause, however, is tiny particles of cuttings, rust or sand, accounting for approximately 80% of the failures (Tameson, 2019).

2.3.4.4 Sensors and Controllers

Sensor and controller failures will often result in a process failure, which might have fatal consequences. Lukat (2015), divide sensor failures into four categories: (1) Manufacturing defects caused by faulty materials or poor workmanship; (2) Defects caused by premature failure in the field and covered by the manufacturer's warranty; (3) Random failures that just happen over time; (4) Field failures caused by ageing and "wear and tear". The most common, however, are failures due to wear and tear. These include mechanical damage, electric overload as a result of misconnection during inspection or repair work, and corrosion from ingress of moisture into the sensor. These failures also apply to controllers.

2.3.4.5 General

Bearings: Since there are several different types of bearings in us for a wide range of applications, it is challenging to establish base failure rates for a distinct bearing design. This problem is further enhanced by the many different bearing sizes, material properties, complexity and load capacity, amongst others (Naval Surface Warfare Center, 2012).

In Bloch and Budris (2014), it is stated that "most bearings fail at an early age because of static overload, wear, corrosion, lubricant failure, contamination, or overheating." A study by SKF USA showed that lubrication-related failures (inadequate and contaminated lubrication) account for 54% of all bearing failures, see Figure 2.15. Bloch and Budris (2014) refer to another study from an oil refinery showing similar results, see Figure 2.16.

An older study from Versicherungs-AG (1978) investigated the causes of 1400 rolling-bearing and 530 plain-bearing failures. The results can be seen in Table 2.1. Here, it is suggested that between approximately 30-40% of the failures are caused by wear- or lubrication related processes.

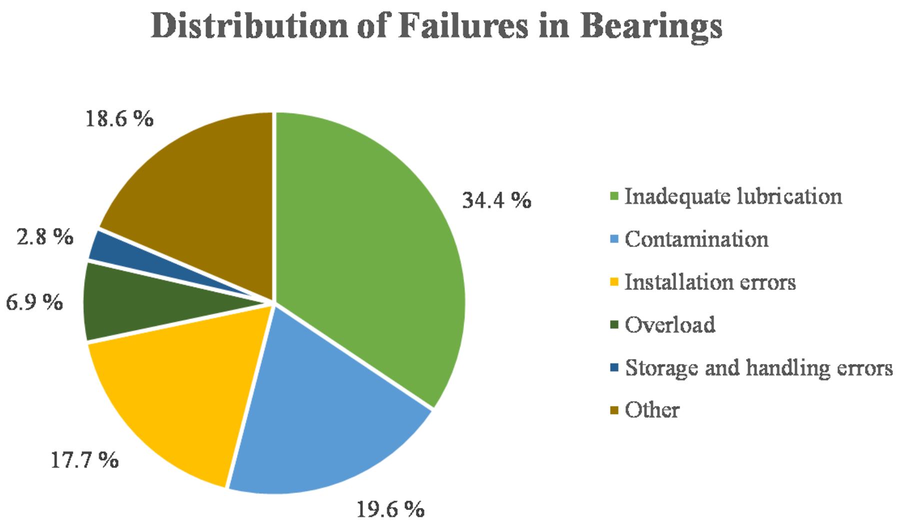


Figure 2.15: Distribution of failures in bearings. Adapted from (Bloch and Budris, 2014).

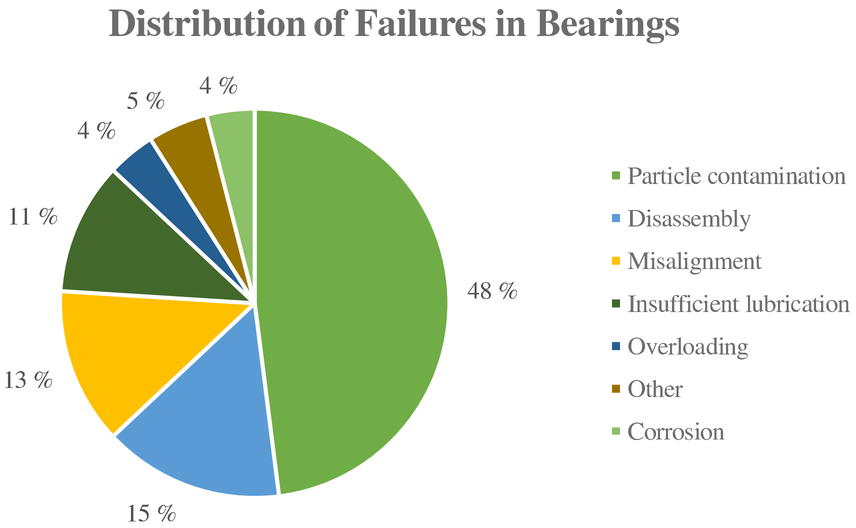


Figure 2.16: Distribution of failures in bearings in an oil refinery. Adapted from (Bloch and Budris, 2014).

Table 2.1: Failure causes of rolling and plain bearings. Adapted from (Versicherungs-AG, 1978).

Failure cause	**Rolling bearings**	**Plain bearings**
Vendor problems	30.1%	23.4%
Workmanship	14.4%	10.7%
Errors in design/application	13.8%	9.1%
Wrong material of construction	1.9%	3.6%
User-induced problems	65.9%	69.6%
Operational errors, maintenance deficiencies, failure of monitoring equipment	37.4%	39.1%
Wear	28.5%	30.5%
External problems	4.0%	7.0%
Contaminated lubricants; intermittent of oil supply system	4.0%	7.0%

Shafts: A shaft is used to transmit power or motion, in this case from the belt drive to the separator bowl. Shafts are generally designed for an infinite life, thus having a relatively low failure rate, and the effect of shaft damage on other components is often more serious (Naval Surface Warfare Center, 2012). Nevertheless, according to Raut and Raut (2014), fatigue is one of the most common causes of shaft failure. This statement is in agreement with one industry study on the cause of shaft failures in rotating machinery (Brooks and Choudhury, 1993), suggesting that 25% of failures are caused by fatigue. See Figure 2.13 for a summary of the findings. Another study for motor applications suggest that fatigue could account for more than 90% of shaft failures (Sachs, 1993). These failures do, however, include the effects of corrosion and other shaft stresses such as mechanical loads, repair processes and temperature. (Bonnett, 2000).

Seals and gaskets: A wide range of seals exist. They do, however, share some common types of failure modes, the primary one being leakage. All seals can fail as a result of different environmental influences, often a combination, such as ”temperature, pressure, fluid incompatibilities, time and human factors” (Ashby, 2005). According to Ashby (2005), another important reason for failure is that seals often are damaged during installation and maintenance.

Furthermore, Ashby state that the perhaps most well-known seal failure mode amongst elastomers is compression set, i.e. permanent deformation after prolonged stresses. The next most common type of failure is nibbling and extrusion. Another common failure mode, usually associated with O-rings, is a spiral failure. Here, the seal is sliding and rolling at the same time. This twisting causes the seal to develop cuts in a spiral pattern on its surface. Finally, normal wear is a common seal failure (Ashby, 2005).

2.3.5 Previous Studies and Analyses

To the knowledge of the author, there exist a limited amount of risk and incident analyses that focus on HFO purifiers. Some analyses that include fuel purifiers do, however, exist. Most of these are applications of the Reliability Centered Maintenance (RCM) methodology developed by Moubray, which includes Failure Modes and Effect Analysis (FMEA). The latter often include an assessment of the consequences as well, then abbreviated FMECA.

Wabakken (2015) assessed whether RCM was an applicable method to develop maintenance programs for different systems. The thesis applied the method on an engine and the auxiliary systems onboard a vessel within Wilhelmsen Ship Management's (WSM) fleet. From the FMECA analysis, purifier failure may be a result of a blockage, wear and tear, or assembly error. These failure modes were given failure rates (i.e. mean time between failure) of 10 years, five months and 1.5 years, respectively. These rates were expert opinions provided by WSM. Wabakken pointed to the potentially high cost and time-consumption caused by a failure of the purifiers as the reason for the high risk index values.

Jacobsen (2016) has also applied RCM principles in the analysis of fuel systems. The thesis aimed at establishing a procedure that can help identify barriers in the design of unmanned engine rooms for oceangoing merchant vessels. The procedure was based on the RCM methodology and applied in a case study to identify barriers in a fuel oil system using HFO. In the FMECA conducted, ”separator failure” was the only failure mode included for the purifiers. The consequences and likelihoods of failure were divided into three levels, with values from one to three, with a risk index for each combination. This division was based on a risk matrix used by shipping company Solvang ASA. The separator was considered to have moderate risk, i.e. it may be acceptable. For comparison, four components had unacceptable risk, and equally many had an acceptable risk.

A fuel oil purification system has also been used by Mokashi et al. (2002) to demonstrate the use of RCM in the maritime industry. However, the analysis does not include all failure modes for the functional failures investigated. Additionally, only the most severe consequences are considered. The failure modes shown were ”speed to slow” and ”low fuel oil temperature”, resulting in failure to remove impurities in the fuel oil and loss of liquid seal in the purifier, respectively. Based on its consequences, frequency, probability of consequences, and detection rating, the risk index of failure mode ”speed to slow” was considered unacceptable. Implementing the proposed action, consisting of an inspection of the friction pads to be undertaken every 3000 h, reduced the risk index to an acceptable level. The failure mode ”low fuel oil temperature” was denoted acceptable.

In their paper, Hadi et al. (2018) assessed the risk of the fuel oil system of a fishing vessel. Also here an FMEA was conducted. The only purifier failure mode included was blockage of the separator. Amongst the analysed items in the fuel system, this failure mode had the second highest risk index. As in (Wabakken, 2015), Hadi et al. denote the high risk index to the high cost and time-consumption that follows such failures.

Faturachman et al. (2014) has also assessed the risk associated with fuel oil systems onboard ships by applying the FMEA methodology. The only purifier failure mode looked into here was ”bad cleaning”, resulting in reduced combustion efficiency in the main engine. The severity class of the failure mode was denoted as ”critical”. In the FMEA, four failure modes were labelled ”critical”, while equally many were labelled ”catastrophic”. Only one failure mode was described as ”marginal”. Alas, it is difficult to draw any conclusions about the actual criticality of the purifier from this analysis.

Another application of FMEA on a marine engine fuel system is the one by Cicek et al. (2010). Also here, the analysis is quite limited, only considering two purifier failure modes: abnormal sound caused by defective bearings, and inadequate flow range as a result of inadequate pumping pressure or high viscous oil. Compared to the other components analysed, these failure modes obtained risk indexes in the lower range.

2.4 Failure Modes, Effect and Criticality Analysis

The purpose of this section is to describe the method used to analyse the HFO purifiers; FMECA. The objectives, issues addressed, and the methodology itself is described. Additionally, several incident reports regarding HFO purifiers across the Klaveness fleet, from 2015-2019, are analysed. However, this analysis does not follow any specific methodology. The procedure for analysing the incident reports is described in Chapter 4.

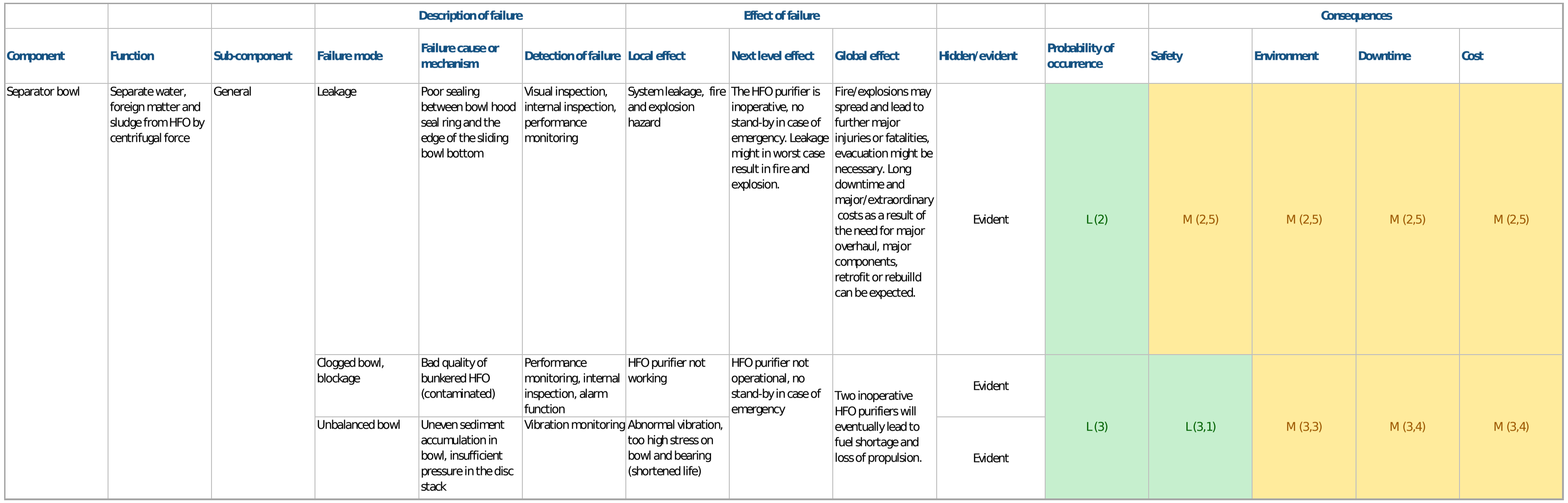
FMECA is a systematic technique for failure analysis, originally developed by the U.S. Military in the 1940s, which published the first guideline on the topic, Military Standard MIL-P-1629 ”Procedures for Performing a Failure Mode, Effects and Criticality Analysis”, on November 9, 1949 (Military, 1949). The function of an FMECA is, according to the IEEE Std. 352-2016, to ”consider each major part of the structures, systems, and components (SSC), how it may fail (the mode of failure), and what the effect of the failure on the SSC would be (the failure effect)” (IEEE, 2016). In short, the main objective of an FMECA is to highlight failure modes with relatively high probabilities and severity of consequences, thus allowing corrective actions to be directed where it will produce the highest value. As a result, an FMECA is a set of both critical and non-critical component failures. The analysis is typically organised by creating a worksheet like the one shown in Figure 2.17, which is an excerpt from the analysis conducted in this thesis. Another example of such a worksheet can be found in (Rausand and Høyland, 2004).

2.4.1 Objectives

According to IEEE Std. 352-2016 (IEEE, 2016), the objectives, or purposes, of an FMECA are to:

1. To assist in selecting design alternatives with high reliability and high safety potential during early design phases.

2. To ensure that all conceivable failure modes and their effects on the operational success of the system have been considered.



			Description of failure			Effect of failure					Consequences			
Component	Function	Sub-component	Failure mode	Failure cause or mechanism	Detection of failure	Local effect	Next level effect	Global effect	Hidden/evident	Probability of occurrence	Safety	Environment	Downtime	Cost
Separator bowl	Separate water, foreign matter and sludge from HFO by centrifugal force	General	Leakage	Poor sealing between bowl hood seal ring and the edge of the sliding bowl bottom	Visual inspection, internal inspection, performance monitoring	System leakage, fire and explosion hazard	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage might in worst case result in fire and explosion.	Fire/explosions may spread and lead to further major injuries or fatalities, evacuation might be necessary. Long downtime and major/extraordinary costs as a result of the need for major overhaul, major components, retrofit or rebuilld can be expected.	Evident	L (2)	M (2,5)	M (2,5)	M (2,5)	M (2,5)
			Clogged bowl, blockage	Bad quality of bunkered HFO (contaminated)	Performance monitoring, internal inspection, alarm function	HFO purifier not working	HFO purifier not operational, no stand-by in case of emergency	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (3)	L (3,1)	M (3,3)	M (3,4)	M (3,4)
			Unbalanced bowl	Uneven sediment accumulation in bowl, insufficient pressure in the disc stack	Vibration monitoring	Abnormal vibration, too high stress on bowl and bearing (shortened life)			Evident					

Figure 2.17: Excerpt of the FMECA conducted in this thesis.

3. To list potential failures and identify the magnitude of their effects.
4. To develop early criteria for test planning and the design of test and checkout systems.
5. To provide a basis for quantitative reliability and availability analyses.
6. To provide historical documentation for future references to aid in the analysis of field failures and consideration of design changes.
7. To provide input data for tradeoff studies.
8. To provide a basis for establishing corrective action priorities.
9. To assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, and automatic and manual override.

An FMECA is mainly a qualitative analysis and is often the first step of a systems reliability study. It is widely used in the early stages of product and system design and development to reveal design areas that have to be improved to meet specified reliability requirements. However, an FMECA include a large amount of information that is just as useful for maintenance planning and operation of the system under review. Therefore, it may be useful to integrate the FMECA into the maintenance planning system and update it as system failures and malfunctions are uncovered (Rausand and Høyland, 2004).

2.4.2 Issues Addressed

An FMECA is relatively straightforward to conduct, as it does not require any advanced analytical skills of those performing the analysis. Unlike a complete reliability analysis, that requires comprehensive data input that includes material properties, design details, and component failure rates, an FMECA can be undertaken with limited design information. As the FMECA is not ”primarily concerned with the rate of occurrence or frequency of failure”, it can still give a good indication of the reliability of the structure, system or component under review. The premise, however, is that the analyst has sufficient knowledge of the system and the environment in which it operates (IEEE, 2016; Rausand and Høyland, 2004). The basic questions the be answered by an FMECA may, according to IEEE, include:

1. How can each part conceivably fail?
2. What mechanisms might produce these modes of failure?
3. What could the effects be if the failures did occur?
4. Is the failure in the safe or unsafe direction?
5. How is the failure detected?
6. What inherent provisions are provided in the design to compensate for the failure?

2.4.3 Methodology

NEK, The Norwegian Electrotechnical Committee, distinguish between three phases when considering the activities undertaken during an FMECA: planning, performing and documenting (NEK, 2018). An overview of a generic FMECA methodology can be seen in the flowchart in Figure 2.18. It should be noted that this specific flowchart is extensive and that the activities here can be tailored to the suit the specific application.

2.4.3.1 Planning

Before conducting an FMECA, one has to go through several preparatory steps. This is done to ensure that the analysis is performed as effectively and efficiently as possible. Also, this is necessary to obtain a good result. The depth to which they are performed will depend on the complexity of the structure, system or component (SSC) being reviewed, as well as the experience and knowledge the analyst has with such, or similar, SSC (IEEE, 2016). Different standards, such as IEEE Std. 352-2016, IEC 60812:2018 and MIL-STD-1629A, as well as Rausand and Høyland (2004), all list several preparatory steps. They are not very different from one another. In the planning stage of the analysis in this thesis, a combination of the preparatory steps described by Rausand and Høyland (2004) and in IEEE (2016) was followed:

1. Definition of the system to be analyzed. Which components are within the boundaries of the system (IEEE, 2016; Rausand and Høyland, 2004).
2. Definition of the main functions (missions) of the system and its operational modes (Rausand and Høyland, 2004).
3. System breakdown into subsystems that can be handled effectively. Provide a list of components for each subsystem (Rausand and Høyland, 2004)
4. Review of system functional diagrams and drawings to determine interrelationships between the various subsystems, these could, for instance, be illustrated by block diagram.
5. Describe any operational and environmental conditions or stresses that may affect the system and its operation (IEEE, 2016; Rausand and Høyland, 2004).

Additionally, to obtain a good and useful analysis, it is essential to have sufficient information about the system. This information could, for instance, be system drawings, engineering manuals, equipment and maintenance history, and failure data, amongst others. It is, however, difficult to obtain accurate failure data. This difficulty has to do with both commercial sensitivity and the various operational profiles and continuously changing working environments for different ships. Therefore, the failure data from one ship might not be applicable for another. Furthermore, a single ship owner or company ”is not likely to have enough sample size for the data to be reliable” (Mokashi et al., 2002). As a result, FMEA’s and FMECA’s are often qualitative, or they only provide rough estimates for the failure rates to indicate the most critical failure modes.

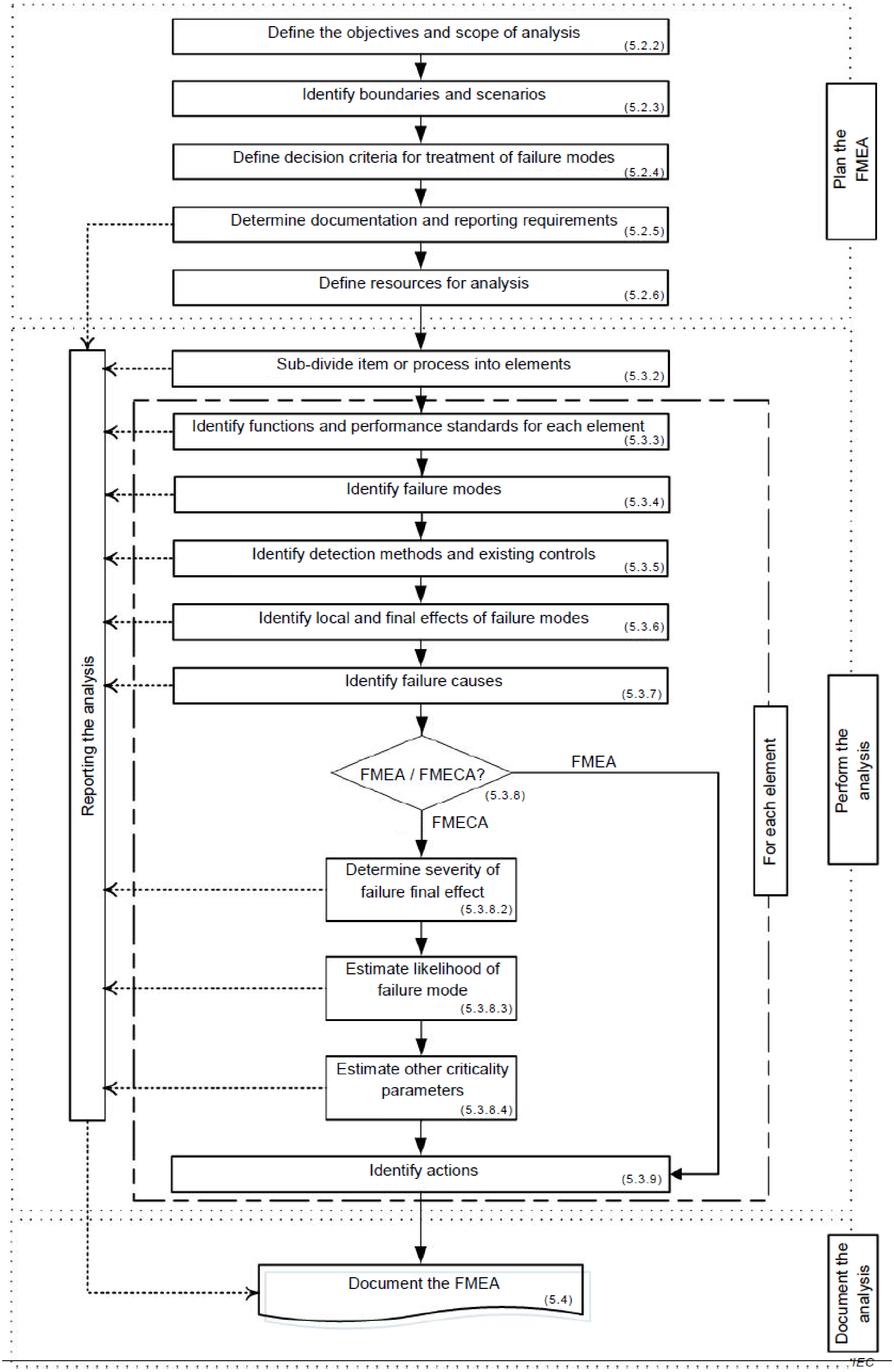


Figure 2.18: Overview of activities undertaken during the FMECA process. From (NEK, 2018)

2.4.3.2 Performing

The process of performing the actual FMECA can be seen in the flowchart in Figure 2.18, and does not require any further explanation. Each of the columns given in the worksheet in Figure 2.17 are described below (Rausand and Høyland, 2004).

Component (col. 1): The name of the component or equipment (hereafter referred to as item) being reviewed. This could, for instance, be a reference to a drawing.

Function (col. 2): The function(s) of the item(s) is (are) described.

Failure mode (col. 4): A failure mode is a nonfulfillment of the functions described in column 2. For every item's function and operational mode, all failure modes are identified and registered. The failure modes can be defined at different levels of detail. What is appropriate may vary from situation to situation. JA1011 (1999) state that it is important that ”failure modes shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy”. Also, the list of failure modes should include those that have happened before, those currently being prevented by the maintenance program, and those who have not yet but are considered not unlikely to happen (JA1011, 1999).

Failure cause or mechanism (col. 5): Here, the possible failure causes, e.g. corrosion, fatigue, excessive tension, or assembly error, that may lead to the failure modes mentioned above are recorded.

Detection of failure (col. 6): The different ways the failure modes can be detected are documented here. This may be different alarms, testing, vibration monitoring and visual observations. One distinguishes between evident failures (instantly detected when they occur) and hidden failures (usually detected only during testing).

Effect of failure (col. 7-8): Here, the effects ”if no specific task is done to anticipate, prevent, or detect the failure” is described. Also here, the level of detail can vary. It can range from local effects on the given component to global effects on the entire system, e.g. a ship or oil refinery.

Probability of occurrence (col. 9): The probability of occurrence can be given either qualitatively or quantitatively. In the absence of adequate failure data, a qualitative probability assessment is done instead. This is often based on tables describing the failure rate with words, e.g. ”very high”, ”high”, ”moderate”, ”low” and ”remote”. These occurrence categories are often further described in terms of words and associated frequency. E.g. a ”remote” is ”unlikely to happen”, with a frequency of, e.g. 1 in 1 000 000.

Hidden or evident (col. 10): It is often useful to distinguish between hidden and evident failures. Hidden failures are those that are revealed only upon demand or by functional testing. These failures are often more critical than evident failures.

Consequences (col. 11): The consequences of each failure mode are usually divided into different consequence categories. In (JA1011, 1999), it is stated that this categorization process shall clearly distinguish between events with safety and environmental consequences and those with economic consequences only. The severity of the consequences is often given on a qualitative scale, as with the probability of occurrence (col. 9). Combined with the probability of occurrence, it forms a risk index, indicating whether the risk is tolerable or not.

2.4.3.3 Documenting

An FMECA is a living document that can be used in all stages of product development, from conceptual design to data collection and maintenance planning. Therefore, it is of utmost importance that the analysis is well documented, structured and easy to understand. Otherwise, the analysis is likely to be discarded when it has served, what seems to be, its purpose - i.e. when the analysis is completed. An FMECA is typically documented in some worksheet. The worksheet shown in Figure 2.17, an extract from the analysis carried out as a part of this thesis, is one example of how an FMECA can be documented.

2.5 Incident Investigation

It is essential that incidents, including near misses and other non-conformities, are thoroughly investigated and analysed. According to Sutton (2014), incident investigation combined with the appropriate follow-up provides ”one of the most effective means of improving the safety and reliability of process analysis”. An incident analysis differs from other risk management programs like hazards analysis and management of change (MOC). While an incident analysis investigates failures that have already happened, the objective of a hazards analysis and MOC is to anticipate problems so that corrective measures can be taken before a failure occurs. Sutton (2014) list several disadvantages with such methods:

1. The analyses are theoretical and speculative, and plausible failure mechanisms and events are likely to be overlooked.
2. The actual risk level is hard to predict as the values for frequency of occurrence and consequences usually are very approximate. Also, the consequence predictions are often influenced by the analyst’s own experiences.

3. Most serious events often have multiple causes. These can be difficult to predict, and some might seem implausible, even for experienced hazards analysis teams.
4. It is difficult to predict and quantify human error, a reason for many major incidents.

Incident investigation and analysis, on the other hand, will help identify weaknesses in a company's maintenance programme and system, thus providing insight to how the system can be improved to prevent recurrence of similar incidents. Therefore, incident reports should be looked upon as a valuable resource. By analysing incident reports, one can, amongst others, gain valuable insights into the root causes of failures, improve machinery setup, minimise downtime in the future and improve maintenance programs. Well documented incidents can also aid in solving future incidents that might occur. McHatton (2017) lists four ways equipment breakdowns and incident investigations can be turned into opportunity:

1. ”Pinpoint the cause of failure to fix underlying problems.” Instead of addressing the root cause of incidents, those performing maintenance will often perform a quick fix instead. A quick fix might seem like a good solution in the short term; however, it may increase downtime in the long term. Comprehensive incident reports will help maintenance personnel better understand why the failure happened, and further help prevent the same from happening in the future.
2. ”Understand how the fault was fixed to equip yourself in future.” Detailed incident reports can help to identify and solve similar problems more quickly in the future. For instance, if someone discovers a fault that has happened before, they can look up the report and find out how the problem can be fixed, potentially saving maintenance resources in terms of time and money.
3. ”Action 'Follow-up' advice to prevent future equipment breakdown.” Follow-up advises, explaining any risks or issues that cannot be fixed immediately, should be a part of the incident report. Such advice can help fix recurring incidents once and for all.
4. ”Feed breakdown information back into improvement programs.” When a breakdown occurs, the goal is to get back to normal as fast as possible. Once the system is up and running again, it is essential that the failure is not forgotten. It is essential to ”find a way to holistically track” all incidents and non-conformities such that advice for maintenance program improvement can be given.

A proper report has to be written to maximise the potential of incident investigations. This is the final step of the investigation, and Sutton (2014) state that ”the importance of writing a good report cannot be overemphasised”. A more thorough description of incident investigation and root cause analysis can be read in Chapter 11 of ”Process Risk and Reliability Management” (Sutton, 2014).

2.5.1 Incident Report Structure

There is no correct answer as to how an incident report should be structured and what it should contain. However, an incident report should, generally, attempt to answer three questions according to Sutton

(2014):

1. What is/was the problem? I.e. what caused the failure and what were the consequences.
2. What is/was the solution? I.e. what was/has to be done to fix the failure.
3. What is the cost? I.e. what is/was the cost, considering time, money and people, of implementing the actions given in question two

An example from the industry of how an incident report could be structured is given in Section 4.2.1. An actual incident report can be seen in Appendix C.

Chapter 3

Condition Monitoring Pilot in Klaveness

In this chapter, the condition monitoring pilot initiated by Klaveness in 2018 is described in more detail. First, the short and long term benefits of implementing condition monitoring are presented, followed by Klaveness' key takeaways from the pilot project. Then, an example of how vibration analysis successfully has discovered an impending failure in an HFO purifier is given. Before the fleet-wide installation of CM equipment, Klaveness need to decide whether to opt for online or offline condition monitoring, as in the pilot. Advantages and disadvantages are presented along with their initial recommendation. Finally, incident history across the fleet is presented, followed by their proposal for which equipment to be monitored.

3.1 Background and Ambitions

The vision of Torvald Klaveness is "Improving the nature of shipping", which underpins their commitment to change and improve the shipping industry. Their ambitions are to become the leading digital bulk operator, build a global energy effective combi service and provide the most useful and intuitive digital services in shipping. Their vision and values are quantified in, amongst others, their operational targets, as seen in Figure 3.1.

Historically, maintenance in the shipping industry has been either corrective or pre-planned. I.e. after a breakdown or calendar-based, based on equipment running hours, or distance travelled, respectively. This is still the case today. However, condition-based maintenance (CBM) and predictive maintenance (PdM) is becoming increasingly more popular to increase asset reliability and decrease maintenance costs. Unlike corrective and planned maintenance, CBM and PdM are based on the measurement of different equipment parameters to decide if or when maintenance should be performed.

In 2018, Klaveness conducted a CBM pilot project on two of their combination carriers, MV Balboa (built in 2016) and MV Ballard (built in 2017). Here, offline and manual vibration monitoring equipment was installed on a considerable amount of equipment, mostly compressors, pumps and engines. The

Figure 3.1: Klaveness' operational targets.

complete list of components can be found in Appendix B. The pilot was initiated to help build knowledge and better understand the benefits and limitations of CBM and PdM, as Klaveness does not have significant experience within this area from before. They want to utilize the experience from the pilot to decide on equipment maker and scope for condition monitoring onboard their CLEANBU fleet. In the long term, they hope that this can help them move towards a more predictive maintenance regime in the future. It is also quite obvious that such a project is a step in the right direction for Klaveness to achieve its ambitions and operational goals, as presented in Figure 3.1. The benefits of such a maintenance regime is presented in Section 3.2.1 and 3.2.2.

3.2 Short and Long-Term Benefits of Condition Monitoring

3.2.1 Short Term Benefits

Before the pilot project, several short term benefits of piloting condition-based monitoring onboard two CABU2 vessels were presented, see Figure 3.2. The symbols indicate what Klaveness has done or followed up as part of the pilot project. Green is completed, yellow is unresolved and red is not completed. The benefits are elaborated below:

- **Operations Center (OC) dashboard:** The data gathered through CBM onboard the pilot vessels can be presented in the proprietary tool of the CM supplier, in this case, IKM Instrutek. The data can also be extracted through an application programming interface (API) to Klaveness' internal dashboard.
- **Digital Class development:** DNV GL has invited Klaveness to participate in developing the class of the future, "Digital Class", as a part of the Operations Center Pilot project. E.g. potential class approval of condition-based monitoring of auxiliary engines based on data analytics, which will

Figure 3.2: Short term benefits of piloting CBM on two CABU vessels.

not be possible without collecting data on the operation of the equipment onboard.

- **Vibration monitoring:** By conducting a condition-based monitoring pilot onboard a CABU, sensors can be located at critical points to monitor vibrations and the effectiveness of vibration dampers.
- **Get supplier experience before CLEANBU delivery:** The pilot is essential to get familiar with the condition monitoring equipment and its quality, the analytics solution and supplier performance. Thus, the rest of the fleet can be equipped with the best possible setup.
- **Centralized maintenance function trials in OC pilot:** One of Klaveness ambitions is to have dedicated resources onshore that monitors maintenance performance and drive continuous improvement efforts. The data gathered in the pilot can, therefore, be the starting point of a centralized maintenance function.
- **Organization increases knowledge regarding CBM:** Klaveness has no significant experience with CBM based on equipment monitoring and data analysis. Such a pilot would help build knowledge and better understand the benefits and limitations of condition-based monitoring.

3.2.2 Long Term Benefits

More and more people are seeing the benefits of being more proactive when it comes to maintenance, especially in the shipping industry. Ships usually employ a limited crew, making time and resource management an essential part of a well functioning vessel. Klaveness list the following long term benefits of implementing condition-based monitoring fleet-wide:

- **Spare part stock reduction:** By switching to a condition-based maintenance approach, spare parts can be ordered ’just-in-time’ when measurements and prognostics suggest it, thus reducing the number of spare parts and inventory cost. This is considered as ”one of the most important indirect benefits of a predictive maintenance strategy” (Van Horenbeek et al., 2013).
- **Enabler of data analytics and machine learning:** Data analytics is an essential focus for Klaveness going forward, especially when considering their ambition to become the leading digital bulk

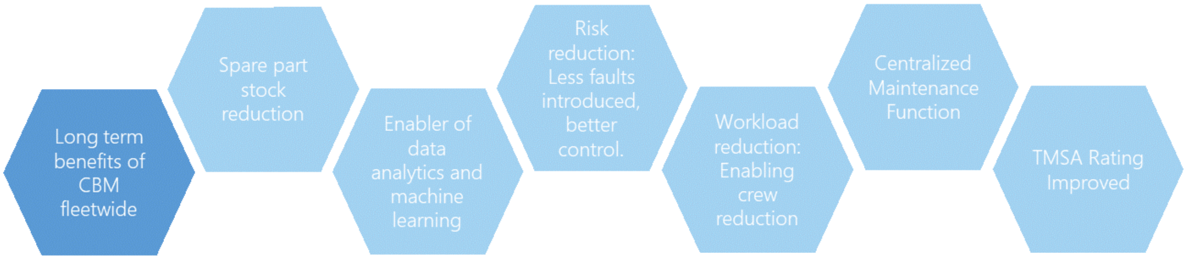


Figure 3.3: Long term benefits of condition-based monitoring fleet-wide in Klaveness.

operator and provide the most useful and intuitive digital services in shipping. Data availability will also be critical to enable vessels to be enrolled to ”Digital Class”. The overall ambition is to class vessels based on data, with as little physical presence as possible.

- **Risk reduction and better control with less fault introduced:** There is an inherent risk of introducing new faults into the system and components being maintained (Nowlan and Heap, 1978; Selvik and Aven, 2011). Condition monitoring will increase the quality of periodic condition control and, hopefully, help to uncover mistakes in maintenance at an early stage. This will likely reduce the number of breakdowns and the general risk level onboard (Mobley, 2002; Shin and Jun, 2015).

- **Enabling crew reduction through workload reduction:** Unnecessary breakdowns and overhauls can be eliminated by implementing a condition monitoring programme. Thus, valuable labour hours can be freed and enable crew reduction (Sundberg and Ab, 2003). Klaveness considers it difficult to reduce the workload and the number of crews without changing the maintenance strategy to condition-based.

- **Centralized maintenance Function:** Another of Klaveness’ ambitions is to have dedicated resources onshore that monitors maintenance performance, drive continuous improvement efforts and shift the mindset from reactive to proactive. Condition monitoring equipment will be important, if not essential, tool to improve the information and documentation that a centralized function will utilize to make optimal maintenance decisions.

- **TMSA rating improved:** ”The Tanker Management and Self Assessment (TMSA) programme provide companies with a means to improve and measure their safety management systems” (Oil Companies International Marine Forum, 2019). The TMSA rating of Klaveness Ship Management (KSM) will be an important parameter that customers will focus on going forward. Condition Monitoring is required to achieve level 4 in the subject of Vessel Reliability and Maintenance.

3.3 Condition Monitoring Pilot on MV Balboa and MV Ballard

3.3.1 Key Takeaways

The CM pilot project has provided Klaveness' with valuable knowledge and experience before installing condition monitoring equipment on eligible vessels throughout their fleet. Their key takeaways from the pilot are presented below:

- Manual/offline monitoring of condition introduces new challenges. Each ship needs to be followed up from ashore to ensure monitoring is being done as intended. Handover between the crew is critical, and one must ensure that there are procedures in place for this. Also, proper monitoring depends on the motivation and competence of selected personnel.
- Manual/offline monitoring somewhat contradicts the ambition of doubling the capacity of personnel onboard and onshore. Annual time spent doing measurements onboard is approximately 120 hours, and there is follow-up requirement on personnel ashore to ensure measurements are done correctly.
- It is an entirely new experience for Klaveness to have an updated and objective overview of the condition of a wide range of equipment onboard. Given that the stated condition is correct, which needs to be verified going forward, this introduces a new level of control. Also, the ships need clear instructions on what to report when overhauls are carried out on equipment that has been identified as in various stages of breakdown. This is to compare CM analysis with the observed condition of the equipment.
- Data transfer from ship to shore is a very manual process where the monitoring device needs to be connected to the Master's laptop to carry out the transfer. Vessels report that this procedure has failed several times. This does, however, seem to be working satisfactorily after the monitoring routes were divided into six.
- Condition monitoring has been implemented in the PMS of the two pilot vessels. This will then enable them to remove the regular condition checks based on sound/visual. Going forward, it is a recommendation to start increasing maintenance intervals of the monitored equipment – with a target of reducing the number of maintenance labour hours.
- It is too early to claim that the pilot has demonstrated the ability to prevent breakdowns; however, the main SW (sea water) pump on MV Balboa has shown early signs of failure and needs to be monitored closely. Going forward, vessels should be required to carry out vibration measurements following each overhaul to pick up any failures introduced as a result of poor maintenance.

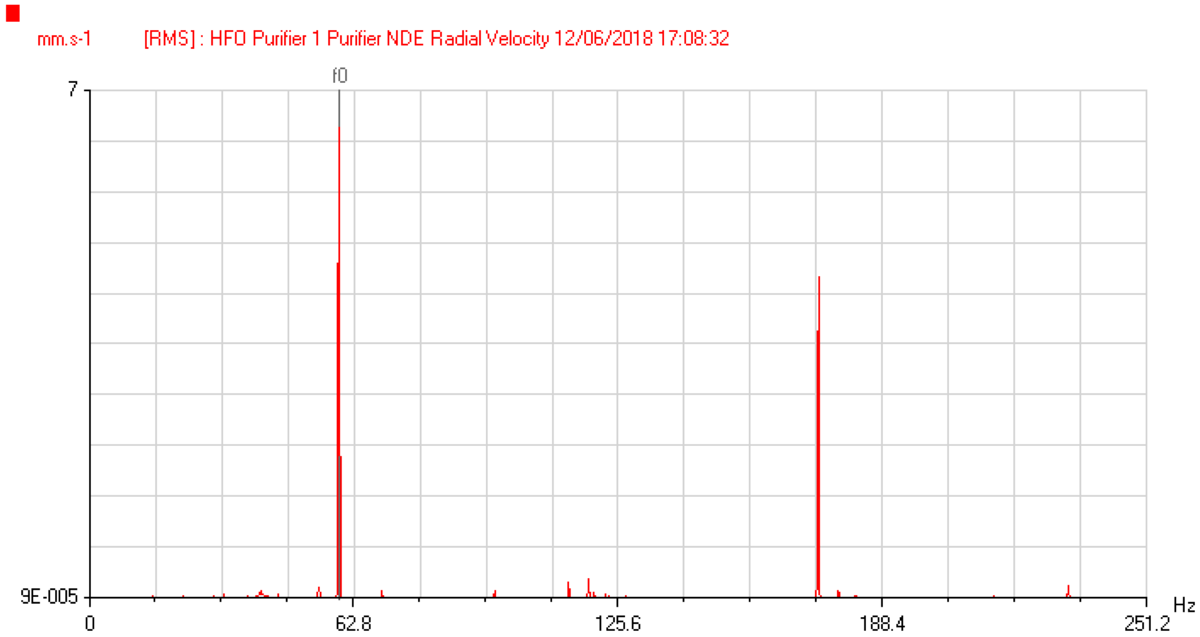


Figure 3.4: Velocity spectrum, 12.06.2018, on the non drive end (NDE) of the Electric Motor of the Purifier.

3.3.2 Vibration Analysis Example

During June 2018, IKM Instrutek ASA implemented an offline CM system on various rotating equipment onboard MV Ballard. This implementation included the two HFO purifiers, both equipped with five measuring points: two on the electric motor and three on the separator. The baseline report, which contains the analysis from the baseline measurements acquired by the MV Ballard crew, indicated unbalance in one of the purifiers. The velocity spectrum can be seen in Figure 3.4.

High overall velocity, 8.04 mm/s RMS (root-mean-square) at running speed, on the non-drive end (NDE) of the electric motor, can be seen in Figure 3.4. The analysis from IKM shows an increased amplitude at 1x running speed, marked ”f0” in the figure, at a frequency of approximately 60 Hz. Typically, this indicates an unbalance in the unit. Another peak can also be seen at around 170 Hz. Based on the analysis, the purifier was given status as a stage 1 defect: an early stage of a defect. According to IKM’s severity chart, this represents ”an initial condition or change in condition that can develop to a defect over time”. Usually, no action is needed, and the development of the defect is further monitored. However, in this case, IKM recommended to check its foundation, tighten bolts, check for looseness over the whole unit, and also clean the fan blades on the NDE of the electric motor as a first measure.

New vibration measurements were performed in December 2018, and the analysis showed decreased overall velocity levels on the NDE of the electric motor. It was concluded that the levels had normalized. See Figure 3.5 for a comparison between the two measurements.

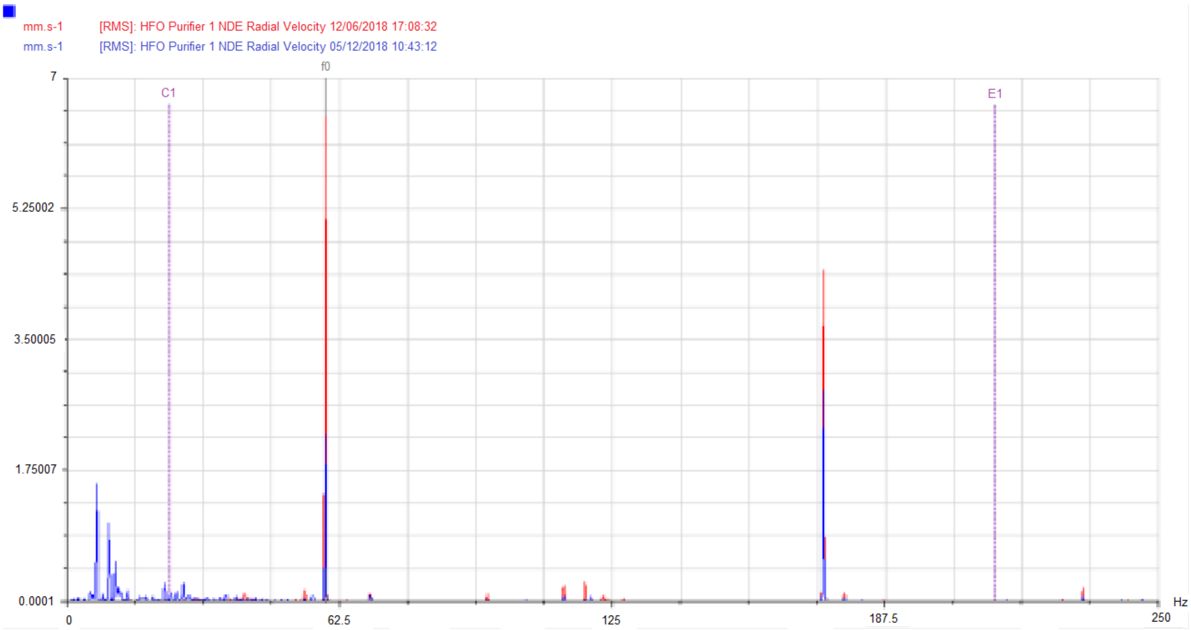


Figure 3.5: Velocity spectrum on the non drive end (NDE) of the Electric Motor of the Purifier. Red: 12.06.2018, Blue: 05.12.2018.

3.4 Offline or Online Condition Monitoring

As aforementioned, the pilot project utilised offline and manual vibration monitoring equipment. An important decision is, therefore, whether to continue with offline monitoring or to proceed with real-time online monitoring instead. Advantages and disadvantages of the two methods are described in Section 2.2.1.1. Additionally, through the pilot, Klaveness has gained valuable knowledge and experiences that speak both for and against offline condition monitoring.

One of the best arguments for implementing offline monitoring in the entire fleet is the relatively low installation cost. Furthermore, the regularity of offline monitoring increases the experience and understanding of the normal condition of the monitored assets. Also, Klaveness believe that this results in higher crew awareness and knowledge of vibration monitoring, as opposed to online monitoring. However, this requires proper handover routines. On the other hand, offline monitoring has proved to be a tedious job. Klaveness estimate that between 60-120 hours will be spent doing measurements onboard annually. The fact that the crew onboard needs to manually conduct uploads also contributes to making it a time-consuming job. The pilot has also shown that uploading of data has tended to fail. Problems with uploading data can, of course, also occur with online monitoring equipment. Moreover, there will also be follow-up work on personnel ashore to ensure that measurements are done correctly, further increasing the number of labour hours spent on monitoring.

Another disadvantage with implementing offline monitoring is that the crew needs to be certified if one wants to obtain a CM notation from a classification society, e.g. DNV GL, thus increasing the cost of implementation. Also, this certification has to be coordinated by the crewing department.

Real-time online monitoring, on the contrary, avoids many of the problems associated with offline monitoring. Foremost, the workload on both crew and shore personnel are drastically reduced, thus freeing up a substantial amount of work hours. This might also justify the higher installation costs compared to offline monitoring. The continuous data flow from ship to shore should also eliminate the problems experienced with manual uploading of data. Secondly, there is no certification requirement for the crew if one wants to obtain a CM notation. Another essential point is that this is the most ”Future Operations” compatible solution, i.e. the solution that will take Klaveness the furthest concerning reaching their ambitions to reduce OPEX with 30% and double the capacity of personnel onboard and onshore.

After conducting the pilot and assessing the advantages and disadvantages of the two methods, there is a strong recommendation for online condition monitoring, pending cost considerations.

3.5 Klaveness’ Proposal for Equipment To Be Monitored

After the pilot period, a qualitative review of the equipment monitored was conducted to evaluate where condition monitoring would add value when being installed on eligible vessels in the fleet. The selection of equipment to be monitored or not can be seen in Table 3.1. The total number of monitored components will be more than halved, from 56 to 27. The decision not to install monitoring equipment on much of the machinery is based on a high-level analysis of incidents that partly support this decision. It is based on the criticality of the system for the operation of the ship, whether it is redundant or not, how expensive unexpected failures might be and if they could have been detected by vibration monitoring, or the size of the equipment (e.g. only fans over a certain number of kW will be monitored). Not at least, the incident history of the equipment has been an important factor. See Section 3.5.1 for a summary of the incident history across the fleet.

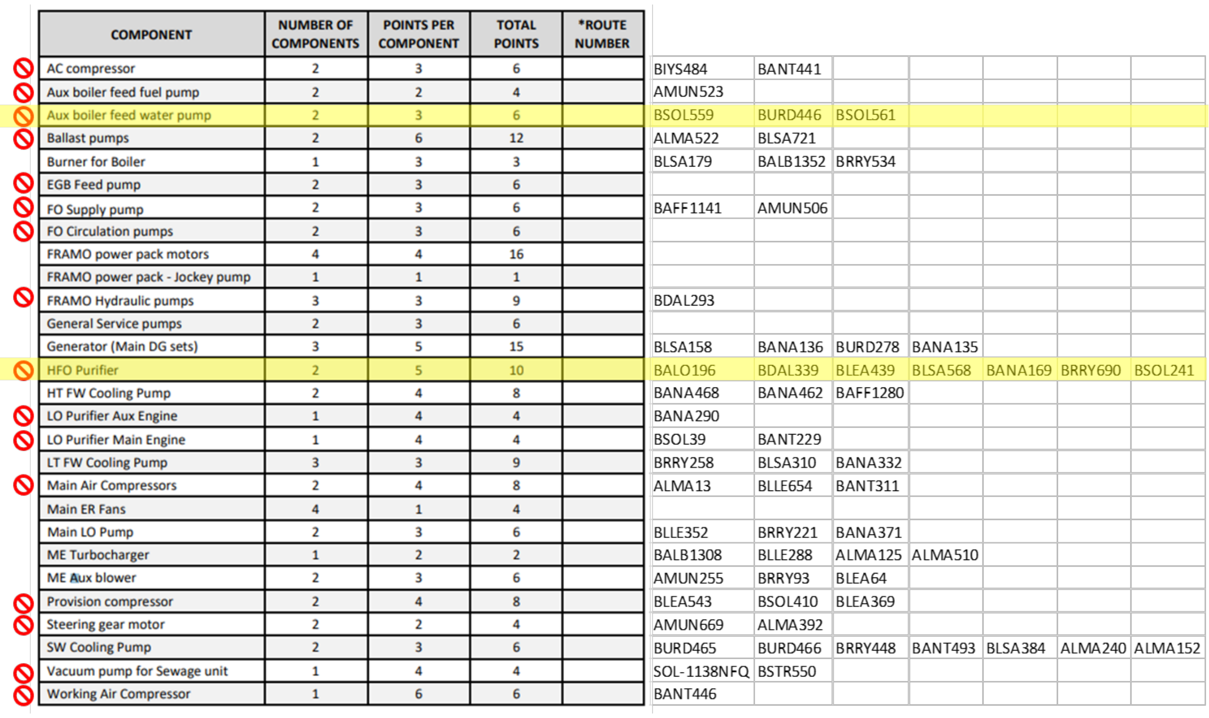
The most significant change was to remove the hydraulic FRAMO pumps for cargo, ballast and slop from the scope. These were never fitted with sensors as it was necessary to install a junction box on deck. Furthermore, they are monitored through regular hydraulic oil analysis, which the manufacturer of the pumps, FRAMO, consider being sufficient. Also, they do not recommend vibration monitoring for these pumps.

3.5.1 Incident History Across the Fleet

Looking through the incident history of HFO purifiers across the fleet, Klaveness has put together a list of some of the breakdowns and failures that might have been detected by vibration monitoring, see Figure 3.6. It is important to note that this list should not be considered a complete overview of all breakdowns and failures across the fleet. An incident plot can also be seen in Figure 3.7, depicting incidents that were ’likely’ (orange) or ’very likely’ (green) to be discovered by vibration monitoring. The plot is based on the list in Figure 3.5.1, but it is updated and slightly changed. It needs to be pointed out that the expenses, given in brackets, only account for the cost of spare parts. It does not include any other costs associated

Table 3.1: Equipment covered in the pilot project (Component column) and equipment proposed for fleet-wide installation (Monitor column).

Component	**Units**	**Monitor**	**Not Monitor**
AC Compressor	2		✗
Aux Boiler Feed Fuel Pump	2		✗
Aux Boiler Feed Water Pump	2		✗
Ballast Pumps	2		✗
Burner for boiler	1	✓	
EGB Feed Pump	2		✗
FO Supply Pump	2		✗
FO Circulation Pumps	2		✗
FRAMO Power Pack Motors	4	✓	
FRAMO Power Pack Jockey Pump	1	✓	
FRAMO Hydraulic Pumps	3		✗
General Service Pumps	2	✓	
Generator (Main DG sets)	3	✓	
HFO Purifier	2		✗
HT FW Cooling Pump	2	✓	
LO Purifier Aux Engine	1		✗
LO Purifier Main Engine	1		✗
LT FW Cooling Pump	3	✓	
Main Air Compressors	2		✗
Main ER Fans	4	✓	
Main LO Pump	2	✓	
ME Turbocharger	1	✓	
ME Aux Blower	2	✓	
Provision Compressor	2		✗
Steering Gear Motor	2		✗
SW Cooling Pump	2	✓	
Vacuum Pump for Sewage Unit	1		✗
Working Air Compressor	1		✗
Total	56	27	29



	COMPONENT	NUMBER OF COMPONENTS	POINTS PER COMPONENT	TOTAL POINTS	*ROUTE NUMBER							
🚫	AC compressor	2	3	6		BIYS484	BANT441					
🚫	Aux boiler feed fuel pump	2	2	4		AMUN523						
🚫	Aux boiler feed water pump	2	3	6		BSOL559	BURD446	BSOL561				
🚫	Ballast pumps	2	6	12		ALMA522	BLSA721					
	Burner for Boiler	1	3	3		BLSA179	BALB1352	BRRY534				
🚫	EGB Feed pump	2	3	6								
🚫	FO Supply pump	2	3	6		BAFF1141	AMUN506					
🚫	FO Circulation pumps	2	3	6								
	FRAMO power pack motors	4	4	16								
	FRAMO power pack - Jockey pump	1	1	1								
🚫	FRAMO Hydraulic pumps	3	3	9		BDAL293						
	General Service pumps	2	3	6								
	Generator (Main DG sets)	3	5	15		BLSA158	BANA136	BURD278	BANA135			
🚫	HFO Purifier	2	5	10		BALO196	BDAL339	BLEA439	BLSA568	BANA169	BRRY690	BSOL241
	HT FW Cooling Pump	2	4	8		BANA468	BANA462	BAFF1280				
🚫	LO Purifier Aux Engine	1	4	4		BANA290						
🚫	LO Purifier Main Engine	1	4	4		BSOL39	BANT229					
	LT FW Cooling Pump	3	3	9		BRRY258	BLSA310	BANA332				
🚫	Main Air Compressors	2	4	8		ALMA13	BLLE654	BANT311				
	Main ER Fans	4	1	4								
	Main LO Pump	2	3	6		BLLE352	BRRY221	BANA371				
	ME Turbocharger	1	2	2		BALB1308	BLLE288	ALMA125	ALMA510			
	ME Aux blower	2	3	6		AMUN255	BRRY93	BLEA64				
🚫	Provision compressor	2	4	8		BLEA543	BSOL410	BLEA369				
🚫	Steering gear motor	2	2	4		AMUN669	ALMA392					
	SW Cooling Pump	2	3	6		BURD465	BURD466	BRRY448	BANT493	BLSA384	ALMA240	ALMA152
🚫	Vacuum pump for Sewage unit	1	4	4		SOL-1138NFQ	BSTR550					
🚫	Working Air Compressor	1	6	6		BANT446						

Figure 3.6: List of equipment and incidents that might have been detected by vibration monitoring. The highlighted equipment should be reconsidered. The red symbol indicates equipment that will not have vibration monitoring equipment installed.

with the incident, such as any labour hours spent investigating the cause of the incident, ordering of necessary spare parts, carrying out the actual maintenance or possible downtime or off-hire.

As can be seen from Figure 3.6 and 3.7 above, it has been decided not to install vibration monitoring equipment on the 'Auxiliary boiler feed water pump' and 'HFO Purifier'. However, of the equipment not to be monitored, these two are among those with the most failures that potentially could have been discovered by vibration monitoring, with three and seven incidents, respectively. When having a closer look at the equipment list versus incidents, Klaveness believes that they should reconsider removing the 'Auxiliary boiler feed water pump' and 'HFO Purifier'. For instance, looking at the list, the purifiers have had just as many incidents that could have been discovered as the 'SW Cooling Pump', which will be monitored in the future. Based on its history of incidents that could have been avoided, and the importance of the purifiers in the fuel oil treatment system, the thesis will focus on the HFO purifiers and whether it would be beneficial to equip them with vibration monitoring equipment.

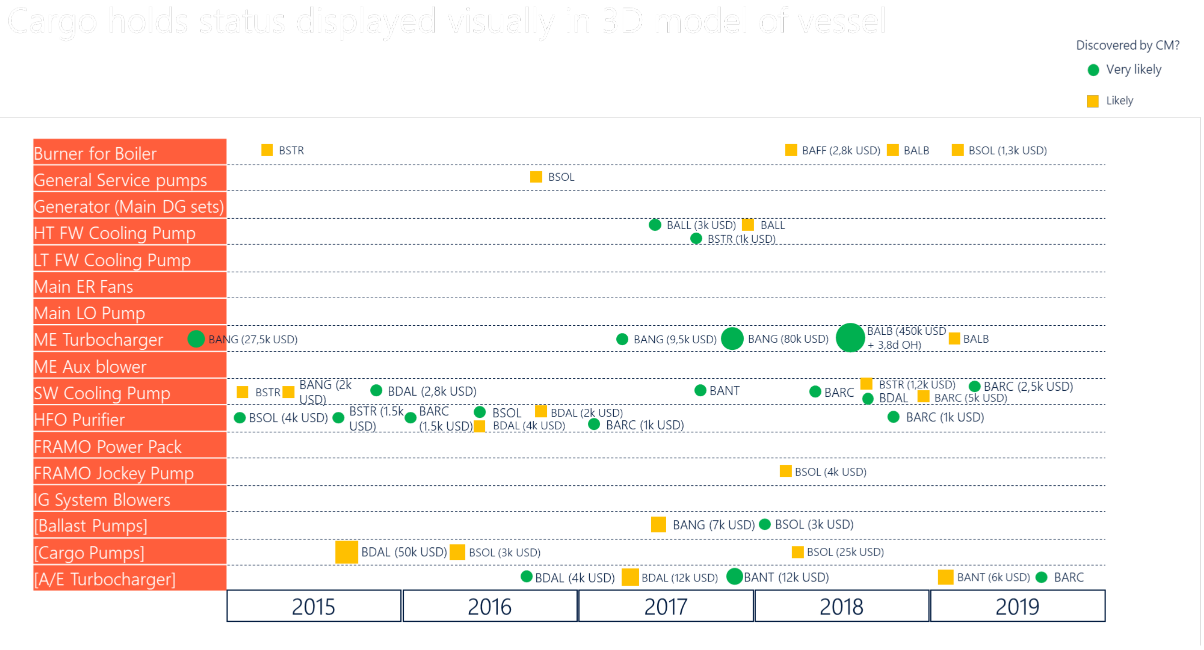


Figure 3.7: Incident history plot, from 2015-2019, of equipment proposed for vibration monitoring.

Chapter 4

Method

The purpose of this chapter is to describe how the analyses of the HFO purifiers and associated incident reports were conducted. First, the process of the Failure Modes, Effects and Criticality Analysis (FMECA) is described, followed by a description of how the incident reports were analysed. The FMECA analysis was carried out in parallel with the incident report analysis, which provided valuable input to the FMECA, especially in terms of failure modes.

4.1 Failure Modes, Effect and Criticality Analysis

The analysis is carried out step by step, as described in Section 2.4. It consists of three parts, namely planning, performing and documenting.

4.1.1 Planning

A satisfactory result of an FMECA is the product of thorough preparations. As described in Section 2.4, the preparatory steps listed below were undertaken. Before this, all the necessary information and data was collected. From Klaveness the author received: P&ID for the fuel oil purifying system; engineering manual for the Alfa Laval P 615 separator; fifty incident reports from twelve ships in their fleet; condition monitoring reports for the two pilot ships from their monitoring equipment supplier IKM Instrutek; PowerPoint presentation of the condition monitoring pilot evaluation.

Step 1: Definition of the system to be analyzed. Which components are within the boundaries of the system.

A fuel oil treatment system consists of several components, further described in Section 2.3.1: settling tanks, feed pumps, pre-heaters, separators, service tanks, supply pumps and finally main and auxiliary engines. In this thesis, the analysis focuses solely on the HFO purifier, i.e. the separator. The system boundaries are drawn as depicted in Figure 4.1.

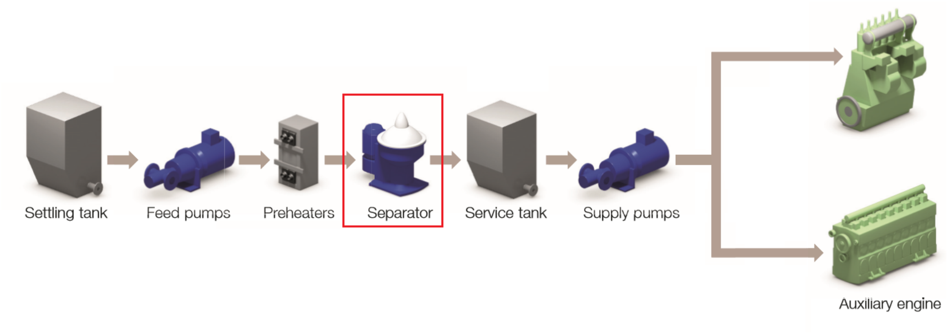


Figure 4.1: System boundaries (red) for the analysis of the HFO purifiers. Adapted from (Alfa Laval, 2018a).

Step 2: Definition of the main functions (missions) of the system and its operational modes.

The function of the HFO purifier is to separate undesirable liquid and solid contaminants, such as water, dust and catalytic fines, from the heavy fuel oil. This is done using centrifugal force. The design and functions of the separator are described in more detail in Section 2.3.3.

The fuel oil treatment consists of two purifiers, as classification societies like DNV GL require that the system should be redundant. In the systems studied, one separator is operated continuously while the other is in standby. If the fuel is not properly treated, the engine may be severely damaged or destroyed.

Step 3: System breakdown into subsystems that can be handled effectively. Provide a list of components for each subsystem.

The purifier can be divided into several subsystems. This division was done based on the separator's engineering manual (Alfa Laval, 2018a) and the incident reports. The subsystems and their functions (italic), as well as their sub-components, are listed below. It should be noted that the subsystems include, but are not limited to, these sub-components. The sub-components included in the analysis are those considered to be the main ones of the different subsystems. For the separator bowl and its sub-components, it is referred to the engineering manual (Alfa Laval, 2018a).

- **Electrical motor:** *Drive the separator via a belt power transmission.*

  Components: Rotor, stator, bearings, shaft, windings and brushes.

- **Power transmission:** *Transmit power between the electric motor and the separator.*

  Components: Belt, bowl spindle and friction coupling.

- **Inlet and outlet:** *Feed untreated fuel oil to and discharge treated oil from the separator bowl.*

  Components: Pipes, hoses and solenoid valve (sensor block).

- **Controller and sensors:** *Controlling and monitor the operation of the separator, perform all* *necessary alarm functions.*

Components: Central Processing Unit (CPU), speed, temperature and pressure transmitter.

- **Separator bowl:** *Separate water, foreign matter and sludge from HFO by centrifugal force.*

  Components: Bowl and gravity discs.

Step 4: Review of system functional diagrams and drawings to determine interrelationships between the various subsystems, these could, for instance, be illustrated by block diagrams.

A functional block diagram was created based on the abovementioned subsystem division and the P&ID of the fuel oil purifying system given in Appendix A, see Figure 4.2. Since the in- and outlet only consist of piping, hoses and valves, they are not represented by blocks in the functional block diagram depicted in Figure 4.2. Instead, the inlet is represented by the line ”unprocessed oil”, while the outlet is given as ”clean oil to service tank”. Furthermore, the controller supervises the entire operation of the system, performing monitoring, control, and alarm functions.

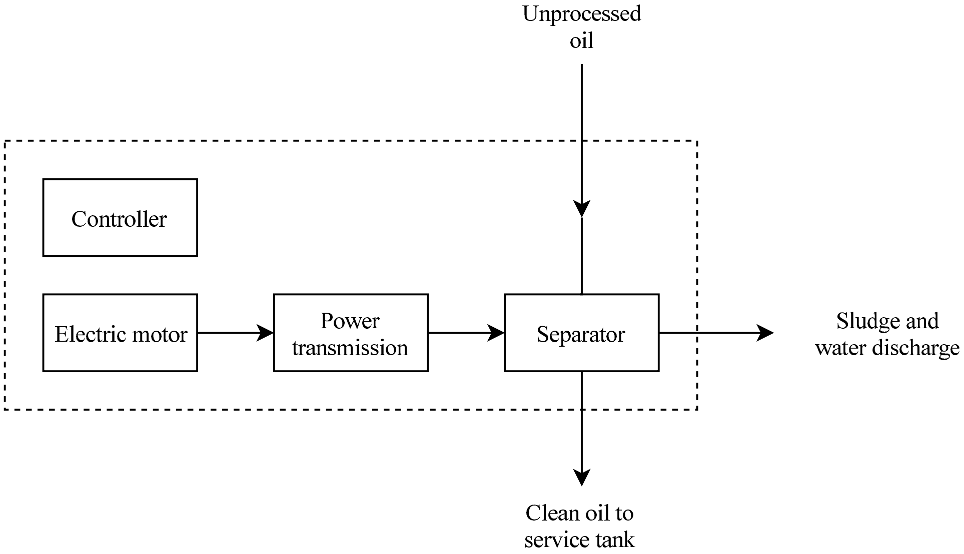


Figure 4.2: Functional block diagram of the HFO purifier.

Step 5: Describe any operational and environmental conditions or stresses that may affect the system and its operation.

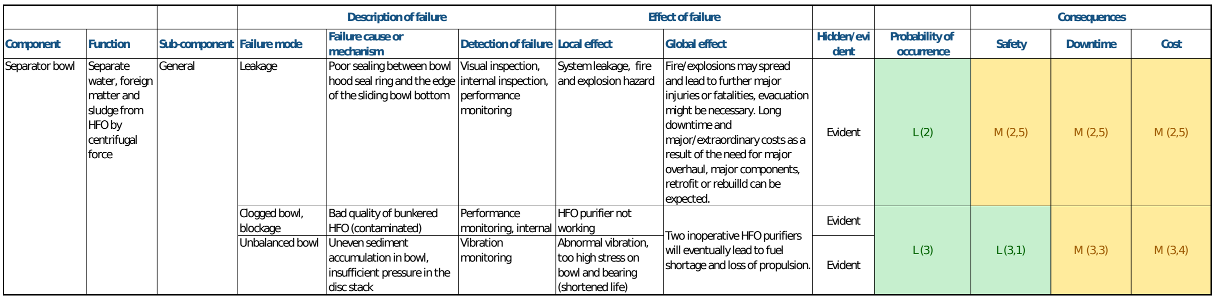
Purifiers are usually located in a separate room. On some ships, however, they are located on the engine room bottom floor. The purifiers operate together with pre-heaters, as they require that the fuel oil is heated before being fed into the separator bowl. As a result, the purifier room usually is rather hot. Additionally, inflammable gases and leakage might accumulate in the purifier room. Therefore, since fuel oil is present in abundance, together with air for combustion and heat sources (e.g. hot oil or electrical short circuit), the purifier room is prone to catching fires.

4.1.2 Performing

The process of performing the FMECA followed the flowchart seen in Figure 2.18, however, not in the same order. The worksheet was structured in Microsoft Excel before the actual analysis was started. The setup and different elements in the worksheet was decided based on existing FMECA's found in relevant textbooks (Rausand and Høyland, 2004), research papers (Faturachman et al., 2014), standards (IEEE, 2016; Military, 1949; NEK, 2018) and former Master's theses (Jacobsen, 2016; Wabakken, 2015). An excerpt from the worksheet can be seen in Figure 2.17, Section 2.4.3.

Components and Sub-Components

First, which components to include in the analysis was decided. This decision was based upon the abovementioned subsystem division and the analysed incident reports. The incident reports provided information about components that have failed before, and to some degree, how they failed. As stated earlier, it is essential that the analysis include the failure modes that have happened before, in addition to those who have not yet happened (JA1011, 1999). Since the earliest of the received incident reports are from 2012, they give an overall picture and a good indication as to which components should be included in the analysis. An excerpt from the FMECA worksheet describing the components and their functions, as well as their sub-components, is given in Figure 4.3. Since shafts, bearings, seals and gaskets, are part of several subsystems, these are analysed separately and on a general basis, and not as a part of any subsystem.



			Description of failure			Effect of failure				Consequences		
Component	Function	Sub-component	Failure mode	Failure cause or mechanism	Detection of failure	Local effect	Global effect	Hidden/evident	Probability of occurrence	Safety	Downtime	Cost
Separator bowl	Separate water, foreign matter and sludge from HFO by centrifugal force	General	Leakage	Poor sealing between bowl hood seal ring and the edge of the sliding bowl bottom	Visual inspection, internal inspection, performance monitoring	System leakage, fire and explosion hazard	Fire/explosions may spread and lead to further major injuries or fatalities, evacuation might be necessary. Long downtime and major/extraordinary costs as a result of the need for major overhaul, major components, retrofit or rebuilld can be expected.	Evident	L (2)	M (2,5)	M (2,5)	M (2,5)
			Clogged bowl, blockage	Bad quality of bunkered HFO (contaminated)	Performance monitoring, internal	HFO purifier not working	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (3)	L (3,1)	M (3,3)	M (3,4)
			Unbalanced bowl	Uneven sediment accumulation in bowl, insufficient pressure in the disc stack	Vibration monitoring	Abnormal vibration, too high stress on bowl and bearing (shortened life)		Evident				

Figure 4.3: Excerpt from the FMECA analysis.

Failure Modes

After all the components and sub-components were decided upon, the next step was to identify the possible failure modes for each of them. The failure modes were determined based on the analysed incident reports and the Handbook of Reliability Prediction Procedures for Mechanical Equipment by Naval Surface Warfare Center (2012). There exist a vast amount of failure modes for different components, some more plausible than others. This analysis is quite detailed, with a large number of failure modes for many of the components. See Figure 4.3.

Failure Mechanisms and Causes

The next step was to determine the potential underlying causes of each failure. As with the failure modes, this was based on the analysed incident reports, the handbook by Naval Surface Warfare Center (2012), as well as the author's knowledge. It is important to be aware of that one failure mode may have several potential failure causes or mechanisms. The cause of the incident is often compound, and there may be several underlying reasons. One of the problems encountered when analyzing the incident reports was the lack of descriptions of what may have caused them. See Figure 4.3 for an example of different failure modes for the separator bowl.

Detection of Failure

How the different failure modes can be detected is an interesting part of the FMECA. For Klaveness to make the right decision as whether to install vibration monitoring equipment on the HFO purifiers in their fleet, it is essential to know if the failures actually can be detected by vibration monitoring. This part answers the first question stated in the objectives section (1.2), asking how the failure modes with the highest probabilities of occurrence and severity of consequences can be detected. The method of detection for each failure is based on the available literature, such as (Bloch, 2012; Scheffer and Girdhar, 2004), discussions with Klaveness and the author's knowledge and intuition. An example can be seen in Figure 4.3.

Effect of Failure

The effects of each failure were divided into local effects on the given component, next level effects on the HFO purifier system, and global effects on the ship as a whole. The effects of each failure are based on the handbook by Naval Surface Warfare Center (2012), the author's knowledge and discussions with Klaveness. The next level effects and global effects describe worst case scenarios.

Probability of Occurrence and Consequences

The final step of the analysis was to determine the probability of occurrence and severity of the consequences of each failure mode. This was a qualitative assessment based on a risk matrix used in an FMECA performed by DNV GL on behalf of Klaveness, see Appendix C. The risk matrix was also the basis for the different consequence categories in the analysis: safety, downtime, and costs.

The probability of occurrence is based on the estimation of failure rates for the different components and sub-components of the HFO purifier system. Due to difficulties with obtaining relevant and exact failure data on failure mode level, the assessment of the probability of failure was conducted on component and sub-component level, based on the incident reports provided by Klaveness. See Section 4.1 for an explanation of the component division of the purifier system, Section 4.2.2.1 and 5.1.1 for how the failure rates were calculate, and Section 5.1.1 the results.

The consequences are a result of discussions between Klaveness and the author and are to a large degree based on Klaveness' own experiences with the equipment. The two consequence categories ”Downtime” and ”Cost” are explained further below:

Downtime: When considering the severity of consequences associated with next level effects, it is assumed that the downtime is for one separator, and not the ship as a whole. A breakdown will most likely cause a downtime between 1-10 days, i.e. the severity concerning downtime is in category 3 in the risk matrix. However, this assumes that all necessary spare parts are available onboard. If these are not available, the downtime may be longer than ten days, i.e. category 4. When considering the global effects, caused by a breakdown of both purifiers, it is assumed that the purifiers are repaired simultaneously. Thus, the downtime is in the same category as for the next level effects.

Cost: A high-level analysis of breakdowns conducted by Klaveness show that the cost of spares associated with the breakdown of one purifier is in the range 1,000-5,000 USD. However, this does not include costs of labour hours (onboard, procurement, ship management), freight forwarding, handling in port and agent costs. Therefore, it is reasonable to assume that the actual cost usually will exceed 5,000 USD but seldom exceed 20,000 USD. As a result, the severity of a purifier breakdown concerning cost will be in category 3 in the risk matrix. It is assumed that the breakdown of both purifiers will result in costs ending up in category 4.

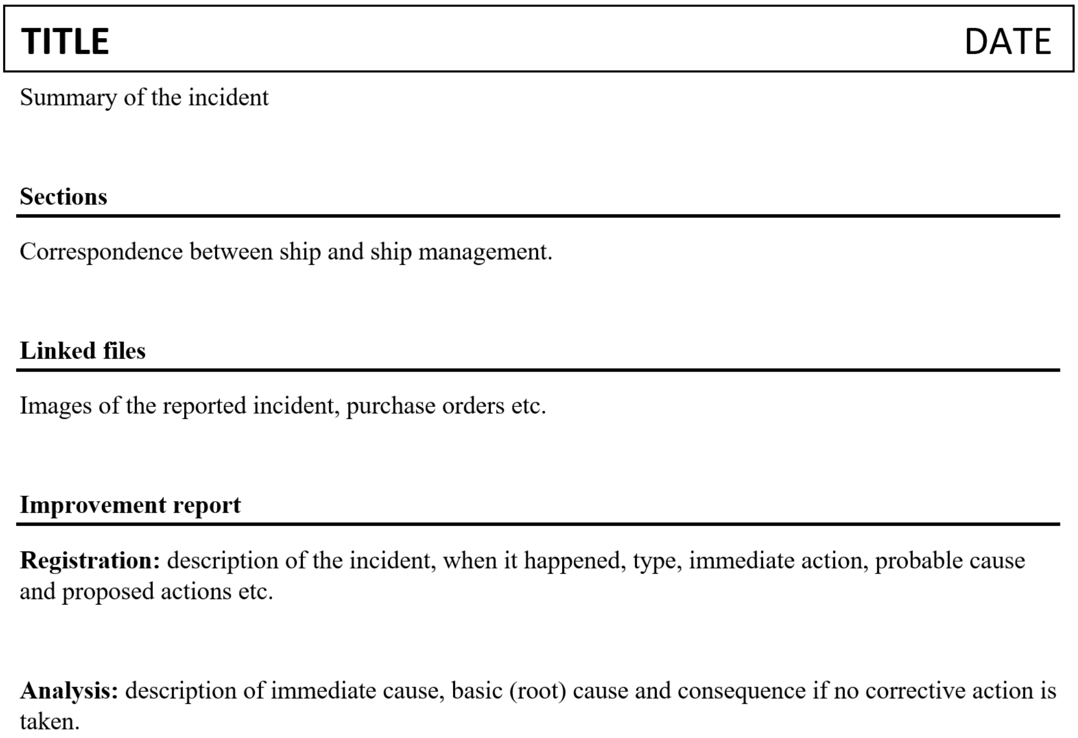
4.1.3 Documenting

The FMECA analysis was documented along the way. The worksheet was structured in Microsoft Excel and continually updated throughout the analysis process. Because of the very long mean time between failure (MTBF) for the entire system, see Section 5.1.1, the consequences have been assessed for both next-level effects and global effects. See Appendix D for the complete FMECA worksheets.

4.2 Incident Analysis

As stated in the objectives of the thesis, Section 1.2, one of the questions to be answered was what kind of information that can be extracted from the incident reports regarding HFO purifiers in the Klaveness fleet, and if any of these incidents could have been detected by vibration monitoring. The basis for answering this question is 50 incident reports that are, directly or in some way, related to HFO purifiers onboard different ships in Klaveness' fleet of combination carriers and container ships. The incident reports are from 2012 until the 19th of April 2019 and cover incidents from twelve different ships.

Most of the incidents analysed in this thesis are defined as nonconformities. The result of these incidents has mostly been material damages of varying severity, from worn out seals to electrical motors having to be renewed. These failures have not posed any significant threat to the safety onboard. Based on the descriptions, it is difficult to determine the severity of the incidents defined as near accidents. Some are related to minor breaches of maintenance procedures which could cause minor accidents, whereas most of them are described as material damage equal to those labelled as nonconformities.



TITLE **DATE**

Summary of the incident

Sections

Correspondence between ship and ship management.

Linked files

Images of the reported incident, purchase orders etc.

Improvement report

Registration: description of the incident, when it happened, type, immediate action, probable cause and proposed actions etc.

Analysis: description of immediate cause, basic (root) cause and consequence if no corrective action is taken.

Figure 4.4: General structure of the incident reports in Klaveness.

4.2.1 Incident Report Structure

Klaveness has a template for their incident reports which is used throughout the fleet, thus simplifying the analysis work to a certain degree. The reports follow the same general structure: summary of the incident, written correspondence between the ship and ship management, relevant attachments and an improvement report describing the incident, corrective actions and underlying causes, amongst others. The general structure of the incident reports is depicted in Figure 4.4. An example of what an incident report could look like can be found in Appendix C. The incident reports that have been read are of varying quality. Whereas some are well structured, have a high level of detail and are easy to read, others are much less comprehensive and clear, thus sometimes making it difficult to understand what has gone wrong and what was done to fix the problem.

4.2.2 Analysis Process

To be able to analyse the incident reports in an attempt to find any relations between the incidents on the purifiers, it was deemed necessary to gather all the information in one place. Microsoft Excel was chosen as the easiest and most appropriate platform for the purpose. The entire analysis process was carried out as follows:

Step 1: A large number of the incident reports, counting fifty in total, was read. This was done to gain a better understanding of how the reports were built up and what kind of information they contained.

Because of its simplicity, flexibility and data visualisation abilities, Excel was chosen as the most suitable tool for further analysis.

Step 2: All the information in each incident report was directly transferred, not treated in any way, to a Microsoft Excel spreadsheet to gather all reports in one place. Each row in the spreadsheet represents one incident report. The titles of the different columns in the spreadsheets are taken from the headlines found in the incident reports. It should be noted that the different reports do not necessarily contain the same information. As a result, several of the columns might be empty in some of the reports. An excerpt from the spreadsheet can be seen in Figure 4.5.

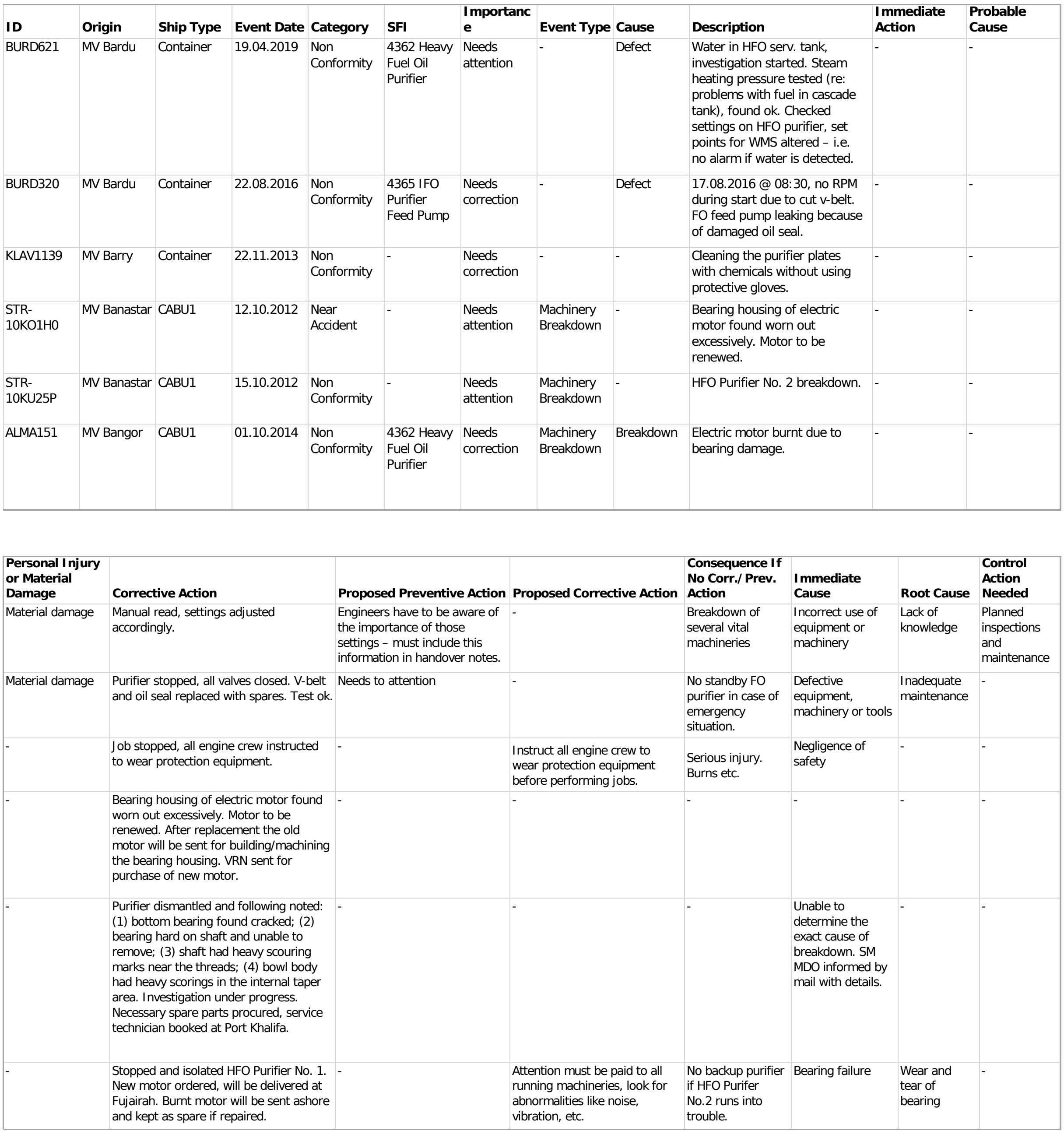
Step 3: After gathering all the information in one place, all incident reports that were not directly related to the HFO purifiers were removed from the scope. For example, incidents regarding HFO feed pumps, the purifier sludge tank and heat exchangers were discarded. These are parts of the fuel oil treatment system; however, they are not within the system boundaries set for this analysis. The number of incident reports eligible for further analysis was reduced from 50 to 42.

Step 4: When all unrelated incidents were discarded, the remaining incidents were reviewed again. The purpose was to rewrite the information and remove everything unnecessary or superfluous, thus making it easier to understand what the incident reports describe. Additionally, two of the columns were removed: the column describing the ”Immediate action” taken was merged with the ”Corrective action” column, and the ”Probable cause” column was merged with ”Immediate cause”. This merging was done because few reports used the terms ”Corrective action” and ”Probable cause”, but described the same type of information as in the columns they were merged with.

Step 5: The incident reports were then further simplified, only keeping the information considered as interesting and relevant for further analysis. The goal was only to list the faulty or damaged equipment from each incident, i.e. reducing the entire description to one or several specific parts, in addition to the underlying causes. An excerpt from this spreadsheet can be seen in Figure 4.6.

One of the main problems in this stage was that several reports use different names for the same components. Based on the engineering manual for the separator, (Alfa Laval, 2018a), it was possible to determine whether the different reports were describing the same component or not. Any uncertainties were discussed and clarified with Klaveness. The equipment was then categorized into major components of the HFO purifier: power transmission, electrical motor, inlet and outlet, separator and electronic equipment (i.e. controllers and sensors).

Then, the underlying causes were addressed. When writing the reports, these causes can be chosen from a list, with the possibility of adding remarks. The reports that had not provided ”Immediate cause” and



ID	Origin	Ship Type	Event Date	Category	SFI	Importance	Event Type	Cause	Description	Immediate Action	Probable Cause
BURD621	MV Bardu	Container	19.04.2019	Non Conformity	4362 Heavy Fuel Oil Purifier	Needs attention	-	Defect	Water in HFO serv. tank, investigation started. Steam heating pressure tested (re: problems with fuel in cascade tank), found ok. Checked settings on HFO purifier, set points for WMS altered – i.e. no alarm if water is detected.	-	-
BURD320	MV Bardu	Container	22.08.2016	Non Conformity	4365 IFO Purifier Feed Pump	Needs correction	-	Defect	17.08.2016 @ 08:30, no RPM during start due to cut v-belt. FO feed pump leaking because of damaged oil seal.	-	-
KLAV1139	MV Barry	Container	22.11.2013	Non Conformity	-	Needs correction	-	-	Cleaning the purifier plates with chemicals without using protective gloves.	-	-
STR-10KO1H0	MV Banastar	CABU1	12.10.2012	Near Accident	-	Needs attention	Machinery Breakdown	-	Bearing housing of electric motor found worn out excessively. Motor to be renewed.	-	-
STR-10KU25P	MV Banastar	CABU1	15.10.2012	Non Conformity	-	Needs attention	Machinery Breakdown	-	HFO Purifier No. 2 breakdown.	-	-
ALMA151	MV Bangor	CABU1	01.10.2014	Non Conformity	4362 Heavy Fuel Oil Purifier	Needs correction	Machinery Breakdown	Breakdown	Electric motor burnt due to bearing damage.	-	-

Personal Injury or Material Damage	Corrective Action	Proposed Preventive Action	Proposed Corrective Action	Consequence If No Corr./Prev. Action	Immediate Cause	Root Cause	Control Action Needed
Material damage	Manual read, settings adjusted accordingly.	Engineers have to be aware of the importance of those settings – must include this information in handover notes.	-	Breakdown of several vital machineries	Incorrect use of equipment or machinery	Lack of knowledge	Planned inspections and maintenance
Material damage	Purifier stopped, all valves closed. V-belt and oil seal replaced with spares. Test ok.	Needs to attention	-	No standby FO purifier in case of emergency situation.	Defective equipment, machinery or tools	Inadequate maintenance	-
-	Job stopped, all engine crew instructed to wear protection equipment.	-	Instruct all engine crew to wear protection equipment before performing jobs.	Serious injury. Burns etc.	Negligence of safety	-	-
-	Bearing housing of electric motor found worn out excessively. Motor to be renewed. After replacement the old motor will be sent for building/machining the bearing housing. VRN sent for purchase of new motor.	-	-	-	-	-	-
-	Purifier dismantled and following noted: (1) bottom bearing found cracked; (2) bearing hard on shaft and unable to remove; (3) shaft had heavy scouring marks near the threads; (4) bowl body had heavy scorings in the internal taper area. Investigation under progress. Necessary spare parts procured, service technician booked at Port Khalifa.	-	-	-	Unable to determine the exact cause of breakdown. SM MDO informed by mail with details.	-	-
-	Stopped and isolated HFO Purifier No. 1. New motor ordered, will be delivered at Fujairah. Burnt motor will be sent ashore and kept as spare if repaired.	-	Attention must be paid to all running machineries, look for abnormalities like noise, vibration, etc.	No backup purifier if HFO Purifer No.2 runs into trouble.	Bearing failure	Wear and tear of bearing	-

Figure 4.5: Excerpt from the spreadsheet containing all the incident reports, untreated. The bottom image is a continuation of the top one.

”Root cause” were assigned appropriate causes based on incident reports with similar (types of) failures. Two of the categories, ”Lack of skill” and ”Lack of knowledge” has been merged to ”Lack of skill/knowledge”, as these are closely related. Furthermore, some incidents had their causes changed to seemingly more appropriate ones. For example, based on the description in one report, faults had most likely been introduced to the system during maintenance, resulting in a failure. Thus, the immediate cause was changed from ”Defective equipment, machinery or tools” to ”Failure to follow repair/maintenance instructions”, and the root cause labelled as ”Excessive wear and tear” was changed to ”Lack of skill/knowledge”.

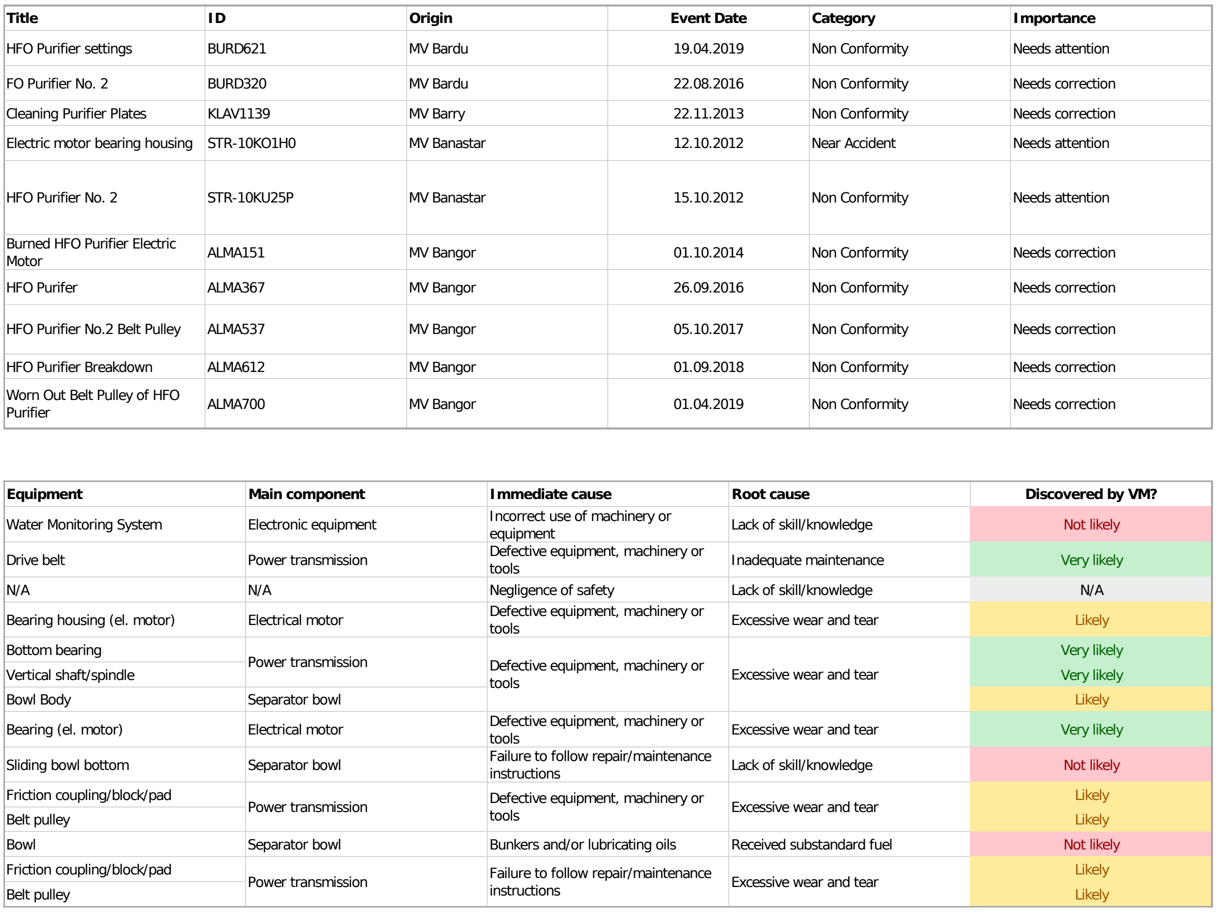
Finally, one column describing whether the incident could have been discovered by vibration monitoring was added to the spreadsheet. This is important for further analysis of the events to be able to answer the questions stated in the objectives. After analyzing the reports in more detail, it was seen that several of the incidents involved failures on more than one component or sub-component. Based on the information given in these incident reports, it was unclear which of the components or sub-components failed first, and whether the other failures occurred as a result of the first one or if they had already failed but not been revealed yet. For example, one incident report described the failure of a lower ball bearing, rotor and stator in one of the electric motors. Based on the incident description, it seemed very likely that the rotor and stator failure was due to the failure of the lower ball bearing. Therefore, each of the equipment failures was categorized as very likely to have been detected by vibration monitoring.

The probability of the sub-components involved in the incident being detected by vibration monitoring was given on a qualitative scale: very likely, likely, or unlikely. The probability assigned to each sub-component was based on the author’s knowledge, and the literature referred to in Section 2.2.1. This assessment was reviewed, and any uncertainties were clarified, during a discussion between the author and Karsten Moholt, a company working with lifetime extension of rotating equipment through smart maintenance. The author received positive feedback on the initial assessment conducted of which sub-components that could have been detected by vibration monitoring.

For the incidents involving more than one sub-component, the likeliness of the incident being detected by vibration monitoring was determined by the likeliness of detection for the different sub-components involved. For example, if an incident involved two sub-components that were very likely to have been detected by vibration monitoring and one sub-component that was not, the incident would most likely have been detected by vibration monitoring.

Step 6: The analysis was also carried out in Microsoft Excel. At this stage, four more incidents were removed from the scope. These were incidents related to (1) cleaning equipment without protective gear; (2) not cleaning up properly after maintenance; (3) special tool breaking during maintenance and (4) special tools could not be found when needed during maintenance. The incidents were not related to any system failure and were, therefore, not deemed relevant for further analysis.

The distribution of incidents concerning event date, incident category, equipment involved, and which



Title	ID	Origin	Event Date	Category	Importance
HFO Purifier settings	BURD621	MV Bardu	19.04.2019	Non Conformity	Needs attention
FO Purifier No. 2	BURD320	MV Bardu	22.08.2016	Non Conformity	Needs correction
Cleaning Purifier Plates	KLAV1139	MV Barry	22.11.2013	Non Conformity	Needs correction
Electric motor bearing housing	STR-10KO1H0	MV Banastar	12.10.2012	Near Accident	Needs attention
HFO Purifier No. 2	STR-10KU25P	MV Banastar	15.10.2012	Non Conformity	Needs attention
Burned HFO Purifier Electric Motor	ALMA151	MV Bangor	01.10.2014	Non Conformity	Needs correction
HFO Purifer	ALMA367	MV Bangor	26.09.2016	Non Conformity	Needs correction
HFO Purifier No.2 Belt Pulley	ALMA537	MV Bangor	05.10.2017	Non Conformity	Needs correction
HFO Purifier Breakdown	ALMA612	MV Bangor	01.09.2018	Non Conformity	Needs correction
Worn Out Belt Pulley of HFO Purifier	ALMA700	MV Bangor	01.04.2019	Non Conformity	Needs correction

Equipment	Main component	Immediate cause	Root cause	Discovered by VM?
Water Monitoring System	Electronic equipment	Incorrect use of machinery or equipment	Lack of skill/knowledge	Not likely
Drive belt	Power transmission	Defective equipment, machinery or tools	Inadequate maintenance	Very likely
N/A	N/A	Negligence of safety	Lack of skill/knowledge	N/A
Bearing housing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Likely
Bottom bearing	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
Vertical shaft/spindle				Very likely
Bowl Body	Separator bowl			Likely
Bearing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
Sliding bowl bottom	Separator bowl	Failure to follow repair/maintenance instructions	Lack of skill/knowledge	Not likely
Friction coupling/block/pad	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Likely
Belt pulley				Likely
Bowl	Separator bowl	Bunkers and/or lubricating oils	Received substandard fuel	Not likely
Friction coupling/block/pad	Power transmission	Failure to follow repair/maintenance instructions	Excessive wear and tear	Likely
Belt pulley				Likely

Figure 4.6: Excerpt from the spreadsheet for the incident analysis. The bottom picture is a continuation of the top one.

subsystem they belong to, immediate cause and root cause, was investigated. The distributions were plotted as histograms. Each of the failure categories, types of equipment involved, main components, immediate and root causes were compared to the qualitative assessment of whether they could have been discovered by vibration monitoring. The results are given in Section 5.

4.2.2.1 Failure Rate Estimation

Failure rate estimation techniques are based on gathering failure data. This data can be roughly divided into manufacturers own field return data, end-user field data or data obtained from industry databases, comprising failure data from several companies. All of them can provide useful information; however, they do all have advantages and disadvantages.

While manufacturer field return data is real, and failures are often thoroughly investigated, there are several uncertainties regarding the failure rates. This could be how many failures are actually returned, and whether it is assumed that all failures are returned or not, and how many of the returned failures are classified as failures by the manufacturer.

The industry databases could contain a large amount of data, as failure rates are gathered from a large number of companies. One of the most prominent databases is Offshore and Onshore Reliability Data (OREDA). However, using a database like this to obtain failure rates for this thesis may be problematic as the equipment most likely differs from those onboard a ship, both for design and operational profile and environmental conditions.

The final way of estimating failure rates is based on a company's data. As opposed to manufacturer return field data and industry databases, the failure data of one single company is most probably less extensive. Dependent on the amount of data, this could make the failure rate estimations more uncertain. On the other hand, the data is highly relevant as the failures come from equipment that has worked under the same environmental conditions and with similar operational profiles.

In this thesis, the failure estimation was based on Klaveness' incident reports on HFO purifiers. The 42 analysed reports cover the period between 12.10.2012 to 01.04.2019, or approximately 6.5 years. Furthermore, as the incidents are from 12 different ships, the reports cover approximately 78 ship years in total. Then, the failure rate and mean time to failure (MTTF) for the different components and sub-components was estimated, see Table 5.1-5.4 in Section 5.1.1.

These failure rates are for only one purifier. However, the HFO purifier has redundancy, as depicted in Figure 4.7. This means that one purifier is kept in standby and is activated if the first purifier fails. Since the reserve item carries no load in the waiting period before activation, the redundancy is passive. Therefore, in order for the HFO purifier system to fail, both purifiers have to be out of operation at the same time. If the purifier is being repaired after it fails, the failure rate of the system can be written as (Dudley et al., 1993):

$$\lambda_{n/n+1} = \frac{n(n\lambda + (1+P)\mu)\lambda}{\mu + n(P+1)\lambda} \tag{4.1}$$

where:

$\lambda_{x/y}$ = the effective failure rate of the redundant configuration where x of y units are required for success
n = number of active on-line units
λ = failure rate of an individual HFO purifier unit (incidents/hour).
μ = repair rate ($\mu = 1/M_{ct}$, where M_{ct} is the mean corrective maintenance time in hours
P = probability switching mechanism will operate properly when needed ($P = 1$ with perfect switching)

There have been 38 incidents leading to an HFO purifier failure, and the incident reports cover a time span of $01.04.2019 - 12.10.2012 = 2363$ days $= 6.47$ years. As the incidents are from 12 different ships, the incident reports cover $6.47 \cdot 12 = 77.7$ ship years. Then, the failure rate of an individual HFO purifier unit is calculated by:

$$\lambda_{HFO\,purifier} = \frac{38}{2362/365 * 12} = 0.489\ [h^{-1}] \tag{4.2}$$

or given as MTTF

$$MTTF_{HFO\,purifier} = \frac{1}{\lambda_{HFO\,purifier}} = 2.04355\ years = 17,901.5\ hours \tag{4.3}$$

Using Equation 4.1 for different repair rates, assuming perfect switching, one can obtain effective mean time between failure (MTBF) of the system for different mean corrective maintenance times (M_{ct}), i.e. the average time it takes to repair the purifier. See Section 5.1.1 for the failure rate estimation for the HFO purifier system, its components and sub-components.

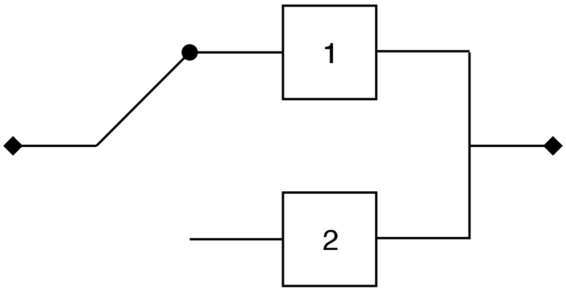


Figure 4.7: Standby system with two items.

Chapter 5

Results

5.1 Failure Modes, Effects and Criticality Analysis (FMECA)

First, the results from the failure rate estimation are presented. These form the basis for the assessment of the probability of failure for the different components and sub-components in the HFO purifier system. Then, the worksheet, i.e. the results of the FMECA, is presented.

5.1.1 Failure Rate Estimation

As discussed in Section 4.2.2.1, the failure rate and MTTF for the different components and sub-components in the purifier system is estimated based on the number of incidents over a given time. These results are given in Table 5.1, 5.2-5.4. These results are for one purifier. However, the HFO purifier has redundancy, meaning that one purifier is kept in standby and is activated if the first purifier fails. Since the reserve item carries no load in the waiting period before activation, the redundancy is passive. Therefore, in order for the HFO purifier system to fail, both purifiers have to be out of operation at the same time. If the purifier is being repaired after it fails, the failure rate of the system can be estimated by using Equation 4.1. Using this equation for different repair rates, assuming perfect switching, we can estimate the effective mean time between failure (MTBF) of the system, see Table 5.5. It can be seen that the HFO purifier system, consisting of two purifiers, have a mean time between failure of approximately 113 years if the repair time of one purifier is two weeks.

Table 5.1: Failure estimation of main components.

Component	**Frequency**	λ^* [year^{-1}]	**MTTF**** [year]
Electrical motor	7	0.090	11.1
Separator Bowl	7	0.090	11.1
Electronic Equipment	8	0.103	9.7
Inlet/Outlet	8	0.103	9.7
Power Transmission	14	0.180	5.5
Total (i.e. one purifier)	44***	0.567	1.8

* $\lambda =$ incident frequency/total no. of ship years, where the number of ship years is 78.

** MTTF 1/λ.

*** The number of failures are higher than the number of incidents because more than one main component was involved in some of the incidents.

Table 5.2: Sub-component failure estimation for all parts.

Equipment	**Frequency**	λ^* [year^{-1}]	**MTTF**** [year]
Centripetal Pump Chamber Cover	1	0.013	77.7
Hose	1	0.013	77.7
Rotor	1	0.013	77.7
Seal	1	0.013	77.7
Sensing Liquid Pump	1	0.013	77.7
Sight Glass	1	0.013	77.7
Stator Winding	1	0.013	77.7
Three-Way Valve	1	0.013	77.7
Water Monitoring System	1	0.013	77.7
Wing Insert	1	0.013	77.7
Belt Pulley	3	0.039	25.9
Friction Coupling/Block/Pad	3	0.039	25.9
Controller	4	0.052	19.4
Sensor	4	0.052	19.4
Bowl	6	0.077	12.9
Drive Belt	6	0.077	12.9
Sensor Block	6	0.077	12.9
Shaft/spindle	6	0.077	12.9
Bearing (incl. housing)	11	0.142	7.1

* $\lambda =$ incident frequency/total no. of ship years, where the number of ship years is 78.

** $MTTF = 1/\lambda$.

Table 5.3: Sub-component failure estimation for all parts when excluding the the electrical motors.

Equipment	**Frequency**	λ^* [year^{-1}]	**MTTF**** [year]
Centripetal Pump Chamber Cover	1	0.013	77.7
Hose	1	0.013	77.7
Seal	1	0.013	77.7
Sensing Liquid Pump	1	0.013	77.7
Sight Glass	1	0.013	77.7
Three-Way Valve	1	0.013	77.7
Water Monitoring System	1	0.013	77.7
Wing Insert	1	0.013	77.7
Belt Pulley	3	0.039	25.9
Friction Coupling/Block/Pad	3	0.039	25.9
Controller	4	0.052	19.4
Sensor	4	0.052	19.4
Bearing (incl. housing)	5	0.064	15.5
Shaft/spindle	5	0.064	15.5
Bowl	6	0.077	12.9
Drive Belt	6	0.077	12.9
Sensor Block	6	0.077	12.9

* $\lambda =$ incident frequency/total no. of ship years, where the number of ship years is 78.

** $MTTF = 1/\lambda$.

Table 5.4: Sub-component failure estimation for the electrical motors.

Equipment	**Frequency**	λ^* [year^{-1}]	**MTTF**** [year]
Stator Winding	1	0.013	77.7
Rotor	1	0.013	77.7
Shaft	1	0.013	77.7
Bearing	6	0.077	12.9

* $\lambda =$ incident frequency/total no. of ship years, where the number of ship years is 78.

** MTTF 1/λ.

Table 5.5: Mean time between failure for the passive redundant purifier system.

Mean Corrective Maintenance Time, M_{ct}[hour]	**Repair Rate**, μ [hour^{-1}]	**MTBF** [hour]	**MTBF** [year]
1	1.00000	320,499,505	36,587
2	0.50000	160,267,654	18,295
4	0.25000	80,151,729	9,150
8	0.12500	40,093,766	4,577
12	0.08333	26,741,112	3,053
24	0.41667	13,388,457	1,528
48	0.02083	6,712,130	766
72	0.01389	4,486,688	512
96	0.01042	3,373,967	385
120	0.00833	2,706,334	309
144	0.00694	2,261,245	258
168 (1 week)	0.00590	1,943,325	222
336 (2 weeks)	0.00298	989,564	113

The system failure rates are based on the number of incidents directly related to failure of the HFO purifier system, i.e. 38 incidents. The equipment involved in these incidents are all within the system boundaries.

5.1.2 FMECA Worksheet

The results of the FMECA can be seen in Appendix D. Concerning the consequences of failure, the severity was assessed both with respect to next level effects, i.e. on the HFO purifier itself, and global effects, concerning the ship as a whole. The reason for doing so is the extremely long MTBF for the HFO purifier system as a whole. If one of the purifiers fail, it is almost certain that it is repaired before the standby purifier also breaks down. As a result, the next level effects are those that normally will occur.

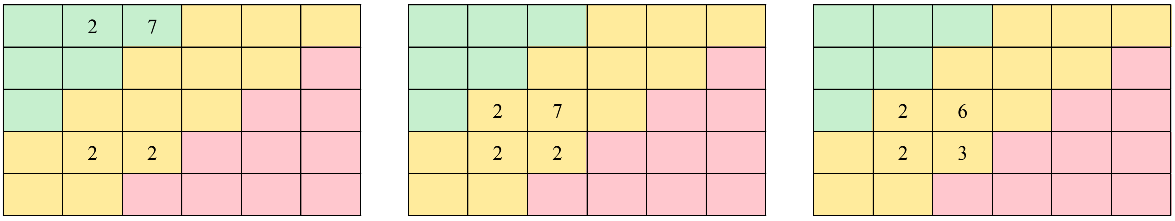
5.1.3 Risk Matrix

The severity of consequences for failures of the different components in the HFO purifier systems was based on the risk matrix provided by Klaveness, see Appendix C. The likelihood of occurrence combined with the severity of consequence gives a score in the risk matrix. A description of these scores are given below:

- **Low** (green): Monitoring actions are required to identify whether the risk rises to medium level.
- **Medium** (yellow): Risk reduction measures must be taken if their respective costs are not disproportionately high as compared to their attained benefits (ALARP principal); actions need to be taken to manage and measure risk.

- **High** (red): Actions must be taken to reduce risk to at least the medium level.

The distribution of these scores for the FMECA analyses was calculated. The distribution for the FMECA where the consequences were based on next level effects are shown in Figure 5.1, while for the FMECA were they are based on global effects are shown in Figure 5.2.



🟩	🟩 2	🟩 7	🟨	🟨	🟨
🟩	🟩	🟨	🟨	🟨	🟥
🟩	🟨	🟨	🟨	🟥	🟥
🟨	🟨 2	🟨 2	🟥	🟥	🟥
🟨	🟨	🟥	🟥	🟥	🟥

(a) Safety

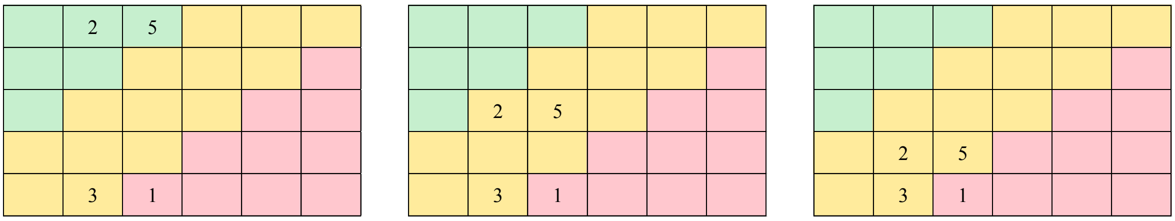
🟩	🟩	🟩	🟨	🟨	🟨
🟩	🟩	🟨	🟨	🟨	🟥
🟩	🟨 2	🟨 7	🟨	🟥	🟥
🟨	🟨 2	🟨 2	🟥	🟥	🟥
🟨	🟨	🟥	🟥	🟥	🟥

(b) Downtime

🟩	🟩	🟩	🟨	🟨	🟨
🟩	🟩	🟨	🟨	🟨	🟥
🟩	🟨 2	🟨 6	🟨	🟥	🟥
🟨	🟨 2	🟨 3	🟥	🟥	🟥
🟨	🟨	🟥	🟥	🟥	🟥

(c) Cost

Figure 5.1: Distribution of failure consequences considering next level effects in the FMECA with respect to safety, downtime and cost.



🟩	🟩 2	🟩 5	🟨	🟨	🟨
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(a) Safety

🟩	🟩	🟩	🟨	🟨	🟨
🟩	🟩	🟨	🟨	🟨	🟥
🟩	🟨 2	🟨 5	🟨	🟥	🟥
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🟨	🟨 3	🟥 1	🟥	🟥	🟥

(b) Downtime

🟩	🟩	🟩	🟨	🟨	🟨
🟩	🟩	🟨	🟨	🟨	🟥
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🟨	🟨 2	🟨 5	🟥	🟥	🟥
🟨	🟨 3	🟥 1	🟥	🟥	🟥

(c) Cost

Figure 5.2: Distribution of failure consequences considering global effects in the FMECA with respect to safety, downtime and cost.

When considering severity of consequences as a result of the next level effects, it can be seen that all the failures fall within either the green or yellow section of the risk matrix. While the likelihood of occurrence is on the lower side, the severity of consequences are somewhat higher. The high consequences are associated with leakages in the system leading to fire and explosion. When considering the next level effects, it is considered that any fire or explosion is limited to the purifier and machinery space, thus not spreading to the rest of the ship.

The distribution of failure consequences when considering global effects resembles the one considering next level effects. Compared to the consequences of next level effects, the severity of consequences associated with the global effects tend to be worse. This has to do with the assumption of fire and explosions spreading to other parts of the ship instead of being limited to the purifier and machinery space. Here, the increase in cost will also be considerably higher.

5.2 Incident Report Analysis

The starting point for the analysis was 50 incident reports that were, either directly or in some way, related to HFO purifiers onboard twelve different ships in the Klaveness' fleet of combination carriers and container ships. The reports are from 12.10.2012 to 01.04.2019, approximately 6.5 years. Several incidents were removed from the scope before the analysis was conducted, reducing the number of incidents from 50 to 38. The removed incidents were either related to equipment outside the system boundaries, as depicted in Figure 4.1 and 4.2, or they were not actual system failures. See Section 4.2.2 for further description. The results of the analysis are given in the sections below.

5.2.1 Incident Dates

The 42 incident reports related to the HFO purifiers were plotted as a histogram showing the distribution of incidents from 2012 to 2019. The incident distribution is shown in Figure 5.3 below.

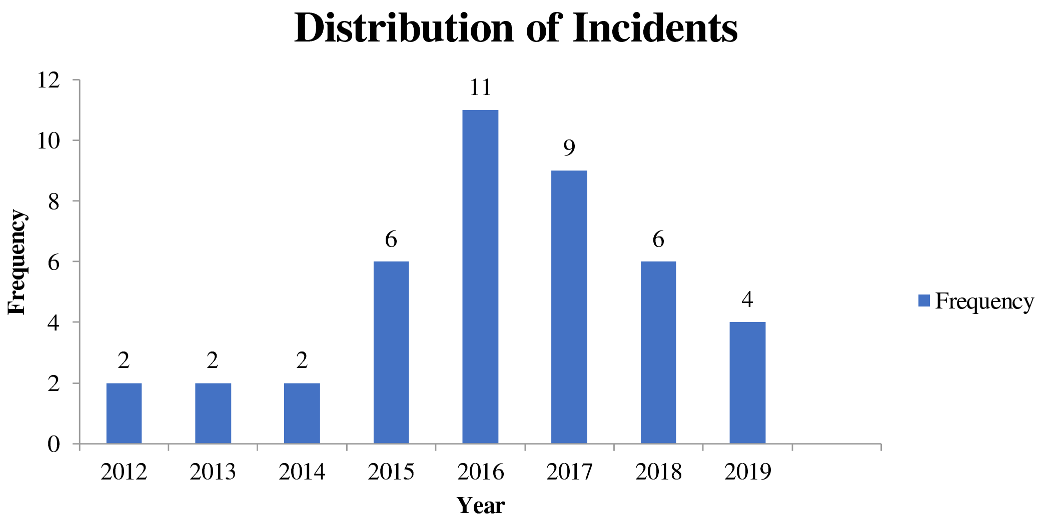

Figure 5.3: Distribution of Incidents per year.

It should be noted that four of these incidents were non-system failures. These occurred in 2013 (one incident), 2015 (one incident) and 2017 (two incidents). In the following results, these four incidents are removed from the scope.

5.2.2 Failure Categories

Each of the incident reports states a failure category in the summary section in the beginning. The distribution of failure categories and share of incidents that could potentially (i.e. very likely or likely) have been detected by vibration monitoring, is given in Figure 5.4 below.

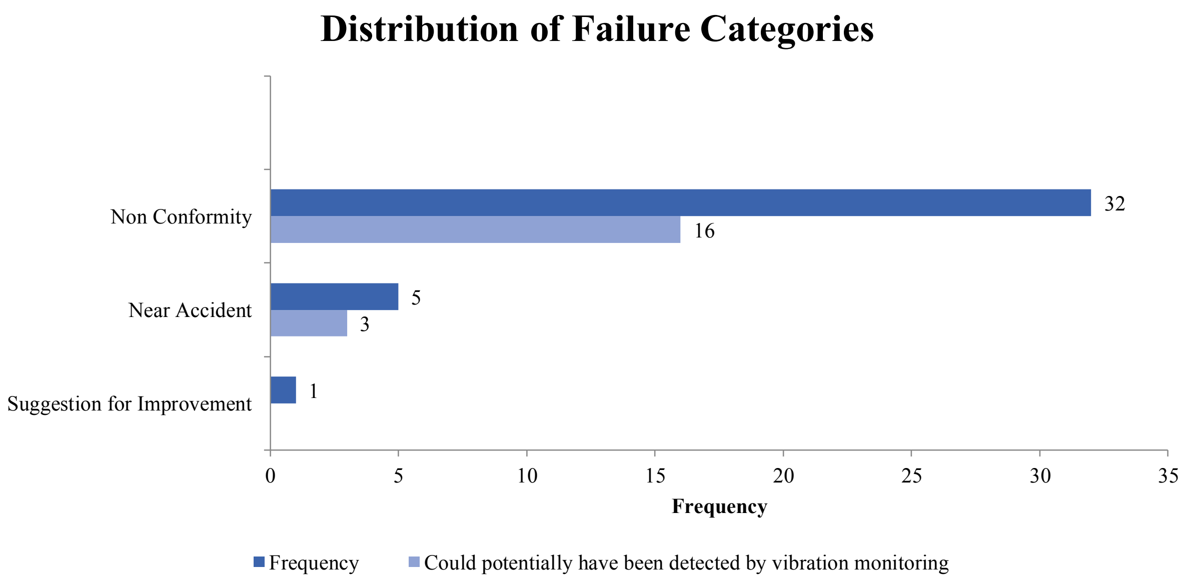

Figure 5.4: Distribution of failure categories and share of incidents that could potentially have been detected by vibration monitoring.

The one incident labelled ”Suggestion for Improvement” was regarding a defect speed sensor, preventing the purifier from obtaining its operational speed. Compared to the other incident reports, this could just as well have been labelled as a ”Non Conformity”.

5.2.3 Equipment Involved

The equipment that was involved, i.e. defect or damaged in some way, was analysed. The frequency of occurrence of each type of equipment involved in the incidents was plotted as a histogram. The frequency of occurrence was compared to the share of incidents that could potentially have been detected by vibration monitoring, which has been verified and discussed with Karsten Moholt. The distribution is shown in Figure 5.5 below.

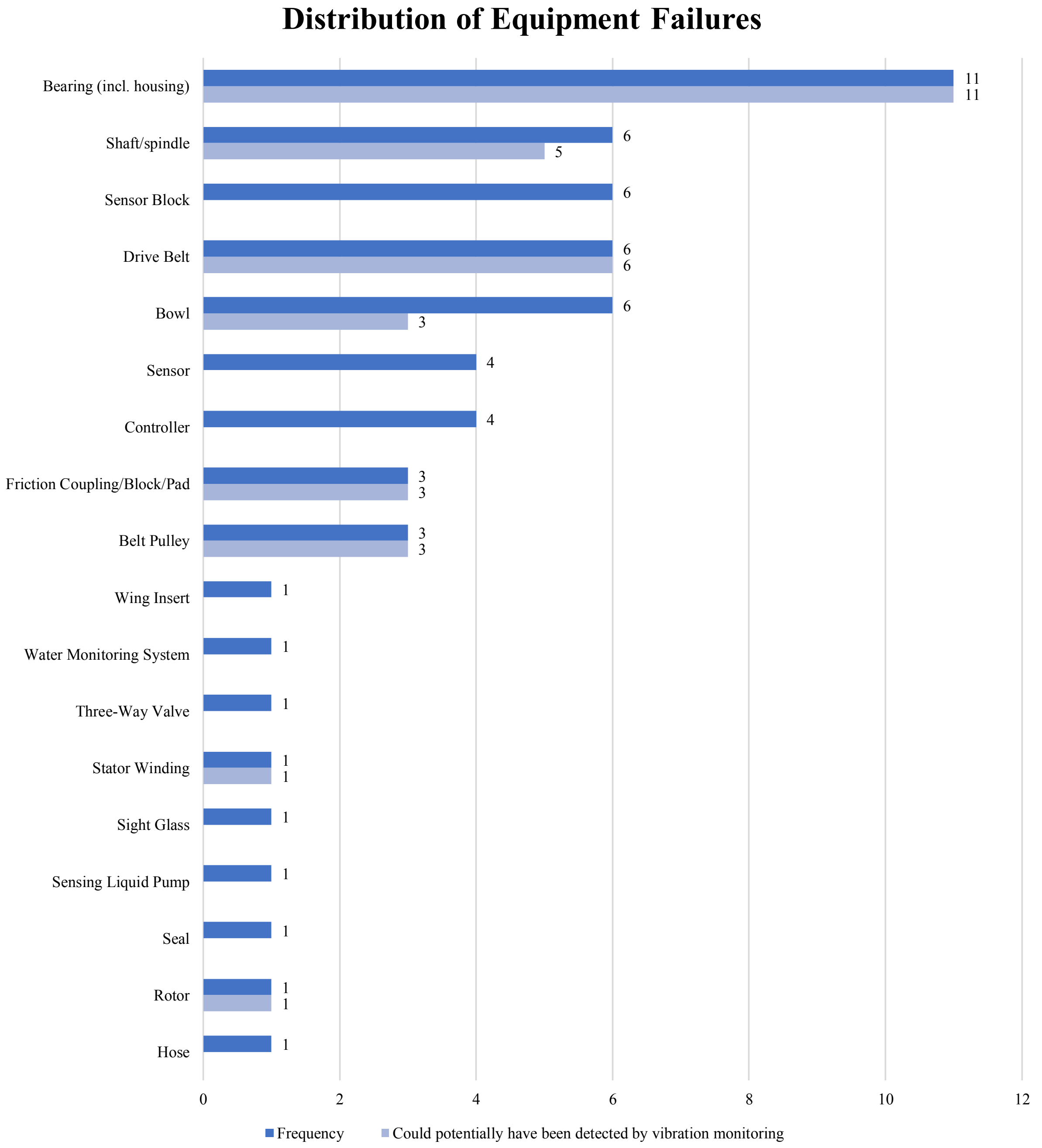

Figure 5.5: Distribution of equipment failures and share of these that could potentially have been detected by vibration monitoring.

The total number of equipment failures is 60, of which 33, or 55%, could potentially (i.e. very likely or likely) have been detected by vibration monitoring. The number of equipment failures is higher than the number of incidents because several types of equipment were defective or damaged in several of the incidents.

5.2.4 Main Components

As described in Section 4.1, the HFO purifier system was divided into several main components. The distribution of failures in each of these main components, and share of these that could potentially (i.e. very likely or likely) have been detected by vibration monitoring is depicted in Figure 5.6 below.

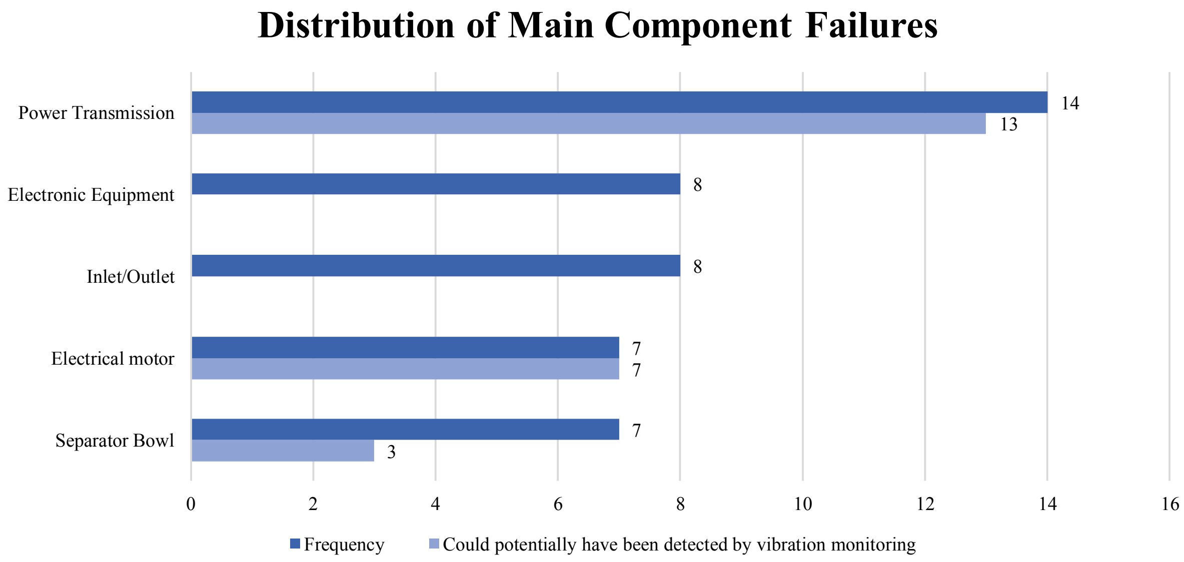

Figure 5.6: Distribution of main component failures and share of these that could potentially have been detected by vibration monitoring.

As with the distribution of equipment failures, the number of main component failures are higher than the number of incidents because several main components had equipment with defects or damages in some of the incidents.

5.2.5 Immediate Cause

As described in Section 4.2.2, most of the incident reports stated an immediate cause and a root cause. The reports that had not provided any causes were assigned appropriate causes based on the incident description and incident reports with similar (types of) failures. Furthermore, some incidents had their causes changed to seemingly more appropriate ones. The distribution of immediate causes and share of these that could potentially have been detected by vibration monitoring is shown in Figure 5.7 below.

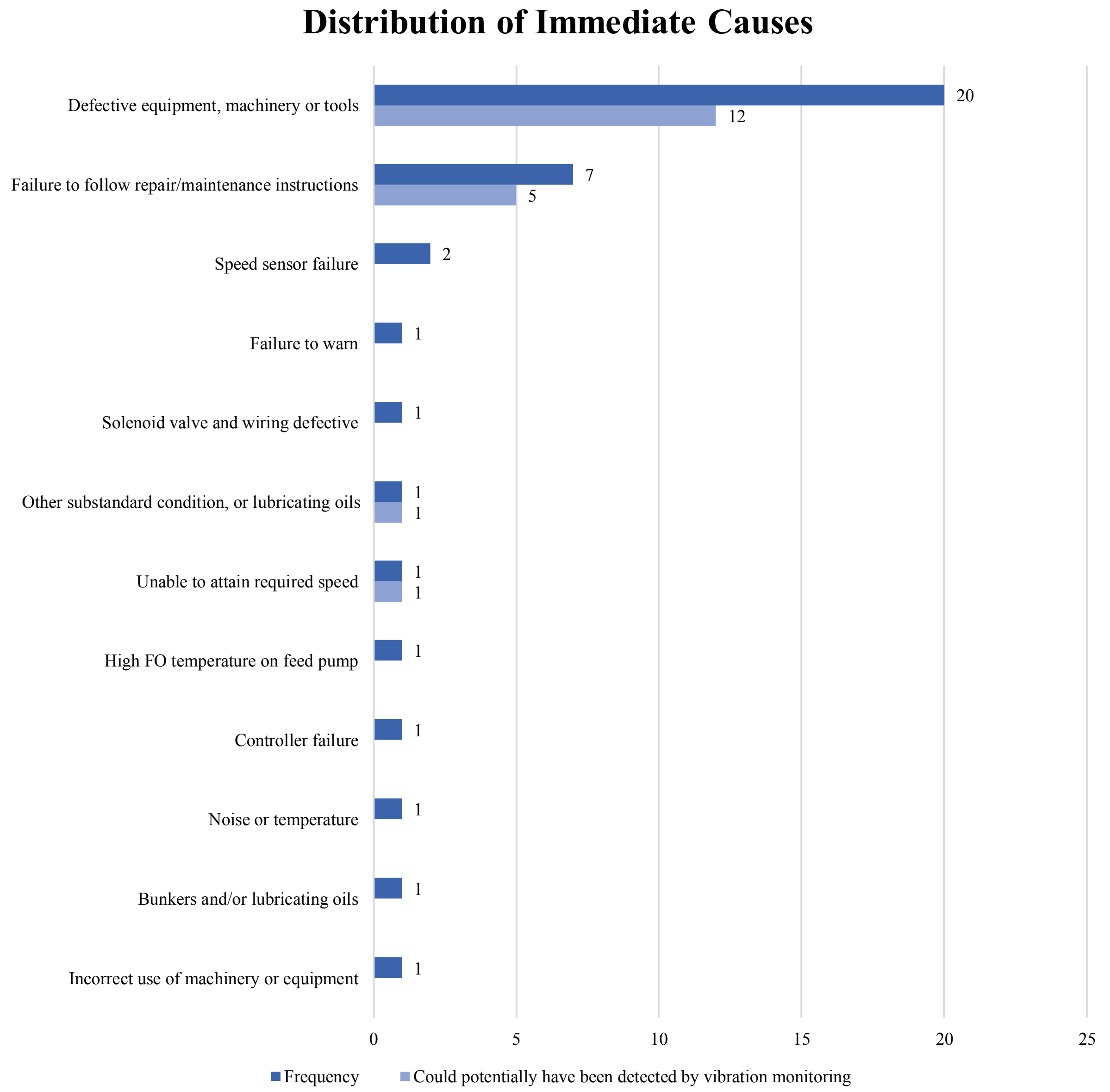

Figure 5.7: Distribution of immediate causes and share of these that could potentially have been detected by vibration monitoring.

As can be seen, most immediate causes, 27 out of 38, belong to the two categories ”Defective equipment, machinery or tools” and ”Failure to follow repair/maintenance instructions”. These categories are broad, and it is difficult to say much about the immediate cause of the failure. The categories with only one entry appear to be incidents where it has been attempted to pinpoint the immediate cause. It should be noted that it is not necessarily easy to know what the immediate cause is, which might explain the high number of incidents described with the more general immediate causes categories.

Furthermore, it can be seen that 50% of the incidents, and 60% with immediate cause ”Defective equipment, machinery or tools”, could potentially (i.e. very likely or likely) have been detected by vibration monitoring.

5.2.6 Root Cause

The distribution of root causes, and share of these that could potentially have been detected by vibration monitoring, is shown in Figure 5.8.

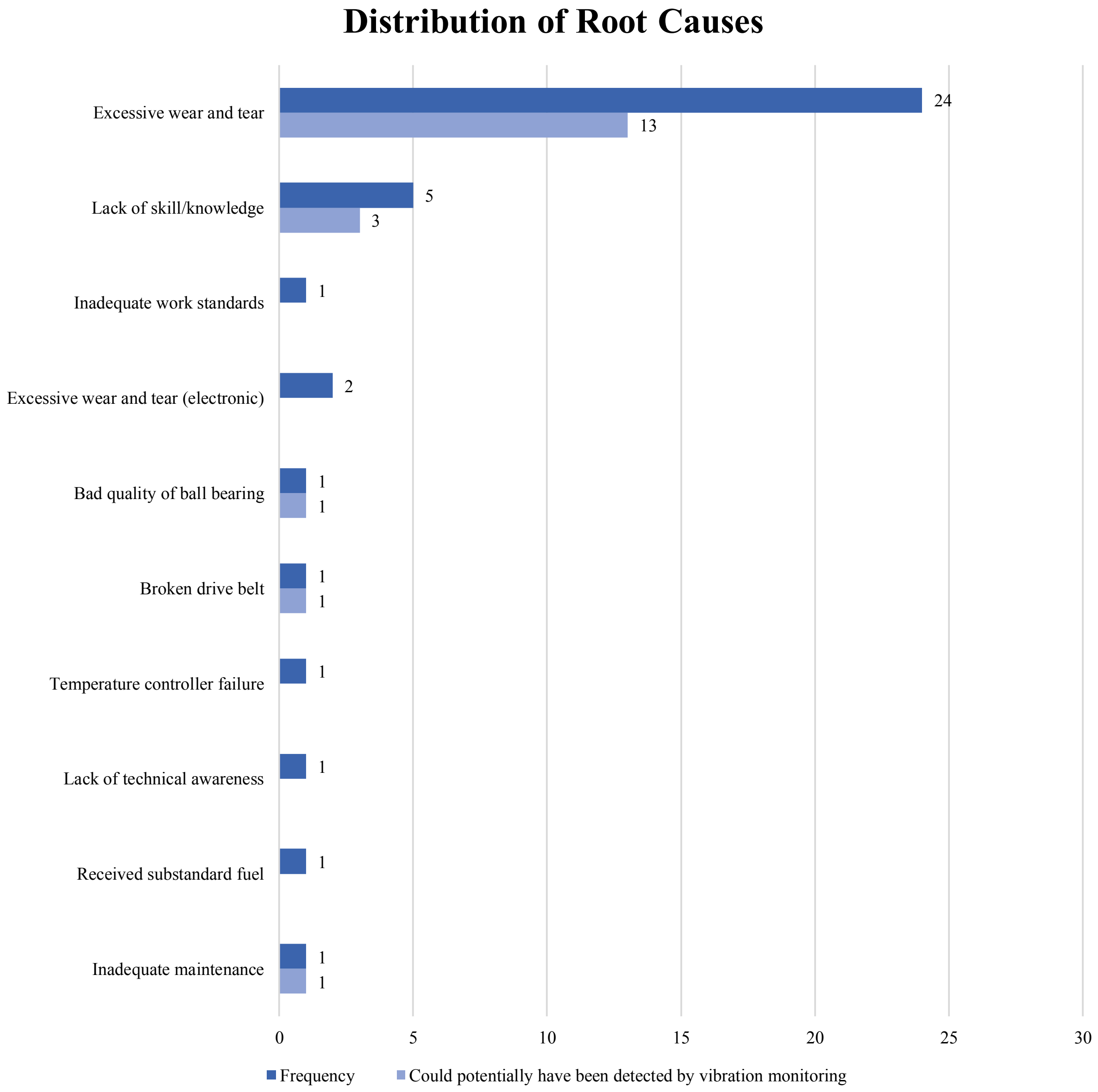

Figure 5.8: Distribution of root causes and share of these that could potentially have been detected by vibration monitoring.

As with the distribution of immediate causes, most of the root causes, 29 out of 38, belong to two categories: ”Excessive wear and tear” and ”Lack of skill/knowledge”. Also here it has been attempted to pinpoint the root cause for some of the incidents instead of labelling them as, for example, ”Excessive wear and tear”, a category which covers many types of failures.

Furthermore, it can be seen that 50% of the incidents, and more than half of the incidents caused by ”Excessive wear and tear”, could potentially (i.e. very likely or likely) have been detected by vibration monitoring,

5.2.6.1 Summary

A summary of the proportion of incident failure categories, main components, sub-components, immediate causes and root causes that were either very likely or likely to have been detected by vibration monitoring is given in Table 5.6 below.

Table 5.6: Summary of the results from the incident analysis.

	Potentially detected by VM
Failure Categories	50 %
- Very likely	*68 %*
- Likely	*32 %*
Main Components	52 %
- Very likely	*70 %*
- Likely	*30 %*
Sub-Components	56 %
- Very likely	*59 %*
- Likely	*41 %*
Immediate Cause	50 %
- Very likely	*68 %*
- Likely	*32 %*
Root Cause	50 %
- Very likely	*68 %*
- Likely	*32 %*

Independent of which incident category one looks at, it can be seen that at least half of the incidents or failures would either very likely or likely have been detected by vibration monitoring.

Chapter 6

Discussion

The discussion chapter of this thesis is divided into several parts. First, the available data, which forms the basis for the analyses, are discussed. This is followed by a discussion of the FMECA and incident analysis and their results. Finally, the incident reports, their structure, and how they are written, are discussed.

6.1 Available Data

Documenting incidents and failure data is an essential part of the ability to improve long term asset reliability. Knowing when and understanding how equipment fails allows for corrective measures to be taken and directed where it will produce the greatest value. Thus, future failures can be mitigated or even eliminated.

The information and results from failure data analysis can be used to determine the most appropriate maintenance strategies for eliminating failure root causes. This could, for example, be through vibration monitoring of rotating equipment, performance monitoring, more frequent inspections, new equipment designs or revision of operating procedures. Thorough failure data analysis may also provide a solid foundation for further analysis of parameters such as the MTTR and the total cost associated with a failure. However, it is essential to stress the fact that any failure analysis is only as good as the quality and quantity of the gathered data. Uncertain data will most likely result in uncertain results.

This failure data can be obtained from various sources. The division of failure data sources, as mentioned in Section 4.2.2.1, comprise end-user maintenance records, industry databases, reliability standards, handbooks, manufacturer data, documented reliability studies, expert opinions and published papers (Houtermans and Capelle, 2007). Houtermans and Capelle (2007) state that ”the most preferred data is always the data from the plant itself”. The failure behaviour and rate of an asset or component are dependent on, amongst others, environmental parameters, its operational use and the company’s maintenance strategy. As the data used in this thesis comes from incident reports, it was undoubtedly the most relevant and appropriate to use in the analyses conducted in this thesis.

There is, however, a few downsides with the incident reports and the failure data they provide. The incident reports are of varying quality, and several of the incident reports are either lacking important information, or the descriptions of the incidents and their possible causes, as well as what was done to fix the failures, are undetailed or of poor quality. This is further discussed in Section 6.4. Moreover, when considering the data quantity, it should be noted that the quantity of failure data collected from the incident reports are somewhat limited. The incident reports are collected from twelve ships, spanning over approximately 6.5 years. Hence, the reports cover a period of 78 ship years, i.e. the total operational lifetime of three or four ships.

Nevertheless, the data used in this thesis is, as mentioned above, the most relevant for the conducted analyses. Despite its somewhat limited extent in quantity, it should contribute to indicate as to whether Klaveness should equip the HFO purifiers in their fleet with vibration monitoring equipment. This is one of the main questions, as stated in the objectives of this thesis. The results may also help Klaveness in optimizing the maintenance of these purifiers, primarily concerning the overall maintenance strategy.

6.2 Failure Modes, Effects and Criticality Analysis

The first questions stated in the objectives, Section 1.2, asked what failure modes were the ones with the highest probability of occurrence and severity of consequences, and additionally, how can these be detected. As mentioned earlier, the severity of consequences was assessed both for the next level and global effects. A review of the probability of occurrence for the different components and sub-components are presented, followed by a discussion of the severities of consequences.

6.2.1 Probability of Occurrence

As discussed previously, the data used in this thesis for assessing the probability of occurrence is the most relevant and appropriate; however, somewhat limited in extent. It is of great importance to be aware of the limited amount of data used to assess failure rates in this thesis and how this can affect the reliability predictions. The accuracy of failure rate estimations and reliability predictions is dependent on the amount of data available. The more data available, the more accurate the calculation will be. With such a small amount of data, as was available for the analyses in this thesis, the final results may give a false sense of confidence. The outcome of the analyses and calculations may also be a result of coincidences and the possibility of underreporting of failures. However, since the data used to calculate failure rates in this thesis are Klaveness' field data from twelve ships and 78 ship years, the estimates are deemed reasonable and believed to give a fair indication.

When assessing the severity of consequences, the probability of occurrence is mainly concerning failures on subsystem level (component column in the FMECA). This was done based on the limited data available and due to the difficulty of obtaining relevant and applicable failure data on failure mode and sub-component level from other sources. However, the probability of occurrence when considering the electrical motor, inlet and outlet, is on sub-component level. For the electrical motor, bearing failures constitute six out of nine failures. Therefore, the likelihood of failure on the bearings is separated from failures on the other sub-components of the electrical motor. For the inlet and outlet, leakage of the solenoid valve constitute most of the recorded failures and is therefore separated from failures on pipes and hoses.

The probability of occurrence is further discussed in Section 6.2.2.

6.2.2 Consequences of Next Level and Global Effects

The next level effects are those that occur when one purifier breaks down. When looking at the FMECA worksheet in Appendix D, it can be seen that the likelihood of failure for the components and sub-components are in category 2 or 3, meaning that they are either not expected to happen or expected to occur once or so within the lifetime of a vessel. The components and sub-components that are most likely to fail, i.e. category 3, is the power transmission system, the solenoid valve, the separator bowl, controllers and sensors, and bearings and shafts in general.

Looking at the FMECA and the summary of the incident report analysis in Appendix D, it can be seen that these component and sub-component failures are those that could have been detected by vibration monitoring. Going back to Table 5.1, it is seen that these components constitute more than 60% of the total failures. For these subsystems and sub-components, the severity of a possible failure concerning safety is also low. It is considered to be in category 1, i.e. ”no or superficial injuries”, for all of these components. However, the consequences to downtime and cost are considerably higher, being given severity of 3 both for downtime and cost. This means a downtime between 1-10 days and a considerable cost impact requiring expensive spares or logistics (2,000 USD cost 20,000 USD), respectively. These relatively high consequences related to downtime and costs indicate that there exists a great potential for installing vibration monitoring on this equipment.

The most severe consequences, however, are related to leakages in the system, as this might result in fires and explosions. These leakages can occur in pipes, hoses, solenoid valves and the separator bowl. If this were going to happen, the severity related to safety, downtime and cost would be worse than for failures of the power transmission system, electrical motor or an unbalanced separator bowl. It was assumed that a fire in the HFO purifier room would not spread further to differentiate between the severity of consequences related to the next level and global effects. The severity is given a score of 4 for all the consequence categories, implying single fatality or permanent disability, a downtime between 10-60 days, and a major cost impact (20,000 - 200,000 [USD]).

Failures related to electronic equipment such as controllers and sensors are also likely to occur once or so within the lifetime of a vessel. Nor can these be detected by vibration monitoring. The severity of consequences with respect to downtime and cost is within category 3 for both downtime and cost.

The global effects are those that occur when both purifiers break down at the same time, or that the standby purifier breaks down while the other is being repaired. A fire spreading to other parts of the ship than the purifier or machinery space is also a global effect. Compared to the probability of one purifier breaking down, the probability of the entire HFO purifier system breaking down is much smaller. From Table 5.1, the MTBF of one purifier was estimated to be approximately 1.8 years. The MTBF for the system, however, is more than 60 times longer. This MTBF depends on the average time it takes to repair one purifier. As can be seen from Table 5.5, the MTBF is approximately 36,587 years and 113 years, for a mean corrective maintenance time of 1 hour and two weeks, respectively. In the FMECA, the probability of leakages resulting in a fire is, however, assumed to be the same both when looking at the next level and global effects.

As can be seen from the FMECA, the most severe consequences are related to failures on components that vibration monitoring is not capable of detecting. As with the consequences of next level effects, these are also related to failures involving leakages. However, the consequences of a fire spreading to other parts of the ship are considered to be even more severe than a fire only within the purifier or machinery space. The severity is given a score of 5, which means it will result in multiple fatalities, downtime of more than 60 days and costs exceeding 200,000 USD. To detect these failures, other methods must be used. In the case of leakages from the solenoid valves, these could be detected by inspections with ultrasound equipment. Other alternatives are, of course, more frequent and thorough visual and internal inspections. Any other leakages can also be detected by visual and internal inspection. Additionally, performance monitoring may be a possible solution.

If one look at the failures not involving leakages or that is results of electronic equipment, vibration monitoring is very likely or likely to detect these. The severity of consequences of these are low when it comes to safety; however, they are high when considering the possible downtime and costs. It is assumed that the downtime is similar regardless of the number of purifiers breaking down - the downtime would not be longer than the time it takes to repair one of them. The cost associated with a failure of the system is at least twice as high as for the breakdown of one purifier. The breakdown of both purifiers would also cause delays, which will have a significant impact on the costs.

To summarize, the most critical failures concerning safety, downtime and cost, cannot be detected by vibration monitoring. To avoid these failures, other measures are needed. Nevertheless, more than 60% of the occurred failures could most likely have been detected by vibration monitoring. These failures can in the worst case lead to downtime of up to two months, depending on the number of purifiers that are out of operation, the severity of the failures and whether spare parts are readily available onboard. A breakdown of one purifier will result in a downtime of at least one day. As mentioned in Section 4.1.2, the cost of spares associated with the breakdown of one purifier is in the range 1,000-5,000 USD. When taking into account the cost of labour hours (onboard, procurement, ship management), freight forwarding, handling in port and agent costs, it is reasonable to assume that the actual cost usually will exceed 5,000 USD.

An example can illustrate the potential savings of implementing vibration monitoring. Looking at the summary of the results from the incident report analysis, see Table 5.6, it can be seen that 50% or more of the incidents could have been detected by vibration monitoring. As given in Table 5.1, the MTBF of one purifier is 1.8 years. If one considers a fleet consisting of as many ships as Klaveness operate, which is close to 135, these would together experience $135/1.8 = 75$ purifier failures per year. If half of these could be avoided with vibration monitoring, and one estimate that an average of 30% of these failures are of such severity that the cost exceeds 5,000 USD, one would avoid at least $(75/2) \cdot 0.3 = 11.25 \approx 11$ such failure every year, thus saving a minimum of 55,000 USD per year.

6.3 Incident Analysis

The second question stated in the objectives, Section 1.2, asked what kind of information that could be extracted from the incident reports regarding HFO purifiers in the Klaveness fleet, and whether any of these incidents could have been detected by vibration monitoring.

As presented in Section 4.2.2, the reports were systematically reviewed and structured in a Microsoft Excel worksheet. The information that can be directly extracted from the reports is given in Figure 4.5. Further, the information considered most interesting and important for further analysis was extracted from reports, see Appendix D.

A discussion of the different histograms presented in Section 5.2 is presented below:

6.3.1 Failure Categories

Only three different failure categories were encountered in the incident report analysis: nonconformity, near accident and suggestion for improvement. As stated in Section 5.2, the one incident labelled ”Suggestion for Improvement” could have been labelled as a nonconformity instead.

Most of the incidents, 32 of 38, were categorised as nonconformities, i.e. non-fulfilment of requirements. Since there is one category for near accident-incidents and one for suggestions for improvement, those categorised as nonconformities contain everything between, including any accidents. When considering failure categories, the fact that half of the nonconformities, and half of the incidents in total, were very likely or likely to have been detected by vibration monitoring indicates that it might be a right decision to install vibration monitoring equipment on the HFO purifiers.

What is perhaps most interesting here is that 3 of 5 incidents that were near accidents could be revealed by vibration monitoring. However, the incident descriptions reveal that most of these describe material damage to the equipment involved. How the incident potentially could have resulted in an accident is not described. Most of those incidents could, therefore, also have been categorised as nonconformities.

The reports were further analysed as the failure categories alone do not provide much information about the incidents.

6.3.2 Equipment Failures

The 38 analysed incident reports described failures on a total of 59 sub-components. Among these, 56%, or 33 sub-components, were either very likely or likely to have been detected by vibration monitoring. If all the failures on electronic equipment (controller, sensors and water monitoring system) and any leakages (i.e. pipes, hoses, sensor block and valves), which cannot be detected by vibration monitoring, are discarded, this number increases to 79%.

Among the top five sub-components that fail most often, constituting 60% of the failures, more than 70% of these failures could most likely have been detected by vibration monitoring. These are also among the sub-components with the most costly spares. Failures on the sensor block are among the top five failing sub-components that could not be detected by vibration monitoring. These failures could, however, have been detected by ultrasound inspection.

Based on the results of the distribution of equipment failures, a fleet-wide installation of vibration monitoring equipment seems to be a right and correct decision.

6.3.3 Main Component Failures

When looking at the distribution of incident, or failures, on a higher level, it can be seen that more than half, 52%, of the incidents most likely would have been detected by vibration monitoring. If we also here discard the incidents related to electronic equipment and those involving leakages, which cannot be detected by vibration monitoring, the number of main component failures that most likely could have been detected increases to 82%. As with the distribution of failures on sub-components, this indicates that a fleet-wide installation of VM equipment on HFO purifiers is likely to be beneficial.

6.3.4 Immediate and Root Causes

If the underlying causes are considered, instead of looking at failure categories or failure of components and sub-components, it can be seen that VM would have most likely detected 50% of the incidents.

One interesting takeout in the distribution of immediate causes is that 5 out of 7 incidents resulting from ”failure to follow repair/maintenance instructions” could have been revealed by VM. As mentioned in Section 1.1, it is not uncommon that faults are introduced to a system during disassembly and maintenance, causing failures shortly after. Therefore, it would be beneficial if such failures could be prevented by vibration monitoring.

When considering the distribution of root causes, there is an overweight of incidents caused by ”excessive wear and tear”. As discussed later on, in Section 6.4, this category is rather unclear and ambiguous. If one takes a closer look at the incident reports, see Appendix D, it can be seen that the distribution of excessive wear and tear-caused incidents with respect to main components resembles the distribution of main component failures. Ergo, more than 60% of incidents caused by excessive wear and tear are related to either the power transmission, the electrical motor or separator bowl, of which more than 8 out of 10 were very likely or likely to have been detected by VM.

6.4 Incident Reports

Accidents and incidents onboard a ship can result in economic losses, environmental damage, injuries to personnel or even fatalities, further leading to loss of reputation. Therefore, prevention and reducing the number of incidents are of vital importance to all ship owners and operators. Proper incident investigation and analysis is essential to identify weaknesses in a system or a company's maintenance programme. This will aid in providing insight into how the system or maintenance programme can be improved to prevent recurrence of similar incidents in the future. The final step of the investigation is to write a report. The incident reports should be looked upon as a valuable resource, and according to Sutton (2014), ”the importance of writing a good report cannot be overemphasised”.

Having reviewed and analysed all the incident reports, there are several aspects of the reports that the author believes could have been improved for Klaveness to benefit even more from them in the future. This includes both the report template and how those responsible for documenting the incident writes the reports.

When analysing event reports, as done in this thesis, it is desirable to quickly understand what type of incident it is, its criticality, and which equipment is involved, at least at a higher level. This makes it easier to categorise the events for further analysis and is especially important for complex assets comprising a wide range of different machinery and equipment, such as ships. In Klaveness, this information is given in the summary part of each report, as depicted in Figure 4.4 and that can be seen in the example report in Appendix C.

In the 42 incident reports analysed in this thesis, the incident category and importance was given for all incidents. However, the SFI code was given in only six out of ten reports. SFI is an international classification system for the maritime and offshore industry, and provides a functional subdivision of technical and financial information of a ship or rig. The reason why just above half of the analysed reports have stated this is unknown to the author. The SFI code should be included in every incident report to ease the process of categorising incidents by, for example, equipment or machinery in the future. A suggestion would be to make this field in the incident mandatory, thus preventing completion of the report before this is determined.

Another field in the analysed reports that often lacked information was ”event type”. This field is a part of the ”improvement report” section of the reports. The event types are only mentioned in less than two out of ten reports. These event types were either ”machinery breakdown” or ”property damaged”. For each of these reports, one could argue that either two of these event types would have been suitable based on their incident description. Since less than twenty per cent of the reports stated the event type, this field does seem superfluous. However, it may be of interest to categorise incidents based on the event type. This presupposes, of course, that this field is completed in each report and that one can choose between several events that make it possible actually to differentiate the incidents. As with the abovementioned SFI codes, it may be an idea to make also this field mandatory.

Furthermore, when reading through the ”Improvement report” part of the incidents, see Figure 4.4, it is inevitable to notice that several of the reports are poorly written. Common to many is a lack of comprehensive descriptions, often combined with poor language and grammar, which make the analysis of the reports more difficult and time-consuming than necessary.

Among the first fields to be filled out in this section is a description of the incident. One thing that was common in the event descriptions is that they often included an explanation of the ”Immediate” and ”Corrective” action taken, fields that are described later on as well. It appears to be uncertainty about what type of information should be included in each of these three fields. Not only does this make the analysis process more cumbersome, but it also makes it harder for maintenance personnel to effectively use past incident reports to correct similar errors or failures if they occur in the future. Ideally, the incident description and explanation of actions taken should be as detailed and descriptive as possible. That way, the reports can potentially serve as a guide for how to fix reoccurring problems, as well as a helpful tool in future incident investigations. Based on the analysed reports, a suggestion would be to merge the two fields ”Immediate action” and ”Corrective action” into one input field, as only one of them is used in each of the analysed reports. It will most likely be more straightforward for the person writing the report to have to deal only with one entry, as well as it would potentially make future reports more consistent content-wise.

Moreover, there also seem to be uncertainty about the difference between the entries describing ”Proposed preventive” and ”Proposed corrective” action, two entries of paramount importance. It is imperative to carefully consider and describe in detail what could have been changed or done differently when an incident has occurred. Only then can the same events be prevented from happening again in the future. The definition of preventive and corrective action can be found in most ISO standards, e.g. in ISO 9001, The International Standard for Quality Management Systems (QMS):

- **Preventive action:** action to eliminate the cause of a detected non-conformity or other undesirable situation.
- **Corrective action:** action to eliminate the cause of a potential non-conformity or other undesirable situation.

As can be seen from the two definitions, preventive actions are proactive, taken to prevent incidents from ever occurring. This could, for example, be risk assessments, e.g. FMECAs, the development of work instructions, training of personnel and other regular preventive actions such as audits and inspections. Corrective actions, on the other hand, are reactive, taken to prevent the recurrence of incidents. These are typically product or event focused. Examples of corrective actions are root cause analysis, process or product redesign, and improvements to maintenance schedules or spare part stock management.

The Cambridge Dictionary defines ”preventive” as ”intended to stop something before it happens”. Based on this definition, it is understandable that most of the incident reports, approximately 70%, have described preventive actions instead of corrective actions, used in approximately 15% of the reports. ”Corrective” is defined as ”intended to improve a situation” in the Cambridge Dictionary. Nevertheless, whether either one is used most likely depends on the report writer’s interpretation of the two expressions. As with the abovementioned ”Immediate” and ”Corrective” actions, it may also here be beneficial to merge the two entries. One could opt for one of them or name it, for instance, ”Proposed improvement actions” or something similar.

Another essential part of the incident reports is the consequence description. It is beneficial that it is detailed and describes the damage potential of the incident if no action is taken. By explaining the severity of possible consequences, it is easier to highlight the most critical incidents. Otherwise, the incidents may not receive sufficient attention and resources to fix the problem, or they may, in the worst case, be ignored. The consequence description should not only be concerning machinery damage, as is the case with several of the analysed reports, but also describe any consequences related to safety, environment, system availability and possible compliance breach resulting in loss of reputation. The risk matrix used in this thesis could be a useful tool to help describe the consequences.

The final part of the incident report is the ”Analysis”, describing immediate causes, root causes and control actions needed. As mentioned earlier, also this is a crucial part of the report, especially the identification of the root cause. Pinpointing the exact cause and location of the failure is necessary to fix the underlying problems and help prevent the same from happening in the future. Else, the maintenance personnel may perform a quick fix instead, which may increase downtime in the long run.

Even though nine out of ten incident reports stated the immediate and root cause, it is a potential problem that some of the most used cause categories are somewhat unclear, thus not providing much information about the actual cause of the incidents. For instance, more than half of the reports described the root cause of the incidents as a result of ”excessive wear and tear”, which could cover many different causes to failure. This category is slightly ambiguous and unclear and does not provide much information about the underlying causes of the incidents. In the reports, there is an opportunity to add any additional remarks to elaborate the immediate and root cause; however, this was seldom used. Adding such remarks should be emphasised among the maintenance personnel.

To conclude, there are several aspects of the incident reports that could be improved for Klaveness to benefit even more from them in the future. This applies to both the structure and the actual content of the report, i.e. what is being written. For the first part of the incident reports, the summary section, there is a lack of description of what equipment is involved, with only six out of ten reports stating the SFI code. The titles of the reports may give an indication; however, these are not suitable to use for categorisation. Another common problem is that the event type is only given in two out of ten reports. If it is desirable to sort incident reports based on either the equipment or event type, it should be considered to make these entries mandatory, thus preventing completion of the report before this is written.

Furthermore, several of the reports are poorly written. Many are incomplete and lack comprehensive incident descriptions and explanations of improvement actions, both preventive and corrective, and consequences if no action is taken. This is often combined with poor language and grammar, which make the analysis work increasingly more difficult and time-consuming.

It is also possible that the incident report template contains too many entries, some of which could be merged. It should be considered to merge the ”Immediate action” and ”Corrective action” entries into one, as it is evident that there is uncertainty about which one should be used. The same is proposed for the ”Proposed preventive action” and ”Proposed corrective action”, which can advantageously be combined into for example ”Proposed improvement actions”. Having fewer entries will not only cause less confusion and make it easier to write incident reports, but it will also contribute to making future incident reports more consistent.

Moreover, describing the immediate and root causes in more detail by adding additional remarks should be emphasised. However, writing a good incident report may sometimes be challenging. In addition to the abovementioned suggestions, other measures that should be considered to increase the overall quality of the incident reports are training in writing incident reports, and have examples of good incident reports readily available for the maintenance personnel. The latter could also be an integrated part of the tool used to write the reports. It could, for instance, be readily available by clicking a button next to the input field, or the input field could by default contain an example of how it can be written. This is often referred to as placeholder text.

Finally, it would be of great interest and value if the incident reports included the repair times associated with the failures. Together with the cost of spares, this would make it easier to assess the total cost of failure. This is important to accurately measure the effectiveness, or return on investment, of the maintenance programme or strategy.

Chapter 7

Conclusion

The overall objective of this thesis was to assess whether it would be beneficial for Klaveness to equip HFO purifiers with vibration monitoring equipment onboard their ships in a fleet-wide installation. In line with the research questions formulated, this thesis has analysed and determined the failures with the highest probabilities of occurrence and severity of consequences and described how these could be detected. The FMECA methodology was utilised for this purpose. Furthermore, several incident reports regarding HFO purifiers in the Klaveness fleet was analysed to determine what kind of information can be extracted from them and whether any of these incidents could have been detected by vibration monitoring. The analyses were carried out in parallel.

Due to a somewhat limited amount of incident reports with a detailed description of root causes, combined with the difficulty of obtaining relevant and applicable reliability data on failure mode level, the probability of occurrence was determined for the subsystems and their components instead. See Section 4.1.1 for a description of the subsystems and their sub-components.

The subsystem failing most frequently, constituting 14 out of the 44 analysed failures, is the power transmission system with an MTTF of 5.5 years, followed by the inlet and outlet system and electronic equipment (controllers and sensors), each with an MTTF of 9.7 years.

Considering failures on sub-component level, bearings and bearing housings fail most often, with an MTTF of 7.1 years. Then follows shafts, the solenoid valve (i.e. sensor block), the drive belt and separator bowl, each with an MTTF of 12.9 years. For a complete list of estimated failure rates for subsystems and components, see Table 5.1-5.5.

When looking at the severity of consequences, it can be seen that the most critical failures are those resulting in leakages in the system, potentially leading to fire or explosions with the possibility of spreading to other parts of the ship. A worst case scenario will result in multiple fatalities, downtime of more than two months and extraordinary costs incurred. However, vibration monitoring is not capable of detecting leakages. Other measures must be taken to reveal leakages. These measures could, for instance, be more frequent and thorough visual and internal inspections, and inspections with ultrasound equipment to reveal leaking valves.

The failures that could have been detected by vibration monitoring are mainly those related to the power transmission system, the electrical motor and unbalance of the separator bowl, which constitutes more than 60% of the total failures analysed. When looking at the distribution of failures of subsystems, it can be seen that more than half, 52%, of these most likely would have been detected by vibration monitoring. This number increase to 82% if failures related to electronic equipment and those involving leakages, which cannot be detected by vibration monitoring, are discarded. Going down one level, considering the different sub-components, 56% of the failures were either very likely or likely to have been detected by vibration monitoring. Also here, if incidents related to electronic equipment and leakages are discarded, this number increases to 79%. It is referred to Table 5.6 for a summary of the failures that could have been detected by VM for failure categories, subsystems, sub-components, immediate and root causes.

The thesis has shown that the most critical failures concerning the severity of consequences cannot be detected by VM. However, those failures that could potentially have been detected constitute more than half of the failures analysed. Among these, approximately 80% were either very likely or likely to have been detected. Furthermore, the top five sub-components that fail most often constitute 60% of the total number of failures, whereas 70% of these would most likely also have been detected by VM.

Based on the results of the distribution of failures, the author believes that a fleet-wide installation of vibration monitoring equipment of the HFO purifiers is a good and correct decision.

Chapter 8

Further Work and Recommendations

The information and data behind the results and conclusions are based on experiences and field data collected by Klaveness, information from the purifier manufacturer, discussions with providers of condition monitoring equipment, and relevant literature within the topic. It should be emphasised that the analyses may contain minor errors. Before a final decision is taken, some recommendations to further work are given.

First, due to the somewhat limited amount of data available, it would be beneficial to include incidents and failures regarding similar types of machinery, equipment and components onboard the ships. Increasing the amount of relevant data would increase the quality of the reliability estimations and bring further confidence to the final results. Secondly, it would be of interest to analyse the system reliability more thoroughly, for instance, by Monte Carlo simulations or Markov analysis. Furthermore, a life-cycle cost (LCC) analysis should be carried out to determine whether a fleet-wide installation of VM equipment on HFO purifiers is a cost-effective method to prevent failures.

Since an FMECA has already been conducted, it is also recommended that an analysis based on the Reliability Centered Maintenance (RCM) method (Moubray, 1997) is conducted, as this is usually based on the information obtained in an FMECA. RCM is a common method for identifying the most suitable maintenance type and frequency for various equipment. Such an analysis would help determine whether the current maintenance strategy is cost-optimal, or whether, and how, it could be more efficient.

Moreover, due to the severity of the most critical failures discovered in the FMECA, these should be further investigated, for example, by fault tree analysis (FTA) or event tree analysis (ETA). Following that, suitable measures for the prevention and detection of these should be assessed.

Finally, for Klaveness to benefit even more from the incident reports in the future, the recommendations discussed in Section 6.4 should be considered. These recommendations apply to both the structure and content of the reports.

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Bibliography

Ahmad, R. and Kamaruddin, S. (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering*, 63(1):135–149.

Alfa Laval (2018a). Separator manual - High speed separator P 615.

Alfa Laval (2018b). The Alfa Laval Adaptive Fuel Line.

Ashby, D. M. (2005). Diagnosing common causes of sealing failures. *Chemical Engineering*, 112(6):41–45.

Babicz, J. (2008). *Wärtsilä encyclopedia of ship technology*. Baobab Naval Consultancy.

Barszcz, T. (2019). *Vibration-Based Condition Monitoring of Wind Turbines*. Springer.

Bell, R., Heising, C., O'donnell, P., Singh, C., and Wells, S. (1985). Report of large motor reliability survey of industrial and commercial installations. ii. *IEEE Transactions on Industry applications*, 21(4):865–872.

Bellias, M. (2017). The evolution of maintenance. [Accessed 4 September 2018].

Blanchard, B. S., Verma, D. C., and Peterson, E. L. (1995). *Maintainability: a key to effective serviceability and maintenance management*, volume 13. John Wiley & Sons.

Bloch, Heinz P. ; Geitner, F. K. (2012). *Machinery Failure Analysis and Troubleshooting: Practical Machinery Management for Process Plants*, volume 2. Elsevier Science, 4 edition.

Bloch, H. P. and Budris, A. R. (2014). *Pump user's handbook: life extension*. Fairmont Press.

Bloch, H. P. and Geitner, F. K. (1997). *Practical Machinery Management for Process Plants: Volume 2: Machinery Failure Analysis and Troubleshooting*. Elsevier.

Bonnett, A. H. (2000). Root cause ac motor failure analysis with a focus on shaft failures. *IEEE transactions on industry applications*, 36(5):1435–1448.

Braun, S. et al. (1986). Mechanical signature analysis: theory and applications.

Brooks, C. and Choudhury, A. (1993). Fracture mechanisms and microfractographic features. *Metallurgical Failure Analysis; McGraw-Hill: New York, NY, USA*, pages 119–211.

Brown, D. (1985). Machine-condition monitoring using vibration analysis: a case study from a nuclear power-plant. *Brüel & Kjaer application notes*, (209):12.

Campos, J. (2009). Development in the application of ict in condition monitoring and maintenance. *Computers in industry*, 60(1):1–20.

Carnero, M. C. (2005). Selection of diagnostic techniques and instrumentation in a predictive maintenance program. a case study. *Decision support systems*, 38(4):539–555.

Cicek, K., Turan, H. H., Topcu, Y. I., and Searslan, M. N. (2010). Risk-based preventive maintenance planning using failure mode and effect analysis (fmea) for marine engine systems. In *2010 Second International Conference on Engineering System Management and Applications*, pages 1–6. IEEE.

Dhillon, B. (1989). *Life cycle costing: techniques, models and applications*. Routledge.

DNV GL (2014). The future of shipping.

DNV GL (2017). Creating Value from Data in Shipping - Practical Guide.

DNV GL (2019a). DNV GL rules for classification: Ships (RU-SHIP), Part 7 Fleet in service, Ch.1 Survey requirements for fleet in service. .

DNV GL (2019b). DNV GL rolls out remote surveys for all vessels. [Accessed 5 June 2019].

Dudley, B., Morris, S., and Feduccia, A. (1993). The rome laboratory reliability engineer's toolkit.

El Saddik, A. (2018). Digital twins: the convergence of multimedia technologies. *IEEE MultiMedia*, 25(2):87–92.

Faturachman, D., Mustafa, S., Octaviany, F., and Novita, T. D. (2014). Failure mode and effects analysis of diesel engine for ship navigation system improvement. *International Journal of Service Science, Management and Engineering*, 1(1):6–16.

Gates Corporation (2014). Check Your Drive Before You Wreck Your Drive. [Accessed 4 June 2019].

Hadi, S., Priharanto, and Latief (2018). Failure mode and effect analysis (fmea) applied for risk assessment of fuel oil system on diesel engine of fishing vessel.

Hameed, Z., Hong, Y., Cho, Y., Ahn, S., and Song, C. (2009). Condition monitoring and fault detection of wind turbines and related algorithms: A review. *Renewable and Sustainable energy reviews*, 13(1):1–39.

Henriksen, S. (2015). Sier nei til beaching av skip. [Accessed 19 September 2018].

Higgs, P. A., Parkin, R., Jackson, M., Al-Habaibeh, A., Zorriassatine, F., and Coy, J. (2004). A survey on condition monitoring systems in industry. In *ASME 7th Biennial Conference on Engineering Systems Design and Analysis*, pages 163–178. American Society of Mechanical Engineers.

Houtermans, M. and Capelle, T. V. (2007). Reliability engineering & data collection. In *Proceedings of the Second International Conference on Systems*, page 42. IEEE Computer Society.

IEEE (2016). IEEE 352-2016 - Guide for General Principles of Reliability Analysis of Nuclear Power Generating Station Systems and Other Nuclear Facilities. *2016*.

Inmarsat (2019). Global Xpress. [Accessed 8 April 2019].

Instrument, S. (2016). Maersk Line installs SPM online condition monitoring on container ships. [Accessed 23 April 2019].

International Maritime Organization (2010). International safety management code (ISM code) and guidelines on the implementation of the ISM code. *London: International Maritime Organization*.

JA1011, S. (1999). Evaluation criteria for reliability-centered maintenance (rcm) processes. *Society for Automotive Engineers*.

Jacobsen, N. H. (2016). Application of rcm principles to identify barriers in design of unmanned engine rooms for oceangoing merchant vessels. Master's thesis, NTNU.

Jardine, A. K., Lin, D., and Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical systems and signal processing*, 20(7):1483–1510.

Knutsen, K., Manno, G., and Vartdal, B. (2014). Beyond condition monitoring in the maritime industry. *DNV GL Strategic Research & Inovation Position Paper*.

Lazakis, I., Dikis, K., Michala, A. L., and Theotokatos, G. (2016). Advanced ship systems condition monitoring for enhanced inspection, maintenance and decision making in ship operations. *Transportation Research Procedia*, 14:1679–1688.

Linton, E. M. (2011). Coast guard reliability-centered maintenance. *Naval Engineers Journal*, 123(1):25–30.

Lipsith, G. (2019). Smarter than human? How AI is revolutionising maintenance. [Accessed 22 April 2019].

Lukat, R. (2015). Understanding Pressure Sensor Failure and Reliability. [Accessed 5 June 2019].

MARINTEK (2016). Possible hazards for engines and fuel systems using heavy fuel oil in cold climate. *2016*.

MarketsandMarkets Research Private Ltd. (2018). Machine condition monitoring market, by product (vibration monitoring, thermography, ultrasound emission, lubricating oil analysis, corrosion monitoring, and motor current signature analysis), component, application, and geography — global forecast to 2024. *2018*.

McHatton, D. (2017). How to turn equipment breakdown into golden opportunities. [Accessed 30 May 2019].

Military, U. (1949). Procedures for performing a failure mode, effects and criticality analysis, united states military procedure mil-p-1629. *1949*.

Mobley, R. K. (2002). *An introduction to predictive maintenance*. Elsevier.

Mokashi, A., Wang, J., and Vermar, A. (2002). A study of reliability-centred maintenance in maritime operations. *Marine Policy*, 26(5):325–335.

Moubray, J. (1997). *Reliability-centered maintenance*. Industrial Press Inc.

Naval Surface Warfare Center (2012). *Handbook of reliability prediction procedures for mechanical equipment*. Carderock Division, Naval Surface Warfare Center.

NEK (2018). NEK IEC 60812:2018 - Failure modes and effects analysis (FMEA and FMECA). *2018*.

Nowlan, F. S. and Heap, H. F. (1978). Reliability-centered maintenance. Technical report, United Air Lines Inc San Francisco Ca.

O'Donnell, P. (1985). Report of large motor reliability survey of industrial and commercial installations. i. *IEEE Transactions on Industry Applications*, 21(4):853–864.

O'Donnell, P., Heising, C., Singh, C., and Wells, S. (1987). Report of large motor reliability survey of industrial and commercial installations. iii. *IEEE Transactions on Industry Applications*, 23(1):153–158.

Oil Companies International Marine Forum (2019). About TMSA. [Accessed 20 May 2019].

Orhan, S., Aktürk, N., and Celik, V. (2006). Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies. *Ndt & E International*, 39(4):293–298.

Randall, R. B. (2011). *Vibration-based condition monitoring: industrial, aerospace and automotive applications*. John Wiley & Sons.

Rausand, M. and Høyland, A. (2004). *System reliability theory: models, statistical methods, and applications*, volume 396. John Wiley & Sons.

Raut, S. P. and Raut, L. P. (2014). A review of various techniques used for shaft failure analysis. *International Journal of Engineering Research and General Science*, 2(2):2091–2730.

Renwick, J. T. and Babson, P. E. (1985). Vibration analysis—a proven technique as a predictive maintenance tool. *IEEE Transactions on Industry Applications*, (2):324–332.

Sachs, N. (1993). Failure analysis of mechanical components. *Maintenance Technology*, 6(9):28–33.

Scheffer, C. and Girdhar, P. (2004). *Practical machinery vibration analysis and predictive maintenance*. Elsevier.

Selvik, J. T. and Aven, T. (2011). A framework for reliability and risk centered maintenance. *Reliability Engineering & System Safety*, 96(2):324–331.

Shiklo, B. (2018). A Digital Twin Approach to Predictive Maintenance. [Accessed 22 April 2019].

Shin, J.-H. and Jun, H.-B. (2015). On condition based maintenance policy. *Journal of Computational Design and Engineering*, 2(2):119–127.

Shorten, D. (2012). Marine machinery condition monitoring. why has the shipping industry been slow to adopt. *TECHNICAL INVESTIGATIONS DEPARTMENT (ed.). Lloyd's Register EMEA, United Kingdom*.

Sundberg, A. and Ab, S. (2003). Management aspects on condition based maintenance–the new opportunity for maritime industry. In *Proceedings of the 9th international conference on marine engineering systems*.

Sutton, I. (2014). *Process risk and reliability management*. Gulf Professional Publishing.

Tam, A., Chan, W., and Price, J. (2006). Optimal maintenance intervals for a multi-component system. *Production Planning and Control*, 17(8):769–779.

Tameson (2019). Solenoid valve troubleshooting: the most common failure modes. [Accessed 5 June 2019].

Thorsen, O. V. and Dalva, M. (1994). A survey of faults on induction motors in offshore oil industry, petrochemical industry, gas terminals and oil refineries. In *Proceedings of IEEE Petroleum and Chemical Industry Technical Conference (PCIC'94)*, pages 1–9. IEEE.

Van Horenbeek, A., Buré, J., Cattrysse, D., Pintelon, L., and Vansteenwegen, P. (2013). Joint maintenance and inventory optimization systems: A review. *International Journal of Production Economics*, 143(2):499–508.

Versicherungs-AG, A. (1978). *Handbook of loss prevention*. Springer.

Wabakken, I. (2015). Application of rcm to construct a maintenance program for a maritime vessel. Master's thesis, NTNU.

Wingrove, M. (2018). Five technologies to transform vessel maintenance. [Accessed 22 April 2019].

WNS (2019a). Top 3 Trends in Shipping and Logistics. [Accessed 15 April 2019].

WNS (2019b). Shipping and Logistics - Ocean Shipping Industry. [Accessed 15 April 2019].

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Appendix A

HFO Purifier System P&ID

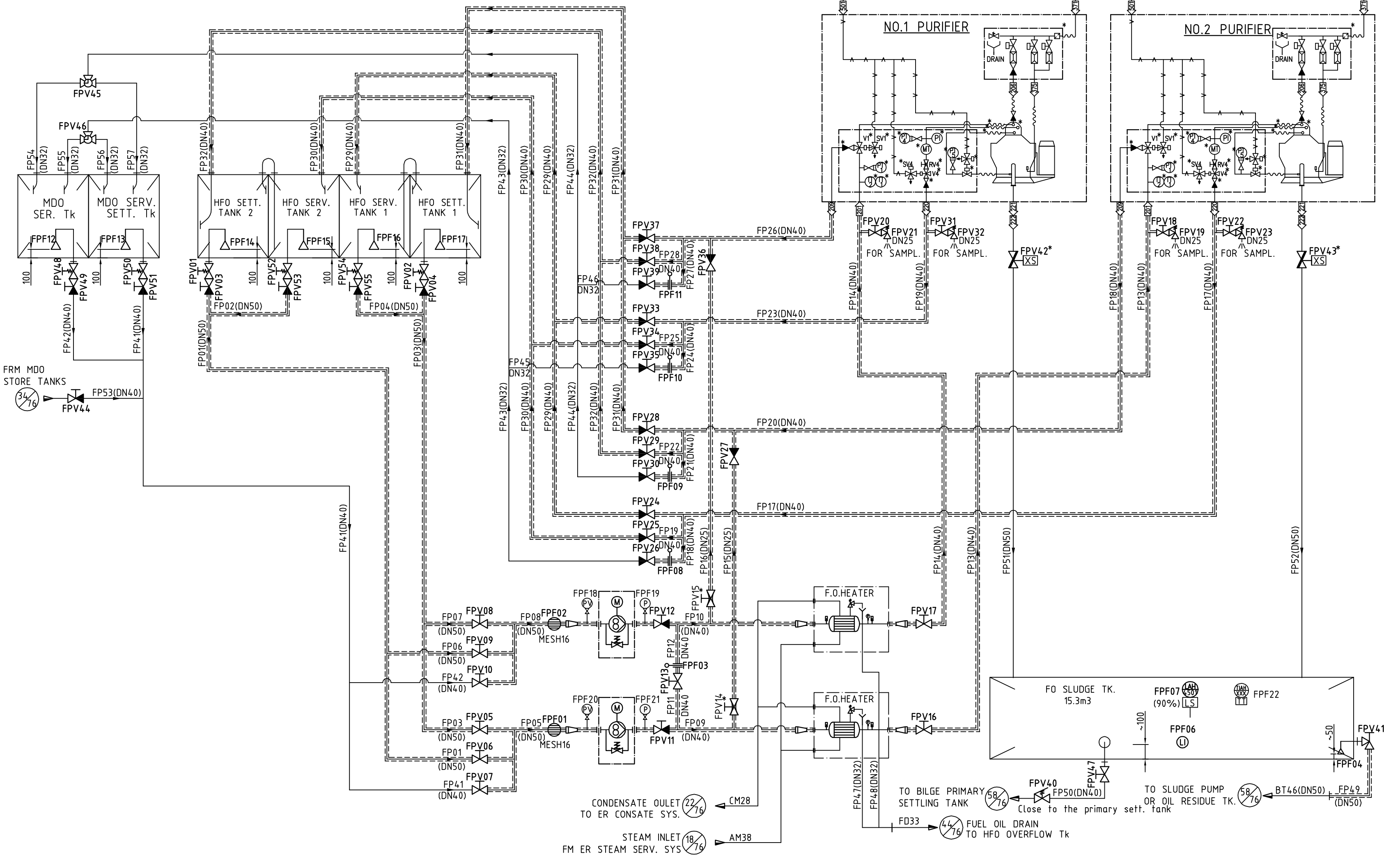
P&ID Fuel Oil Purifying System

See next page.

F.O PURIFYING SYSTEM	OH120 540 21	PAGE 38

FO PURIFIER CONNECTIONS:

NO.	DESCRIPTION	SIZE
201	FO INLET TO PURIFIER	DN25
209	OIL RECIRCULATION TO TK	DN25
220	CLEAN OIL OUTLET	DN25
221/222	WATER OUTLET/SLUDGE OUTLET	DN50
371	OPERATING WATER	DN25
501	OPERATING AIR	DN25

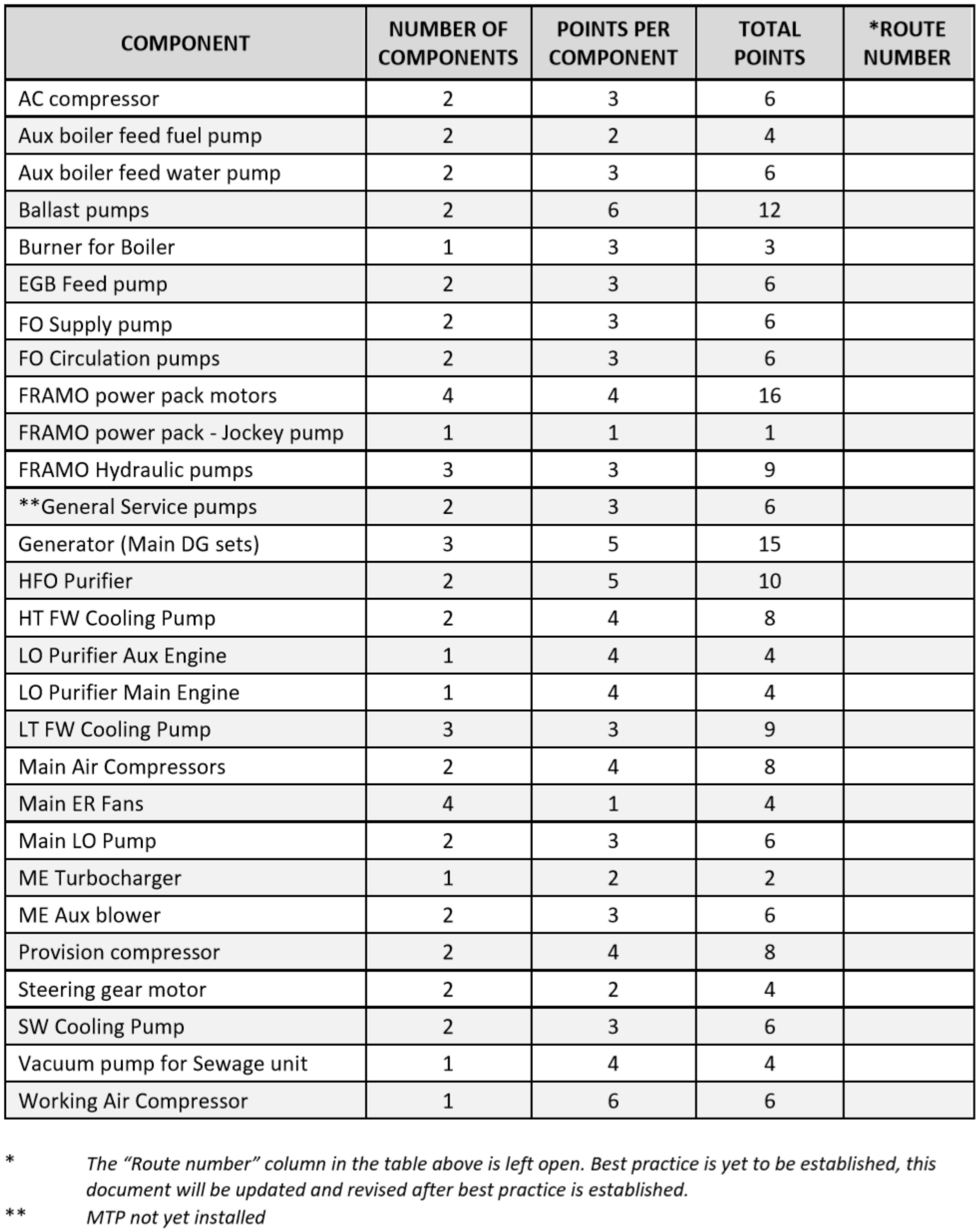


Appendix B

Condition Monitoring Pilot

List of Monitored Components

See next page.



COMPONENT	NUMBER OF COMPONENTS	POINTS PER COMPONENT	TOTAL POINTS	*ROUTE NUMBER
AC compressor	2	3	6	
Aux boiler feed fuel pump	2	2	4	
Aux boiler feed water pump	2	3	6	
Ballast pumps	2	6	12	
Burner for Boiler	1	3	3	
EGB Feed pump	2	3	6	
FO Supply pump	2	3	6	
FO Circulation pumps	2	3	6	
FRAMO power pack motors	4	4	16	
FRAMO power pack - Jockey pump	1	1	1	
FRAMO Hydraulic pumps	3	3	9	
**General Service pumps	2	3	6	
Generator (Main DG sets)	3	5	15	
HFO Purifier	2	5	10	
HT FW Cooling Pump	2	4	8	
LO Purifier Aux Engine	1	4	4	
LO Purifier Main Engine	1	4	4	
LT FW Cooling Pump	3	3	9	
Main Air Compressors	2	4	8	
Main ER Fans	4	1	4	
Main LO Pump	2	3	6	
ME Turbocharger	1	2	2	
ME Aux blower	2	3	6	
Provision compressor	2	4	8	
Steering gear motor	2	2	4	
SW Cooling Pump	2	3	6	
Vacuum pump for Sewage unit	1	4	4	
Working Air Compressor	1	6	6	

* *The "Route number" column in the table above is left open. Best practice is yet to be established, this document will be updated and revised after best practice is established.*

** *MTP not yet installed*

Figure B.1: List of monitored components in Klaveness' CM pilot project.

Appendix C

Incident Report

Incident Report Example

See the two subsequent pages.

Memo

Printed: 09.05.2019

HFO Separator Leakage

07.10.2018

Origin:	**Balao**	ID: BALO395
Category:	**Non Conformity, Balao**	
Ref.No.:		
SFI:	**4362 HEAVY FUEL OIL PURIFIER**	
Importance:	**Needs correction**	
Cause:	**Breakdown**	
Responsible:		

Prewarning: 06.11.2018 Deadline: 05.01.2019 Executed: 22.11.2018

Sections

[redacted] **22.11.2018 10.26.34**

CLOSED 22.11.2018 by [redacted]

CLOSING REMARK:
Good day 1Eng

Thanks for your report. I recomend that you place VRN for parts needed in spare.

IR closed from office side.

Reg [redacted]

[redacted] **23.10.2018 12.53.01**

Forwarding to SM.
[redacted]

Improvement Report

Incident date	05.10.2018
Subject	Engine room equipment / spares / maintenance
Department	Engine
Description	On 05.10.2018 In port of Melbourne, on checking routine in engine room, duty engineer found on HFO purifier in service fuel oil around. Purifier was immediately stopped. After isolate fuel and cleaning around we start to investigate problem. Was found that leakage was coming from inside Sensor Block from one Solenoid valve from discharge line. Also we noted that some leakage was coming from flexible hose from discharge line.
Personal Injury or Material Damage	Material damage
Corrective Action	Solenoid valve vas replaced with one valve new witch was spare on boad and flexible hose was taken from another HFO purifier in stand by.
Proposed preventive action	Solenoid valves and hose are working on high termperatore and need to inspected more oftern, also for flexible hoses IN-OUT no need to be in tension when are in operation.
Consequence if no corrective/preventive action	When engine room is unattended, we can have fuel oil spill in engine room.
Immediate cause	
Select from list	Defective equipment, machinery or tools
Remarks (optional)	Leakage was minor and purifier was not given alarm for low pressure discharge.

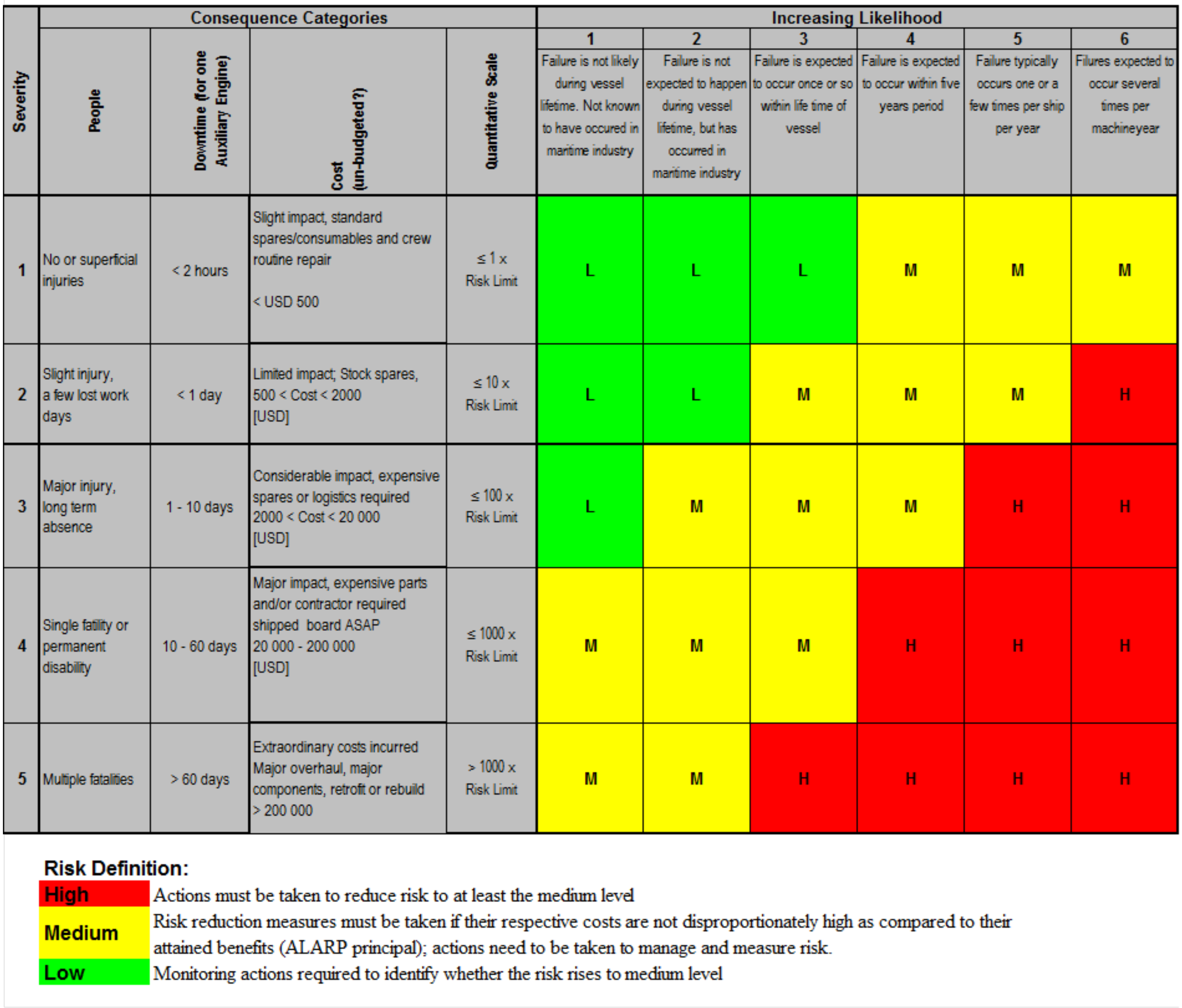
Root cause

Select from list	Excessive wear and tear
Remarks (optional)	

Control action needed

Select from list	Other (Add remark below)
Remarks (optional)	Spare parts need to be ordered and stored.

Risk Matrix



Severity	Consequence Categories				Increasing Likelihood					
	People	Downtime (for one Auxiliary Engine)	Cost (un-budgeted?)	Quantitative Scale	1 Failure is not likely during vessel lifetime. Not known to have occured in maritime industry	2 Failure is not expected to happen during vessel lifetime, but has occurred in maritime industry	3 Failure is expected to occur once or so within life time of vessel	4 Failure is expected to occur within five years period	5 Failure typically occurs one or a few times per ship per year	6 Filures expected to occur several times per machineyear
1	No or superficial injuries	< 2 hours	Slight impact, standard spares/consumables and crew routine repair < USD 500	≤ 1 x Risk Limit	L	L	L	M	M	M
2	Slight injury, a few lost work days	< 1 day	Limited impact; Stock spares, 500 < Cost < 2000 [USD]	≤ 10 x Risk Limit	L	L	M	M	M	H
3	Major injury, long term absence	1 - 10 days	Considerable impact, expensive spares or logistics required 2000 < Cost < 20 000 [USD]	≤ 100 x Risk Limit	L	M	M	M	H	H
4	Single fatlity or permanent disability	10 - 60 days	Major impact, expensive parts and/or contractor required shipped board ASAP 20 000 - 200 000 [USD]	≤ 1000 x Risk Limit	M	M	M	H	H	H
5	Multiple fatalities	> 60 days	Extraordinary costs incurred Major overhaul, major components, retrofit or rebuild > 200 000	> 1000 x Risk Limit	M	M	H	H	H	H

Risk Definition:

High	Actions must be taken to reduce risk to at least the medium level
Medium	Risk reduction measures must be taken if their respective costs are not disproportionately high as compared to their attained benefits (ALARP principal); actions need to be taken to manage and measure risk.
Low	Monitoring actions required to identify whether the risk rises to medium level

Figure C.1: Risk Matrix.

Appendix D

Results

FMECA Worksheet, Next Level Effects

The FMECA worksheet considering the consequences of next level effects can be seen in the subsequent four pages.

			Description of failure			Effect of failure				Consequences		
Component	Function	Sub-component	Failure mode	Failure cause or mechanism	Detection of failure	Local effect	Next level effect	Hidden/evident	Probability of occurrence	Safety	Downtime	Cost
Power transmission	Transmission of power between electrical motor and separator	Belt	Improper operating tension	Installation error	Vibration monitoring	Excessive vibrations and eventual belt failure	HFO purifier not operational, no stand-by in case of emergency	Evident	L (3)	L (3,1)	M (3,3)	M (3,3)
			Pulley/sheave misalignment	Installation error	Vibration monitoring, internal inspection	Belt cracking and eventual failure						
			Worn pulley/sheave	Incorrect tension		Rapid wear rate on belt						
			Foreign objects in belt drive assembly	Operating environment		Belt wear and eventual failure						
			Belt slip	Insufficient tension	Vibration monitoring, internal inspection, listening	Excessive wear on belt						
			Belt fatigue	Excessive tensions	Vibration monitoring, internal inspection	Broken belt						
			Chemical contamination	Operating environment		Belt wear and eventual failure						
		Bowl spindle	See component "Shafts"		Vibration monitoring	Damaged or broken spindle	HFO purifier not operational, no stand-by in case of emergency	Evident				
		Friction coupling	Worn flexing element or shaft bushings	Excessive shaft misalignment	Vibration monitoring, internal inspection	Damaged or broken friction coupling	HFO purifier not operational, no stand-by in case of emergency	Evident				
			Ruptured elastomeric flexing element, sheared hub pins or teeth	Torsional shock overload	Vibration monitoring, internal inspection							
			Fatigue of flexing element, hub pins, or discs	Excessive starts and stops, torsional vibration	Vibration monitoring, internal inspection							
			Shaft bearing failure	Lubricant failure, excessive shaft misalignment, operational temperature extremes	Vibration monitoring, internal inspection							
			Loose hubs on shaft	Torsional shock overload, high peak-to-peak torsional overload	Vibration monitoring, internal inspection							
			Worn gear teeth	Lubrication failure, high peak-to-peak overload	Vibration monitoring, internal inspection							
			High pitched hammering or clacking noise	Excessive shaft misalignment, loose hubs or bolt connections, lubricant failure	Vibration monitoring, listening							
			Swollen, distorted, or cracked elastomeric flexing member, severe hub corrosion	Chemical attack, excessive heat	Vibration monitoring, internal inspection							
Electrical motor	Drive the separator via a belt power transmission	Rotor	Sheared armature shaft, cracked rotor laminations	Fatigue, misalignment, bearing failure	Performance monitoring, internal inspection	Seized, armature rubbing stator	HFO purifier not operational, no stand-by in case of emergency	Evident	L (2)	L (2,1)	M (2,3)	M (2,3)
		Bearings	Worn bearing	Excessive static load, belt misalignment, frequent starts and stops under heavy loads, lubrication problem, contamination, overloading or high temperature	Vibration monitoring, internal inspection	Noisy, heat buildup, armature rubbing stator, motor seized	HFO purifier not operational, no stand-by in case of emergency	Evident	L (3)	L (3,1)	M (3,3)	M (3,3)
			Bearing failure	Shaft misalignment, incorrect coupling, belt misalignment, incorrect belt tension, worn bearing	Vibration monitoring, internal inspection	Noisy operation, motor failure		Evident				
		Windings	Open/shorted winding	Insulation breakdown, high ambient temperature, high altitude, mechanical overload, frequent stops and starts, dirt buildup on cooling fins, vibration, mechanical schock	Performance monitoring, internal inspection	Motor won't start, motor failure, sparking at brushes	HFO purifier not operational, no stand-by in case of emergency	Evident	L (2)	L (2,1)	M (2,3)	M (2,3)
		Brushes	Worn brushes (fail to open)	Improper maintenance, contamination, high temperature, improper contact pressure	Performance monitoring, listening	Excessive sparking, chatter or hissing noise, motor runs too fast or too slow under load, motor won't run	HFO purifier not operational, no stand-by in case of emergency	Evident				
		Shaft	See "Shafts" under "General".		Vibration monitoring	See "Shafts" under "General".	HFO purifier not operational, no stand-by in case of emergency					
		Other	Cracked housing	Fatigue, external shock, vibration	Vibration monitoring, visual inspection	Leakage of dust into motor, shorted or seized	HFO purifier not operational, no stand-by in case of emergency	Evident				
			Noisy operation	Worn or bent shaft, shaft alignment, mechanical vibration, base plate distortion, broken motor mounts	Vibration monitoring, listening	Heat buildup		Evident				
			Motor overheating	Frequent starts, incorrect supply voltage, high ambient temperature, polyphase voltage unbalance >1%, motor overload, blocked ventilation	Thermography, internal inspection	Short motor life, motor failure		Evident				
			Overload tripping	Incorrect supply voltage, excessive load speed	Alarm function, performance monitoring, functional test	Motor won't start		Evident				

Inlet and outlet, frame	Feed untreated oil to and discharge treated oil from the separator bowl	Pipe (inlet/outlet)	Damaged connector	Corrosion, improper torque on fitting, gasket failure	Visual inspection, performance monitoring	Gradual increase in system leakage, fire and explosion	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage may in worst case result in fire and explosion.	Evident	L (2)	M (2,4)	M (2,4)	M (2,4)
			Burst failure	Rapidly applied load, pressure transients		Catastrophic pipe assembly failure, fire and explosion hazard						
			Buckling failure	Insufficient piping supports		Immediate leakage above system requirements, fire and explosion hazard						
			Bending failure	Bend radius less than allowable		Immediate leakage above system requirements, fire and explosion hazard						
			Crack in rigid pipe	External stress		System leakage, fire and explosion hazard						
			Leakage	Chemical attack/improper thread sealant		Gradual increase in system leakage, fire and explosion hazard						
			Fatigue failure	Water hammer from upstream component		System fluid leakage, fire and explosion hazard						
		Hose	Excessive fluid temperature	High fluid temperature caused by excessive flow velocity	Thermography	Premature hose failure, fire and explosion hazard	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage might in worst case result in fire and explosion.	Evident				
			Fractured hose	Excessively small bend radius, hose bend immediately behind the coupling	Visual inspection, performance monitoring	Reduced ability to withstand internal pressure, fire and explosion hazard						
			Hose leakage	Continuous exposure to high temperature, chemical deterioration	Visual inspection, performance monitoring	Loss of hose flexibility, fire and explosion hazard						
			Inner tube failure	Inadequate compatibility with fluid	Performance monitoring, internal inspection	Eventual hose failure, fire and explosion hazard		Hidden				
		Solenoid valve (sensor block)	Leakage	Dirt particles (cuttings/rust/sand) on the valve seat or in orifices	Visual and internal inspection	Improper flow, gradual increase in system leakage, fire and explosion hazard	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage might in worst case result in fire and explosion.	Evident	L (3)	M (3,4)	M (3,4)	M (3,4)
			Damaged seal	Damaged or worn membranes, seals and O-rings	Visual and internal inspection	Improper flow, the valve does not shut off or leaks, fire and explosion hazard		Evident				
			Not opening/closing correctly	Bad power supply (incorrect voltage and frequency) or connections, flow direction does not match with indicators on the valve, pressure are outside the specified limits, damaged or burnt out coil	Performance monitoring, alarm function	No/wrong fuel output/discharge	The HFO purifier is inoperative, no stand-by in case of emergency. A not properly functioning purifier might cause damage to main machinery.	Hidden		L (3,1)	M (3,3)	M (3,4)
Separator bowl	Separate water, foreign matter and sludge from HFO by centrifugal force	General	Leakage	Poor sealing between bowl hood seal ring and the edge of the sliding bowl bottom	Visual inspection, internal inspection, performance monitoring	System leakage, fire and explosion hazard	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage might in worst case result in fire and explosion.	Evident	L (3)	M (3,4)	M (3,4)	M (3,4)
			Clogged bowl, blockage	Bad quality of bunkered HFO (contaminated)	Performance monitoring, internal inspection, alarm function	HFO purifier not working	HFO purifier not operational, no stand-by in case of emergency	Evident		L (3,1)	M (3,3)	M (3,3)
			Unbalanced bowl	Uneven sediment accumulation in bowl, insufficient pressure in the disc stack	Vibration monitoring	Abnormal vibration, too high stress on bowl and bearing (shortened life)		Evident				

Controller & Sensors	Controlling and monitor the operation of the separator, perform all necessary alarm functions	Controller	Incorrect settings	Altered settings because of human error	Alarm function, functional test, casual observation	HFO purifier not functioning properly	Controller or sensor errors can cause damage to the HFO purifier, making it inoperative. No stand-by purifier in case of emergency	Hidden	L (3)	L (3,1)	M (3,3)	M (3,3)
			Malfunctioning	Problem with main circuit board or electronic module		Controller is not operational						
		Sensors (individual)	Incorrect signal from sensor element	Reduced signal level, impedance mismatch, A/D conversion error	Alarm function, functional test, performance monitoring, casual observation	Potential processing error	Controller or sensor errors can cause damage to the HFO purifier, making it inoperative. No stand-by purifier in case of emergency	Hidden				
			Loss of signal from sensor element	Chip failure, corroded sensor		Loss of signal to processor		Evident				
			Complete loss of signal in transmission line	Broken or disconnected wire		Loss of signal to processor						
			Signal error in transmission line	Power line interference		Potential processing error		Hidden				
			Incorrect signal in computation device	Error in algorithm		Processing error						
			Power supply loss of voltage	Power supply malfunction		Loss of signal to processor		Evident				
			Improper response to information recipient	Incorrect interpretation, system malfunction, error in algorithm		Potential system malfunction		Hidden				
			Calibration error	Software error, error in algorithm		Potential system malfunction						
			Battery energy depletion	Battery malfunction		Loss of signal to processor						
Parts found in several of the components are described below:												
Bearings, ball/roller (not el. motor)	Reduce friction between moving components, support loads and guide components turning relative to one another	N/A	Fatigue damage	*Mechanism:* Spalling of raceway, brinelling, smearing. *Cause* : Heavy, prolonged load, excessive speed, shock load, excessive vibration	Vibration monitoring, internal inspection	Bearing wear and eventual bearing failure	HFO purifier not operational, no stand-by in case of emergency	Evident	L (3)	L (3,1)	M (3,3)	M (3,3)
			Noisy bearing	*Mechanism* : Surface fatigue, glazing, microspalling of stressed surfaces. *Cause* : Loss of lubricant, housing bore out of round, corrosive agents, distorted bearing seals								
			Bearing seizure	*Mechanism* : Crack formation on rings and balls/rollers, skidding. *Cause* : Inadequate heat removal capability, loss of lubricant, high temperature, excessive speed,								
			Bearing vibration	*Mechanism* : Scuffing, fretting, pitting of surfaces. *Cause* : Misalignment, housing bore out of round, unbalanced / excessive load, inadequate housing support								
			Presence of electric currents	*Mechanism* : Pits on raceways and balls, corrosion. *Cause* : Extensive pitting of surface caused by electric current								

Shafts (not el. motor)	Transmit power between two parts, or between a source that produces power to the machine absorbing it	N/A	Bent shaft	Excessive load/torque, impact loads, bearing failure	Vibration monitoring, internal inspection	Assembly vibration, damaged bearing, impeller, wear ring, mechanical seal, gear box	HFO purifier not operational, no stand-by in case of emergency	Evident	L (3)	L (3,1)	M (3,3)	M (3,3)
			Excessive shaft deflection	Dynamic load on shaft, reversing loads, critical shaft speed exceeded, unbalanced load		Eventual shaft damage, damaged bearing, impeller, wear ring, mechanical seal, gear						
			Shaft misalignment	Improper assembly, worn bearings, excessive load		Assembly vibration, damaged bearing, impeller, wear ring, mechanical seal, gear box						
			Damaged surface finish	Corrosion, contaminants, manufacturing process, thermal expansion at high temperatures		Shaft bearing failure						
			Shaft fatigue/fracture	Stress riser at fillet, stress concentration at keyway, shaft radii changes, bending fatigue, excessive velocity, high torque load		Damaged bearing, impeller, wear ring, mechanical seal, gear box						
			Fretting corrosion	Relative movements of tightly fitted parts		Surface cracks, eventual shaft failure, bearing/gear/coupling corrosion						
Static seals and gaskets	Join systems together by preventing leakage, contain pressure, or exclude contamination	N/A	Leakage	Wear due to: contaminants, misalignment, vibration or poor surface finish	Visual inspection, internal inspection, performance monitoring, alarm function	Broken seal or gasket causing leakage, fire and explosion hazard	The HFO purifier is inoperative, no stand-by in case of emergency. Leakage might in worst case result in fire and explosion.	Evident	L (2)	M (2,4)	M (2,4)	M (2,4)
				Elastic deformation or gasket/seal distortion due to: extreme temperature, misalignment, seal eccentricity, extreme loading/extrusion or compression set/overtorqued bolts								
				Surface damage or embrittlement due to: inadequate lubrication, contaminants, fluid/seal degradation, thermal degradation, idle periods between component use, exposure to atmosphere/ozone, excessive temperature								
				Creep due to: fluid pressure surges, material degradation, thermal expansion & contraction								
				Compression set due to: excessive squeeze to achieve seal, incomplete vulcanization, hardening/high temperature								
				Installation damage due to: insufficient lead-in chamfer, sharp corners on mating metal parts, inadequate protection of spares								

FMECA Worksheet, Global Effects

The FMECA worksheet considering the consequences of global effects can be seen in the subsequent four pages.

			Description of failure			Effect of failure				Consequences		
Component	Function	Sub-component	Failure mode	Failure cause or mechanism	Detection of failure	Local effect	Global effect	Hidden/evident	Probability of occurrence	Safety	Downtime	Cost
Power transmission	Transmission of power between electrical motor and separator	Belt	Improper operating tension	Installation error	Vibration monitoring	Excessive vibrations and eventual belt failure	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (2)	L (2,1)	M (2,3)	M (2,4)
			Pulley/sheave misalignment	Installation error	Vibration monitoring, internal inspection	Belt cracking and eventual failure						
			Worn pulley/sheave	Incorrect tension		Rapid wear rate on belt						
			Foreign objects in belt drive assembly	Operating environment		Belt wear and eventual failure						
			Belt slip	Insufficient tension	Vibration monitoring, internal inspection, listening	Excessive wear on belt						
			Belt fatigue	Excessive tensions	Vibration monitoring, internal inspection	Broken belt						
			Chemical contamination	Operating environment		Belt wear and eventual failure						
		Bowl spindle	See component "Shafts"		Vibration monitoring	Damaged or broken spindle		Evident				
		Friction coupling	Worn flexing element or shaft bushings	Excessive shaft misalignment	Vibration monitoring, internal inspection	Damaged or broken friction coupling		Evident				
			Ruptured elastomeric flexing element, sheared hub pins or teeth	Torsional shock overload	Vibration monitoring, internal inspection							
			Fatigue of flexing element, hub pins, or discs	Excessive starts and stops, torsional vibration	Vibration monitoring, internal inspection							
			Shaft bearing failure	Lubricant failure, excessive shaft misalignment, operational temperature extremes	Vibration monitoring, internal inspection							
			Loose hubs on shaft	Torsional shock overload, high peak-to-peak torsional overload	Vibration monitoring, internal inspection							
			Worn gear teeth	Lubrication failure, high peak-to-peak overload	Vibration monitoring, internal inspection							
			High pitched hammering or clacking noise	Excessive shaft misalignment, loose hubs or bolt connections, lubricant failure	Vibration monitoring, listening							
			Swollen, distorted, or cracked elastomeric flexing member, severe hub corrosion	Chemical attack, excessive heat	Vibration monitoring, internal inspection							
Electrical motor	Drive the separator via a belt power transmission	Rotor	Sheared armature shaft, cracked rotor laminations	Fatigue, misalignment, bearing failure	Performance monitoring, internal inspection	Seized, armature rubbing stator	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (2)	L (2,1)	M (2,3)	M (2,4)
		Bearings	Worn bearing	Excessive static load, belt misalignment, frequent starts and stops under heavy loads, lubrication problem, contamination, overloading or high temperature	Vibration monitoring, internal inspection	Noisy, heat buildup, armature rubbing stator, motor seized		Evident				
			Bearing failure	Shaft misalignment, incorrect coupling, belt misalignment, incorrect belt tension, worn bearing	Vibration monitoring, internal inspection	Noisy operation, motor failure		Evident				
		Windings	Open/shorted winding	Insulation breakdown, high ambient temperature, high altitude, mechanical overload, frequent stops and starts, dirt buildup on cooling fins, vibration, mechanical schock	Performance monitoring, internal inspection	Motor won't start, motor failure, sparking at brushes		Evident				
		Brushes	Worn brushes (fail to open)	Improper maintenance, contamination, high temperature, improper contact pressure	Performance monitoring, listening	Excessive sparking, chatter or hissing noise, motor runs too fast or too slow under load, motor won't run		Evident				
		Shaft	See "Shafts" under "General".		Vibration monitoring	See "Shafts" under "General".						
		Other	Cracked housing	Fatigue, external shock, vibration	Vibration monitoring, visual inspection	Leakage of dust into motor, shorted or seized		Evident				
			Noisy operation	Worn or bent shaft, shaft alignment, mechanical vibration, base plate distortion, broken motor mounts	Vibration monitoring, listening	Heat buildup		Evident				
			Motor overheating	Frequent starts, incorrect supply voltage, high ambient temperature, polyphase voltage unbalance >1%, motor overload, blocked ventilation	Thermography, internal inspection	Short motor life, motor failure		Evident				
			Overload tripping	Incorrect supply voltage, excessive load speed	Alarm function, performance monitoring, functional test	Motor won't start		Evident				

Inlet and outlet, frame	Feed untreated oil to and discharge treated oil from the separator bowl	Pipe (inlet/outlet)	Damaged connector	Corrosion, improper torque on fitting, gasket failure	Visual inspection, performance monitoring	Gradual increase in system leakage, fire and explosion	Fire/explosions may spread and lead to further major injuries or fatalities, evacuation might be necessary. Long downtime and major/extraordinary costs as a result of the need for major overhaul, major components, retrofit or rebuilld can be expected.	Evident	L (2)	M (2,5)	M (2,5)	M (2,5)
			Burst failure	Rapidly applied load, pressure transients		Catastrophic pipe assembly failure, fire and explosion hazard						
			Buckling failure	Insufficient piping supports		Immediate leakage above system requirements, fire and explosion hazard						
			Bending failure	Bend radius less than allowable		Immediate leakage above system requirements, fire and explosion hazard						
			Crack in rigid pipe	External stress		System leakage, fire and explosion hazard						
			Leakage	Chemical attack/improper thread sealant		Gradual increase in system leakage, fire and explosion hazard						
			Fatigue failure	Water hammer from upstream component		System fluid leakage, fire and explosion hazard						
		Hose	Excessive fluid temperature	High fluid temperature caused by excessive flow velocity	Thermography	Premature hose failure, fire and explosion hazard		Evident				
			Fractured hose	Excessively small bend radius, hose bend immediately behind the coupling	Visual inspection, performance monitoring	Reduced ability to withstand internal pressure, fire and explosion hazard						
			Hose leakage	Continuous exposure to high temperature, chemical deterioration	Visual inspection, performance monitoring	Loss of hose flexibility, fire and explosion hazard						
			Inner tube failure	Inadequate compatibility with fluid	Performance monitoring, internal inspection	Eventual hose failure, fire and explosion hazard		Hidden				
		Solenoid valve (sensor block)	Leakage	Dirt particles (cuttings/rust/sand) on the valve seat or in orifices	Visual and internal inspection	Improper flow, gradual increase in system leakage, fire and explosion hazard		Evident	L (3)	M (3,5)	M (3,5)	M (3,5)
			Damaged seal	Damaged or worn membranes, seals and O-rings	Visual and internal inspection	Improper flow, the valve does not shut off or leaks, fire and explosion hazard		Evident				
			Not opening/closing correctly	Bad power supply (incorrect voltage and frequency) or connections, flow direction does not match with indicators on the valve, pressure are outside the specified limits, damaged or burnt out coil	Alarm function, functional test, performance monitoring	No/wrong fuel output/discharge	Improper purification may cause reduced combustion efficiency or breakdown of fuel pumps or the main engine. Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion	Hidden		L (3,1)	M (3,3)	M (3,4)
Separator bowl	Separate water, foreign matter and sludge from HFO by centrifugal force	General	Leakage	Poor sealing between bowl hood seal ring and the edge of the sliding bowl bottom	Visual inspection, internal inspection, performance monitoring	System leakage, fire and explosion hazard	Fire/explosions may spread and lead to further major injuries or fatalities, evacuation might be necessary. Long downtime and major/extraordinary costs as a result of the need for major overhaul, major components, retrofit or rebuilld can be expected.	Evident	L (2)	M (2,5)	M (2,5)	M (2,5)
			Clogged bowl, blockage	Bad quality of bunkered HFO (contaminated)	Performance monitoring, internal inspection, alarm function	HFO purifier not working	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (3)	L (3,1)	M (3,3)	M (3,4)
			Unbalanced bowl	Uneven sediment accumulation in bowl, insufficient pressure in the disc stack	Vibration monitoring	Abnormal vibration, too high stress on bowl and bearing (shortened life)		Evident				

Controller & Sensors	Controlling and monitor the operation of the separator, perform all necessary alarm functions	Controller	Incorrect settings	Altered settings because of human error	Alarm function, functional test, casual observation	HFO purifier not functioning properly	Improper purification may cause reduced combustion efficiency or breakdown of fuel pumps or the main engine. Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Hidden	L (3)	L (3,1)	M (3,3)	M (3,4)
			Malfunctioning	Problem with main circuit board or electronic module		Controller is not operational						
		Sensors (individual)	Incorrect signal from sensor element	Reduced signal level, impedance mismatch, A/D conversion error	Alarm function, functional test, performance monitoring, casual observation	Potential processing error		Hidden				
			Loss of signal from sensor element	Chip failure, corroded sensor		Loss of signal to processor		Evident				
			Complete loss of signal in transmission line	Broken or disconnected wire		Loss of signal to processor						
			Signal error in transmission line	Power line interference		Potential processing error		Hidden				
			Incorrect signal in computation device	Error in algorithm		Processing error						
			Power supply loss of voltage	Power supply malfunction		Loss of signal to processor		Evident				
			Improper response to information recipient	Incorrect interpretation, system malfunction, error in algorithm		Potential system malfunction		Hidden				
			Calibration error	Software error, error in algorithm		Potential system malfunction						
			Battery energy depletion	Battery malfunction		Loss of signal to processor						
Parts found in several of the components are described below:												
Bearings, ball/roller (not el. motor)	Reduce friction between moving components, support loads and guide components turning relative to one another	N/A	Fatigue damage	*Mechanism:* Spalling of raceway, brinelling, smearing. *Cause* : Heavy, prolonged load, excessive speed, shock load, excessive vibration	Vibration monitoring, internal inspection	Bearing wear and eventual bearing failure	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (3)	L (3,1)	M (3,3)	M (3,4)
			Noisy bearing	*Mechanism* : Surface fatigue, glazing, microspalling of stressed surfaces. *Cause* : Loss of lubricant, housing bore out of round, corrosive agents, distorted bearing seals								
			Bearing seizure	*Mechanism* : Crack formation on rings and balls/rollers, skidding. *Cause* : Inadequate heat removal capability, loss of lubricant, high temperature, excessive speed.								
			Bearing vibration	*Mechanism* : Scuffing, fretting, pitting of surfaces. *Cause* : Misalignment, housing bore out of round, unbalanced / excessive load, inadequate housing support								
			Presence of electric currents	*Mechanism* : Pits on raceways and balls, corrosion. *Cause* : Extensive pitting of surface caused by electric current								

Shafts (not el. motor)	Transmit power between two parts, or between a source that produces power to the machine absorbing it	N/A	Bent shaft	Excessive load/torque, impact loads, bearing failure	Vibration monitoring, internal inspection	Assembly vibration, damaged bearing, impeller, wear ring, mechanical seal, gear box	Two inoperative HFO purifiers will eventually lead to fuel shortage and loss of propulsion.	Evident	L (3)	L (3,1)	M (3,3)	M (3,4)
			Excessive shaft deflection	Dynamic load on shaft, reversing loads, critical shaft speed exceeded, unbalanced load		Eventual shaft damage, damaged bearing, impeller, wear ring, mechanical seal, gear						
			Shaft misalignment	Improper assembly, worn bearings, excessive load		Assembly vibration, damaged bearing, impeller, wear ring, mechanical seal, gear box						
			Damaged surface finish	Corrosion, contaminants, manufacturing process, thermal expansion at high temperatures		Shaft bearing failure						
			Shaft fatigue/fracture	Stress riser at fillet, stress concentration at keyway, shaft radii changes, bending fatigue, excessive velocity, high torque load		Damaged bearing, impeller, wear ring, mechanical seal, gear box						
			Fretting corrosion	Relative movements of tightly fitted parts		Surface cracks, eventual shaft failure, bearing/gear/coupling corrosion						
Static seals and gaskets	Join systems together by preventing leakage, contain pressure, or exclude contamination	N/A	Leakage	Wear due to: contaminants, misalignment, vibration or poor surface finish Elastic deformation or gasket/seal distortion due to: extreme temperature, misalignment, seal eccentricity, extreme loading/extrusion or compression set/overtorqued bolts Surface damage or embrittlement due to: inadequate lubrication, contaminants, fluid/seal degradation, thermal degradation, idle periods between component use, exposure to atmosphere/ozone, excessive temperature Creep due to: fluid pressure surges, material degradation, thermal expansion & contraction Compression set due to: excessive squeeze to achieve seal, incomplete vulcanization, hardening/high temperature Installation damage due to: insufficient lead-in chamfer, sharp corners on mating metal parts, inadequate protection of spares	Visual inspection, internal inspection, performance monitoring, alarm function	Broken seal or gasket causing leakage, fire and explosion hazard	Fire may spread and lead to further major injuries or fatalities, evacuation might be necessary. Long downtime and major/extraordinary costs as a result of the need for major overhaul, major components, retrofit or rebuild can be expected.	Evident	L (2)	M (2,5)	M (2,5)	M (2,5)

Incident Report Analysis

See next page.

Title	ID	Origin	Event Date	Category	Importance	Equipment	Main component	Immediate cause	Root cause	Discovered by VM?
HFO Purifier settings	BURD621	MV Bardu	19.04.2019	Non Conformity	Needs attention	Water Monitoring System	Electronic equipment	Incorrect use of machinery or equipment	Lack of skill/knowledge	Not likely
FO Purifier No. 2	BURD320	MV Bardu	22.08.2016	Non Conformity	Needs correction	Drive belt	Power transmission	Defective equipment, machinery or tools	Inadequate maintenance	Very likely
Cleaning Purifier Plates	KLAV1139	MV Barry	22.11.2013	Non Conformity	Needs correction	N/A	N/A	Negligence of safety	Lack of skill/knowledge	N/A
Electric motor bearing housing	STR-10KO1H0	MV Banastar	12.10.2012	Near Accident	Needs attention	Bearing housing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Likely
HFO Purifier No. 2	STR-10KU25P	MV Banastar	15.10.2012	Non Conformity	Needs attention	Bottom bearing	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
						Vertical shaft/spindle				Very likely
						Bowl Body	Separator bowl			Likely
Burned HFO Purifier Electric Motor	ALMA151	MV Bangor	01.10.2014	Non Conformity	Needs correction	Bearing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
HFO Purifer	ALMA367	MV Bangor	26.09.2016	Non Conformity	Needs correction	Sliding bowl bottom	Separator bowl	Failure to follow repair/maintenance instructions	Lack of skill/knowledge	Not likely
HFO Purifier No.2 Belt Pulley	ALMA537	MV Bangor	05.10.2017	Non Conformity	Needs correction	Friction coupling/block/pad	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Likely
						Belt pulley				Likely
HFO Purifier Breakdown	ALMA612	MV Bangor	01.09.2018	Non Conformity	Needs correction	Bowl	Separator bowl	Bunkers and/or lubricating oils	Received substandard fuel	Not likely
Worn Out Belt Pulley of HFO Purifier	ALMA700	MV Bangor	01.04.2019	Non Conformity	Needs correction	Friction coupling/block/pad	Power transmission	Failure to follow repair/maintenance instructions	Excessive wear and tear	Likely
						Belt pulley				Likely
HFO Purifier High Temp. on Crankcas Oil	BALO196	MV Balao	22.03.2016	Near Accident	Needs attention	Sight glass	Power transmission	Wrong installation of parts, failure to follow repair/maintenance instructions	Lack of skill/knowledge	Not likely
						Vertical shaft/spindle				Likely
						Vertical shaft spacer				Likely
						Bearing housing (separator)				Likely
HFO Separator Leakage	BALO395	MV Balao	05.10.2018	Non Conformity	Needs correction	Sensor block (solenoid valve)	Inlet/outlet	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
						Flexible hose (discharge line)	Inlet/outlet			Not likely
FO Purifier No. 2 damage parts after maintenance	BANA169	MV Banak	01.09.2015	Non Conformity	Needs correction	Centripetal pump chamber cover	N/A	Failure to follow repair/maintenance instructions	Inadequate work standards	Not likely
						Sensing liquid pump				Not likely
Oil and water coming out of the HFO purifier sensor block	BANA244	MV Banak	18.06.2016	Non Conformity	Needs correction	Sensor block	Inlet/outlet	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
HFO Purifier no. 2 leaking 3-way pneumatic valve	BANA566	MV Banak	01.04.2019	Non Conformity	Needs Correction	3-way valve (pneumatic valve)	Inlet/outlet	Noise or temperature	Excessive wear and tear	Not likely
						Shaft seal	Power transmission			Not likely
0093 FO Purifier No. 1 Speed Sensor	BANT45	MV Bantry	06.09.2013	Suggestion for Improvement	Needs correction	Speed sensor	Electronic equipment	Speed sensor failure	Excessive wear and tear (electronic)	Not likely
011 EPC 50 controller HFO Purifier No. 1 malfunction	BANT201	MV Bantry	02.02.2015	Non Conformity	Needs correction	Controller	Electronic equipment	Controller failure	Excessive wear and tear (electronic)	Not likely
Fire Hazard in Purifier Room	BANT395	MV Bantry	10.01.2017	Near Accident	Needs correction	N/A	N/A	Negligence of safety	Lack of skill/knowledge	N/A
FO Purifier No. 2 Speed Sensor Cable	BDAL249	MV Bakkedal	02.06.2015	Non Conformity	Needs correction	Speed sensor (cable)	Electronic equipment	Speed sensor failure	Lack of technical awareness. Unprotected cable wire installation.	Not likely
FO Purifier Special Tool	BDAL257	MV Bakkedal	23.06.2015	Non Conformity	Needs attention	Special tool	Other	Defective equipment, machinery or tools	Lack of skill/knowledge	N/A
FO Purifier Temperature Controller Malfunction	BDAL332	MV Bakkedal	12.03.2016	Near Accident	Needs correction	Temperature controller	Electronic equipment	High FO temperature on feed pump	Temperature controller failure	Not likely
HFO Purifier No. 2 breakdown	BDAL339	MV Bakkedal	22.04.2016	Non Conformity	Needs attention	Fan (shaft), vertical shaft/spindle, upper ball bearing	Power transmission	Failure to follow repair/maintenance instructions	Lack of skill/knowledge	Likely
Lock Ring of HFO Purifier in Bad Condition	BDAL366	MV Bakkedal	27.09.2016	Near Accident	Needs correction	Drive belt	Power transmission	Failure to follow repair/maintenance instructions	Lack of skill/knowledge	Very likely
						Bowl lock ring	Separator bowl			Likely
HFO Purifier 1 & 2 EPC Front Module Trouble	BDAL486	MV Bakkedal	28.06.2017	Near Accident	Needs correction	Controller	Electronic equipment	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
HFO Purifier No. 1 Wing Insert	BIYS298	MV Barcarena	21.02.2016	Non Conformity	Needs correction	Wing insert	Separator bowl	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
FO. Purifier No. 2 Belt Pulley	BIYS311	MV Barcarena	11.04.2016	Non Conformity	Needs correction	Bearings (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
						Friction coupling/block/pad	Power transmission			Likely
						Belt pulley				Likely
HFO Purifier Electric Motor Shaft worn out	BIYS534	MV Barcarena	27.04.2018	Non Conformity	Needs attention	Shaft (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
Broken Drive Belt of Fuel Oil Purifier	BLEA24	MV Baleares	12.03.2014	Non Conformity	Needs correction	Drive belt	Power transmission	Unable to attain required speed	Broken drive belt	Very likely
HFO Purifier leaks fuel in solenoid valve	BLEA312	MV Baleares	20.09.2016	Non Conformity	Needs correction	Sensor block (solenoid valve)	Inlet/outlet	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
HFO Purifier No. 2 Belt worn out	BLEA403	MV Baleares	04.05.2017	Non Conformity	Needs correction	Drive belt	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
HFO Purifier #1 Belt worn out and Vertical Shaft bearing damage	BLEA439	MV Baleares	21.08.2017	Non Conformity	Needs correction	Drive belt	Power transmission	Other substandard condition, or lubricating oils	Excessive wear and tear	Very likely
						Vertical shaft bearing				Very likely
HFO Purifier No. 1 Sensor Block Failure	BLEA516	MV Baleares	25.09.2018	Non Conformity	Needs correction	Sensor block (solenoid valve)	Inlet/outlet	Solenoid valve and wiring defective	Excessive wear and tear	Not likely
HFO Purifier No. 1 Sensor Block Damaged	BLSA568	MV Balsa	18.07.2017	Non Conformity	Needs attention	Sensor block (solenoid valve)	Inlet/outlet	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
						Pressure transmitter				Not likely
HFO Purifier No. 2 Solenoid valve of Sensor block worn out	BLSA571	MV Balsa	04.08.2017	Non Conformity	Needs attention	Sensor block (solenoid valve)	Inlet/outlet	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
HFO Purifier No. 1	BRRY525	MV Barry	10.06.2017	Non Conformity	Needs correction	Controller	Electronic equipment	Defective equipment, machinery or tools	Excessive wear and tear	Not likely
No Stby HFO Purifier and Special Tools Missing	BRRY613	MV Barry	26.11.2017	Non Conformity	Needs correction	Special tool	Other	Special tools missing	Inadequate work standards	N/A
HFO Purifier No. 1	BRRY690	MV Barry	18.07.2018	Non Conformity	Needs correction	Bowl	Separator bowl	Failure to warn	Excessive wear and tear	Not likely
						Controller	Electronic equipment			Not likely
HFO Purifier No. 2	BRRY694	MV Barry	21.07.2018	Non Conformity	Needs correction	Drive belt	Power transmission	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
						Vertical shaft/spindle				Very likely
HFO Purifier No. 2 Breakdown	BRRY794	MV Barry	28.01.2019	Non Conformity	Needs attention	Bowl	Separator bowl	Failure to follow repair/maintenance instructions	Excessive wear and tear	Likely
						Vertical shaft/spindle	Power transmission			Very likely
						Bearings				Very likely
#244 FO Purifier Electric Motor Breakdown	BSOL241	MV Banasol	01.04.2015	Non Conformity	Needs correction	Lower ball bearing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Bad quality of ball bearing	Very likely
						Rotor (el. motor)				Very likely
						Stator winding (el. motor)				Very likely
FO Purifier Electric Motor	BSOL378	MV Banasol	19.06.2016	Non Conformity	Needs correction	Bearing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely
No. 2 Fuel oil purifier Electric Motor	BSTR236	MV Banastar	30.09.2015	Non Conformity	Needs correction	Bearing (el. motor)	Electrical motor	Defective equipment, machinery or tools	Excessive wear and tear	Very likely