Identifying and eliminating weak points in ship's machinery plants

A step towards continuously unmanned engine rooms

J.P. Colon
Marine Technology – SDPO - Ship design
SDPO.17.042.m

Identifying and eliminating weak points in ship's machinery plants

A step towards continuously unmanned engine rooms

By

J.P. Colon

To obtain the degree of Master of Science at the Delft University of Technology

Student number: 4079027

Thesis committee:	Prof. ir. J.J. Hopman	TU Delft
	Dr. ir. R.G. Hekkenberg MSc	TU Delft, supervisor
	Dr. ir. H.P.M. Veeke	TU Delft

Delft, January 9, 2018

Front cover photo: Engine room of the Pioneering Spirit, by J.P.Colon

Abstract

Autonomous sailing is considered by many to be the next big thing in the shipping sector. Many companies, including Rolls Royce and DNV are investing heavily in research that helps in the development of autonomous shipping. Most research is currently being done regarding autonomous navigation, communication and cyber security. What is often neglected in these studies is the need for maintenance within the engine room. With all ships having multiple crew members solely dedicated to keep the engine room going, their absence will have a big impact on the design of engine rooms.

This paper aims to find what equipment will become a weak point in engine rooms once these are no longer occupied and maintained by crew members, and how these weak points can be eliminated. With the absence of reliability data that corrects for maintenance and crew interference, this paper tries to find these weak points by analysing crew member behaviour. It is assumed that if a crew members spends more time on equipment, or deals with it more frequently, then that piece of equipment is less reliable.

In order to find what equipment can be seen as a weak point, a redundancy reduced risk index was created. This index is a combination of the frequency index, which states how often engineers spend time on equipment, the severity index, which lists the consequences of failure for equipment, and the redundancy index, which is dependent on the level of redundancy of components. The redundancy reduced risk index is split into three levels: low, medium, and high risk. Medium and high-risk components were considered weak points, while low risk components were not.

For all high risk and for most medium risk components, solutions were generated which will reduce the risk index of the components or system overall. For some components, the risk was deemed acceptable, as any solutions would be too costly to justify the risk reduction. Solutions were split into two categories: specific solutions, which were all catered to specific components, and a bulk solution, which was the installation of a second drive train. A second drive train would include a second main engine, gearbox, propeller and rudder.

With the solutions found, the two categories were subjected to a financial analysis to see if they are commercially viable. The solutions were applied to ships of four different sizes, ranging from a 6,000 GT feeder to an 85,000 GT capesize bulk carrier. For these ships, the OPEX were calculated and divided into four categories: Operational costs, fuel costs, capital costs and crew costs. The initial investment for the machinery plant was also calculated. This was the basis to finding the increased cost for solutions found in this paper.

Using these specific solutions, the machinery plants will become roughly 50% more expensive, while adding a second drive train will increase the machinery cost by 110%. It is assumed that these solutions will eliminate the need for a crew and therefore eliminate all crew costs. Using these figures, it was found that the specific solutions will lead to a potential yearly savings of $600,000.– for all ship sizes, and adding a second drive train will lead to a potential yearly savings of $500,000 – for the small ship and $163,000.– for the larger ships.

With both the specific solutions and the second drive train, the machinery plant is deemed reliable enough for continuously unmanned operation, which proves the technical feasibility of continuously unmanned engine rooms.

Acknowledgements

A lot of time and effort, as well as many frustrations have been put into the end result of this thesis. There are some people whom without I could not have done it within a reasonable time, or at all. I would like to thank them here.

First of all, I would like to thank my daily supervisor, Robert Hekkenberg, whose remarks and our many discussions have led to valuable insights which helped raise this thesis to a new level. His support helped me through the difficult starting period and kept me thinking positively when things did not go as planned.

I would also like to thank Sven Oosterwaal and Frank Homan from Anthony Veder, as well as Gaby Steentjes from Marin for being so kind in helping me validate this research, as well as providing me with the basis needed for this paper.

Next, I would also like to thank Ruude te Selle and Martin de Koning who provided me with the right contacts I needed for my research, and helped me get on board ships to aid me with my research

Many thanks go to my girlfriend, Yasmin, who made me lots of cups of coffee when I needed them the most, and helped me back up whenever I was down. The fact that this thesis lies in front of you today, can mostly be accredited to her constant encouragement and support, it could not have been done without her.

Contents

List of figures

List of tables

List of symbols

Symbol	**Meaning**	**Unit**
F	Frequency	$[yr\text{-}1]$
R	Risk	$[\text{-}]$
S	Severity	$[\text{-}]$
RI	Risk Index	$[\text{-}]$
FI	Frequency Index	$[\text{-}]$
SI	Severity Index	$[\text{-}]$
$P(F)$	Chance of failure	$[\text{-}]$
TBF	Time between failures	$[s]$
TBR	Time between repairs	$[s]$
$\dot{m}$	Fuel usage	$[ton/day]$
c	Constant	$[\text{-}]$
∇	Displacement	$m3$
CGT	Compensated Gross Tonnage	$[ton]$
GT	Gross Tonnage	$[ton]$
A	Constant	$[\text{-}]$
B	Constant	$[\text{-}]$

List of abbreviations

Abbreviation	**Meaning**
ALARP	As low as reasonably possible
CAPEX	capital expenses
CGT	Compensated Gross Tonnage
CM	Condition Monitoring
CW	Cooling Water
DE	Diesel-Electric
DNV GL	Det Norske Veritas Germanischer Lloyd
ECA	Emission Controlled Area
FI	Frequency Index
FO	Fuel Oil
GT	Gross Tonnage
HFO	Heavy Fuel Oil
HT	High Temperature
IFO380	Intermediate Fuel Oil
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
LO	Lubrication Oil
LT	Low temperature
MDO	Marine Diesel Oil
OPEX	Operational Expenses
OREDA	The offshore and Onshore Reliability Data project
R&D	Research & Development
RBI	Risk-Based Inspection
RCM	Reliability Centred Maintenance
RI	Risk Index
RRRI	Reliability Reduced Risk Index
SI	Severity Index
SW	Seawater
ULSFO	Ultra Low Sulphur Fuel Oil

1 Introduction

This chapter will give an introduction the paper. The first paragraph gives the reason for considering autonomous shipping. Paragraph 2 reflects on past projects on autonomous shipping. Paragraph 3 describes the problem discussed in this paper, and tells why weak points are hard to identify. Next, the fourth paragraph describes the paper goals, and the fifth paragraph defines the scope of the paper.

1.1 Why consider autonomous shipping?

The concept of autonomous shipping has been around for decades, but interest has peaked over the last few years. There are a few reasons for this. Since the economic collapse in 2008 and current low shipping rates and fuel prices, personnel costs account for a larger cut of the OPEX than they did previously. According to Rødseth, personnel can account for up to 36% of the total OPEX, and will only rise and become more dominant in the age of slow steaming. [1].

Next to cutting costs, the shipping sector is having increased difficulty in finding enough personnel willing to spend months on board of a ship, with a projected shortage of up to 150.000 officers for the world's fleet by 2025. [2] [3]. Eliminating personnel on board and moving them to a shore based control centre would increase the attractiveness of work in the shipping sector.

The concept of autonomous transport has been tried by the automotive industry, and they are ever coming closer to fully autonomous vehicles. Although many challenges still exist, public acceptance of self-driving cars has increased dramatically. Many cars already possess some form of autonomous driving, ranging from lane keeping abilities to fully autonomous navigation. The aviation sector has been using auto-pilots for decades now, and it seems only a logical step for the shipping sector to follow suit.

It has been theorized that autonomous shipping could improve safety as well. Several studies reported that 65 to 96% of all marine accidents are caused by human error [4]. A lot of accidents happen due to fatigue or boredom, both of which are not a problem for machines. However, mixing manned and unmanned vessels could pose a challenge. Next to that, unmanned shipping will probably lead to other sorts of accidents, which may not be foreseeable at the moment. It would be too easy to say that eliminating the human factor would increase safety by 65 to 96%, as humans are also responsible for solving and preventing a lot of problems. Because most of these problems go unreported or undocumented, it is hard to say how much safety would improve.

However, making ships autonomous poses other challenges than those found in the automotive and aviation sectors. For the automotive industry, making cars autonomous means replacing one person: the driver. For the aviation industry, if the stewards are disregarded, making planes autonomous would replace two or three pilots. For ships, it often means replacing a crew of 14 to 20 people. Similarly, for cars, the sole purpose of the driver is to navigate safely from A to B. Pilots perform mostly navigational tasks as well. For both these sectors, maintenance is done in between operational hours, in specialized locations, by people who do not travel with the vehicle. For the crew of a ship, navigation is the main concern for crew on the bridge, but other crew members are responsible for things like maintenance, cargo handling and mooring, while the ship is operational. For a ship to be fully automated, all of these tasks have to be accounted for.

1.2 Past projects on autonomous shipping

One of the first large scale projects that has been done to investigate the possibilities and viability of autonomous shipping is the MUNIN project conducted under the 7th framework of the European Commission (unmanned-ship.org). Rolls Royce is currently doing research as well in their AAWA project [5]. DNV GL has designed the ReVolt ship concept as a proof of concept for autonomous ships. [6]

Both MUNIN and AAWA focus on navigation and communication, and are more focused towards autonomous ships, which are not necessarily unmanned. However, when trying to design a completely unmanned ship, more problems arise than just navigation and communication. Many tasks that are currently done by a ship's crew are not so easily replaced by a machine. Examples of these tasks include handling mooring lines and cargo, as well as performing maintenance and repairing broken equipment.

Of these tasks, especially maintenance and repair seems to be something that is often neglected in studies into autonomous shipping. It is mostly assumed that different maintenance strategies are the solution to this problem. The AAWA states that the systems on board of an autonomous ship *"need to be designed to be resilient to failure and extended maintenance intervals"*[5]. The findings of MUNIN include that *"Current preventative maintenance procedures need to be updated to ensure operability during intervals at sea for components that currently have been designed to be replaceable during voyage."*[1]. DNV GL tries to dodge the problem altogether by removing all moving parts from the ship and switch to electric propulsion based on batteries which are charged when the ship calls at a port. [6]

However, equipping engine rooms with equipment that is resistant to failure or placing batteries will require significant investments. Equipment that never (or very rarely) breaks down, or equipment with long maintenance intervals is more expensive than current equipment. It might not even be available due to a lack of demand from ship owners. DNV GL's ReVolt's batteries alone are estimated to cost around 10.00USD/kWh. With 5.5 MWh installed, this means the batteries will cost 5.5 million USD, and will have to be replaced at least once during its 30-year lifespan. They say the initial CAPEX of the ship will be about 1.5 million USD more than of a conventional ship. Note that this is for a ship of only 60 meters in length, which suggest capital investments in batteries for larger ships will be even more. [7]

1.3 The problem of identifying weak points in engine rooms

The easiest solution to overcome unexpected failures of machinery, is to install a completely redundant machinery plant. If all machinery has an identical twin, which can operate completely separately, then anything that fails will always have a backup. An alternative to installing completely redundant engine rooms, is to install redundancies or redesigns for components or equipment which are weak points in the system. In this paper, we define the term weak point as follows:

Weak point: *A (part of) a system within a machinery plant that poses a high risk for the continuation of service if not attended to by the crew.*

Since risk is probability multiplied by consequence, a component that has a high risk of causing system failure is high risk because the chance of it breaking down is high, or because the consequences of breakdown are large. Weak points can be identified by checking breakdown records and seeing what the most common cause of failure is. Brocken has performed an extensive study on breakdowns of ships in German waters, and found that most breakdowns were connected to the main engine and the steering mechanism. [8]

However, breakdown records do not document failures which are prevented or solved by a crews' interference, nor do they document partial failure. They could therefore be a false representation of possible weak points. When crew can no longer interfere with machinery, the number of weak points in an engine room will rise, as machinery that might not have been a problem before, because it was easy to deal with for the crew, could become a problem when there is no crew on board. In order to be able to design a machinery plant that is properly equipped for unmanned shipping, all of the weak points, including these new ones, must be identified and dealt with. Another way to look at possible weak points in machinery plants, including undocumented ones, is to see what equipment requires maintenance or repair the most often.

Most maintenance is predictable and performed according to maintenance strategies as found in paragraph 2.3.4. It usually comes down to maintenance that has to be done after a certain amount of time has passed. Equipment usually comes with a repair schedule, where certain maintenance has to be done every time a certain time interval has passed. For example, maintenance plans can include 3-monthly maintenance, that has to be done every 3 months, as well as yearly maintenance, which has to be done every year. Most equipment gets a major overhaul every couple of years, usually between 2 and 5 years, where it is completely taken apart and certain components are replaced, even if they're not broken. Maintenance schedules are usually provided by the manufacturer, but are often not readily available to the public, and therefore hard to quantify.

With most equipment having a 3-monthly maintenance cycle, the question arises why an autonomous ship shouldn't just sail into port for maintenance every 3 months, have all the maintenance done, and continue on its way. There are several reasons why this might not work. First of all, not all equipment has a 3-monthly maintenance cycle. This means that some equipment would have to last longer than intended, while other equipment might have to be maintained earlier than necessary. Secondly, as paragraph 2.3.4 explains, most failures that occur are due to infant mortalities. Failures due to infant mortalities can occur when a product is brand new, but can also occur after equipment has been taken apart for maintenance. By maintaining equipment more often than necessary, not only extra costs are made, but possible extra risks are introduced as well. An example would be that of the Dutch navy, where reducing the maintenance interval of certain equipment reduced the number of failures, as most were introduced right after maintenance.

Unplanned maintenance, although the name suggests otherwise, can sometimes be predicted, but usually not far in advance. Machinery often gives some warning before complete failure. This warning can be in the form of an actual warning from a sensor, or by emitting more heat or noise. More advanced sensing techniques have led to an increased time range at which faults can be predicted. However, with some exceptions, most techniques have not come so far that required maintenance can be predicted weeks in advance.

For most equipment, it is hard to find how often they need to be maintained, as it is often proprietary knowledge. It is even harder to find out how often equipment needs to be repaired, as it is often simply unknown. When asked about what equipment breaks down the most, all engineers that participated in the interviews conducted for this paper, answered with 'it depends'. Where every ship had its own faults, and some equipment that worked perfectly on one ship, broke down constantly on another. The only other way to find out what equipment needs attention more often, is then by finding out what equipment actually gets the most attention from engineers.

By analysing an engineers' workday, it should be possible to find out what equipment gets most of their attention, which could be a good indication of what machinery could be a weak point. Unfortunately, most engineers do not keep a record of their work. Most of the time, schedules are available, but these are often interrupted by unforeseen tasks, such as emergency repairs. These tasks often do not get documented either.

This poses a problem: it is not possible to find out what components can be weak points through breakdown records, as they cannot be applied to unmanned ships; they always take crew in account. Similarly, weak points cannot be found either by analysing their maintenance intervals, as these are often proprietary knowledge. The next step would be analysing what engineers actually do, but their schedules are inaccurate, if kept at all. Finally, the last thing that can be tried is to estimate how often engineers perform certain tasks, and linking this to reliability.

This paper assumes there is a correlation between how much time an engineer spends on certain equipment, and how reliable that equipment is. If someone expected that their car was about to break down, they would check up on it more often than someone who fully trusts their car to work all the time. The same can be expected of engineers: if they assume a part is about to break down, or if a component has a tendency to unexpectedly stop working, they will automatically check up on that component more often. Using this method, the reliability of individual components can be estimated and quantified, which can then be used to find weak points.

1.4 Project goals

The goal of this paper is to find possible weak points in engine rooms, which will cause the most problems for unmanned ships, and provide solutions to eliminate these weak points. The most interesting weak points are those that will have the highest risk. Failures that lead to loss of propulsion, manoeuvring capabilities or loss of power, are the most important ones. These weak points will be tracked down by analysing how often on-board engineers spend time on equipment.

This will be done by setting up a risk index, which combines a frequency and a severity index. The frequency index will be a list of how often engineers pay attention to certain machinery, divided over several activities. It is assumed that engineers pay attention to machines that are more prone to failure more frequently. The severity index will list the consequences of failure per machine. To compensate for redundant equipment, the risk index will be used to create the Redundancy Reduced Risk Index (RRRI). The RRRI can be an indication of what equipment will cause the most problems when they're left unattended at sea. After finding weak spots, an attempt will be made to find solutions to these problems, as well as the financial viability of these solutions for different sizes of ships.

1.5 Scope

Due to time constraints in this research, it will not be possible to find weak points and their solutions for every type of ship within the world fleet. Since most specialized ships, such as dredgers, lifting vessels or pipe-laying vessels are dependent on their crew for things other than navigation and movement, it is highly unlikely that they will ever be unmanned, at least in the foreseeable future. Therefore, this paper will focus on merchant ships only. It is probable that the first autonomous vessels will be short sea vessels. Both Rolls Royce's AAWA and DNV GL’s ReVolt are short sea ships, and therefore this paper will focus on merchant vessels used for short sea shipping. It is assumed these vessels will either be coasters or feeders in European waters. For the solution finding phase, larger ships will be taken into account as well to find the financial viability of unmanned shipping for larger sized vessels.

This paper will not try to find all weak points on an entire ship, but will focus on the machinery plant. The focus will be on machinery within the engine room and steering mechanism. Machinery spanning the entire ship, such as the firefighting and ballast systems, will not be taken into account. Due to the disparity between mechanical and electrical components within engine rooms, as well as the lack of expertise of the author in electrical systems, they will be touched upon briefly, but only be taken into account in general terms.

2 Problem definition and literature

This chapter will give the outline of this paper. First of all, an overview is given of the current tasks that are performed by engineers in machinery plants. Next, an outline of the actual problem is given. Third, current literature on the subject is given and the knowledge gap is found. Lastly, the research question and sub questions are defined.

2.1 Current tasks performed by engineers in machinery plants

To be able to properly assess weak points in engine rooms, it is important to know what tasks are currently performed by engineers. When it is known what engineers do all day, it is possible to find out which tasks are important. When engine rooms become unmanned, the engineers won't be able to perform these tasks. The absence of some actions and tasks will have a bigger impact on unmanned engine rooms than others.

In the current situation, most commercial ships have at least 4 crew members dedicated to the engine room. Their tasks can be broken down into four major categories:

1. Checking and observing equipment.
2. Maintaining equipment (performing planned maintenance)
3. Repairing equipment (performing unplanned maintenance)
4. Operating equipment

Engineers check the condition of most machinery and equipment at least once per day. They observe the state and status of machinery, and try to find any defects that might be present. Whenever sensors report a faulty piece of equipment, they check it out to see what is wrong. Most of the observations are done by sight, but an engineer uses all senses to identify problems. For instance, an engineer can smell smoke, or taste water leaks whether they are salt or fresh water. An engineer can sense heat coming off equipment, or feel vibrations.

If equipment requires maintenance, it is usually an engineer's job to perform it. For some equipment, an external service engineer is brought in to perform maintenance. Maintenance is performed based on manuals and an engineers' insight. The maintenance interval is determined depending on the maintenance strategy as discussed in paragraph 2.3.4. In this paper, maintenance is defined as planned maintenance, which can be predicted and scheduled.

Unplanned maintenance means that engineers are required to repair or maintain equipment before it is required according to the maintenance schedule. In most cases this means that equipment has broken, and a human is required to get it back to working order. Unplanned maintenance can be critical, meaning it needs to be done at the next possible moment, or non-critical, meaning it can wait until a convenient time to repair it. Criticality is usually determined by the consequences of the breakdown of equipment.

Although most equipment can be controlled remotely from the bridge, some equipment still needs the physical presence of an engineer in the engine room to operate. In some cases, engineers prefer to operate equipment directly instead of remotely, as it is usually easier to detect any problems with machinery when standing right next to them

Equipment is often outfitted with sensors that can read and determine that status of equipment, which it relays to the control room or bridge. The control room is often situated near the engine room and is a way for engineers to escape from the heat and noise that are often present in engine rooms. The sensors will notify engineers when they detect problems with machinery. The engineer will then try to find out what is wrong.

2.2 Problem definition

There are still many hurdles to overcome before unmanned ships can become a reality. One of these hurdles is the reliability of engine room machinery. Since there is no one on board to repair things when they break, it is important that unmanned vessel is reliable enough to ensure continuity in case of failure. On manned vessels, engineers in the engine room ensure this continuity; an option that is no longer available on unmanned vessels.

The problem with current reliability records of ships, is that they all take engineers and regular maintenance into account. Reliability records such as OREDA [9] only register defect equipment, even with maintenance, but do not register near-misses or equipment that would have broken down if engineers had not intervened. Any data that is available is therefore skewed and not usable to make accurate prediction regarding reliability of unmanned vessels. This paper will attempt to fill in the missing piece of data by collecting data about the influence of engineers on reliability. In doing so, weak points for autonomous engine rooms will be identified, as the equipment that currently requires the most attention of engineers is assumed to be less reliable when there are no engineers around. The end result of this paper will be a list of weak points in engine rooms, and suggestions on how to design engine rooms in such a way that these weak points are eliminated as much as possible.

2.3 Literature

As this paper is about finding and solving weak points in unmanned engine rooms, it is important to know what the literature says about multiple subjects. The first paragraph will give an overview of past and current research regarding autonomous shipping. Next, the duties of engineers, which will have to be replaced or dealt with on autonomous ships, are listed. As there are already some rules in place regarding unmanned machine rooms, they are given and discussed in the third paragraph. As most of an engineer's duties consist of performing maintenance, the fourth paragraph discusses maintenance strategies and product lifecycles. Lastly, the knowledge gap and reason for this paper is defined.

2.3.1 On autonomous shipping

One of the first large project concerning autonomous shipping is the MUNIN project (Maritime Unmanned Navigation through Intelligence in Networks), which finished in 2016 and was led by Frauenhofer CML [10]. The AAWA (the Advanced Autonomous Waterborne Application Initiative), which is done by Rolls Royce Marine [5] is another large project. Both projects envision an autonomous ship capable of sailing the world by itself, albeit with supervision from an On-shore Control Centre (OCC). The role of the OCC is to provide top-level instructions to the ship and to take over control in situations where the ship is unable to assess or react to a situation. DNV GL is also working on an autonomous vessel, the ReVolt, which is fully electric.

The MUNIN project mostly focused on remote sensing, exploring the possibilities for ships to become aware of their surroundings and react accordingly. They touched other subjects as well, including ship-to-shore communication but also repair and maintenance. With regard to maintenance and repair, their solution would be to work out a maintenance strategy that works for unmanned shipping and switching to equipment that is more reliable. They have also want to implement an Autonomous Engine and Monitoring and Control system, which will be able to autonomously control the engine room and deal with emergencies. [11] The biggest change to the engine room that they propose, is switching to distillate, so called 'clean' fuels. The main reason for this was to eliminate the need for switching between fuel when leaving and entering Emission Controlled Areas (ECAs), which was a risk *'… too high for an autonomous operation.'* [12]. The conclusions about autonomous navigation were positive, where a demonstration at the end of the project proved that objects, both small and large, were observable and identifiable at sufficient range for the ship to react and navigate around the obstacles.[2],[1], [4], [13], [14]

The AAWA has four primary focus points. The first point is to ensure the ship has a situational awareness and can navigate autonomously. The second point explores the legal side of unmanned ships. The third focal point explores the safety and security of the ship with regard to external threats such as piracy. They also touch briefly on the subject of reliability of machinery, but only state that it needs to be improved. The last point is commercial viability. In order to make autonomous shipping interesting for companies, we need to know if it is commercially viable. Their initial conclusion is that it should be possible with the current technologies, but that there is a lot of work to be done in the legal department. The challenges are mostly in combining these technologies in a commercially viable way, and the ability to adapt regulations to allow for autonomous shipping. Their vision is to have the first remotely controlled ship by the end of the decade. [5]

DNV GL's ReVolt suggests that the maintenance problem can be solved by going fully electric. The design has no rotating parts within the ship's hull; electric motors are fitted within azimuth thrusters. By minimizing the number of moving parts, they minimize maintenance. Although the initial investment for all the batteries is substantial, they claim that the ReVolt could save up to 34 million USD over its 30-year lifespan. [6], [7]

As can be seen, both MUNIN and AAWA only touch briefly on the maintenance and repair side of autonomous shipping, leaving it as a problem that will be looked at more closely in a later stage of developments. Early adaptations for engine rooms are mostly a combination of increasing the redundancy of the entire system and switching to cleaner fuels. MUNIN predicts that switching to cleaner fuels will result in a net higher cost than with regular ships, as cleaner fuels are much more expensive. The only way to save money would be to alter ship designs in such a way that they become more fuel efficient as well. A worst-case scenario pictures a loss of almost 30 million USD over a projected lifetime, almost all of it coming from the higher price of using MDO instead of HFO. A best-case scenario estimates a savings of more than 23 million USD over a ships lifetime. Other estimates range between a savings of 1 to 8 million USD. [15]

The Danish Maritime Authority has asked the Technical University of Denmark (DTU) to do a pre-analysis on autonomous shipping. Their focus was mainly on ferries, as Denmark has a lot of them, many of which are due for replacement soon. Because ferries usually do short distance trips, and spend relatively long periods in port, they seem to be the ideal candidate for electrical propulsion. Electrical propulsion requires much less maintenance than diesel based systems, and is much more reliable. They propose that if ferries were to sail autonomously, using an electric propulsion plant powered by batteries charged in port would be the best way to go. [16]

2.3.2 On engineer's time distribution

When looking for information regarding an engineer's duties and time distribution, very little literature can be found. Most literature regarding engine rooms consists either of design tools developed to aid in the detailed design of engine rooms, or the physical and mental well-being of engineers on board. According to the STCW/CONF.2/34, certain skills are expected of engineers. These skills include being able to maintain equipment, both electrical and mechanical, according to the manuals. The engineer should be able to judge the state of machinery, and be able to do small, on-board repairs as long as proper documentation and spare parts are provided. [17]

These tasks can no longer be performed on board on unmanned ships, and either need to be done when a ship calls at a port, or they need to be made unnecessary through design changes.

2.3.3 On unmanned engine rooms

Det Norske Veritas states in their class rules on periodically unmanned engine rooms, that *“The extent of automation shall be sufficient to permit unattended engine room operation for 24 hours, or for the maximum continuous operation time when less than 24 hours.”*[18]. This means that ships with the class notation for periodically unmanned engine rooms, must be able to sail for 24 hours without anyone present in the engine room. DNV requires special monitoring and sensing equipment for these engine rooms. They must be able to shut themselves down whenever a critical failure occurs. Next to that, they must be able to inform the bridge and the engineers that something is wrong. The engines must be able to be controlled from the bridge, but may also be required to restart themselves after an automatic shutdown. There is no mention of sending information about the engine room status to anyone not on board the ship. [18]

With the maximum time that an engine room can be unattended being only 24 hours, there could be some legal issues with permanently unmanned engine rooms. It also means there is not much experience in leaving engine rooms unattended for prolonged periods of time, and therefore unknown what would happen if engine rooms were unmanned for longer periods.

2.3.4 On Maintenance strategies and product lifecycles

Both MUNIN and AAWA suggest that better maintenance strategies can help in the development of unmanned engine rooms. However, there are many different maintenance strategies. Maintenance and repair can be split into three different categories: corrective maintenance, preventative maintenance, and predictive maintenance, also called condition-based maintenance. Corrective maintenance means that a component is repaired after it breaks down, and can be considered unplanned maintenance. Preventative maintenance is maintenance that is performed before the breakdown of a component. Most preventative maintenance is based on past experience, and does not take into account the current state of equipment. It usually consists of doing maintenance after a certain time or operating hours. An example of preventative maintenance would be people who bring their cars to the garage for every 50.000km driven, or once a year. The problem with preventative maintenance is that it could be very cost inefficient: Parts that are still perfectly fine could be replaced, while parts that might need repair could not be a part of a preventative maintenance program. An upside of preventative maintenance is that it is usually quite easy to plan and schedule. Next to that, usually equipment is taken apart for maintenance, and then put together, which can introduce new faults into the system, increasing the chance of a breakdown shortly after maintenance. This is a phenomenon called ‘infant mortality’, which refers to the increased chance of failure at the start of a products lifecycle, or, in this case, at the start of a new maintenance term. [19]

Condition-based maintenance can be split into three categories. All these categories rely on condition monitoring, where the condition of a components is frequently checked, and its condition established.

The first is reliability centred maintenance (RCM), where maintenance intervals ensure the best reliability. The second is risk-based inspection (RBI), where maintenance schedules are made based on risk analyses instead of reliability analyses. This means that some components are allowed to break down as long as the consequences of breakdown are small. The last category is condition monitoring (CM), which is defined by the British Standards as: "*the continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance*" [20]. This is a computer-aided maintenance strategy that determines what needs maintenance based on the condition of a component, and can be used as long as data for the component is available.[21] CM is the most advanced of the three, not just relying on monitoring of equipment, but also on predictions based on the data obtained from monitoring.

However, engineers also play a big role in identifying and diagnosing problems in the engine room. Even though most malfunctions can be picked up by sensors, not everything can. Machines with damaged bearings or gears might produce other sounds than usual, but if no vibration sensor is installed on the machine, sensors will not pick it up. Since it is safe to say that no engine room can be perfect, and something will break down eventually, autonomous ships will need to be able to identify and diagnose serious problems in their engine rooms. Many faults will be able to be diagnosed by humans when the ship is in port, but it would be preferable if an autonomous ship can self-diagnose most of its problems. It would not necessarily be required for the ship to know -what- is wrong, but it would be good if a ship can diagnose that -something- is wrong. If the ship can notify personnel on land that it has detected that something is wrong, they can send someone on board the next time the ship calls port.

A comprehensive study on the causes of failure of equipment installed on aircraft and marine vessels done by DNV GL identified 6 different failure rate patterns divided into two sets: age related failures and random failures. Age related failures are failures that can be directly tied to the age of the product. These failures are again divided into three categories, and can be found in Figure 2.1. The first category is the so called 'bathtub curve', where most failures occur either during the start of the lifetime of a product or much later, at the end of life expectancy. The second category is where product wear out, and a sharp increase of failures can be seen after a certain time period. The third category is fatigue, where a products' failure rate slowly increases over time due to material fatigue. These three categories only accounted for 11% of the total failures.

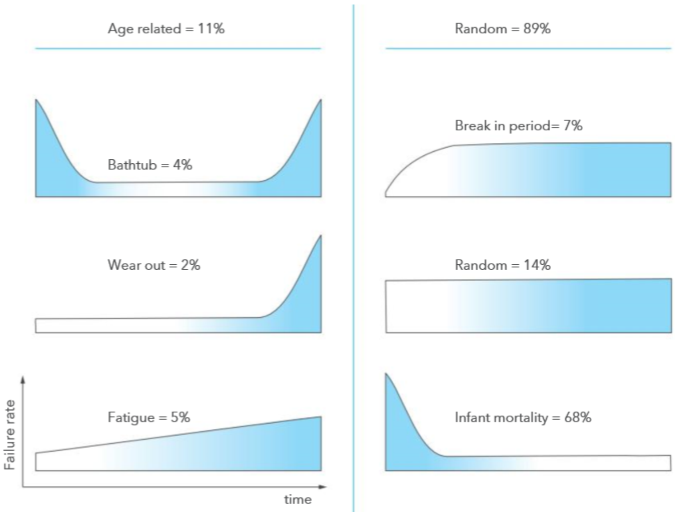

Figure 2.1: Failure rate patterns and their distribution [19]

The second set of failure categories include a break in period, where failure is low at the start of the products' lifetime, which slowly increases over time and eventually stabilizes. The second category includes all random failures, which means the failure rate stays constant over the course of a product's lifetime. The last category is infant mortality, which accounts for the most failures: 68%. Infant mortality is a term which means that items either break quite shortly after the start of their lifetime, or otherwise will complete their expected lifetime.

Since only 11% of the failures is age related, this again shows the importance of predictive maintenance. Using preventative maintenance, which is fully dependent on time, will only be able to prevent roughly 11% of all failures, whereas predictive maintenance is performed based on the condition of equipment. It can, if it's predictive abilities are good enough, prevent more failures in two ways; by catching failures before they happen, and by reducing infant mortality after (possibly unnecessary) maintenance. [19]

Most maintenance done in engine rooms today is preventative maintenance based on operational hours. This is important to know, as the frequency that something is maintained based on operational hours, is a sign of the reliability of the component. If something needs maintenance every 500 hours, it can be considered less reliable than something that needs maintenance every 1,000 hours.

2.3.5 Knowledge gap

Currently, a lot of research is being done on autonomous vessels, but the focus is mostly on navigation and communication. Although most large-scale projects do mention the troubles of reliability, they mostly mention redundancy, cleaner fuels and increased maintenance as the solution to this problem. [5], [11]

There are quite extensive records of breakdowns at sea, the largest being OREDA [9], which has recorded breakdowns very specifically starting in 1985. However, OREDA is only used in the offshore industry, and also contains a lot of information gathered on offshore platforms; not only ships. Some naval authorities have records of breakdowns within coastal waters, such as the German records Brocken used for his paper. [8], [22]. Most companies also hold records of breakdowns of ships within the company, but this is often not common knowledge and something companies are unwilling to share.

With the limited availability of reliability records, and the even more limited availability of maintenance records, there is currently little to none public information on the impact of human intervention on engine room reliability. Without this information, possible flaws or problems could be overlooked when designing engine rooms for unmanned vessels. It is therefore important to find out happens to reliability of current engine rooms if they would no longer be manned.

It can be assumed that engine rooms for unmanned ships will not just be the same ones as installed in manned ships, but in order to be able to properly design engine rooms for unmanned ships, weak points need to be identified to be able to deal with them.

2.4 Research Questions and sub questions

This paper will try to give these answers through the following research question and accompanying sub questions:

- What equipment and machinery in engine rooms of commercial trade vessels will become weak points when ships become autonomous and what changes to engine rooms are necessary and possible to enable a ship to sail reliably and cost-effectively without a crew?

Sub questions:

1. How do engineers help in making sure engine rooms stay operational?
2. What is the role of the crew in preventing, determining and solving problems within machinery?
3. What types of problems can occur, and what is their cause?
4. How often do these problems occur and what is done to solve them?
5. In the event of machine failure or when a component breaks, what are the consequences in terms of loss of functionality, time to repair, and cost?
6. How can these insights help in determining weak points in engine rooms where autonomy is concerned?
7. Which solutions are available to eliminate these weak points?
8. Which of these solutions is the most desirable and attainable?

3 Method

This chapter describes the method used to find the answers to the research questions. First, paragraph 3.1 describes the method and provides a justification on why this method was chosen. Next, the method to determine chances of failure using the frequency index is presented in section 3.2. Third, the method to determine consequences of failure using the severity index is given in paragraph 3.3. The next section, 3.4, describes and defines the system breakdown that will be used in the assessment. Section 3.5 defines the risk index, and paragraph 3.6 expands on this by introducing the redundancy reduced risk index. After this, in paragraph 3.7, the financial analysis is described. Lastly, section 3.8 gives an overview of the method to find solutions to weak points.

3.1 Method justification and overview

In order to be able to quantitatively asses any weak points in engine rooms, it is important to be able to find the chances and consequences of failure for machinery and equipment. Because all breakdown records are based on manned ships with crew performing maintenance, they inadvertently take the crew of a ship into account. This means they give a false representation of incidents that would happen on any possible unmanned ships, and can therefore not be used to find weak points that would be specific to unmanned vessels. They can give a good general overview for possible weak points, but they would not be complete, or they would give a false representation of weak points.

Because the big change for unmanned vessels would be the lack of physical interaction from crew during trips on board of vessels, it can be assumed that machinery that requires most maintenance and inspection at sea will become a weak point when on-sea maintenance is no longer available. One way of identifying weak points would therefore be to check what machinery requires maintenance the most often. There are several ways to do this:

- Most machinery comes with a manual that indicates maintenance intervals for certain parts, usually given in operating hours. [23]
- Most engineers have a schedule, based on these manuals, indicating when and what needs to be done.

The problem with both these methods is that they only take planned maintenance into account, and do not give indications for unplanned maintenance. Interviews with several engineers have indicated that about 15% of all maintenance done is unplanned, and therefore a significant portion of maintenance cannot be found in manuals or schedules.

To be able to identify all maintenance done, both planned and unplanned, an overview is needed of all maintenance done by engineers on board of ships. Unfortunately, most engineers do not keep a logbook of what work has been done, and even if they do, it is not public knowledge and has not been found. When asked about incidents in machine rooms, and what machines the engineers thought would be the weak points, the answer was unilaterally ‘it depends’. Every ship has their own weak points, and every engineer has different ideas about what machines would constitute as weak points. In order to get an impartial view of what constitutes as a weak point, it appears that the only other way to get this information is by asking engineers how they spend their time in the engine room. This information can then be used to find weak points.

If an engineer spends more time on certain equipment, or checks up on it more frequently, this is an indication that he feels like the equipment is less reliable. This means there is a correlation between how often engineers check machinery and the reliability of that machinery. It can then be assumed that equipment is less reliable when an engineer checks up on it more often. It can also mean that certain equipment is a good indicator of the overall health of a system, if it gets checked often. Just like a car owner checks their lubrication oil level from time to time to see how the lubrication oil is doing, instead of going past every pipe to check it for leaks. This is the assumption this paper utilizes to find weak spots in engine.

This paper will create four indices. The first being the frequency index (FI), which will list the frequency distribution of how often engineers interact per machinery component. The second index is the severity index (SI), which will list the consequences of failure for these same components. By combining these indices, the risk index (RI) is found, which will give an overview of weak points in engine rooms. To be able to compensate for built-in redundancies, the risk index is then used to create a redundancy reduced risk index (RRRI). The machinery components that are to be assessed are found through a system breakdown analysis. When the RRRI is found, it is validated through expert opinions, where a few experienced engineers will judge whether it is correct or not.

When the RRRI is made and validated, this will result in an overview of weak points in engine rooms. With these weak points identified, several solutions will be presented, and a cost-analysis will be done for these solutions. The end result of this paper will be recommendations for redesigns for engine rooms.

An overview of the method used in this paper can be found in Figure 3.1.

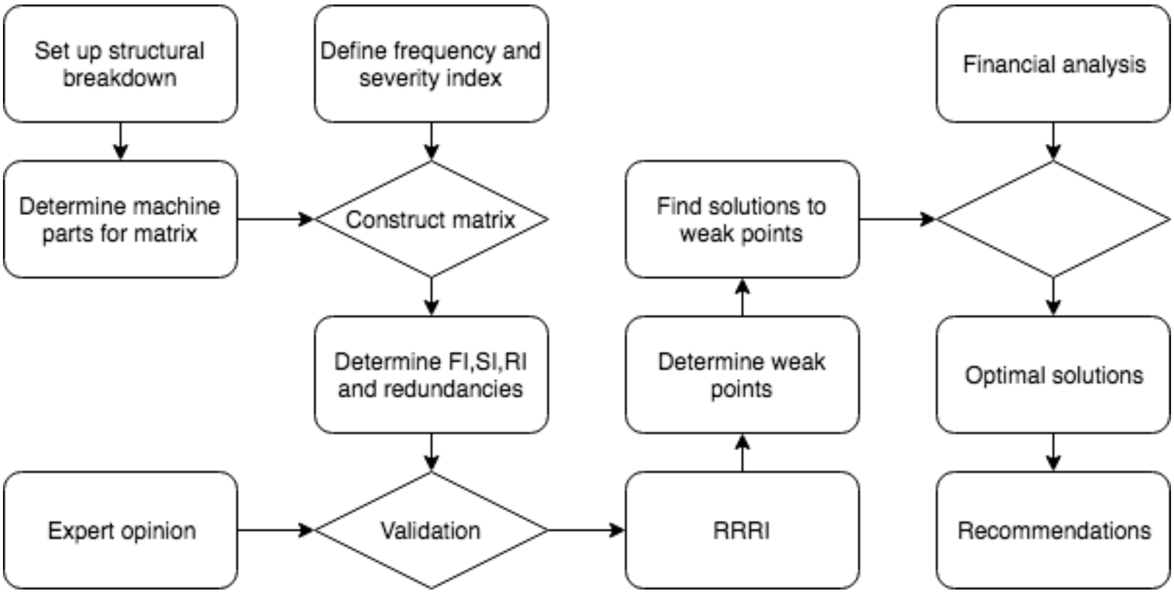

Figure 3.1: Method structure

3.2 Determining the chances of failure

To be able to do a quantitative assessment, an analysis will be done to determine how often engineers perform certain actions. This paper assumes there is a correlation between how much time an engineer spends on certain equipment, and how reliable that equipment is. If someone expected that their car was about to break down, they would check up on it more often than someone who fully trusts their car to work all the time. The same can be expected of engineers: if they assume a part is about to break down, or if a component has a tendency to unexpectedly stop working, they will automatically check up on that component more often. Similarly, equipment that gives a good indication of the health of a system will be checked more often as well.

This analysis will assess three key actions: Checking the status of equipment, performing maintenance (planned maintenance), and repairing equipment after breakdown (unplanned maintenance). The terms used in this paper are defined as follows:

> **Checking status:** *Actively checking the status of machinery, either by reading gauges or sensor data, or by using human sense to determine the state of equipment (e.g. listening for strange noises or feeling for vibrations)*
>
> **Performing planned maintenance:** *Performing maintenance on equipment according to planning. Both the moment (when) and the duration (how long) of the maintenance can be easily predicted and held to.*
>
> **Performing unplanned maintenance:** *Performing repairs or maintenance before this maintenance is planned. Either the moment (when) or the duration (how long) of the maintenance are hard to predict. Unplanned maintenance can both be critical or non-critical. Critical unplanned maintenance must be performed as soon as possible, while non-critical unplanned maintenance can wait until a convenient moment.*

These three actions can give a good indication of the reliability of machinery. If an engineer checks certain equipment more often than others, it can be an indication that he expects it to break more often, or because sensors cannot provide him with all the information on the machines' status. If machinery requires regular planned maintenance, this could become a problem for unmanned vessels, because maintenance opportunities are limited. If it requires regular unplanned maintenance, this can either be seen as machinery being unreliable, or a maintenance planning being too lenient. It can be expected that equipment that requires more planned or unplanned maintenance, is checked more often by engineers as well. They cannot be seen as independent variables, but all are important.

The International Maritime Organization (IMO) has created a frequency index that is to be used in risk assessments. This index is defined in frequency per year per ship, and is mostly used to calculate risks for ships. Because this index is mostly used for large events which do not occur often, the exact index will not be used in this paper. However, it will be used as a basis for the frequency index used in this paper. The table as presented by the IMO can be found in Table 3.1.

Table 3.1: Frequency index as defined by IMO [24]

Frequency index			
FI	Frequency	Definition	F (Per ship per year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of 10 ships, i.e. likely to occur a few times during the ship's life	0.1
3	Remote	Likely to occur once per year in a fleet of 1,000 ships, i.e. likely to occur in the total life of several similar ships	10^{-3}
1	Extremely remote	Likely to occur once in the lifetime (20 years) of a world fleet of 5,000 ships.	10^{-5}

To make sure the analysis is quantifiable, a similar frequency index is introduced to be able to equally assess different variables. Frequency levels range from 1 to 5, where a 1 indicates a low frequency and 5 indicates a high frequency. Table 3.2 lists the definition of each frequency index for the three actions. The table lists the number of occurrences per ship year.

Table 3.2: Frequency indexes, values are in occurrences per ship year

Frequency index				
FI	Frequency	Checking equipment	Performing planned maintenance	Performing unplanned maintenance
5	Frequent	1000	100	10
4	Reasonably probable	100	10	1
3	Somewhat probable	10	1	0.1
2	Remote	1	0.1	0.01
1	Extremely remote	0.1	0.01	10^{-3}

To give a sense of these numbers, as well as how they will be used to define the frequency indices for components, Table 3.3 defines the frequencies.

Table 3.3: Frequency index explained

Frequency [per ship per year]	**Definition**
1000	Multiple times per day
100	Once a day to once a week
10	Once a week to once a month
1	Once every 3 months to once a year
0.1	Once every 5 to 10 years
0.01	Once in a ships’ lifetime
10^{-3}	Once in a fleets’ lifetime

It is important to realise that a component that gets checked often does not always have a tendency of itself to break down, but it can be a good indicator of the overall health of other systems. Examples of these are tanks, which very rarely break, but still get checked often. They get checked often because tanks that accumulate impurities or drain faster than expected, can indicate a leak or failure somewhere else in the system. Components like this will be explicitly mentioned, and these reasons will also be taken into account during the solution making process.

3.3 Determining the consequences of failure

Because risk is defined as chance of failure multiplied by consequence, it is important to know what the consequences of failure are for different pieces of equipment. Consequences of failure can range from none to catastrophic, but most often the consequence is somewhere in between. Breakdown of certain parts of machinery does not necessarily mean that the machine itself stops working. Often, machines can still function, but at limited capacity, or machinery can remain functioning for a certain number of hours. This is especially the case in redundant set ups.

Just like the frequency index, the IMO has defined a severity index to be used in risk assessment, which takes into account either injury or loss of life, or damage to the ship. This severity index is cannot be applied directly in this context, as consequences cannot be measured in injuries or loss of life for unmanned ships. However, it can still be used as a basis for a severity index for this paper. The severity index as defined by the IMO can be found in Table 3.4.

Table 3.4: Severity index as defined by IMO [24]

Severity index				
SI	Severity	Effects on human life	Effects on ship	S (equivalent fatalities)
1	Minor	Single or minor injuries	Local equipment damage	0.01
2	Significant	Multiple or severe injuries	Non-severe ship damage	0.1
3	Severe	Single fatality or multiple severe injuries	Severe damage	1
4	Catastrophic	Multiple fatalities	Total loss	10

To be able to compare both the chance and consequence of failure, the consequence of failure is defined in a severity index. The severity index ranges from 1 to 5, with a 1 meaning that the consequences of failure are negligible, and a consequence of 5 is catastrophic.

The severity index for autonomous vessels cannot be based on loss of life, as there are no humans on board. Instead, the severity index can be based on loss of functionality of the ships' main functions. For autonomous vessels, we can define three main functions:

- Propulsion; being able to move forward and backward.
- Manoeuvrability; being able to steer and move laterally.
- Communication and control; making sure the ship, as well as others, knows what it’s doing, as well as knowing the ship’s health and status.

To be able to give a severity index on a system level, these functions can be reduced to certain systems in the engine room. Propulsive power is delivered by the main engine, through the gearbox to the propulsor. Manoeuvrability is done by the rudder and bow thrusters. Although communication and control is classically a function that is tied to the bridge of a ship, they still require power to function. Therefore, in order to keep these systems functional, the third function will be tied to a function of the engine room: generating and distributing electricity. This is done by the generator sets and the electrical system.

The severity levels used in this paper will be based on these three functions, and how well the ship can still perform them after breakdown of a component. This would include any redundant equipment. The severity index looks at the consequences if all of the machinery breaks down, even if redundancies are installed. The effect of redundancy in this paper will be discussed in paragraph 3.6. The severity index will consist of three parts: propulsion, manoeuvring and power. The definition for each severity index can be found in Table 3.5.

Table 3.5: Severity index for consequences of failure

Severity index (SI)				
SI	Severity	Propulsion	Manoeuvring	Power
1	Negligible	Negligible loss of propulsion	Ship can still manoeuver properly	Negligible loss of power; all systems continue working normally
2	Minor	Small decline in propulsive abilities; can still retain position in bad weather. Complete loss of propulsion within a week if left unchecked.	Small decline in manoeuvrability; might drift in bad weather	Cannot provide full power to some systems. Complete loss of power within a week if left unchecked.
3	Significant	Large decline in propulsive abilities; speed drops significantly and might be in trouble in bad weather. Complete loss of propulsion within 24 hours if left unchecked.	Large decline in manoeuvrability, unable to stay in position in bad weather	Non-vital systems, such as refrigeration of cargo, might shut down. Complete loss of power within 24 hours if left unchecked.
4	Severe	Propulsion only possible in mild weather, unable to continue journey but can still get to the nearest port safely. complete loss of propulsion within several hours if left unchecked.	Severely limited in manoeuvrability. Unable to maintain course properly	Only vital systems are still operational; Lights, navigation and communication. Use of electric propulsors no longer possible. Complete loss of power within several hours if left unchecked.
5	Catastrophic	Complete loss of propulsion within an hour.	Complete loss of manoeuvrability, unable to dictate course	Complete loss of power within an hour, effectively a dead ship

3.4 System breakdown

The next step is to create a list of machinery and equipment so that the frequency index and severity index can be specified on an equipment level. To create this list, first a system breakdown is constructed. This system breakdown consists of multiple systems:

- The main engine and its subcomponents, as well as the gearbox
- The auxiliary engine and generator sets
- The fuel oil system
- The lubrication oil system
- The cooling water system
- The starting air system
- The electrical system
- The rudder

There are several ways of determining a system breakdown for ships. The easiest way is to use an existing system breakdown that was made when designing any commercial merchant ship. However, these are all proprietary and not available to the general public, and therefore not an option for this paper. The most used system for creating system breakdowns is the UNAS code, which is a way of categorizing all components of a ship by using standardizing numerical codes. However, just like the proprietary breakdowns, the UNAS code requires a license which unfortunately could not be obtained.

The system breakdown in this paper was created by utilizing machine breakdowns that can be found in manuals of equipment. For this system breakdown, manuals of five machines were used. The following machines were used for the system breakdowns:

- For the main engine, a MAN B&W K98MC-C7-TII is used as reference. This is a two-stroke diesel engine with an output between 36 and 84 MW; suitable for most medium to large size vessels. Although most smaller vessels use a four-stroke engine, information on these was very hard to find. For this analysis, it is assumed that on a top-level breakdown, there is no difference between four- and two-stroke engines, apart from the addition of a gearbox.[25]
- For the auxiliary engine/generators, the reference is the MAN B&W L16/24, a four stroke diesel engine with a continuous rating between the 600 and 1000 kW. [23]
- Since electrical systems are not available in standardized sets, and are also not the main focus of this paper, the system breakdown for the electrical system is limited to the switchboard, transformers, cabling and breakers. Future research in this area might improve the understanding of weak links in the electrical systems of autonomous ships.
- For the steering gear, the reference steering gear is the HS 280-03 produced by Ulstein Friendenbø AS. [26]
- For the gearbox, the Wärtsilä SCV/SCH range was used. [27]

The full system breakdown resulted in a detailed breakdown consisting of 122 components. In order to reduce this number to a quantity which was manageable and widely applicable, the system breakdown was filtered according to the following criterion:

- Any part that can only be repaired or replaced during a major overhaul gets excluded. Examples are the crankshaft of the main engine or fuel heaters. If they were to break the systems that they are a part of are considered broken.
- Any part that is part of a set, or not exclusive to certain equipment, get excluded as well. Examples would be nuts, bolts and valves.
- Any part that is specific to a certain model or brand of the component gets excluded, such as special proprietary hardware.
- Tanks get included, as they themselves don't usually break, but get checked often for contaminations, which leads to breakdown in other components.
- Since the rudder is mostly controlled by opening and closing valves, valves are included in the rudder configuration

The full breakdown can be found as a list in appendix A, the set-up of every system will be further discussed in chapter 4.

3.5 Risk index

With the system breakdown known, we can start filling in the frequency index and severity index. This will be done at first by processing data acquired from interviews with several engineers. The first draft will then be sent to the same engineers, who will comment and make adjustments, validating the data in the process. This will be done for a total of three rounds, after which all the results will be discussed in a last interview. The outcome of this interview is the validated data presented in chapter 5.

With the validated frequency and severity indices, a risk index can be calculated. Risk can be defined according to equation 3.1.

$$R = F \cdot S \tag{3.1}$$

Where R is the risk, F is the frequency and S is the severity. Likewise, we can use the risk index, which is on the same logarithmic scale as the frequency index and severity index as defined in paragraphs 3.3 and 3.2 The risk index can be calculated according to equations 3.2 and 3.3.

$$log(R) = log(F) + \log(S) \tag{3.2}$$

$$RI = FI + SI \tag{3.3}$$

Since this paper has three categories for the frequency index and also three categories for the severity index, the risk index is calculated in this paper according to equation 3.4, where the maximum frequency and severity indices are used to define the risk index. This will ensure that any problematic systems will be clearly represented in the risk index.

$$RI = \max(FI) + \max(SI) \tag{3.4}$$

The risk index used in this paper has the same form as the risk index used by IMO, albeit slightly different values. The risk index as used by IMO can be found in Table 3.6.

Table 3.6: Risk index as defined by IMO[24]

Risk index (RI)					
		Severity (SI)			
		1	2	3	4
FI	Frequency	Minor	Significant	Severe	Catastrophic
7	Frequent	8	9	10	11
6		7	8	9	10
5	Reasonably probable	6	7	8	9
4		5	6	7	8
3	Remote	4	5	6	7
2		3	4	5	6
1	Extremely remote	2	3	4	5

The risk index is a good indication on what machines and equipment can be problematic, and which ones can become weak points. The risk index as used in this paper is defined in Table 3.7. The index ranges from levels 2 to 10, with level 2 being the lowest risk, and level 10 being the highest risk. Risks are divided up into three categories:

- Low risk (green), ranging from a risk index of 2 to 5
- Medium risk (yellow), ranging from a risk index of 6 to 7
- High risk (red), ranging from a risk index of 8 to 10

Table 3.7: Risk index

Risk Index (RI)						
		Severity (SI)				
		1	2	3	4	5
FI	Frequency	Negligible	Minor	Significant	Severe	Catastrophic
5	Frequent	6	7	8	9	10
4	Reasonably probable	5	6	7	8	9
3	Somewhat probable	4	5	6	7	8
2	Remote	3	4	5	6	7
1	Extremely remote	2	3	4	5	6

3.6 Redundancy reduced risk index

The Risk index in and of itself is already a good way to determine weak points in engine rooms, but it overlooks an important measure in dealing with failure: redundant equipment. A lot of equipment and machinery is installed multiple times, often as separate systems, to ensure continuity of its function if one of the components break down. The problem with redundancy for this paper is that it polarizes the severity index, and it is unknown how it affects the frequency index.

The severity index, as defined in this paper, looks at the effect of the breakdown of certain equipment, including all redundancies installed. If for example, a generator fails, the severity index assumes all generators fail, and power will be lost. However, this is not the case in real life. If two generators are installed, and one of the generators breaks down, there is always one to take over its function. This means that if a component is redundant, the severity index would stay at 1, even if one breaks down. This polarity does not help in finding the actual weak spots in the system. This would mean that any piece of equipment that has some form of redundancy, would drop out of the severity index, as all of them would result in an SI of 1. This in turn would make actual low severity equipment and redundant equipment with a high severity indistinguishable. It also neglects the fact that redundant equipment can fail too.

A solution would be to take redundancy into account for the severity, where redundant equipment is not reduced to a severity of 1, but the severity is still lower than it would be for non-redundant equipment. An example would be to possibly lower the severity index for every redundant set up. However, it should also be taken into account that redundancy does not just lower the consequence of a breakdown, but the chance of a breakdown as well, which would then influence the frequency index.

The frequency index that is used in this paper cannot define a time to failure, and therefore it is hard to find the chance that redundant equipment fails at the same time. The failure chance for redundant equipment can be defined according to equation 3.5. At the same way, the chance for double redundant equipment, where three instances of the same equipment are installed, can be calculated according to equation 3.6.

$$P(F_{1+2}) = P(F_1|F_2) = P(F_1) \cdot P(F_2) = P(F1)^2 \tag{3.5}$$

$$P(F_{1+2+3}) = P(F_{1+2}|F_3) = P(F_{1+2}) \cdot P(F_3) = P(F1)^3 \tag{3.6}$$

Where $P(F_1)$ is the chance of failure for machine 1 and $P(F_2)$ is the chance of failure for machine 2. $P(F_{1+2})$ is the chance that both machines fail at the same time. Since both machines are identical, it is assumed that their chances of failure are the same as well.

It is important to realise that the chance of failure for both machines is also influenced by the time it takes to repair equipment. When equipment fails, it will be repaired at the next possible moment; they will not wait until the second machine fails as well. One could redefine $P(F)$ as the chance that something is broken, which would then be defined according to equation 3.7. However, since the actual failure chance is unknown, one could try to find both the time between failures (TBF), and the time between repairs (TBR).

$$P(F_1) = \frac{TBR}{TBF} \tag{3.7}$$

This means that $P(F)$ becomes a ratio of time, defining how much percent of the time equipment is broken. If a worst scenario is assumed, it can be said that equipment breaks down when it should have been maintained. That means TBF can be defined as the maintenance interval. When looking at short sea shipping, the time a ship is at sea is at most a week, which can be used as a measure for TBR.

From the interviews, it was found that most equipment that is maintained on a schedule has a maintenance interval of about three months, or 12 weeks. We can then define the chance of failure for non-redundant, redundant and double redundant equipment according to equations 3.8a, b and c.

$$P(F_1) = \frac{TBR}{TBF} = \frac{1}{12} \approx 0.1 \tag{3.8a}$$

$$P(F_{1+2}) = P(F_1)^2 = \frac{1}{144} \approx 0.01 \tag{3.8b}$$

$$P(F_{1+2+3}) = P(F_1)^3 = \frac{1}{1728} \approx 10^{-3} \tag{3.8c}$$

These equations show us that for every redundancy, the chance of failure drops by about a factor 10, which, due to the logarithmic scale of the frequency index, would correspond to a drop of 1 level.

As mentioned before, the problem of redundancy affects both the severity and the frequency index. For the frequency index, the worst-case scenario results in a drop of failure rate by one order of magnitude. For the severity index, the change is harder to define, but definitely present. In order to not lose the valuable data of either the FI, SI, or RI, but to also take redundancy into account, a new index is introduced: The Redundancy Reduced Risk Index (RRRI). This index is defined as the value of the risk index, with the number of redundancies subtracted. This would mean that for non-redundant equipment, the RI equals the RRRI. For single-redundant equipment, the RRRI is one lower than the RI, while for double-redundant equipment, the RRRI is lower by 2. The RRRI will be used as a way to define weak points, according to the same system as used in the risk index, which can be found in Table 3.7.

Both the high risk and medium risk components will be considered weak points. High risk equipment will very likely become a problem for autonomous ships, and these problems will need to be solved before ships can sail autonomously. Medium risks could potentially become problems, and should be considered for risk reduction. This can be done by using the ALARP principle. The ALARP principle stands for As Low As Reasonably Possible, and means that one should try to lower risks, as long as this is reasonably possible. Investing millions of dollars to slightly lower the risk of certain equipment cannot be seen as reasonable. Effectively it means that for these risks, the low hanging fruits can be solved, but for other risks, they might just have to be accepted. Risks in the lowest category are deemed as acceptable and will not be considered for finding solutions.

3.7 Financial analysis

To find the economic viability for any potential solutions to weak points, a financial analysis will be done to find out the current costs for different sizes of ships. These costs will be divided up into four costs: operational costs, crew costs, voyage costs and capital costs. The financial breakdown will be discussed in chapter 6. The four costs will be used in the solution finding in the following ways:

- It is assumed crew costs completely disappear, this is the ‘buffer’ for the costs associated with an unmanned engine room. This is an overtly optimistic approach, as not all crew costs will entirely disappear. Crew at on-shore control centres still need be paid, as well as crew that would come in from time to time to perform maintenance. However, for a basic financial analysis, this way would be a good indication of the upper limit of the possibilities.
- If more equipment is installed, the costs for this equipment will be added to the vessel’s newbuild price. The extra costs are estimated as a relative increase in total machinery costs. The relative increase will be dependent on the type of solution.
- It is assumed that the same kind of machinery is more expensive for bigger ships than for small ships. The capital costs will increase linearly with this increased newbuild price.
- If there is a change of fuel type, voyage costs will change linearly with the ratio between the old fuel and the new fuel, according to bunker prices in Rotterdam. This assumes that any other costs than fuel are neglected. This is done because other voyage costs, such as port fees or canal fees are very dependent on the route of the ship. Since a generic solution is the goal, these costs are neglected.
- It is assumed the operational costs do not change.

Two different financial analyses will be compared: one where each weak point has their own specific solution, and on where the entire drive train is made redundant. This way, it can be checked if looking for specific solutions is financially better than installing a completely redundant machinery plant. Lastly, some alternatives to propulsion by a diesel engine are subjected to a brief financial analysis.

3.8 Finding solutions

Once the weak points are identified, solutions to overcome these weak points will be discussed. Solutions depend on the weak point but can consist of a number of options. A few examples would be a redundant set up, finding alternatives to the machine part with a lower risk index, or looking at what needs to be done to make a certain part completely unnecessary.

This paper will attempt to find solutions for every high-risk component, which means that any part with an RRRI of 8, 9 or 10, will be reviewed for improvement. Components with a medium RRRI, meaning 6 or 7, will also be looked at, but in some cases a conclusion can be drawn that no solutions are possible or financially viable. Components with an RRRI of 5 or lower will not be looked at.

This paper will also briefly explore some more radical solutions in the form of switching fuels from MDO to either LNG or batteries, as well as the possibilities of switching to diesel-electric propulsion.

With all the solutions found, they will be subjected to a financial analysis to view the financial viability.

4 System breakdown

This chapter will discuss the system breakdown in detail. The first paragraph discusses the type of ship, and consequently, machinery, that will be used as a basis for the analysis in this paper. For the second paragraph, an overview is given of the main engine and its subcomponents. Paragraph 3 will define the auxiliary engine and generator sets. Next, paragraph 4 will give and overview of the fuel oil system, while paragraph 5 describes the lubrication oil system. Paragraph 6 shows the cooling water system, and paragraph 7 defines the starting air system. After this, paragraph 8 will show a basic layout of the electrical system. Finally, in paragraph 9, the rudder is discussed. Finally, in paragraph 10, the exhaust gas system is discussed.

The goal of this chapter is to provide insight in all components that are under consideration in this paper. For every component, their functions are listed, as well as possible risks that have to be taken into account.

4.1 General overview

Because no two engine rooms are the same, the machinery plant used in the analysis in this paper needs to be defined. As the scope of this paper is limited to short-sea ships and feeders in European waters, it is logical to consider their engine rooms for this paper. Most of these ships run on four-stroke diesel engines, connected to the propeller via a gearbox. Since they exclusively sail within emission control area’s (ECAs), they all run on distillate fuels, such as marine diesel oil (MDO). They are usually equipped with a single main engine, and outfitted with at least 2 diesel generators, as well as an emergency generator. The main and auxiliary engines are supported with a fuel oil system, which cleans the fuel oil and prepares it for use. The engines are started with starting air, and cooled with a triple-layer seawater-based cooling system. They are equipped with a rudder at the back and one or two bow thrusters at the bow.

The entire machinery plant can be divided up into a few subsystems. These subsystems are the following:

- The main engine
- The auxiliary engines and the generator sets
- Electrical system
- Auxiliary systems needed to keep the engines running, which include the fuel oil system, lubrication oil system, cooling water system, starting air system and exhaust gas system.
- The rudder, which is vital to manoeuvring.
- Other subsystems, such as the ballast system and firefighting system.

All of these systems will be considered, except for the systems that exists mainly outside of the engine room. These systems would include the rudder, the ballast system and firefighting system. However, since the rudder was proven to often be the cause of a breakdown of ships [22], the rudder will be taken into account.

4.2 Main engine and its subcomponents

Although the main engine is a four-stroke, the system breakdown used in this paper is based on a two-stroke diesel engine: the MAN B&W K98MC-C7-TII [25]. This engine was chosen because its manual included a full list of all components as well as subsystems. It is assumed that from a top-down breakdown approach, they are similar enough to provide the components needed for the breakdown. The engine consists of many parts, but not all will be taken into account for the system breakdown. The criteria for the subsystems taken into account can be found in paragraph 3.4. The components that are taken into account are described in paragraph 4.2.1.

4.2.1 Subcomponents of the main engine

The main engine has the following subcomponents:

- The cylinder covers
- The turning gear and turning wheel
- The piston/cylinder liners
- The driving gear
- All attached pumps
- The manoeuvring system
- The gearbox
- The clutch
- The stern tube seal cover

The cylinder cover sits on top of the cylinders, and is used to seal off the cylinders. This seal needs to be airtight and be able to withstand high pressures, as it needs to contain the explosive combustion that drives the pistons. To get access to the cylinders, the cover needs to be removed.

When the engine needs to be started or when it needs to be overhauled, the pistons need to be brought into a specific position to ensure that the engine will start in the right direction. To do this, the turning gear/turning wheel is used. It rotates the crankcase slowly to the desired position. This is either done by hand or with a small motor.

The pistons sit inside the cylinders, where the walls are covered with a cylinder liner. The cylinder liner is the contact point between the cylinder and the piston, and must be able to withstand high temperatures, vibrations and pressures, while making sure the piston can easily slide along the wall without much friction.

The turbocharger that blows air into the engine, is usually powered by the exhaust gases that come out of the engine at high temperature and velocity. Because they are the first piece of resistance that the exhaust gases meet, this is where the first slowdown of the exhaust gases happens. This is therefore an ideal place for soot to settle.

The driving gear is the connection between the crankshaft and the camshaft, which regulates the timing of all the valves. The driving gear also drives all the pumps that are connected to the engine.

There are three attached pumps: the fuel oil pump, the lubrication oil pump, and the jacket cooling water pump. They are driven directly by the engine through a mechanical link. All of these pumps have electric backups, for when the main engine fails. During engine start-up, the starting air system turns the engine, which in turn powers these pumps.

The manoeuvring system determines the way the engine turns. On four-stroke engines, the manoeuvring system is usually integrated into the gearbox, or the direction of sailing is controlled by a controllable pitch propeller. On two-strokes, the manoeuvring system determines the direction of rotation of the engine itself.

The gearbox is a reduction gearbox, lowering the rotational speed of the engine to a speed suitable for the propulsor. It is coupled to the engine via a clutching mechanism, and can also be used to change the rotating direction of the propeller shaft. On smaller size vessels, the gearbox rarely has a PTO, although some are equipped with a PTI that can be used in emergencies.

The gearbox is connected to the propeller via the propeller shaft. The shaft exits the ship through the stern tube seal cover, which makes sure there is a watertight connection. The stern tube seal cover consists of three seals, and often has an extra emergency seal.

4.3 Auxiliary engines and generator sets

The auxiliary engines and generator sets consist of the following components:

- A basic diesel engine
- Fuel oil pumps
- Lubricating oil pumps
- Cooling water pumps
- The starting air system
- An alternator

The machine room is equipped with a total three auxiliary diesel engines, each of which are connected to a generator. Two of the three generators are both capable of delivering the total required power for the entire ship. Most of the time, one of these two is online while the other is in standby. Sometimes, during special operations where more power is required, both generators will be running. The third generator is the emergency generator, which cannot deliver all the required power, but can deliver enough power to keep all emergency systems such as lights and communication active.

All three generators are connected to the same fuel oil, lubrication oil, cooling water and starting air systems. Usually these systems are connected to the same systems for the main engine, but they can operate independently. More information about these systems is given in paragraphs 4.4 to 4.7.

The alternator is directly connected to the basic diesel engines, and generates the electricity. Each alternator is connected to a different switchboard.

4.4 Fuel oil system

The fuel oil system consists of the following components:

- Bunker tanks
- A settling tank
- A day tank
- Fuel oil centrifuges
- Fuel oil supply pumps
- Fuel oil circulating pumps
- Fuel oil filters

The fuel oil system starts at the bunker tanks, of which there are several. When a ship takes in bunker, it only fills empty bunker tanks, it never tops up tanks which already have fuel in them. This is done to prevent fuel mixing, which can lead to unpredictable behaviour of the engine.

The fuel oil supply pump will pump the fuel oil from the bunker tank, but first it goes through a coarse filter, which takes out any debris that might have been contaminating the bunker tanks. Then, the fuel oil gets pumped into the fuel oil centrifuge, which filters the fuel oil using centrifugal force. Most fuel oil centrifuges are self-cleaning, dumping any waste they produce into the sludge tank. Because centrifuges can take up to two days to properly clean, there is always at least two installed.

After the centrifuge, the fuel oil is filtered one more time with a much finer filter, and then pumped into the settling tank. The settling tank is used to de-aerate the fuel, and to let all the impurities that are still in the fuel after the centrifuges sink to the bottom of the tank, where the waste is put into the sludge tank. The fuel is transported from the top of the settling tank into the day tank through the fuel oil circulation pump.

The day tank, as its name suggests, hold as much fuel as the main engine uses at design speed in 24 hours. Ships usually have one or two. If there are two tanks, they are alternated daily, with one filling up while the other one is in use. If there is only one tank, it is usually filled up continuously. Fuel is transported from the day tank to the main engine through the fuel pump connected to the main engine. The auxiliary engines are usually fed from the same tank.

The fuel oil is filtered a final time before entering the engine. All fuel oil filters are self-cleaning, or self-shooting, which means that they will clean themselves by shooting pressurized air through the filter to get all the waste out. This is a good way to increase their longevity, but it is not a final solution. Eventually the filters get so dirty that pressurized air cannot clean them anymore, and then they need to be replaced. Filters are usually replaced based on their shooting interval, which gets shorter when the filter gets dirtier.

The entire fuel oil system diagram can be found in Figure 4.1.

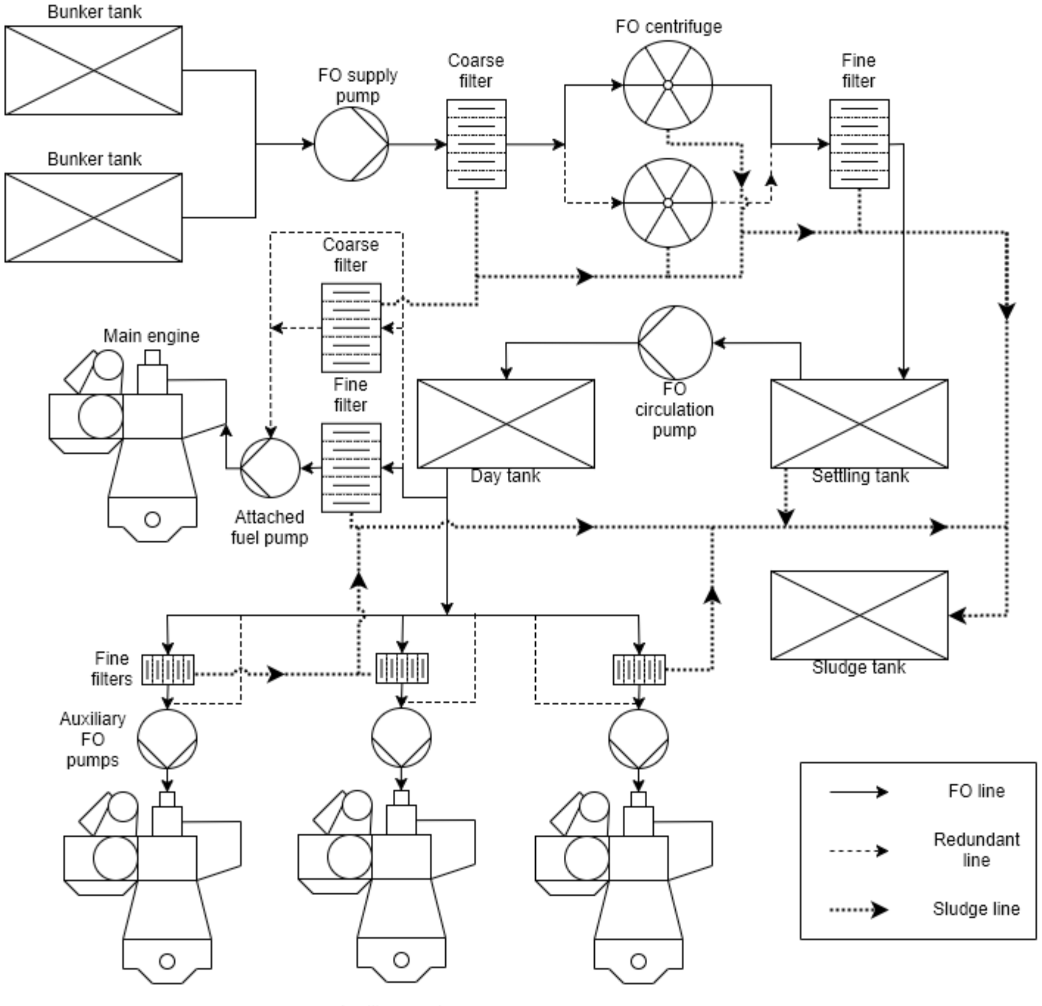

Figure 4.1: Fuel oil system diagram [figure by J.P. Colon]

4.5 Lubrication oil system

The lubrication oil system consists of the following components:

- The lubrication oil transfer pumps
- Lubrication oil full flow filters
- The lubrication oil tank
- The cylinder lubricators
- The lubricating oil service tank
- The lubrication oil centrifuge
- The sump tank

The lubrication oil system makes sure that the main engine and auxiliary engines are properly lubricated, which ensures smooth operation and prevents abrasive damage. Lubrication oil is stored in the lubrication oil tank, and gets transferred to the lubrication oil service tank with the lubrication oil transfer pump.

Lubrication oil then get transferred from the service tank into the sump tank, which sits right below the engine. The sump tank is the storage place for all the lubrication oil that is currently in use. All the lubrication oil that is in in the engine, eventually drips down into the sump tank. The level of the sump tank is kept constant as much as possible, and a sudden increase or decrease of lubrication oil in the sump tank can indicate a problem with the lubrication oil system.

The attached lubrication oil pump then pumps the lubrication oil from the sump tank to the lubrication oil centrifuge, and then through the full flow filter. Both these systems come with a bypass. The lubrication oil is then pumped through to the cylinder lubricators, which inject the lubrication oil into the engine. Each cylinder has multiple injection spots for lubrication oil.

The auxiliary engines get their lubrication oil from the service tank, which is pumped by pumps attached to the auxiliary engines themselves. They each get a full flow filter which also has a bypass. Lubrication oil from the auxiliary engines get caught in their own sump tanks and is recirculated through the auxiliary system. They also share a lubrication oil centrifuge.

The level of the lubrication oil in the sump tank is something that needs to be regulated closely. If the level is too low, the engine might not get enough lubrication, which will result in corrosion. If there is too much lubrication oil, the engine might receive too much lubrication, and the lubrication oil will start to form a mist in the engine. This mist is highly flammable and has explosive properties. All engines come with mist detection and will shut down automatically if a lot of mist is detected. If the engine does not stop and the mist explodes, it will destroy the engine and possibly the entire engine room.

The entire lubrication oil system diagram can be found in Figure 4.2.

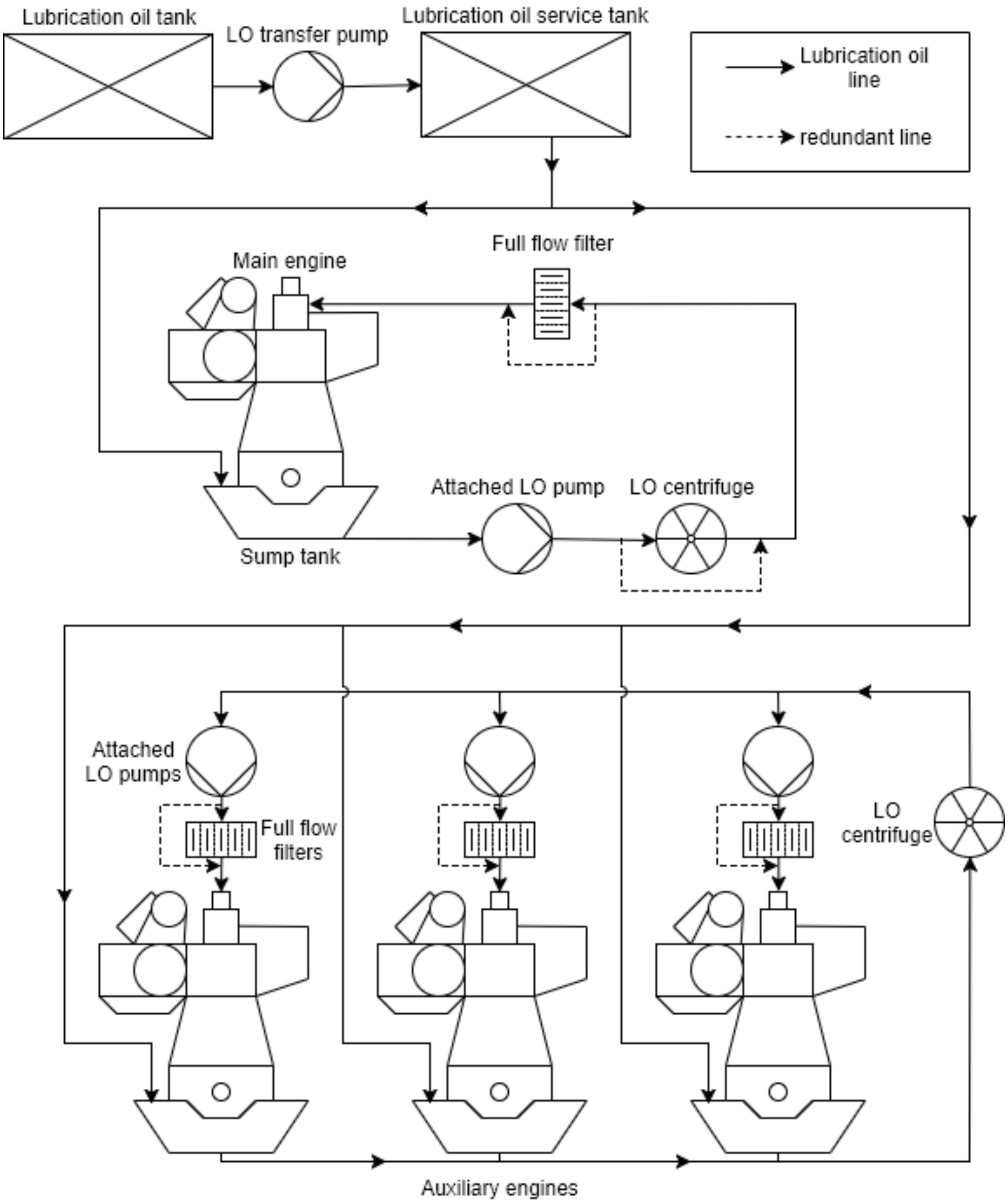

Figure 4.2: Lubrication oil system diagram [figure by J.P. Colon]

4.6 Cooling water system

The cooling water system consists of the following components:

- Seawater cooling pumps
- Central cooling water pumps
- Jacket water cooling pumps
- The de-aerating tank
- The expansion tank
- The fresh water treatment system

The cooling water system consists of three closed systems: the seawater system (SW), the low temperature system (LT), and the high temperature system (HT). Seawater is taken from the seawater chests underwater and pumped to a heat exchanger with the seawater cooling pump, which is always redundant.

The LT water is system is fresh water, which gets stored in the expansion tank, and is pumped around to the main engine and auxiliary engines using the central cooling water pump. The central cooling water pump is always redundant. The LT cooling water doesn't enter the main engine, but is used to cool down the HT cooling water. The LT cooling water is used directly to cool the auxiliary engines.

The HT cooling water is pumped into the main engine with the attached jacket water cooling pump. The jacket water cooling pump is also redundant, with the second pump being driven by an electric motor. The jacket water is stored in a de-aerating tank, which takes out all the air bubbles in the warm water. The jacket water system also comes with a heater, which is used to pre-heat the engine before starting.

To ensure that there is always enough fresh water in the system, and that the water is of proper quality, there is also a fresh water treatment system which uses chemicals to treat the cooling water.

The entire cooling water system diagram can be found in Figure 4.3.

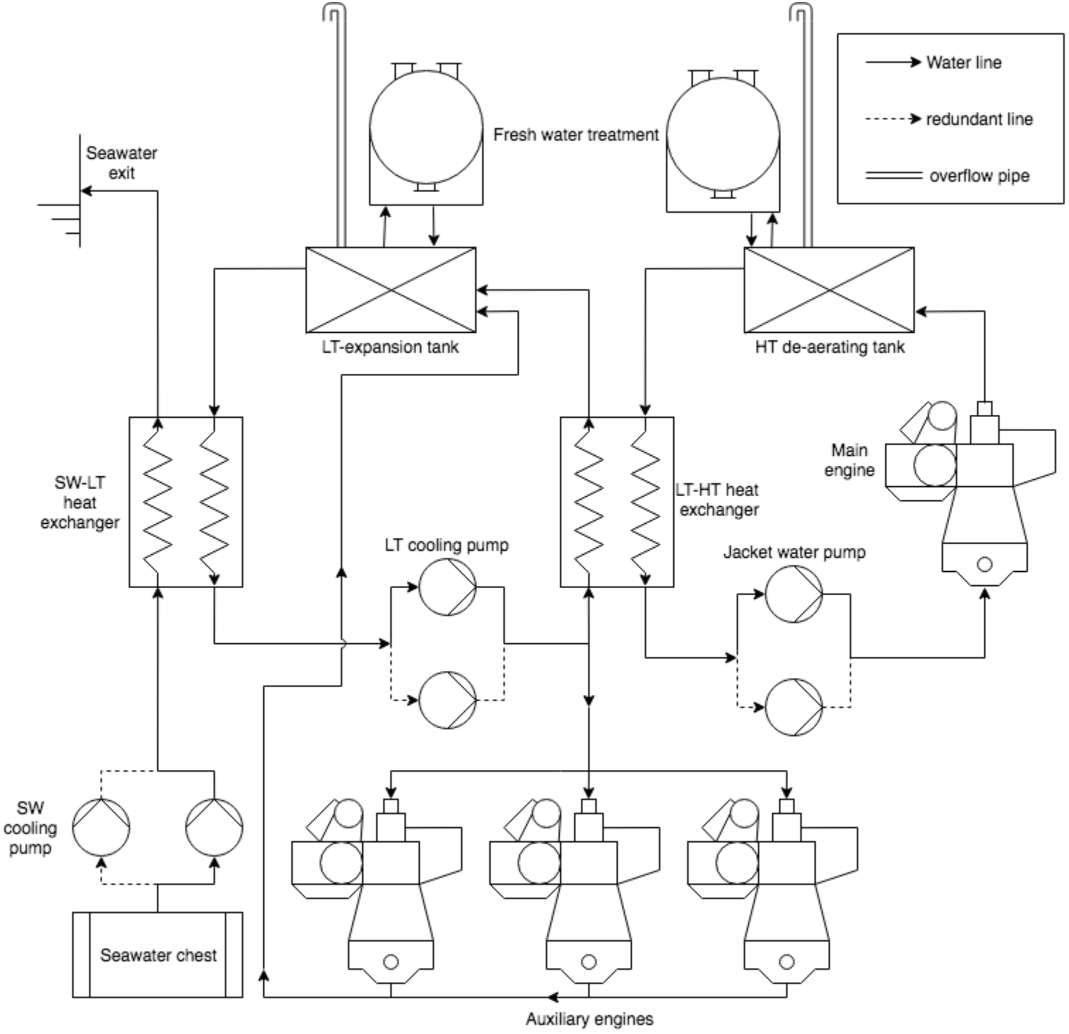

Figure 4.3: Cooling water system diagram [figure by J.P. Colon]

4.7 Starting air system

The starting air system consists solely of the starting air compressors.

The starting air system is used to provide starting air for the main engine and auxiliary engines. It also runs several other systems that require pressurized air. The main compressor, which is also redundant, is used to provide starting air to a pressure vessel, which in turn provides pressurized air to the main engine, but is also branched off to the auxiliary engines to start those. The auxiliary engines have an emergency compressor, which can be started with a battery.

The system diagram for the starting air can be found in Figure 4.4.

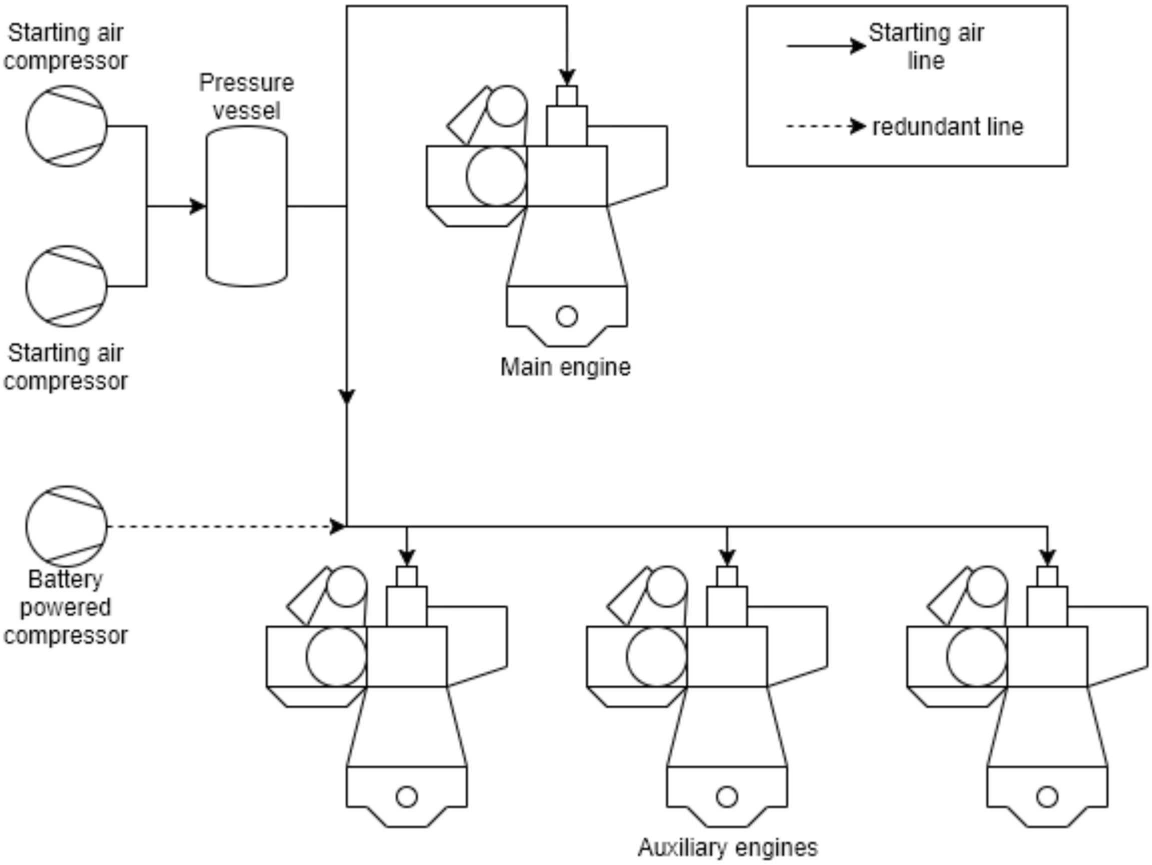

Figure 4.4: Starting air system diagram [figure by J.P. Colon]

4.8 Electrical system

The electrical system consists of the following components:

- The main switchboard
- Transformers
- Cabling
- breakers

The electrical system of a ship is vastly complicated and a study in and of itself, and will therefore not be fully considered for this study. However, the electrical system plays a big part in the engine room, and can therefore not be fully ignored.

The electrical system consists of the generator sets and the economizer, the main switchboard, and a lot of wiring. The main switchboard is split up into two separate systems, but power transfer is available between the two. Next to the main switchboard, all ships are equipped with an emergency switchboard, which is somewhere else on the ship and a completely separate system that can make sure essential systems will still work when the main switchboards fail, as well as making sure that engine can be restarted again.

Each of the two main generators is connected to a different switchboard, and the emergency generator is connected to the emergency switchboard. The generators are equipped with transformers which ensure the correct voltage output. Switchboards are filled with breakers, which prevent short circuiting.

An overview of the electrical system can be found in Figure 4.5.

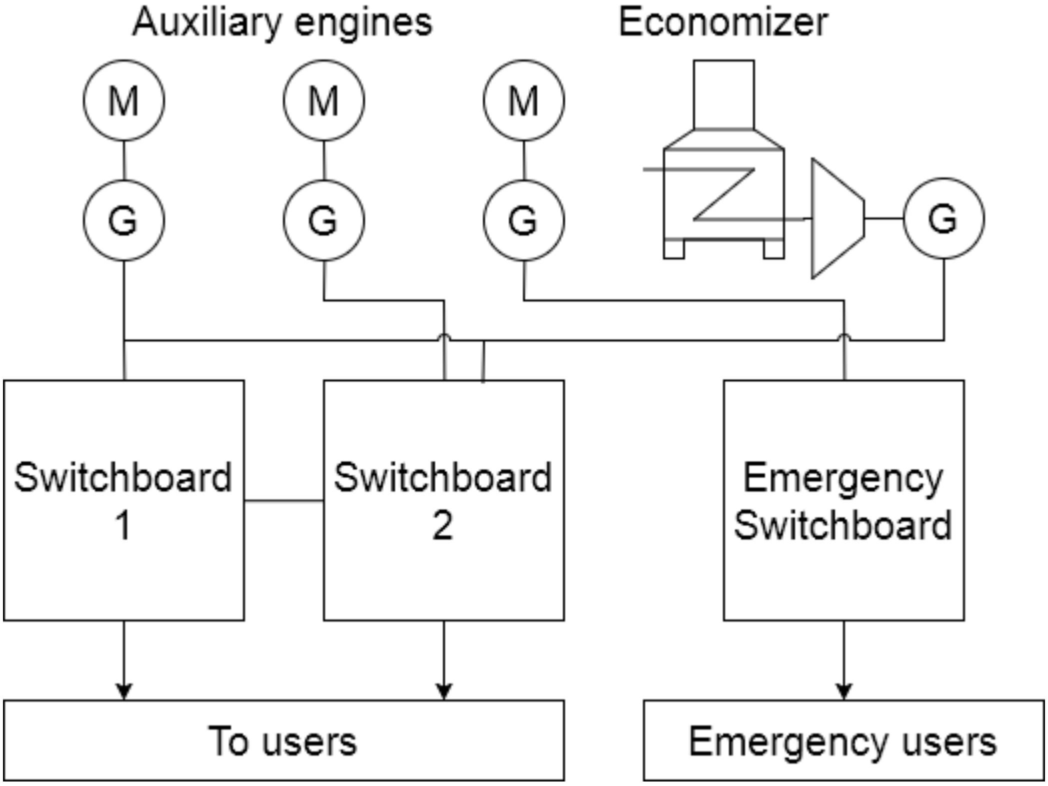

Figure 4.5: Electrical system diagram [figure by J.P. Colon]

4.9 Rudder

The rudder consists of the following components:

- The actuator
- Safety relief valves
- Pump units
- The main control valve
- Electric motors
- The oil tank

The rudder hangs at the back of the ship and is connected to the ship via the actuator, which ensures that the rudder can turn by providing enough torque. The actuator is usually hydraulically driven, and is controlled with the main control valve. The actuator also comes with a safety relief valve, which will make sure the actuator doesn’t get damaged from hydraulic shocks, which can occur when the rudder hits an obstruction. It can also be used to bleed the system in the event of an emergency and when manual control is necessary.

The oil pressure is provided by a pump unit which hangs in the oil tank. The pump unit is driven by an electric motor. Both the pump unit and the electric motor are redundant, but attached to the same oil tank. The tank is separated into two compartments, which are connected through an overflow system. This ensures that if one half of the tank leaks, the other half of the tank can still provide hydraulic oil.

The system diagram for the rudder can be found in Figure 4.6.

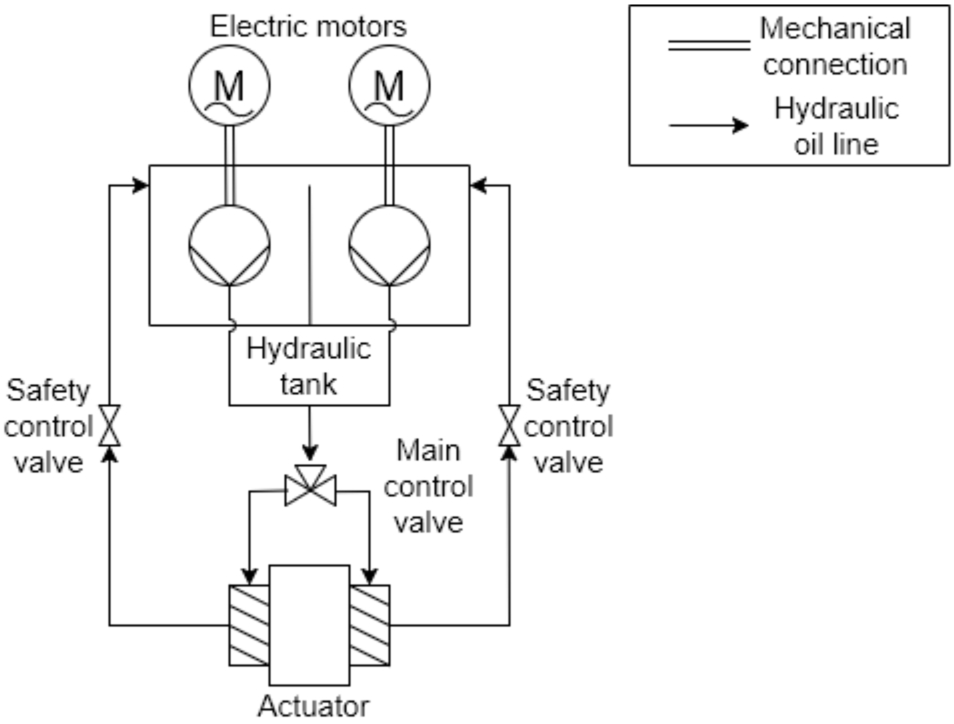

Figure 4.6: Rudder system diagram [figure by J.P. Colon]

4.10 Exhaust gas system

The exhaust gas system consists of the following components:

- The exhaust turbocharger
- The economizer
- The smokestack

The exhaust gas system makes sure that exhaust gases from the main engine and auxiliary engines gets safely transported outside. The exhaust gas system houses the exhaust gas turbocharger, which is used to compress the air going into the main engine.

The exhaust gases are transported to the smokestack, which often houses an economizer or exhaust gas boiler. The economizer is used to heat up water which in turn is used to create steam and subsequently electrical power in a turbine. The smokestack makes sure that exhaust gases are emitted into the atmosphere at an appropriate height, so that the exhaust gases clear the deck and do not foul the superstructure or impair vision astern.

The system diagram for the exhaust gas system can be found in Figure 4.7.

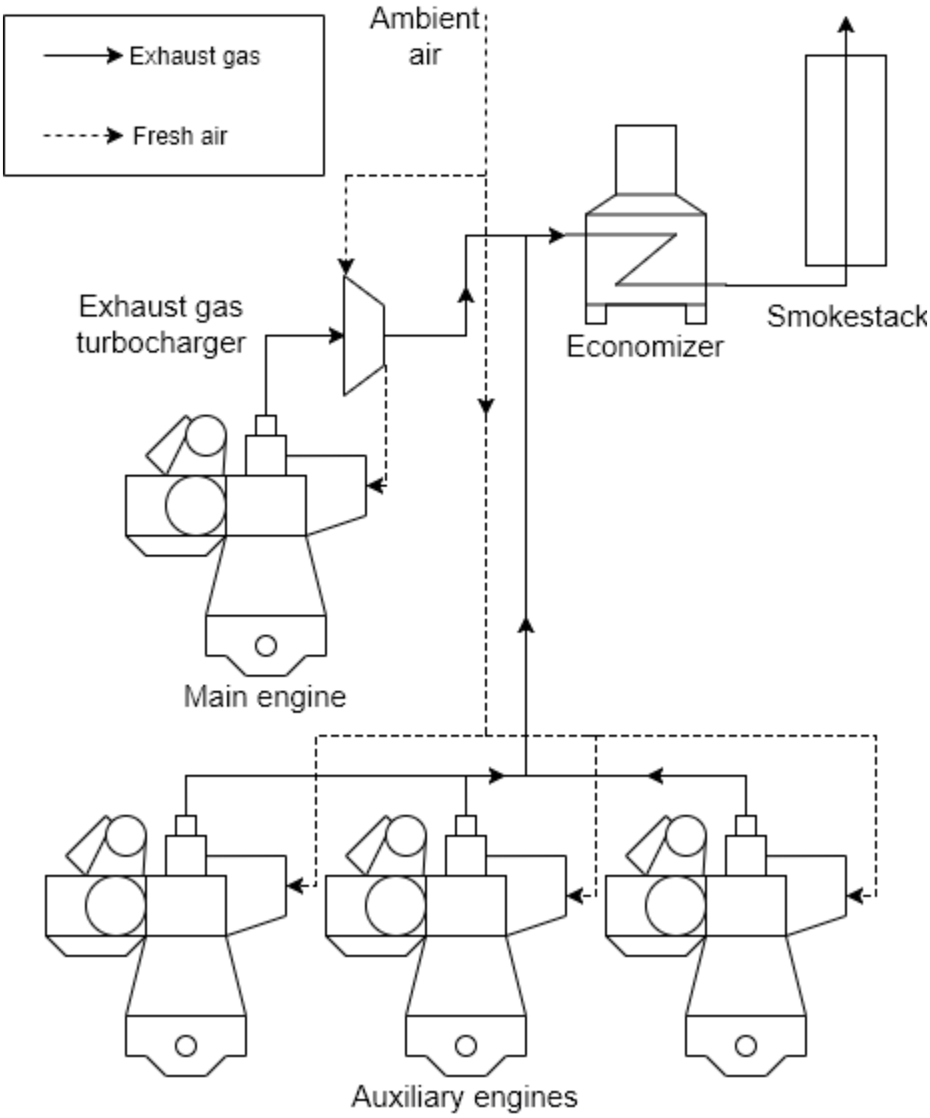

Figure 4.7: Exhaust gas system diagram [figure by J.P. Colon]

5 Creating the risk index and the RRRI

This chapter describes both the risk index and the redundancy reduced risk index for all equipment, as well as giving reasons for why they are this value. The chapter is divided up into the nine different systems as discussed in the previous chapter. The first paragraph discusses the main engine and its subcomponents, as well as the gearbox. The second paragraph looks at the auxiliary engines and generator sets. Next, paragraph 3 gives an overview for the fuel oil system. Paragraph 4 continues with the lubrication oil system, while paragraph 5 is about the cooling water system. Sixth, the starting air system is discussed, and paragraph 7 gives the RRRI for the electrical system. Paragraph 8 discusses the rudder, and the last system to be discussed is the exhaust gas system which is in paragraph 9. The tenth paragraph gives an overview of the results, showing which components are medium and high risk, as well as explaining the reasoning behind them. The final paragraph discusses the difference between the findings of this paper and previous papers.

5.1 Main engine

The RRRI for the main engine and its subcomponents can be found in Table 5.1. The cylinder covers get checked daily for leakages. Apart from leaking, they are not prone to breakdowns and therefore do not get maintained until the overhaul of the engine. The turning gear is only used during overhaul, and usually doesn't get any attention.

The pumps that are attached to the main engine are for the high-pressure fuel oil, the lubricating oil, and the high temperature cooling water. They are directly connected to the crankcase via the driving gears and not prone to break down. Therefore, they do not get checked often, and are only maintained during major overhauls. When using HFO, the HP fuel pumps sometimes get stuck, and are therefore checked weekly.

The manoeuvring system is important during start up, and usually gets checked before every departure. Next to that, many of the safety systems on the engine are hooked up to this system. The pistons and cylinder liners can only get checked by opening up the engine, which only happens during overhauls. Their status is mostly monitored through secondary means such as pressure in the cylinders.

The internal parts of the gearbox are hidden behind the gearbox housing and only checked during overhauls. Clutches don't give a lot of warning before they break down, and are difficult to inspect. The most convenient way to check their status is through the temperature and composition of the lubrication oil. If clutches start grinding, they need to be repaired immediately. The stern tube seal cover is checked multiple times per day for leakages.

A leaky cylinder cover can result in a loss of propulsive power, but can also indicate a more severe problem, such as a broken piston or cylinder. In severe cases, it means a shutdown of the engine is required, but most often a leaky cylinder cover is not catastrophic.

A broken piston or cylinder liner is catastrophic and can destroy an engine if it's not shut down immediately. If the turbocharger stops, the flow of air into the engine will be severely limited, but the engine can still work, albeit at a lower output. A defective driving gear will result in a shutdown of the engine as none of the attached pumps will work anymore. However, all the attached pumps are put in redundantly on a separate electrical system as well, so that their use can still be guaranteed even if the driving gear or the attached pumps themselves stop working. This means that both the attached pumps and the driving gear can be seen as redundant, which brings their RRRI down by one. The manoeuvring system will have a large effect on the manoeuvrability, but this is only really important when going into port, and can be compensated by tugs in emergencies.

If pressure drops on a hydraulic clutch, the springs inside will automatically unclutch it, and propulsive power will drop completely. If the gearbox breaks down, no more power can be delivered to the propeller, making it a high severity. If the stern tube seal fails completely, the engine room will start filling up with water, which can have catastrophic effects if the bilge pumps can't keep up with pumping out water that comes in. The bilge pumps are designed to deal with a leaky seal, but not completely failed one. However, the stern tube seal cover is always double, if not triple redundant, bringing the RRRI down by 2.

Table 5.1: RRRI for subcomponents of the main engine

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Cylinder cover	4	2	1	4	1	1	8	0	8
Turning gear and turning wheel	1	1	1	1	1	1	2	0	2
Piston/ cylinder liner	1	2	1	5	1	1	7	0	7
Driving gear	2	2	1	5	1	1	7	1	6
Attached pumps	3	3	1	5	1	1	8	1	7
Manoeuvring system	4	2	1	1	3	1	7	0	7
Gearbox	3	2	1	5	3	1	8	0	8
Clutch	2	2	2	5	5	1	7	0	7
Stern tube seal cover	5	3	3	5	3	5	10	2	8

5.2 Auxiliary engines and generator sets

The RRRI for the auxiliary engine and generator set can be found in Table 5.2. Just like the main engine, the basic diesel engines running the generators get checked quite often. Most parts attached to these engines get a daily check, and are maintained regularly. Alternators don't have a lot of wear and tear and are checked very rarely.

Most of the subsystems of the generator set do not have a big influence on the propulsion, but they do impact the power generation and manoeuvring capabilities. Because both the rudder and bow thrusters rely on electric motors, failure of the electric systems would impact their use. However, since there is also an economizer on board, at least some functions would still work. All ships are equipped with at least two generators, either of which should be able to provide all the power, so there is always a reserve. Next to that, all ships have emergency generators on board, meaning that if no PTO is present and both gensets fail, the emergency generator takes over. The emergency generator is enough for some power, but won't deliver the same amount of power, meaning non-vital systems will shut down. This double redundancy lowers the RRI by 2. Most pumps within the auxiliary system are not redundant, but each engine has their own set of pumps, which provides the redundancy.

Table 5.2: RRRI for the auxiliary engines and generator sets

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Basic diesel engine	4	2	2	1	3	3	7	2	5
Fuel oil pump	4	2	2	1	1	3	7	2	5
Lubricating oil pump	4	2	2	1	1	3	7	2	5
Cooling water pump	4	2	2	1	1	3	7	2	5
Starting air system	3	2	2	1	1	3	7	2	5
Alternator	2	1	1	1	1	3	7	2	5

5.3 Fuel oil system

The RRRI for the fuel oil can be found in Table 5.3. The bunker tank gets checked about once per week, mostly on fullness. Both the settling tank and day tank get checked every day. The proper functioning of most fuel oil centrifuges, commonly referred to as separators, is very dependent on fuel quality, and therefore they are checked quite often. They are usually self-cleaning, but they do need to be cleaned sometimes, especially when they are not configured correctly, or when the used fuel is particularly dirty. Both fuel oil pumps within the system do not need much attention. The longevity of the fuel filters depends on the quality of the fuel, and their status is monitored by checking the pressure difference over the filter, or by checking the frequency at which they clean themselves. The dirtier they get, the more often they 'shoot'. When the time between each shot gets below a certain threshold, they need to be replaced. This is usually once every few months. Only on very dirty fuels, fuel filters might suddenly clog up, this is however quite rare. Although recently, as a result of mixing in biodiesel with marine diesels, algae can be quite a problem which could clog up the filters.

The loss of all bunker tanks would mean a shutdown within 24 hours, as the settling and day tanks will not be able to be replenished. However, bunker tanks are always split up in compartments, and can be seen as at least double, if not more redundant, which brings the RRRI down by 2 levels. Breakdown of the fuel oil supply pump, which pumps the oil from the bunker tank to the settling tank, as well as breakdown of the fuel oil circulating pump, which circulates oil between the day and the settling tank, would also result in a breakdown in 24 hours. The fuel oil centrifuges in between the bunker tank and settling tank will pose the same problem when breaking down, but these are always set up redundantly, resulting in a lower RRRI. However, the contents of the day tank should be enough to store fuel for 24 hours, at design speed. By slowing down, the fuel supply can be extended by a few days, which would result in the severity index for all these systems to be 3. If all fuel oil filters fail, no more fuel oil will be injected into the engine, and the engine will stop. However, there is always a coarse filter next to the fine filter as a bypass, as well as an unfiltered bypass, making the filters double redundant.

Table 5.3: RRRI for the fuel oil system

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Bunker tank	3	1	1	3	1	3	5	2	3
Settling tank	4	1	1	3	1	3	7	0	7
Day tank	4	1	1	3	1	3	7	0	7
Fuel oil centrifuges	4	3	2	3	1	3	7	1	6
Fuel oil supply pump	2	2	1	3	1	3	5	0	5
Fuel oil circulating pump	2	2	1	3	1	3	5	0	5
Fuel oil filters	4	4	3	5	1	5	9	2	7

5.4 Lubricating oil system

The RRRI for the lubricating oil system can be found in Table 5.4. The lubricating oil transfer pump transfers the lubricating oil from the storage tank to the service tank. It doesn't get much use and therefore isn't checked often. The same goes for the tank itself, as well as the service tank. The sump tank gets checked multiple times a day as it is important for its oil contents to always be at the right level. The full flow filter gets checked daily and gets cleaned or replaced when necessary. The centrifuge gets checked about once a week. The cylinder lubricators are inside the engine and only get checked during engine overhauls.

A lack of lubricating oil can very quickly break an engine, and it is therefore very important that the sump tank has enough lubrication oil in it. If the sump tank leaks, the service tank can still provide oil for a short while, but the engine will very quickly fail. On the other end, if the sump tank gets overfilled and too much lubricating oil gets pumped into the engine, there is a chance of oil mist forming, which, if left unchecked, will cause an internal explosion that will destroy the engine. All engines are therefore outfitted with mist sensors that will shut down the engine if too high concentrations of mist are detected. The LO transfer pump does not get used very often and will not have a high impact if broken. The same goes for the LO tank and service tank. If the full flow filter clogs up, the filter is bypassed, and the lubricating oil goes into the engine unfiltered. This means the engine can still continue running for about 24 hours before the lubricating oil gets too dirty and will start damaging the engine. If the cylinder lubricators, which are the ducts within the engine that the lubrication oil flows through, stop working, the engine will cease operation immediately. However, every piston has multiple lubricators, and the chance of them failing is only present if the lubricating oil is not cleaned and filtered properly. This redundancy brings the RRRI down by two.

Table 5.4: RRRI for the lubrication oil system

	Frequency index (FI)			**Severity index (SI)**			**Risk index**	**Redundancy level**	**RRRI**
	Check	**Maintain**	**Repair**	**Propulsion**	**Manoeuver**	**Power**			
Lubricating oil transfer pump	1	1	1	2	1	1	3	0	3
Lubricating oil full flow filter	4	3	1	3	1	1	7	0	7
Lubricating oil tank	1	1	1	2	1	1	3	0	3
Cylinder lubricators	2	2	1	5	1	1	7	1	6
Lubricating oil service tank	3	1	1	4	1	1	7	0	7
LO centrifuge	3	2	1	3	1	1	6	0	6
Sump tank	5	2	1	4	1	1	9	0	9

5.5 Cooling water system

The RRRI for the cooling water system can be found in Table 5.5. The cooling pumps get a daily visual check, and their subcomponents get checked during maintenance. The de-aerating tank does not get much attention, but the expansion tank does, as its water level indicates any leaks in the system. This means the expansion tank gets checked daily.

If any of the pumps within the cooling water system fail, the engine will overheat and break down within 15 minutes. However, all these pumps come with redundancy, sometimes even double redundancy, which brings their RRRI down by a level. Leaks in the cooling water tanks can get compensated by the fresh water treatment system. The auxiliary engines run on the LT water system, so the jacket water cooling pump only influences propulsion and not power.

Table 5.5: RRRI for the cooling water system

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Seawater cooling pumps	4	2	2	5	1	5	9	1	8
Central cooling water pumps	4	2	2	5	1	5	9	1	8
Jacket water cooling pump	4	2	1	5	1	1	9	1	8
Deaerating tank	2	1	1	2	1	2	4	0	4
Expansion tank	4	1	1	2	1	2	6	0	6
Fresh water treatment	3	4	2	2	1	1	6	0	6

5.6 Starting air system

The RRRI for the starting air system can be found in Table 5.6. The starting air compressors are used by all machines in the engine room that run on compressed air, and they are also used to start up the auxiliary engines. Because they are used so often they get checked often and are maintained regularly.

The starting air compressors connect to several systems which can break down if no air is provided. However, the starting air system always has a redundant compressor for the main engine, but every subsystem usually has an extra compressor as well, making this system double redundant, reducing the RRRI by 2.

Table 5.6: RRRI for the starting air system

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Starting air compressors	3	3	2	4	1	4	7	2	5

5.7 Electrical system

The RRRI for the electrical system can be found in Table 5.7. The electrical system of a ship is vital to its proper functioning, and can become very complex very quickly. The reliability of electrical systems on ships is a study in and of itself, and therefore this system will only be touched upon in very general terms. The main switchboard, together with the breakers inside it, gets checked the most often, about every 3 months. The electrical system does not get a lot of planned maintenance, as they mostly break unexpectedly. Most parts of the electrical system get maintenance from time to time, but it’s usually small maintenance. Both the cabling and breakers can get damaged by vibrations and can break unexpectedly from time to time.

The consequence of the main switchboard failing is catastrophic for the power supply of the ship, but switchboards are divided up into two separate systems, and there is always another emergency switchboard. This double redundancy brings the RRI down by two. Other components breaking in the electrical system usually lead to very localised problems, and therefore have a lower severity. Loss of power can lead to a decline in manoeuvrability due to a loss of thrusters or hydraulic pressure in the rudder.

Table 5.7: RRRI for electrical systems

	Frequency index (FI)			**Severity index (SI)**			**Risk index**	**Redundancy level**	**RRRI**
	Check	**Maintain**	**Repair**	**Propulsion**	**Manoeuver**	**Power**			
Main switchboard	3	3	2	1	5	5	8	2	6
Transformers	3	1	1	2	2	2	5	0	5
Cabling	2	1	3	2	2	2	5	0	5
Breakers	3	1	4	2	2	2	6	0	6

5.8 Rudder

The RRRI for the rudder can be found in Table 5.8. Although all the way at the back, the rudder is quite easy to reach and most of its components get a daily inspection. The only component that cannot be checked is the actuator, as it’s hidden inside the mechanism. Because the rudder is a relatively simple mechanism, it does not need a lot of maintenance apart from the occasional change of the hydraulic oil or major overhaul.

The loss of any components but the safety relief valves and the expansion tank will result in a complete loss of steering capability, but will not have an impact on other systems. If the safety relief valve starts leaking, there will be less flow capabilities and the rudder will have a harder time steering. If the rudder systems break, it will usually mean the rudder will be stuck in a certain position. Steering could still be possible using a bow thruster, although only at very low speeds. Depending on the position of the rudder, maintaining course will be very hard to impossible. If the pump or motor fail, most rudders still have a manual override, but the manual override will not be useful unless people are brought on board.

All the systems, excluding the actuator, are redundantly set up. The oil tank is compartmentalized, with each compartment having its own pump unit. The compartments are connected through an overflow system, meaning that if one compartment starts leaking and empties, the other one will still be available. This reduces the RRRI by one for all components except for the actuator.

Table 5.8: RRRI for the rudder

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Actuator	2	2	1	1	4	1	6	0	6
Safety relief valve	2	2	1	1	3	1	5	1	4
Pump unit	2	2	1	1	4	1	6	1	5
Main control valve	2	2	1	1	4	1	6	1	5
Electric motor	2	2	1	1	4	1	6	1	5
Oil tank	3	1	1	1	3	1	6	1	5

5.9 Exhaust gas system

The RRRI for the exhaust gas system can be found in Table 5.9. The exhaust gas system mostly gets visual checks on the colour of the exhaust gases, and the temperatures are read out constantly. If the exhaust system is not cleaned from time to time, soot fires might start. This is especially the case in obstructions in the exhaust gas system, which include the exhaust gas turbocharger and the economizer. The exhausts themselves don't have to be maintained often, but the turbos running on the exhaust gas and the boilers inside the gas system accumulate the most dirt, and are cleaned by inserting very fine grit into the system which cleans them.

If the exhaust gas system starts to clog up and the engine cannot get rid of the exhaust gas properly, it will start filling up the engine room with smoke. This could be a problem for any humans around but the engine will have no problems with this. If the exhaust turbocharger fails, the engine will not be able to run at full capacity, but it will not shut down completely. A failure in the economizer will result in a loss of power, but this can be compensated by the generator sets. A failure in the economizer itself does not have a very large impact, however, due to the accumulation of soot, it is a potential fire hazard. If there is a leak in the smokestack, the smoke might come out lower than intended, which might damage or dirty the topside of the ship, but will not have a large impact on operability.

Table 5.9: RRRI for the exhaust gas system

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Exhaust turbocharger	4	4	1	4	1	1	8	0	8
Economizer	4	4	2	1	1	3	7	0	7
Smokestack	3	2	1	1	1	1	4	0	4

5.10 Summary and overview

With all the RRRI's constructed, we can get an overview of all the weak points in these systems. Weak points come in two risk categories: High, with a risk index of 8 to 10, and medium, with a risk index of 6 or 7.

5.10.1 High risk components

The weak points with a high RRRI can be found in Table 5.10.

Table 5.10: Risk matrix for high risk components

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Cylinder cover	4	2	1	4	1	1	8	0	8
Gearbox	3	2	1	5	3	1	8	0	8
Stern tube seal cover	5	3	3	5	3	5	10	2	8
Sump tank	5	2	1	4	1	1	9	0	9
Seawater cooling pumps	4	2	2	5	1	5	9	1	8
Central cooling water pumps	4	2	2	5	1	5	9	1	8
Jacket water cooling pump	4	2	1	5	1	1	9	1	8
Exhaust turbocharger	4	4	1	4	1	1	8	0	8

As can be seen, the components with the highest risk include cylinder cover, the gearbox, the stern tube seal cover, the sump tank, the three cooling pumps and the exhaust turbocharger.

The highest ranking component is the sump tank. The sump tank is a special case, as it does not only cause problems when breaking or leaking, it is also an indicator of other defects within the lubricating system. The level of the oil in the sump tank is dependent on several systems within the lubricating system, and a deviation from the norm can mean a problem with any of these components. The sump tank itself is not something that has a tendency to fail, as it is just a tank, without moving components. However, it gets a high-risk rating because of the following three reasons:

- It gets checked often because it is a good indication of the overall health of the lubrication oil system.
- If it does fail, the consequences will be catastrophic. The service tank will be able to provide lubrication oil for a short while, but after that, the engine will stop.
- It is never redundant.

The cylinder covers rank high because they have a tendency to leak, which means that they get checked often. If the cylinder cover does completely fail, the engine will stop. However, most failures involving the cylinder covers are for leaks and cracks, which will reduce the engine output significantly, but will not lead to complete failure immediately. If left unchecked, cracks and leaks can grow and can eventually lead to complete failure of the main engine.

The gearbox is a single point of failure for the propulsion, and is not redundant. This means that in the event of it failing, all propulsion will be lost. This is the main reason for the high-risk index. Gearboxes do not break very often, but bearings inside gearboxes tend to fail from time to time.

Another high-risk component is the stern tube seal cover, which gets checked multiple times per day and would flood the engine room if it failed. However, there are several seals within the seal, as well as emergency seals behind it, making it very redundant. Besides that, unless there is a significant leak, the bilge pumps should be able to keep the engine room from flooding.

The cooling water pumps are arguably one of the most important machines in the system, as without them, all machinery would overheat very quickly. All cooling pumps are set up redundantly at least once, but there are occasions where there are even more cooling pumps.

The exhaust turbocharger tends to get dirty with soot, and therefore gets checked and maintained often, and its failure will mean a drastic decrease in engine output. These are rarely redundant, but they do come with bypass.

5.10.2 Medium risk components

The components with a medium risk index can be found in Table 5.11

The reasons for their medium RRI is explained in the subsequent subparagraphs.

Table 5.11: Risk matrix for medium risk components

	Frequency index (FI)			Severity index (SI)			Risk index	Redundancy level	RRRI
	Check	**Maintain**	**Repair**	**Propulsion**	**Manoeuver**	**Power**			
Piston/ cylinder liner	1	2	1	5	1	1	7	0	7
Driving gear	2	2	1	5	1	1	7	1	6
Attached pumps	3	3	1	5	1	1	8	1	7
Manoeuvring system	4	2	1	1	3	1	7	0	7
Clutch	2	2	2	5	5	1	7	0	7
Settling tank	4	1	1	3	1	3	7	0	7
Day tank	4	1	1	3	1	3	7	0	7
Fuel oil centrifuges	4	3	2	3	1	3	7	1	6
Fuel oil filter	4	4	3	5	1	5	9	2	7
Lubricating oil full flow filter	4	3	1	3	1	1	7	0	7
Cylinder lubricators	2	2	1	5	1	1	7	1	6
Lubricating oil service tank	3	1	1	4	1	1	7	0	7
LO centrifuge	3	2	1	3	1	1	6	0	6
Expansion tank	4	1	1	2	1	2	6	0	6
Fresh water treatment	3	4	2	2	1	1	6	0	6
Main switchboard	3	3	2	1	5	5	8	2	6
Breakers	3	1	4	2	2	2	6	0	6
Actuator	2	2	1	1	4	1	6	0	6
Economizer	4	4	2	1	1	3	7	0	7

Among the medium risk components, there are some components that would have been high risk if they weren't redundant. These include most of the components of the auxiliary engines, as well as the fuel oil filters and the main switchboard.

5.10.2.1 Medium risks in the main engine

Within the main engine, there are a few components with medium risk. The first one is the cylinder liners and pistons. Although one could say these are very redundant, as every cylinder has their own liner and piston, the breakdown of one of these will stop the engine, as a broken piston or cylinder will result in severe damage to the engine if not taken care of immediately.

The attached pumps, although redundant, are very important to the workings of the main engine, and are therefore checked often. Because they are directly attached to the driving gear which is driven by the main engine, they do not have separate electric motors that could fail. This means that they don't have a high chance of failure, unless something else on the main engine fails.

The manoeuvring system is important on two-stroke engines, but less important with four-strokes, as they usually have a gearbox in between that can be used to manoeuver. Next to that, the manoeuvring system can be avoided altogether by installing a controllable pitch propeller.

Simultaneously, because four-strokes use gearboxes, the clutch becomes a medium risk, as it is a single point of failure, which will lead to a total loss of propulsion when broken. Most clutches will unclutch automatically when the oil pressure drops, however, some clutches don't. These would be better for unmanned ships, as it means that there isn't a total loss of propulsion when the clutch breaks.

5.10.2.2 Medium risks in the fuel oil system

Within the fuel oil system, both the settling tank and day tank are marked as medium risk. What is most notable about the fuel oil system is the day tank, which prevents a catastrophic breakdown in the event that one of the preceding components of the fuel oil system break down. Since it stores enough fuel to sail for 24 hours at design speed, it means it can provide fuel for a lot longer when sailing slower. The entire fuel oil system is therefore relatively safe, as long as the day tank, the fuel oil circulation pump and the fuel oil flow filter keep working.

All the other components, although vital for longer trips, do not lead to catastrophic failure. This includes the fuel oil centrifuge, which is relatively high maintenance, but redundant, and therefore not critical.

The fuel oil filter, often regarded as one of the most critical components, only is a medium risk component in this analysis. The main reason for this is the redundancy, with an extra coarse filter but also a bypass, it is not a catastrophic failure if the fine filter clogs up. They get checked every day, but because they are self-cleaning, they last quite long.

5.10.2.3 Medium risks in the lubrication oil system

Within the lubrication oil system, the full flow filter, service tank, the cylinder lubricators and the centrifuge are all considered medium risk. The full flow filters can be bypassed when they clog up, but at some point, this will start affecting the cylinder lubricators themselves, as dirty lubrication oil can clog these up. This will result in a broken engine.

If the service tank fails, the sump tank cannot get replenished, and at some point, there will not be enough lubrication oil in the system. However, the chance of the service tank failing is low, as there are no moving parts.

The centrifuge filters out most of the junk in the lubrication oil, and its failure would put extra strain on the full flow filter, which is bad, but not catastrophic.

5.10.2.4 Medium risks in the cooling water system

For the cooling water system, the only components with a medium risk index are the expansion tank and the fresh water treatment. The expansion tank gets checked every day, because, similar to the sump tank, it is a good indicator of the health of the cooling water system. The expansion tank itself is not prone to breaking down, as it is just a tank. However, if the level in the expansion tank is low, it can indicate that water is leaking from the system. Likewise, if oil is found in the expansion tank, it indicates that somewhere within the system, there is a leak allowing for oil to get inside. Both cases can lead to cooling problems, which in turn lead to a broken engine.

The fresh water treatment requires a lot of maintenance as chemicals need to be added every week to maintain the quality of the fresh water, this leads to it being a medium risk component.

5.10.2.5 Medium risks in the electrical system

The electrical system has two medium risk components: the main switchboard and the breakers. The only reason the main switchboard is a medium risk and not a high risk, is due to its redundant set up. There is always an emergency switchboard that can take over vital functions if the main switchboard fails, and the main switchboard itself is usually divided into two or more sections, to prevent the switchboard from being a single point of failure.

The main reason that the breakers are considered medium risk, is that they need to be repaired quite often. Breakers tend to fail unexpectedly, and therefore most of their maintenance is considered unexpected.

5.10.2.6 Medium risks in the rudder system

For the rudder system, the only risky part is the actuator, as all the others are always sufficiently redundant. The actuator is considered a medium risk because without it, the rudder cannot be used which makes manoeuvring very difficult.

5.10.2.7 Medium risks in the exhaust gas system

Within the exhaust gas system, the only medium risk component is the economizer. The main reason for it being medium risk is the frequency that has to be cleaned and maintained, as it accumulates soot, which can lead to soot fires when not dealt with.

5.11 Similarities and differences with other studies

Now that the weak points have been identified, they can be compared to weak points identified by other studies. Some weak points identified by other studies have not been classified as weak points in this study, while some weak points in this study were not found to be weak points by other studies. The following three paragraphs discusses the differences between the findings of this paper, and those of MUNIN, AAWA and ReVolt.

5.11.1 MUNIN

The goal for MUNIN was to have *“An engine [that] can operate reliably for 500 hours without physical interference from a person in the engine room.”* [11] They have several propositions to ensure that this is possible. Their main concern is the switching of fuel, which they claim can lead to formation of adhesive solids or thermal shocks. Both these will eventually lead to total failure of the engine it is therefore deemed a too high risk for autonomous shipping.

They propose to sail only on distillate fuels, even on the high seas, and predict that the price of distillate fuels will drop significantly due to changes in the world fuel market in the coming ten years. Using only highly distilled fuels, which are cleaned before being pumped on board, would mean that most of the fuel oil system is not necessary for operation.

Distillate fuels as proposed by MUNIN are currently very scarce and expensive, as their intended purity is well above the purity of regular MDO. Although dirty fuels do create some problems, they are not the majority. The only high-risk component found in this study that is affected by fuel quality is the exhaust gas turbocharger, which gets dirty faster when dirtier fuel is used. Their claim that very clean distillate fuels will decline rapidly in price also seems too optimistic.

The sump tank, which has the highest risk index of all components in this paper, does not come forward at all in MUNIN, nor does the stern tube seal cover.

Because MUNIN only looked at large two-stroke engines, they did not consider a gearbox, and therefore did not see it as a critical component. This also means that they did not look at clutching either.

The main engine that MUNIN proposes can control each cylinder separately. If one of the components inside a cylinder fails, the engine can stop injecting fuel into that cylinder and continue operation with a slightly lower power output. However, if a cylinder liner fails, the complete engine still needs to be stopped, making that one of their more critical systems. The same goes for a cracked or leaking cylinder cover, which will lead to an immediate shutdown of the engine.

Even though the result from this study highlights the cooling water system as a potential weak point, MUNIN disagrees because all pumps in the cooling water system are redundant and on standby. Whenever a pump breaks, operations can be continued, and the defective pump can be replaced in port.

In the event of a broken exhaust gas turbocharger, they recommend that sailing can be continued on a reduced load. They too believe it is a critical component, and suggest that a system needs to be developed that can automatically fix and clean the rotor of the turbocharger. [11,p30]

A few of the medium risks identified in this paper are not mentioned by MUNIN to be a problem. The includes the entire auxiliary generator setup, which they claim should be fine since it’s redundant, even though a lot of the subsystems are shared between the two auxiliary engines.

Another risk of which MUNIN states it is not a problem, is the manoeuvring system, which *“… is rarely used during sea operation.”* They claim that *“Therefore, possible failures cannot be determined. Neither are they highly critical.”*[12]. However, this study shows that the manoeuvring system can be critical for autonomous ships.

The economizer is a big part in the design of the autonomous ship of MUNIN, and is responsible for most of the power generation during transit. However, due to its high maintenance needs and the potential power loss during failure, as well as the risk of fire if not maintained properly, show that it can be a critical component for autonomous ships. [11], [12]

Although MUNIN has a lot of right ideas, they seem to put the focus too much on the fuel oil system, and how they can solve the problems that seem to come with dirty fuels. For other problems, they mainly propose increased redundancy on a top level (e.g. adding a second generator), while not increasing redundancies on a lower level (e.g. the lubrication pump for the auxiliary engines). This leads to many single points of failure in systems believed to be redundant.

5.11.2 AAWA

The AAWA does not mention any specific parts that could be a high risk for autonomous ships. They only mention the need for redundancy, as well *as "the introduction of efficient diagnostics and new predictive prognostic algorithms to help assessing and controlling the risk of failures and prescheduling of required maintenance actions as part of overall ship operation planning"*[5].

They stress the need for proper remote monitoring on all systems on the ship, not just the main machinery. This ensures that any problems in the systems can be identified on time.

5.11.3 ReVolt

DNV GL states with the ReVolt that any moving part is too high of a risk to take, and therefore they should be completely avoided. Just like MUNIN, DNV states that the use of heavy fuels brings too much risks. However, instead of opting for cleaner, distillate fuels, they circumvent the problem by going full electric.

Even though DNV states that electric propulsion, powered by batteries, is the best way to solve reliability problems in autonomous ships, they have not published any reliability analyses for their system, and it is therefore very hard to draw conclusions about the actual reliability.

6 Financial analysis

This chapter outlines the financial analysis, which will be used as a basis to judge the viability of solutions to weak points. The first paragraph outlines the breakdown of the financial analysis. The second paragraph shows how the operating costs were found. Next, the crew costs are calculated. Paragraph 4 Shows how the voyage costs are calculated. The capital costs are given in paragraph 5. Since it is important to know the total cost of machinery, they are calculated in paragraph 6. Finally, an overview of all the costs, is given in paragraph 7.

6.1 Financial breakdown

As discussed in paragraph 3.7, The financial breakdown will be the basis of judging solutions for weak points, where the main goal is to make sure that the costs of extra or different machinery do not use up all the financial gain achieved by removing the crew. The financial analysis consists only of a basic cost analysis. Any profits or earnings are not taken into account, only the costs. Because most financial estimations with regard to newbuild price are done using gross tonnage (GT) and not deadweight (DWT), ship sizes are defined by their GT, although a conversion from DWT is made.

To be able to judge whether solutions work on different sizes of ships, four ship sizes are considered:

- A feeder general cargo ship, with a GT of around 6000. They are usually equipped with a four-stroke engine.
- A handysize general cargo ship with a GT of around 20.000. They are usually equipped with a two-stroke diesel.
- A Panamax bulk carrier of around 40.000 GT. Equipped with two-stroke diesel engines.
- A Capesize bulker of around 85.000 GT. Equipped with a two-stroke diesel.

For each of these ship types, the yearly costs are calculated, divided into four categories:

- Operating costs, which include stores & lubricants, insurance, maintenance, administration and other general costs.
- Crew costs
- Fuel costs
- Capital costs, which include both interest and depreciation.

6.2 Operational costs

For the operational costs, estimates made by Stopford [28] are used as a foundation. Stopford used the term ‘operating costs’, which included the operational costs and the crew costs. The operational costs used in this paper are the result of converting Stopford’s operating costs to the ship sizes used in this paper, and then subtracting the crew costs found in the next paragraph. Stopford provides the operating costs in \$/DWT per year. To convert the DWT from his calculation to the GT used in the other calculations, a conversion is made by finding ships with correct size and class, and then finding the corresponding GT. The data can then be extrapolated to find the operating costs for each ship. The costs as given by Stopford can be found in Table 6.1, and the conversions for DWT to GT can be found in Table 6.2.

Table 6.1: Operating costs, taken from table 6.1 from [28]

Cargo capacity DWT	Operating costs [$/DWT/yr]
30.000	40.6
47.000	30.3
68.000	26.0
170.000	12.0

Table 6.2: Deadweight to Gross Tonnage conversion

Cargo capacity DWT	Ship name	corresponding GT	DWT/GT
4470	Maersk Lifter [34]	6821	0.68
30803	Barnacle [35]	19814	1.55
75734	Glykofiloussa [36]	38871	1.95
179527	Cape Tsubaki [29]	93228	1.92

Next, the data from Stopford is extrapolated to the ship sizes used in this paper, and the crew costs are deducted, resulting in the operating costs used in this paper. The results can be found in Table 6.3.

Table 6.3: Operational costs

Ship GT	Size	Operational costs [including crew]	Operational costs [including crew]	Crew costs	Operational costs
[Ton]		[USD/GT/yr]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]
6,000	Feeder	180	1,080	660	420
20,000	Handymax	60	1,200	760	440
40,000	Panamax	44	1,760	860	900
85,000	Capesize	24	2,040	860	1,180

6.3 Crew costs

The crew costs are very dependent on the size of the ship, as a ship's gross tonnage determines the minimum crew requirements. Above 20.000 GT, no extra crew is required, even if the ships get larger. The ITF compiled a list of crew required per ship size, ordered into different functions, as well as their salaries. The resulting salaries can be found in Table 6.4. These salaries already include guaranteed overtime and leave pay.

Table 6.4: Crew salaries by ship size[30]

		Feeder		**Handysize**		**Panamax**		**Capesize**	
Function	Costs [USD/ month]	Crew	Costs [USD/ month]	Crew	Costs [USD/ month]	Crew	Costs [USD/ month]	Crew	Costs [USD/ month]
Master	5,786	1	5,786	1	5,786	1	5,786	1	5,786
Chief engineer	5,270	1	5,270	1	5,270	1	5,270	1	5,270
Chief officer	3,780	3	11,340	3	11,340	3	11,340	3	11,340
1st Engineer	3,780	1	3,780	1	3,780	1	3,780	1	3,780
2nd Officer	3,053	0	0	1	3,053	1	3,053	1	3,053
2nd Engineer	3,053	1	3,053	1	3,053	2	6,106	2	6,106
Electrical engineer	3,053	0	0	1	3,053	1	3,053	1	3,053
Chief steward	3,053	1	3,053	1	3,053	1	3,053	1	3,053
3rd Officer	2,946	1	2,946	0	0	0	0	0	0
3rd Engineer	2,946	1	2,946	1	2,946	3	8,838	3	8,838
Electrician	2,642	1	2,642	0	0	0	0	0	0
Bosun	2,001	1	2,001	1	2,001	1	2,001	1	2,001
Fitter/Repairer	2,001	0	0	1	2,001	1	2,001	1	2,001
AB	1,806	3	5,418	3	5,418	3	5,418	3	5,418
Oiler/Greaser	1,806	0	0	1	1,806	0	0	0	0
Steward	1,806	1	1,806	2	3,612	2	3,612	2	3,612
OS	1,375	0	0	1	1,375	1	1,375	1	1,375
	Totals	**16**	**50,041**	**20**	**57,547**	**22**	**64,686**	**22**	**64,686**
	Total/yr		**600,000**		**690,000**		**780,000**		**780,000**

However, the salaries are not the actual costs to the ship owner, as extra costs such as insurance and pension are not accounted for. To compensate for these, the crew costs are increased by 10% [31]. The resulting crew costs can be found in Table 6.5.

Table 6.5: Crew costs

Ship GT [Ton]	Size	Crew costs [kUSD/yr]
6,000	Feeder	660
20,000	Handymax	760
40,000	Panamax	860
85,000	Capesize	860

6.4 Fuel costs

The fuel costs are extrapolated from the bunker usage given by Stopford, and is calculated with the assumption that the speed of the vessels is roughly the same as the ship they were extrapolated from. The bunker usage is then multiplied by the price of MDO or HFO in Rotterdam, depending on the ship's size. Since Stopford only give bunker usage for large ships, the usage is calculated according to equation 5.1. This equation is based on the twothirds power law for a ships resistance, and assumes that fuel usage decreases at the same rate as resistance.

$$\dot{m} = c \cdot \nabla^{\frac{2}{3}} \qquad (5.1)$$

Where $\dot{m}$ is the fuel usage in ton/day, c is a constant extrapolated from Stopfords data, and has been found to be 0.025. ∇ is the ships displacement, which is assumed to scale with GT. Using this equation, the fuel usage, and therefore the fuel costs, can be found in Table 6.6. The bunker costs are taken from [32] on 31-10-2017 for IFO380 in Rotterdam.

Table 6.6: Fuel costs

Ship GT	Size	Fuel type	Fuel usage	Fuel usage	Fuel costs	Fuel costs
[Ton]			[Ton/day]	[Ton/yr]	[USD/ton]	[kUSD/yr]
6,000	Feeder	MDO(ULSFO)	7.79	2,800	511	1,500
20,000	Handymax	HFO (IFO380)	17.24	6,300	336	2,100
40,000	Panamax	HFO (IFO380)	27.25	9,900	336	3,300
85,000	Capesize	HFO (IFO380)	44.81	16,400	336	5,500

6.5 Capital costs

The capital costs are based on the initial investment, and are extrapolated using Stopford's assumptions. The initial investments are based on newbuilding prices, which are based on Clacksons SIN database for newbuilding for July 2017. Since the newbuilding prices in Clacksons database are based on CGT (compensated gross tonnage), the GT is first converted to CGT according to equation 5.2.

$$CGT = A \cdot GT^{B} \qquad (5.2)$$

Where A and B are constants that are dependent on the ship type[33]. The CGT for each vessel, can be found in Table 6.7, which also lists the price per CGT and the newbuild price.

Table 6.7: Compensated gross tonnage and newbuild prices

Ship GT	Size	Ship type	A	B	CGT	Price	Newbuild price
[Ton]					[Ton]	[USD/CGT]	[Kusd]
6,000	Feeder	General cargo	27	0.64	7,069	1,372	9,700
20,000	Handymax	General cargo	27	0.64	15,276	1,597	24,400
40,000	Panamax	Bulk	29	0.61	18,606	1,270	23,600
85,000	Capesize	Bulk	29	0.61	29,468	1,443	42,500

Next, the capital costs are calculated. The ratio as used by Stopford is around 10.8% of the initial investment as capital costs per year. This brings the capital costs per year to the numbers as given in Table 6.8.

Table 6.8: Capital costs

Ship GT	Size	Initial investment	Capital costs
[Ton]		[MUSD]	[kUSD/yr]
6,000	Feeder	9.7	1,050
20,000	Handymax	24.4	2,640
40,000	Panamax	23.6	2,550
85,000	Capesize	42.5	4,590

6.6 Cost of machinery plant

The cost of the machinery plant is a good basis to be able to find out how much changes to machinery would cost, when solutions are found. For the costs of the machinery plant, the same 4 example ships are used as a basis. Using these ships, their installed power is found. Using the installed power, it is possible to estimate the weight of the machinery, which in turn makes it possible to estimate the total costs of the machinery.

Schneekluth and Bertram estimate the weight of different types of engine based on their power output. The weight estimations they made can be found in Table 6.9.

Table 6.9: Engine weight estimations [34]

Engine type	Engine RPM	Minimum weight	Maximum weight
		[Ton/kW]	[Ton/kW]
Slow speed engines	110-140	0.016	0.045
Medium speed engines in series	400-500	0.012	0.020
Mediums peed engines V-type	400-500	0.008	0.0015

When the weights of the engines are known, an estimation can be made on the total costs of the engine. This estimation is done based on figure 18.12 from Watson's *Practical ship Design* [35]. This figure can be found in Figure 6.1.

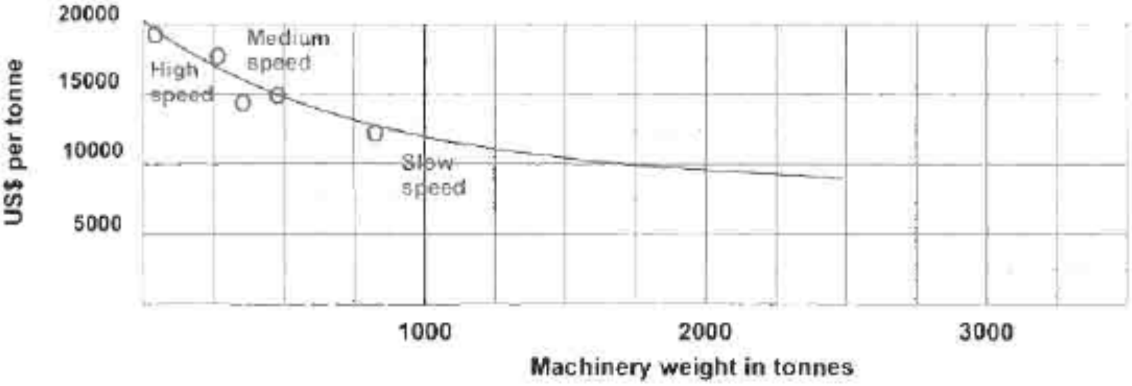

Fig. 18.12. Approximate costs of machinery per tonne. Costs are on a 1993 basis and include materials, labour and overheads.

Figure 6.1: Cost estimation machinery per weight [35]

Using these methods, we can then create Table 6.10 , which gives an overview of the machinery costs per ship type.

Table 6.10: Machinery cost per ship

Ship GT	Size	Ship name	Installed power	Engine type	Machinery weight	Machinery cost
[Ton]			[Kw]		[Ton]	[kUSD]
6,000	Feeder	Maersk Lifter [34]	4,000	In-line medium speed	90	1,260
20,000	Handymax	Barnacle [35]	7,200	Slow-speed	216	2,700
40,000	Panamax	Glykofiloussa [36]	12,200	Slow-speed	366	4,600
85,000	Capesize	Cape Tsubaki [29]	17,800	Slow-speed	534	5,800

6.7 Overview

With all the costs known, the total costs per year can be calculated. The total costs, as well as all the different costs, can be found in Table 6.11.

Table 6.11: Overview of all costs

Ship GT	Size	Initial investment	Operational cost	Crew cost	Fuel cost	Capital cost	Total cost
[Ton]		[kUSD]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]
6,000	Feeder	9,700	420	660	1,500	1,050	3,600
20,000	Handymax	24,400	440	760	2,100	2,640	5,900
40,000	Panamax	23,600	900	860	3,300	2,550	7,600
85,000	Capesize	42,500	1,180	860	5,500	4,590	12,100

As can be seen, the crew costs and operational costs become an increasingly smaller part of the total costs. This is better illustrated in Figure 6.2, where the relative costs per category are shown. This is already a strong indication that it will be difficult for the larger ships to replace the crew, as their cost is only a very small part of the total costs involved. Although the total costs for crew are larger for the bigger ships, so would be the extra investments that need to be made to make sure they can sail autonomously. As investments to engines and engine rooms usually scale with the size of the ship, so will the investments for taking care of the weak points within their engine rooms.

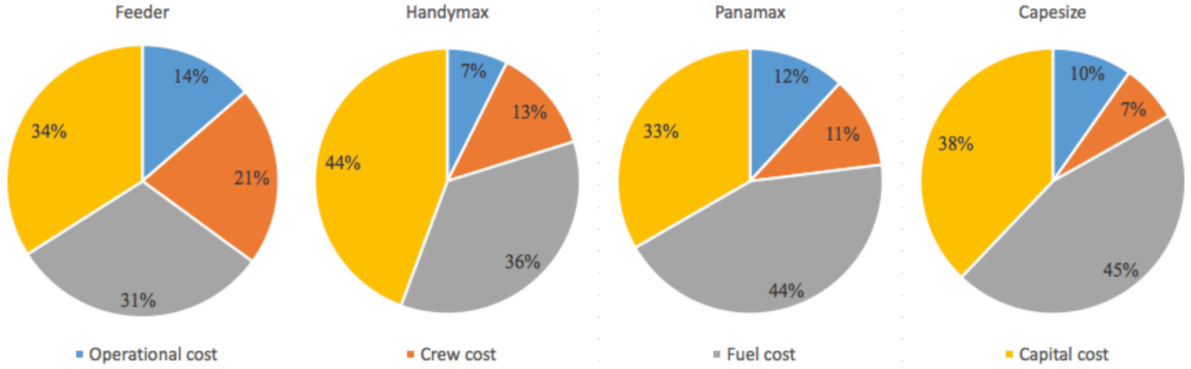

Figure 6.2: Cost distribution

With all costs known, they can be used as a basis for calculating the extra costs involved that will be made when applying solutions found in the next chapter according to the method defined in chapter 3.7.

7 Potential solutions

This chapter explores possible solutions to the problems identified in chapter 5. The first paragraph will give an overview of solutions to foreseen problems as proposed by previous projects such as MUNIN, AAWA and ReVolt. The second paragraph will give solutions to all high-risk components, and paragraph 3 will try to find solutions for medium risk components. The fourth paragraph will give an estimation of the costs involved for these solutions, and will compare them to the results obtained from chapter 6. Next, the fifth paragraph reflects on the possibilities of switching to different methods of propulsion, and what the consequences for those would be. Finally, paragraph 6 will give an overview of recommendations.

7.1 Solutions of previous projects

This paragraph will give an overview to the solutions that are proposed by the previous projects MUNIN, AAWA and ReVolt. They can be found in subparagraphs 1, 2 and 3.

7.1.1 MUNIN

The primary problem that MUNIN found was that the switching of fuels lead to a lot of potential problems, and that it therefore should be avoided at all costs. Their proposed solution to this was to stop using heavy fuel oil altogether, and only sail using distillate, pre-cleaned fuels. They claim this solves all the problems found in the fuel processing plants, such as broken filters or centrifuges, as these would no longer be necessary. They also claim that the costs of these distillate fuels would drop dramatically in the coming 10 to 15 years as demand would rise and fuel refineries would start producing more to meet demand, leading to a more efficient process of distillation.

The biggest change to the main engine would be the use of complete electronic switching of the cylinders, giving them the opportunity to control the use and setting of each cylinder individually. This would mean that if for one cylinder something is amiss, they can stop the use of that single cylinder without having to stop the entire engine. However, since the piston would still be moving, a broken cylinder cover or cylinder liner would still lead to a complete shutdown of the engine. They propose that a detection system needs to be developed which can detect cracks in cylinder covers or cylinder liners.

For the exhaust gas turbochargers, they propose a self-cleaning system, which would be electronically controlled and capable of cleaning the turbocharger once per day. If the turbocharger does break, the engines auxiliary blowers can be used instead.

The cooling water system should be redundant enough with an extra pump per system, as long as it’s always on standby. They do stress the need of extra sensors capable of monitoring any breaks or contaminations in the system.

For the electrical system, redundancies of the major systems on the main switchboard should be good enough, as long as the generators can be restarted automatically if they fail.

Another major design change to the ship is the inclusion of two waterjets at the front of the ship, powered by electric motors. They should be able to ensure steering if the rudder fails. Because they are pointed slightly backwards, they should be able to provide some propulsion if the main engine fails. Including these thrusters at the front is a good way to ensure that a ship can at least get into port if something breaks in the main propulsion plant. Another option would be a PTI on the gearbox, which can provide some thrust through the use of an electric motor if the main engine fails. However, if the gearbox or clutch fails, the PTI will not work either.

They advise additional redundancies on fuel oil and lubrication filters and centrifuges, as well as automatic cleaning systems for these. Another additional redundancy includes the power generation, where one generator should be capable of providing the total power demand, but two are installed.

Another concern that MUNIN presents is the time taken in port when maintenance is carried out by the port crew. By using standard, pluggable units for most machinery, a lot of time can be saved in port.

7.1.2 AAWA

The AAWA, as said before, hasn't done much research into maintenance and repair. Their only concern seems to be the timing of maintenance that needs to be done, and the fact that it can only be done in port. They do not mention any specific machinery problems, but only stress the importance of proper scheduling of maintenance. This should be done with help from advanced diagnostic tools which can help in assessing and predicting the risk of failure for equipment. They also mention the importance of designing easily maintainable equipment, but never say how they would do this.

7.1.3 ReVolt

The ReVolt has a single solution for all the problems that could possibly happen with autonomous vessels, and this solution would be to get rid of all equipment in the engine room and replace with a single giant battery and azipod thrusters with electric motors. This would eliminate all machinery, and therefore also all weak points. By having no moving parts inside the hull, they claim that reliability will not be an issue. The only concern would be the reparability of the azipod thrusters if they do break down. This would mean that the ship would have to be dry-docked if anything happens, which will have large financial consequences.

Paragraph 7.5.2 explores the possibilities of switching to battery power for regular merchant ships. The conclusion is that they are currently too large and expensive to compete with diesel powered ships, especially if they need to have the same range and speed as diesel powered ships.

7.2 Solutions to high risk components

There is a total of 8 high risk components, although three of these are the cooling water pumps. Subparagraph 7.2.1 will list solutions for the cylinder cover, and subparagraph 7.2.2 will show solutions for the gearbox. Next, subparagraph 3 will show solutions for the stern tube seal cover. For the fourth subparagraph, solutions for the sump tank are discussed. Paragraph 5 gives an overview of the options for the seawater cooling pump, central cooling water pump and jacket water cooling pump. Finally, subparagraph 7.2.6 gives the solutions than can solve problems with the exhaust gas turbocharger.

7.2.1 Solution for the cylinder cover

The main engine only has one high risk component, which is the cylinder cover. It is considered high risk because it gets checked daily for leakages and cracks and a leak or crack in the cylinder. It is a component inherent to diesel engines and cannot be removed without the complete redesign of an engine. However, there is a way of installing it in such a way that a crack or leak in the cylinder cover does not have to mean the complete shutdown of an engine.

Currently, diesel engines have a single cylinder cover which covers all the cylinders. By adopting the techniques proposed in MUNIN, which suggests an electronically controlled engine, in which each cylinder can be activated or deactivated, it would be beneficial if each individual cylinder had its own cylinder cover. Cracks and leakages could then be contained by shutting down the cylinder which is not properly sealed anymore. Even though the piston would still be moving, no air or fuel would be injected into the cylinder, and no combustion would take place. Since the main function of the cylinder cover is to contain the pressure created by combustion, removing the combustion would be enough to stop any further damage to the cylinder cover.

7.2.2 Solution for the gearbox

Attached to the main engine is another high-risk component, which is the gearbox. The gearbox is mostly considered high-risk because it is a single point of failure, and it will stop all propulsion if it fails. It does not get checked or maintained that often, and is not very likely to fail.

The only way to make the gearbox redundant is by installing a second main engine and a second propeller, which is expensive. Another option would be removing the gearbox completely by switching from a medium- or high speed four-stroke engine to a low speed two-stroke engine. Two-stroke engines are more expensive than four-strokes, and therefore rarely used in smaller ships. The final solution would be the switch from diesel-direct to diesel-electric propulsion, where diesel generators power electric motors powering the propulsors. Electric motors do not need gearboxes as they can be designed for a wide RPM-Torque range. This would require a significant investment though, as explained in paragraph 7.5.4.

7.2.3 Solution for the stern tube seal cover

The stern tube cover is highly critical because it gets checked multiple times per day on leakages, and complete failure of the stern tube seal would mean the leaking of water into the engine room, which could shut it down and potentially flood and sink the ship.

The only way to remove the stern tube seal completely would be by using azipod thrusters instead of a normal propeller. Any leak in a tube seal would then just flood the azipod and not the entire engine room. Especially if multiple azipods are installed, this would have less effect on propulsion, and the criticality of the seal cover would disappear.

Another option would be the inclusion of a second complete stern tube seal, with a watertight compartment in between. Finally, this problem can also be solved by installing bilge pumps which are powerful enough to pump away any water that would come in through a broken cylinder cover. This would need a designated flooding space underneath any machinery, which can hold any flooding water and provides enough access for the bilge pumps to do their work.

7.2.4 Solutions for the sump tank

The sump tank is the most critical part identified in this paper. This is due to the fact that the lubrication oil levels get checked multiple times per day, and a leaking sump tank would lead to a quick shutdown of the main engine. The sump tank gets checked so often because the levels of lubrication oil inside the sump tank are a very good indication of the overall health of the lubrication system. This means that the sump tank is not necessarily critical itself, but it should be the focal point of measurements.

By increasing the automation and number of sensors in the sump tank, the frequency of checking the sump tank can be lowered, and therefore it’s criticality will decrease. A possible secondary sump tank, which sits beneath the first one and captures any leakages, will increase the redundancy of the sump tank and reduce its criticality as well.

The addition of extra sensors in the sump tank will not prevent faults in the lubrication oil system from happening though, nor will detecting them solve the problem. The sump tank should also be outfitted with an automatic filling and draining system, which can take care of any low or high levels or lubrication oil in the sump tank. If the filling or draining system kicks into action, warning should be sent to the on-shore control centre that the lubrication system should be checked as soon as possible.

7.2.5 Solutions for the cooling water pumps

All the cooling water pumps within the cooling water system are critical, even though they are all redundant. The reason for this is that the loss of any of the three pumps will lead to a shutdown of the main engine within 15 minutes.

There is very little that can be done to reduce the criticality of the cooling water pumps, except increase the redundancy even further.

One could consider an emergency, pumpless, gravity based system where a seawater intake would be right below the surface of the water, and it would have a pipe flowing down directly into the cooling system, with a drain at the bottom of the ship into a tank, which is emptied by a separate pump. The big downside would be that the engine would be directly cooled by salt seawater, which could damage the engine if used for a prolonged duration. However, in emergencies it could be a viable option. Because it would be passive cooling, the engine would have to run slower, reducing its power output.

7.2.6 Solutions for the exhaust gas turbocharger

The final critical component is the exhaust gas turbocharger, which gets checked and maintained often, and is a vital component in the proper workings of the diesel engine. The exhaust gas turbocharger essentially provides ‘free’ energy that is used to compress the air going into the main engine. However, because it deals with the high temperature and highly contaminated exhaust gases, it gets dirty quickly and therefore needs to be cleaned often.

A simple solution to this problem would be the removal of the exhaust gas turbocharger and replacing it by an electrically driven turbocharger. These need a lot less attention, and therefore have a lower frequency index. A downside to this solution is the increase in power and therefore fuel consumption.

7.3 Solutions to medium risk components

There is a total of 19 medium risk components, of which 10 have a RRRI of 7 and 9 have an RRI of 6. For readability, this paragraph is divided up into subparagraphs for each of the component groups. The first subparagraph gives solutions for the medium risk components of the main engine, or which there are 5. The 3 medium risk components of the fuel oil system are discussed subparagraph 2. Paragraphs 3 and 4 outline the lubrication oil system and the cooling water system, where the first has 4 and the second has 2 medium risk components. Next is the electrical system in paragraph 5, which discusses 2 components. Finally, since both the rudder and exhaust gas system only have 1 medium risk component each, they are both discussed in subparagraph 6.

7.3.1 Subcomponents of the main engine

The main engine has a total of 5 medium risk subcomponents. The first subcomponent is the cylinder liner, which neither can be removed, nor can it be made redundant. This makes this a component for which no simple solutions can be found. The component has a medium risk purely because its breakdown would result in the immediate shutdown of the main engine. The engine needs to be shut off because if a piston moves past a broken cylinder liner, it could get stuck and break, or fuel can leak through the cylinder liner into the rest of the engine, which could lead to explosions.

A possible solution to this problem would be to design a system which would allow the decoupling of a piston from the crankshaft. If broken cylinder liners can be detected, which for instance can be done by measuring pressure on both sides of the piston head, then this system would be able to automatically decouple a piston if the cylinder liner was leaking.

Another medium risk component is the driving gear, which controls all the valves that control the flow of gases and fuel. The driving gear can be removed and replaced by electronically switching the valves. This would have the added bonus of extra valve and cylinder control and would allow for the individual shutdown of cylinders. MUNIN had the same proposal.

The pumps attached to the diesel engine, which are mechanically driven by the driving gear, are also medium risk. They would have been a high-risk component if they weren’t already redundant, where the second set of pumps is driven by an electric motor. The three attached pumps, namely for fuel oil, lubrication oil and jacket water are a medium risk because they are vital to the working of the engine, which would shut down if any of the attached pumps malfunctioned. However, they are rarely checked or maintained, which shows they are quite reliable. Since they also come with a redundancy, this would be a component of which a medium risk has to be accepted.

The manoeuvring system is a medium risk component because it’s loss would impact the ability of the ship to sail backwards. However, many four-stroke diesel engines do not come with a manoeuvring system as they are integrated into the gearbox, or not needed because of a controllable pitch propeller. It is a component that could be made redundant, as it is basically a valve that controls the way the starting air is injected into the engine. Making the component redundant would reduce the RRRI from a 7 to a 6, which is still considered medium risk, but since it is not used often, that would be acceptable.

The final medium risk component of the engine and gearbox is the clutch, which has a RRRI of 7, almost exclusively because its failure would result in the total loss of propulsion and manoeuvrability. This loss of propulsion is due to the automatic decoupling of the clutch in the event of a breakdown, which is mostly caused by loss of pneumatic pressure. The easiest way to solve this problem is to make sure the clutch remains clutched when oil pressure drops. If the clutched position would be the default position, and unclutching would require pressure, then even at the loss of pressure, the clutch would remain clutched and the engine can still deliver power to the propulsor.

7.3.2 Fuel oil system

There are 4 medium risk components within the fuel oil system. They are the settling tank, day tank, and the fuel oil filters. All of them have an RRRI of 7, except for the fuel oil centrifuge, which has an RRRI of 6.

Both the settling tank and day tank get checked daily for their fuel levels, which leads to their medium risk. Because the settling tank is used to fill the day tank, if the settling tank fails, the day tank will not be replenished, and fuel will run out within 24 hours. Because the day tank is the vital part in this system, improving it is the easiest way to increase the reliability of the fuel oil system. If the size of the day tank is increased to hold more fuel, or the ship uses a system with two or three day tanks, this would increase the reliability of the fuel oil system greatly.

The fuel oil centrifuge is a medium risk because it gets checked every day. Although the fuel oil centrifuge is vital to the fuel oil treatment, the day tank is a buffer to ensure the centrifuges failure is not immediately catastrophic. Next to that, there are always at least two centrifuges installed, as they take quite long to clean. As with every component that comes before the day tank, improving the day tanks would also reduce the RRRI of the fuel oil centrifuge. The long cleaning period can become a problem for autonomous vessels, so it would be advisable to design fuel oil centrifuges which could be modularly swapped in port, where a dirty centrifuge is replaced by a clean one.

The fuel oil filters are a main concern for MUNIN, but this analysis marks them only as medium risk. Fuel oil filters are mostly self-cleaning, and they are fairly predictable about when they need to be cleaned. The filters clean themselves once a certain pressure difference is exceeded. They do this by blowing air into the filter, which shoots most dirt off. The dirt gets collected in the bilge tank. The shooting of filters does not clean the filters entirely, and over time, more dirt accumulates which cannot be cleaned by the filter itself. This results in a higher frequency of shooting. This frequency is used by engineers to determine whether a filter needs to be changed or not. This can be predicted many days in advance. If filters were to be designed which could use this shooting frequency as a way to predict when they need changing, the filters wouldn’t have to be checked so often, and their criticality would decrease. Next to that, because filters are fairly simple and small machines, they can easily be made more redundant.

7.3.3 Lubrication oil system

The lubrication oil system has 2 components with an RRRI of 6 and 2 with an RRRI of 7. The lubricating oil full flow filter is considered a medium risk component because it gets checked every day. If it clogs up, the filter can be bypassed, but unfiltered lubrication oil can damage the engine if it’s used too long. An easy way to improve this system would be to install a second full flow filter which can take over if the first one clogs up. Next to that, a similar system as for the fuel oil filters can be designed so that the lubrication oil filter can predict when it needs to be replaced. These two things would reduce the criticality of the full flow filter.

The cylinder lubricators are a medium risk because their malfunction would stop the engine. However, in an electronically controlled engine, where each cylinder can be controlled, especially if the pistons themselves can be decoupled, the failure of cylinder lubricator would not mean the shutdown of the entire engine but just one piston. This would reduce the criticality of the cylinder lubricator greatly, to a point where it would be a low risk component.

The lubrication oil service tank is considered medium risk because its failure would mean that lubrication oil in the sump tank cannot be refilled, which would eventually lead to a shortage of lubrication oil and a shutdown of the engine. An easy way to overcome this problem would be to install a bypass around the service tank from the lubrication oil storage tank, or by installing a second service tank.

The LO centrifuge is considered medium risk because both the frequency at which it is checked and the impact it's breakdown would have are in the medium range. The easiest way to reduce the RRRI of the LO centrifuge would be to install a redundant centrifuge. Another option would be the possibility of rerouting lubrication oil from the main engine to the LO centrifuge of the auxiliary engines and vice-versa.

7.3.4 Cooling water system

The cooling water system has two medium risk components: The expansion tank and the fresh water treatment. The expansion tank gets checked daily for contaminations and water level, which results in the higher RRRI. Just like the sump tank, it is a component that gives a good indication of the overall health of the entire system, but isn't necessarily a critical component itself. If the expansion tank is outfitted with proper sensors that can detect contaminations, the expansion tank doesn't have to be checked as often, reducing its criticality. A redundant expansion tank won't help, as contaminations probably originate elsewhere in the system. It won't be easy for an autonomous vessel to detect where the contaminations are coming from, so a system that can cope with a contamination until the ship reaches the next port should be installed.

The fresh water treatment is used to make sure that there is enough fresh water in the cooling system. It has a medium risk mostly because it needs to be maintained quite often. The fresh water treatment requires chemicals to work, which have to be refilled quite often. A simple solution for this would be increase the capacity for chemicals in the fresh water treatment, as well as a smarter system in dosing the chemicals.

7.3.5 Electrical system

The electrical system has two medium risk components: the main switchboard and the breakers within the switchboard. The switchboard is critical because its failure would result in a complete loss of power and manoeuvring. This is also the reason that the switchboard is always double redundant; there are always two main switchboards and an extra emergency switchboard. There are no obvious solutions to reducing the risk of the switchboard further without adding another switchboard, which can be quite expensive, especially considering the switchboard is already double redundant. Therefore, this risk is accepted.

The other medium risk component within the electrical system are the breakers within the switchboards. They are a medium risk due to their repair frequency. They often break unexpectedly, and it is hard to predict when they fail. Breakers tend to get warm before they burn through, and so a temperature-measuring system, such as an infrared camera, could be used to check on the health of the breakers, and they could be replaced when necessary.

7.3.6 Rudder and exhaust gas system

Both the rudder and the exhaust gas system only have 1 medium risk component each, with the first one being the actuator, and the other one being the economizer.

The actuator is considered medium risk due to its big impact in manoeuvrability if it fails. It is also the only single-point of failure (next to the rudder itself) in the rudder system. An option would be to install a dual-rudder system, with each their own actuator, although this would be a rather costly solution. Another option would be to install a backup actuator on top or below the other actuator, and attach it to the same axis.

The economizer is a medium risk component because it has to be cleaned and maintained quite often, and it is quite important for the power generation. However, with the power generation being double redundant with generators, the failure of the economizer should not lead to any problems. The largest risk with the economizer is the chance of soot contamination and soot fires. To prevent this, the crew cleans the exhaust gas system often by inserting grit into the system and letting the high-speed gases grit-blast the inside of the system. This system could be automated, and would solve a lot of the problems.

7.4 Financial analysis

The solutions found in the previous two paragraphs can be split into a few different categories:

- Changes to the main engine, mostly in the form of an electronically controlled diesel engine, where individual cylinders can be controlled and monitored in detail.
- Extra redundancy by adding another, identical component.
- Increasing sensor count on certain components, which would reduce the need to check them.
- Improving the design of the product, by adding extra functions or changing the way the component works.
- Installing a second drive train.
- Accept the risk.

Using the fifth option would increase redundancy across the entire drive chain, and would eliminate the need for many other solutions. However, it is also the most costly solution. Next to that, it does not eliminate the need for some solutions, so they might still be necessary. The costs will be split into two situations: One where all problems are solved using the specific solutions given in the previous paragraphs, and one where a second drive train is added, with some components still needing specific solutions, as they would not be solved with the use of a second drive train.

By using the costs for machinery found in chapter 3.7, some of the costs for solutions can be found for all four different vessels. Because it is not possible to determine the cost for every single solution, each category is estimated to add a certain percentage to the overall machinery costs. The costs will be estimated the following:

- Using a more advanced engine is assumed to be about 25% more expensive than the cost of the regular machinery.
- Extra redundancy of equipment is assumed to add 1% per components to the total machinery cost.
- Increasing sensor count is expected to cost an additional 1% to the total machinery cost per component.
- Improving the design of the product adds an extra 2% to the total machinery cost per component.
- Installing a second drive train will double the total cost of machinery.
- Accepting the risk does nothing.

Using these numbers, it is possible to calculate the extra costs these solutions would bring. These numbers are rough estimates but will be within the same order of magnitude of the actual costs.

For this, it is important to categorize the solutions into the five different categories, and also see what solutions are still necessary in the event of a double drive train. This way, afterwards, the costs can be calculated. Table 7.1 gives an overview of the equipment and what category their solution belongs to.

The components that become automatically redundant when a second drive train is added, are not needed for the second option. This also includes anything that is solved by using an advanced engine. This leaves most of the components that belong to the auxiliary systems.

Table 7.1: Solution categories

<table>
<tr><td colspan="6">Using specific solutions</td></tr>
<tr><th>Advanced engine</th><th>Increase redundancy</th><th>Better sensors</th><th>Second drive train</th><th>Improve/ change design</th><th>Accept</th></tr>
<tr><td>Cylinder cover</td><td>Sump tank</td><td>Sump tank</td><td></td><td>Stern tube seal cover</td><td>Attached pumps</td></tr>
<tr><td>Cylinder liner</td><td>Manoeuvring system</td><td>FO filters</td><td></td><td>Cooling water pumps</td><td>Settling tank</td></tr>
<tr><td>Driving gear</td><td>Day tank</td><td>LO filter</td><td></td><td>Exhaust gas turbocharger</td><td>Fuel oil centrifuge</td></tr>
<tr><td>Cylinder lubricator</td><td>FO filters</td><td>CW expansion tank</td><td></td><td>Clutch</td><td>Main switchboard</td></tr>
<tr><td></td><td>LO filter</td><td>Breakers</td><td></td><td>LO service tank</td><td>Gearbox</td></tr>
<tr><td></td><td>LO service tank</td><td></td><td></td><td>Fresh water treatment</td><td>Actuator</td></tr>
<tr><td></td><td>LO centrifuge</td><td></td><td></td><td>Economizer</td><td></td></tr>
<tr><td colspan="6">Using a second drive train</td></tr>
<tr><th>Advanced engine</th><th>Increase redundancy</th><th>Better sensors</th><th>Second drive train</th><th>Improve/ change design</th><th>Accept</th></tr>
<tr><td></td><td>Day tank</td><td>CW expansion tank</td><td>Gearbox</td><td>LO service tank</td><td>Attached pumps</td></tr>
<tr><td></td><td>LO service tank</td><td>Breakers</td><td>Actuator</td><td>Fresh water treatment</td><td>Settling tank</td></tr>
<tr><td></td><td>LO centrifuge</td><td></td><td></td><td>Economizer</td><td>Fuel oil centrifuge</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>Main switchboard</td></tr>
</table>

Now that it is known how many solutions there are per category, it is possible to compute the increased costs associated with them. These increased costs can be found in Table 7.2.

Table 7.2: Price increase per category

Using specific solutions			
Category	Number of components	Increase in price per component	Total increase in price
Advanced engine	4	25% total	25%
Increase redundancy	7	1%	7%
Better sensors	5	1%	5%
Improve/change design	7	2%	14%
Accept	4	0%	0%
		Total:	50%
Using a second drive train			
Category	Number of components	Increase in price per component	Total increase in price
Advanced engine	0	25% total	0%
Increase redundancy	3	1%	3%
Better sensors	2	1%	2%
Second drive train	2	100% total	100%
Improve/change design	3	2%	6%
Accept	4	0%	0%
		Total:	110%

Using these numbers, it can be concluded that the total price would increase by 50% by solving weak points using specific solutions, and increase by 110% if the second drive train is used. Now it makes it possible to calculate the costs for each ship type. The increased costs per ship type can be found in Table 7.3.

Table 7.3: Price increase of machinery per ship type

Using specific solutions				
Ship type	Machinery cost	Price increase	Price increase	Total price increase
	[kUSD]	[%]	[kUSD]	[kUSD]
Feeder	1,300	50%	600	1,900
Handymax	2,700	50%	1,400	4,100
Panamax	4,600	50%	2,400	7,000
Capesize	5,800	50%	3,000	8,800
Using a second drive train				
Ship type	Machinery cost	Price increase	Price increase	Total price increase
	[kUSD]	[%]	[kUSD]	[kUSD]
Feeder	1,300	110%	1,400	2,700
Handymax	2,700	110%	3,000	5,700
Panamax	4,600	110%	5,100	9,700
Capesize	5,800	110%	6,400	12,200

With the increased costs known, it is possible to see how much the initial investment, and therefore the capital costs increase. These costs can be found in Table 7.4.

Table 7.4: increase in capital costs per ship type

Using specific solutions							
Ship type	Initial investment	Increase in initial investment	New initial investment	Increase in initial investment	Capital costs	Increase in capital costs	New Capital costs
	[kUSD]	[kUSD]	[kUSD]	[%]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]
Feeder	9,700	600	10,300	7%	1,050	70	1,120
Handymax	24,400	1,400	25,800	6%	2,650	150	2,800
Panamax	23,600	2,400	26,000	10%	2,550	250	2,800
Capesize	42,500	3,000	45,500	7%	4,600	320	4,920
Using a second drive train							
Ship type	Initial investment	Increase in initial investment	New initial investment	Increase in initial investment	Capital costs	Increase in capital costs	New Capital costs
	[kUSD]	[kUSD]	[kUSD]	[%]	[kUSD/yr]	[kUSD/yr]	[kUSD/yr]
Feeder	9,700	1,400	11,100	14%	1,050	150	1,200
Handymax	24,400	3,000	27,400	12%	2,650	350	3,000
Panamax	23,600	5,100	28,700	22%	2,550	550	3,100
Capesize	42,500	6,400	48,900	15%	4,600	700	5,300

Finally, with the increase in capital costs found, it is possible to see if the savings on crew costs outweigh the extra capital costs. These results can be found in Table 7.5.

Table 7.5: Potential savings per ship type

Using specific solutions				
Ship type	Crew costs	Increase in capital costs	Percentage of increase in capital costs vs crew costs	Potential savings
	[kUSD/yr]	[kUSD/yr]	[%]	[kUSD/yr]
Feeder	660	70	11%	590
Handymax	760	150	20%	610
Panamax	860	250	30%	610
Capesize	860	320	37%	540
Using a second drive train				
Ship type	Crew costs	Increase in capital costs	Percentage of increase in capital costs vs crew costs	Potential savings
	[kUSD/yr]	[kUSD/yr]	[%]	[kUSD/yr]
Feeder	660	150	23%	510
Handymax	760	350	43%	410
Panamax	860	550	64%	310
Capesize	860	700	81%	160

Now, table can give an overview of the total costs per year, as well as the potential savings. Figure gives a visual representation of the potential savings.

Table 7.6: Overview of costs after modifications

Using specific solutions							
Ship GT	Size	Initial investment	Operational cost	Fuel cost	Capital cost	Total cost	Potential savings
Ton		kUSD	kUSD/yr	kUSD/yr	kUSD/yr	kUSD/yr	kUSD/yr
6,000	Feeder	10,300	420	1,450	1,120	3,000	590
20,000	Handymax	25,800	440	2,100	2,800	5,300	610
40,000	Panamax	26,000	900	3,300	2,800	7,000	600
85,000	Capesize	45,500	1,200	5,500	4,920	11,600	540
Using a second drive train							
Ship GT	Size	Initial investment	Operational cost	Fuel cost	Capital cost	Total cost	Potential savings
Ton		kUSD	kUSD/yr	kUSD/yr	kUSD/yr	kUSD/yr	kUSD/yr
6,000	Feeder	11,100	420	1,450	1,200	3,100	510
20,000	Handymax	27,400	440	2,100	3,000	5,500	440
40,000	Panamax	28,700	900	3,300	3,100	7,300	310
85,000	Capesize	49,000	1,200	5,500	5,300	12,000	160

As can be seen, using these figures, it is beneficial to switch to unmanned ships for every size vessel, with potential savings always being positive. What is also interesting, is that there is a lot of savings potential when not going for the easy solution of adding a second engine. With almost half the associated costs for using specific solutions instead of making everything redundant, this seems to be the better option.

It is notable that it seems that the potential savings for larger ships is larger than the potential savings in the smaller ships, although this only counts when using specific solutions. With potential savings of more than half a million dollars per year for every ship size, it seems that unmanned shipping definitely has potential. If a second engine is added, the potential savings decline with the size of the ship, but even then, the savings stay positive.

However, it should not be forgotten that many of these figures are estimates, and a lot of the costs associated with unmanned shipping are neglected. This would include the costs of starting and running onshore control centres, paying for wages for maintenance crews in port, and the R&D costs associated with autonomous navigation and advanced machinery.

Figure 7.1 illustrates that for small ships, the relative savings are by far the highest, which can lead to better margins, and thus the potential of autonomous shipping still seems to be better for smaller ships. However, since potential savings can be found in all sizes of ships, this might be an indication that eventually, even the largest ships will become autonomous.

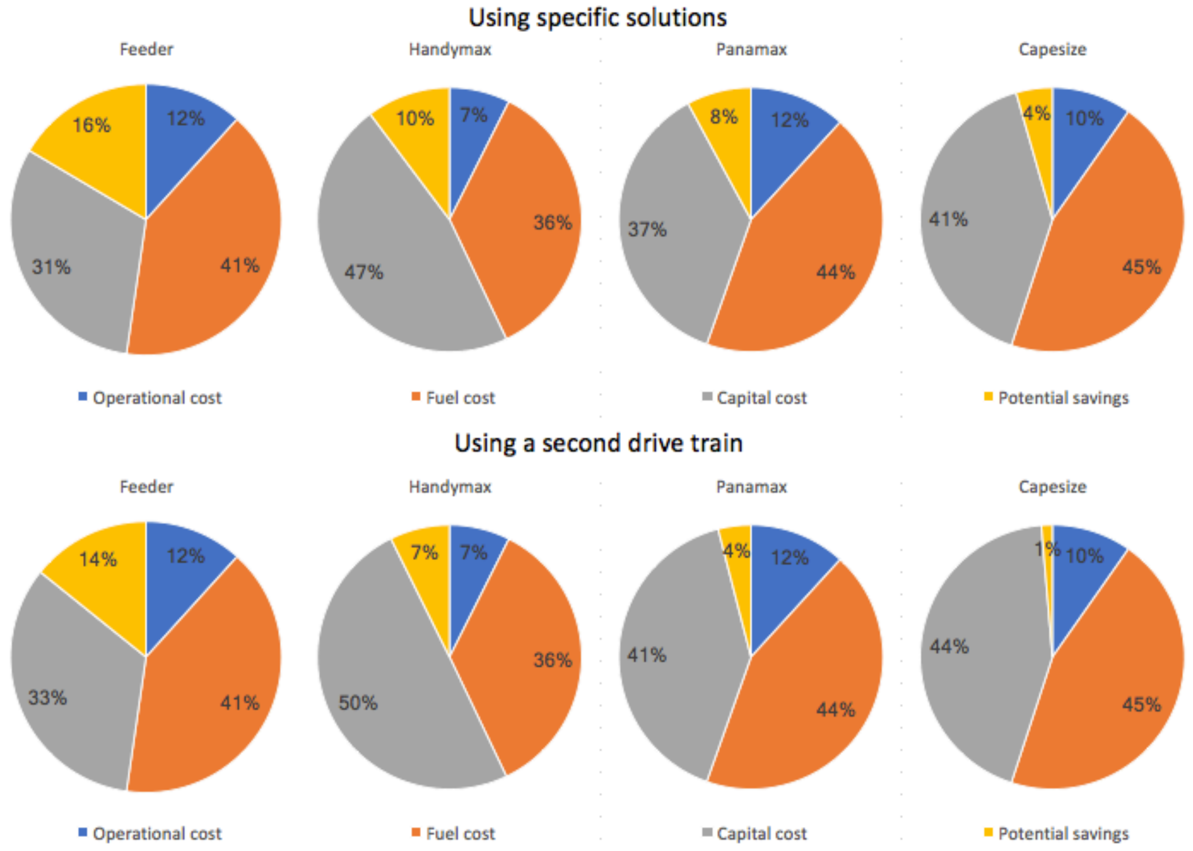

Figure 7.1: Cost overview after modifications

7.5 Possibilities in switching methods of propulsion

What hasn’t been discussed yet in this paper, but what is opted quite often as a solution to all problems in autonomous shipping, is switching fuels from diesel to cleaner fuels such as LNG, batteries or hydrogen. Another option that is often mentioned is switching from diesel-direct to diesel-electric propulsion. This chapter will try to reflect on all 4 and explore the possibilities.

7.5.1 Switching to LNG

The main upside to switching to LNG would be the removal of entire fuel processing plant. LNG is and inherently clean fuel that does not have to be filtered or centrifuged. Most LNG engines are already electronically switched, making them easier to control from a distance.

However, there is not a lot of experience yet with the use of LNG as a fuel in the maritime sector, and it could be that many problems are still unforeseen. If many problems cannot be predicted, then they cannot be planned and designed for, making it hard to use for autonomous vessels.

LNG is a cryogenic liquid that has to be stored in pressurized, super cooled tanks. Most of the pipes that it runs through tend to gather ice if not properly insulated, and the entire system is more prone to brittle breaking due to the temperature. Any cracks in pipes or insulation can lead to the leaking of LNG, which, in its gaseous form at room temperature, is heavier than air and will accumulate in low spaces, creating a fire or explosion hazard.

LNG needs a lot more research before it can safely be said it’s a good alternative to other fuels for autonomous shipping, but it has a lot of potential.

7.5.2 Switching to batteries

The ReVolt is an example of what it would be like for ships to switch from diesel to batteries. However, the ReVolt was designed for short distances at very low speed. If battery powered ships were to ever compete with diesel powered ships, they would be expected to have comparable ranges and speeds.

As a test, it can be calculated how many batteries would be needed for a voyage of a week at regular speed. As can be seen in chapter 6.6, a small feeder has an installed power of 4,000 kW. Assuming an optimal loading of 80%, the ship uses 3,200 kW as propulsion. Assuming a constant load of 3,200 kW for 7 days, 24 hours per day, this would mean the batteries need to store 540,000 kWh of power. DNV GL states that the ReVolt has a battery capacity of 5.5 MWh, or 5,500 kWh, and this requires an extra investment of 1.4 million USD [7]. Extrapolating this figure to a battery of roughly 100 times the size, this would mean that the batteries alone would be 140 million USD. This means that the total initial investment of a battery powered feeder would surge from 10 million USD to 150 million USD.

At the current battery prizes, shipping at the current speeds and distances is not feasible. However, battery technology has been improving quickly in the past few years, and it can be expected that battery prices will drop.

There are prototypes of batteries that have an energy density of 0.4kWh per kg.[7] This would mean that a battery pack of 540.000 kWh would weigh about 1350 tonnes. With a gross tonnage of 6000 tonnes, this means a battery powered feeder would need about a quarter of its capacity for battery weight, and thus would be able to transport only 75% of the amount of cargo as its diesel-powered sisters. This would further impair its ability to provide a return on investment within a feasible timeframe.

7.5.3 Switching to hydrogen

Hydrogen has a lot of potential upsides. With the use of fuel cells, you eliminate emissions, vibrations and heat production. Hydrogen has been proven to work on submarines, where the Germans installed them on their Class 212A submarines [36]. The large downside to using hydrogen as a fuel is its low energy density. Although the energy density is almost three times larger as diesel in terms of KJ/kg, with diesel having about 48MJ /kg and hydrogen between 120 and 142 MJ/kg, depending on the pressure of the gas. However, with a density of only 0.09 kg/m^3, this means the volumetric energy density is around 11 MJ/m^3, while diesel, with a volumetric density of 840 kg/m^3, contains about 40,000 MJ/m^3. [37]

There are some more efficient alternatives to storing hydrogen as a pressurized gas. The first being storing hydrogen in metal hydrides, which can absorb up to 2% of its weight as hydrogen. Another option is the local creation of hydrogen from diesel, through a process called hydrolysis. However, this reaction and the subsequent use of hydrogen as a fuel for fuel cells is less efficient than using diesel engines, and the energy gained from the stored diesel is less than through combustion. [38]

Another problem with hydrogen is that is very flammable, and because it is so light, the smallest crack will cause a leak in the system. If a compartment is not properly ventilated, the build-up of hydrogen could result in an accident similar to what happened to the Hindenburg in 1937.

All things considered, hydrogen is very promising, but the problem of efficient storage of hydrogen still needs to be solved. If this is done, then it might become the dominant way to power vehicles, including ships.

7.5.4 Switching to diesel-electric propulsion

An easy way to improve redundancy would be to switch from diesel-direct to diesel-electric (DE) propulsion. A DE set-up consists of a combination of multiple diesel generators and one or more electric motors that drive the propeller. DE propulsion is mostly used in vessels that have high reliability standards, such as ferries and cruise vessels, or in vessels that have a very wide operational profile, such as dredgers and ships that use dynamic positioning. The two main advantages of DE propulsion are the extra reliability in the form of redundant power generation and propulsion, as well as the flexibility in power production. [39]

DE is a common type of propulsion in specialized vessels such as dredgers, offshore support vessels or tugs, but it is very rare among merchant vessels. The main reason for this is the increased cost associated with a more complicated machinery plant. The main advantages of DE propulsion are of little to no use to common merchant vessels, as they do not require the extra reliability and flexibility that is offered by a DE plant. However, the extra reliability will be a great advantage for autonomous vessels.

DE comes in many forms, but the most common is a setup with 4 generators and 2 electric motors powering a fixed propeller each. A system diagram for such a setup can be found in Figure 7.2. DE always requires an even number of generators to ensure the symmetrical loading of the busbar, which distributes the power over all electric motors.

When looking at the cost of such a configuration, a few assumptions can be made. First of all, it is assumed that the power output of both propellers equals that of the single propeller of direct drive. Assuming true redundancy, each generator must be able to output the total power requirement of one propeller, or half the power of the main engine. This means that for 4 generators, the total installed power is double that of a direct drive engine. Assuming a linear increase and decrease in cost for power output, disregarding the need for alternators, the gensets alone would increase the price of the machinery by 100%. If it is then assumed that the associated cost for electric motors is about half the price per kW as that for a diesel motor, this would further increase the price of the machinery by 50%, giving an overall price increase of 150%. This is a larger increase than either the specific solutions or installing a second direct-drive train.

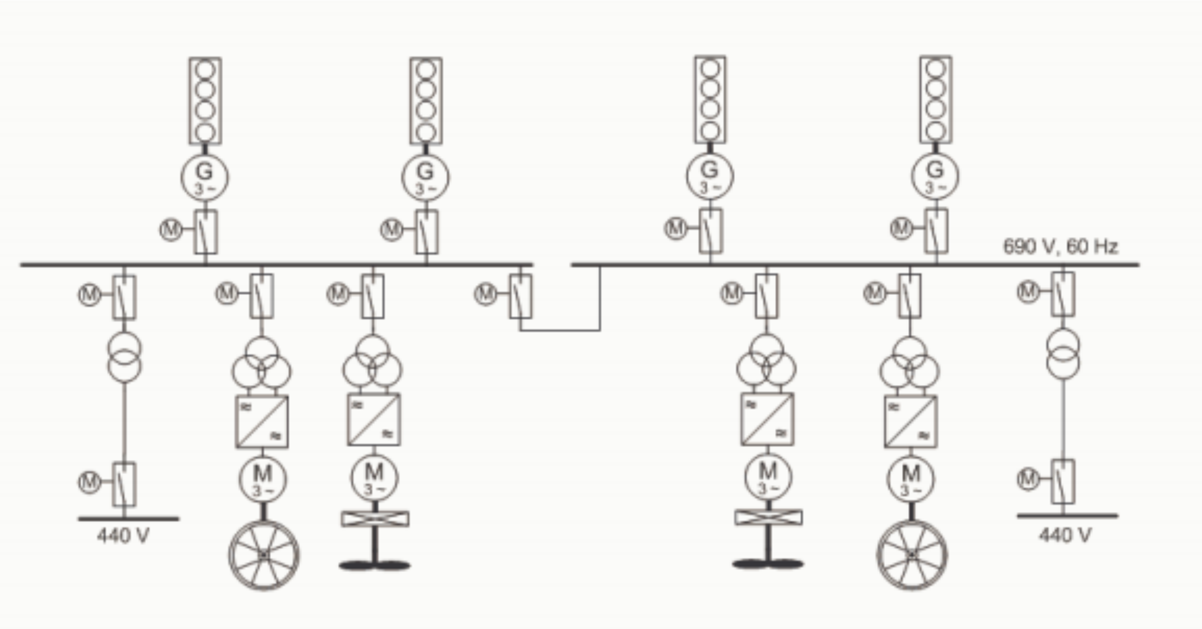

Figure 7.2: Classical DE configuration, as taken from [39]

Having four power generators would increase reliability tremendously, so even though this is a costly option, it is certainly viable. A proper cost-benefit analysis should be able to better analyse the viability of DE for autonomous vessels.

7.6 Recommendations

Out of all explored solutions, the most economically viable are the specific solutions. Therefore, the result of this paper is to consider the following recommendations:

- Design an electronically controlled engine, which has the power to switch off cylinders if necessary, as well as decouple pistons in that cylinder.
- Add a second sump tank underneath the first one, and improve the sensors measuring the lubrication oil levels in the sump tank.
- Increase redundancy on the manoeuvring system, day tank, both the LO and FO filters, as well as the LO service tank and LO centrifuge.
- Equip the LO and FO filters with better sensors to show when they need to be replaced.
- Install sensors in the cooling water tank to sense contaminations in the cooling water system, as well as making sure the system can still perform for a limited time when contaminated.
- Install heat sensors in the switchboards which are able to detect overheating breakers.
- Improve the stern tube seal cover with extra redundancies or by increasing bilge pump capacity.
- Design a passive emergency cooling water system.

- Remove the exhaust gas turbocharger and exchange it for an electrically powered turbocharger.
- Install a bypass around the LO service tank, allowing for the refilling of the sump tank from the LO storage tank.
- Increase capacity of chemicals in the water treatment plant, and design a more efficient and robust water treatment system.
- Design a system that automatically cleans the exhaust gas system and the economizer.

8 Conclusion

It has been investigated what the weak points in engine rooms are with regards to unmanned engine rooms for autonomous vessels. Solutions to eliminate weak points have been generated so that the following research question can be answered: "*What equipment and machinery in machinery plants of commercial trade vessels will become weak points when ships become autonomous, and what changes to engine rooms are necessary and possible to enable a ship to sail reliably and cost-effectively without a crew?".* Several steps have been taken to answer this question. First, in order to find out what equipment is installed on ships, a system breakdown was constructed, which divided equipment up into different systems. Next, a frequency index was introduced, which determined the frequency that engineers either checked, maintained or repaired equipment.

After the frequency index was established, the severity index was created, which lists the consequences of failure for all parts. The severity index is divided up into consequences of three functions of the engine room: Providing propulsion, providing manoeuvrability, and providing power. Finally, for all equipment the level of redundancy was noted, and using the frequency index, the severity index and the level of redundancy, the redundancy reduced risk index was created. This index was then validated using the expert opinion of three engineers.

The redundancy reduced risk index was used to determine weak points in the engine room, where the index is split into three different levels: low-, medium-, and high risk. For the medium and high-risk components, solutions were found in several categories. These categories included developing an electronically switched engine, increasing redundancy, installing better sensors, increasing or changing the design of the component, or installing a complete second engine. For every high-risk component, a solution was found, as well as for most medium risk components. For some of the medium risk components and all low risk components, the risks were accepted.

The solutions were divided into two categories: specific solutions or the installation of a second drive train. These were subjected to a financial analysis, which showed the commercial viability of these solutions on four different sizes of ships. The total cost of the machinery plant increased by 50% for the specific solutions, while the costs increased by 110% if a second drive train was installed. For all investigated ship sizes, the suggested solutions resulted in potential savings ranging between 18% and 1% of the total OPEX per year, with the smaller ships having more relative potential savings than the larger ones, but the larger ones having a higher absolute savings.

In the best-case scenario, ships can save almost $600,000.- per year, with little difference between smaller and larger ships. In the worst-case scenario, savings were still $163,000.- per year for the larger ships, and more than $500,000.– for the smaller ships. It needs to be noted that these numbers are based on rough estimates and exclude any costs made that are not directly related to the engine room but are still necessary to make a ship suited for autonomous sailing.

A few other options that could lead to solutions to many problems in engine rooms were briefly investigated. These options were switching fuel type to LNG, batteries or hydrogen, as well as switching to a diesel-electric drive. LNG has a lot of potential but needs more research into reliability. Batteries were rejected based on the current energy density of batteries and the associated costs. Hydrogen has a lot of potential, but the current technology on storing hydrogen is still lacking, making it inefficient to store large quantities of fuel. Diesel electric propulsion, although more expensive than other solutions, is still a viable option, but it needs a more in-depth cost-benefit analysis before a definitive conclusion can be made.

In conclusion, the recommendation is to utilize specific solutions to weak points in the engine room, instead of installing a completely redundant second engine. This could save up to 60% of the total initial investment associated with machinery plants in autonomous vessels. However, the total investment is still expected to rise by 50% in comparison with manned machinery plants if these changes are applied.

Continuously unattended machinery plants are definitely technically feasible, although a few large problems, in particularly with the main engine, need to be solved. These problems are not impossible to solve, and they should be solved within the next generation of ships.

More research is needed into the reliability of engine room equipment, especially with regard to reliability excluding human interference. Most reliability data assumes regular maintenance, but does not correct for it. Data that can correct for maintenance can help greatly in determining where the weak points will be in autonomous, unmanned engine rooms.

9 Literature

[1] Ø. Jan RØDSETH and H.-C. Burmeister, “Developments toward the unmanned ship,” 2012.

[2] T. Porathe, J. Prison, and Y. Man, “Human Factors in Ship Design & Operation SITUATION AWARENESS IN REMOTE CONTROL CENTRES FOR UNMANNED SHIPS.”

[3] L. Petersen, “BIMCO/ICS MANPOWER REPORT PREDICTS POTENTIAL SHORTAGE OF ALMOST 150,000 OFFICERS BY 2025,” *BIMCO*, 17-May-2016. [Online]. Available: https://www.bimco.org/news/press-releases/20160517_bimco_manpower_report. [Accessed: 04-Sep-2017].

[4] Ø. J. R. Thomas Porathe, Hans-Christoph Burmeister, “Maritime Unmanned Navigation through Intelligence in Networks: The MUNIN project,” in *COMPIT’ 13*, 2013, pp. 177–182.

[5] AAWA, “Remote and Autonomous Ships: The next steps,” 2016.

[6] DNV GL, “The ReVolt - DNV GL,” 2015. [Online]. Available: https://www.dnvgl.com/technology-innovation/revolt/index.html. [Accessed: 05-Sep-2017].

[7] DNV GL, “In Focus - The Future is Hybrid,” 2015.

[8] E. M. Brocken, “Improving the Reliability of JFFS2,” Delft University of Technology, 2016.

[9] DNV GL, *OREDA 2015 - 6th edition -Volume II*, 6th ed. 2015.

[10] “Unmanned-ship.org.” [Online]. Available: unmanned-ship.org. [Accessed: 06-Mar-2017].

[11] M. Schmidt, E. Fentzahn, G. Freyr Atlason, and H. Rodseth, “D8.7: Final Report: Autonomous Engine Room,” 2015.

[12] K. Wehner, H. Schmidt, and E. Fentzahn, “D6.2 Specification concept of the general technical redesign,” 2016.

[13] D.-W.-I. Univ, H.-C. Burmeister, and Ø. J. Rødseth, “Beyond the e-Navigation implementation plan: Development towards the unmanned merchant vessel?”

[14] Ø. Jan RØDSETH and A. Tjora, *Compit’14*, no. May. Redworth, 2014.

[15] L. Kretschmann, O. Rodseth, B. Sage Fuller, H. Noble, J. Horahan, and H. McDowell, “D9.3: Quantitative assessment,” 2015.

[16] M. Blanke, M. Henrique, and J. Bang, “DTU Management Engineering A pre-analysis on autonomous ships,” pp. 1–27.

[17] IMO, “Specification of minimum standard of competence for officers in charge of an engineering watch in a manned engine-room or designated duty engineers in a periodically unmanned engine-room,” in *STCW/CONF.2/34*, 2010, pp. 86–97.

[18] Det Norske Veritas, “Periodically Unattended Machinery Space,” *Rules Classif. Ships*, 2011.

[19] DNV GL, “Beyond condition monitoring in the maritime industry by DNV GL - issuu,” *Strategic research & innovation position paper*, 2015. [Online]. Available: https://issuu.com/dnvgl/docs/dnv_gl_pospaper__6-2014_beyond_cond. [Accessed: 24-Sep-2017].

[20] British Standards Institution, *BS 3811:1993 Glossary of terms used in terotechnology, British Standards Institution - Publication Index | NBS*. British Standards Institution, 1993.

[21] I. Lazakis, O. Turan, and S. Aksu, “Increasing ship operational reliability through the implementation of a holistic maintenance management strategy,” *Ships Offshore*

Struct., vol. 5, no. 4, pp. 337–357, 2010.

[22] Dienststelle Schiffsicherheit BG Verkehr, “Jahresbericht 2013,” 2013.

[23] MAN B&W, “L16/24 Project Guide -Marine.” 2015.

[24] IMO, “IMO MSC-MEPC 2/CIRC.12/REV.1 REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA) FOR USE IN THE IMO RULE-MAKING PROCESS,” 2015.

[25] MAN B&W, “Two stroke Engines,” no. April 2010. Copenhagen, 2010.

[26] Ulstein Frydenbö AS, “Instruction manual Frydenbo Rotary Actuator.” Fyllingsdalen, Norway.

[27] Wärtsilä, “Wärsilä Marine Reduction Gears - main technical data.”

[28] M. Stopford, *Maritime Economics 3e*, 3rd ed. London: Routledge, 2009.

[29] JAPAN SHIP EXPORTERS’ ASSOCIATION, “SEA-japan,” no. 342.

[30] ITF, “ITF UNIFORM "TCC" COLLECTIVE AGREEMENT.” 2015.

[31] “Loonkosten voor de werkgever berekenen.” [Online]. Available: https://www.berekenhet.nl/ondernemen/loonkosten-werkgever.html. [Accessed: 31-Oct-2017].

[32] “Rotterdam Bunker Prices - Ship & Bunker -IFO380.” [Online]. Available: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam. [Accessed: 31-Oct-2017].

[33] OECD, “COMPENSATED GROSS TON (CGT) SYSTEM A NEW COMPENSATED GROSS TON (CGT) SYSTEM -2007 BACKGROUND,” 2007.

[34] H. Schneekluth and V. Bertram, “Ship Design for Efficiency and Economy.”

[35] D. G. M. Watson, *PRACTICAL SHIP DESIGN*, vol. 1. .

[36] A. Psoma and G. Sattler, “Fuel cell systems for submarines: from the first idea to serial production,” *J. Power Sources*, vol. 106, no. 1, pp. 381–383, 2002.

[37] “Energy Density of Hydrogen - The Physics Factbook.” [Online]. Available: https://hypertextbook.com/facts/2005/MichelleFung.shtml. [Accessed: 06-Dec-2017].

[38] G. Sattler, “Fuel cells going on-board,” *J. Power Sources*, vol. 86, no. 1, pp. 61–67, 2000.

[39] MAN B&W, “Diesel-electric Drives Diesel-electric Propulsion Plants,” pp. 1–27.

Appendix A – Complete structural breakdown

Main engine		
	Main engine	
		Bedplate & main bearing
		Frame box
		Cylinder frame and stuffing box
		Cylinder cover
		Crankshaft
		Thrust bearing
		Turning gear and turning wheel
		Axial vibration damper
		Tuning wheel/torsional vibration damper
		Connecting rod
		Piston
		Piston rod
		Crosshead
		Scavenge air system
		Scavenge air cooler
		Auxiliary blower
		Exhaust gas sytem
		Exhaust turbocharger
		Camshaft
		Chain drive
		Indicator drive
		Governor
		Fuel oil pump
		Fuel valve
		Starting air valve
		Starting air system
		Exhaust valve
		Cylinder lubrication
		Manoeuvring system
	PTO	
		Crankshaft gear
		Toothed coupling
		Bedframe
		Alternator
		Oil seal cover
		Rotor
		Stator
		Cooler
		Support bearing
	Fuel oil system	
		Fuel tank

		Fuel tank heater
		Settling tank
		Settling tank heater
		Fuel oil centrifuges
		Fuel oil supply pump
		Fuel oil circulating pump
		Fuel oil heater
		Fuel oil filter
		Fuel oil venting box
	Lubricating Oil System	
		Lubricating oil pump
		Lubricating oil cooler
		Lubricating oil temperature control valve
		Lubricating oil full flow filter
		Lubricating oil outlet
		Lubricating oil tank
		Crankcase venting & bedplate drain pipes
		Cylinder lubricators & service tank
		Cylinder lubrication pump station
	Central cooling water system	
		Seawater cooling pumps
		Central cooler
		Central cooling water pumps
		Central cooling thermostatic valve
		Jacket water cooling pump
		Scavenge air cooler
		Lubricating oil cooler
		Jacket water cooler
		Fresh water generator
		Jacket water preheater
		Daerating tank
		Expansion tank
		Fresh water treatment
	Starting air system	
		Starting air compressors
		Starting air receivers
		Reduction station
		Reduction valve
		Starting and control air pipes
		Turning gear
	Exhaust gas system	
		Exhaust gas compensator after turbocharger
		Exhaust gas boiler
		Exhaust gas silencer

		Spark arrester
Auxiliary engine/Genset		
	Basic diesel engine	
	Fuel oil system	
	Lubricating oil system	
	Cooling water system	
	Compressed air system	
	Combustion air system	
	Exhaust gas system	
	Speed control system	
	Alternator	
Electrical system		
	Main switchboard	
	Transformers	
	Cabling	
	Breakers	
Fresh water system		
	Reverse osmosis unit	
	Sea water pump	
	Pre-treatment unit	
	Memberane cleaning unit	
	Post treatment unit	
	Anti scalant dosing unit	
	Fresh water tank	
Rudder	Actuator	
		Housing
		Cover
		Rotor
		Stoppers
		Vanes
		Safety relief valve
	Pump unit	
		Pump housing
		Hydraulic screw pump cartridge
		Strainer
		Safety relief valve
		Main control valve
		Solenoid valve
		Motor-pump coupling
		Electric motor
		Pressure gauge
		Emergency controls handle
	Expansion tank	

Appendix B – complete redundancy reduced risk matrix

	Frequency index (FI)			**Severity index (SI)**			**Risk index**	**Redundancy level**	**Redundancy reduced risk index**
	Check	Maintain	Repair	Propulsion	Manoeuver	Power			
Cylinder cover	4	2	1	4	1	1	8	0	8
Turning gear and turning wheel	1	1	1	1	1	1	2	0	2
Piston/cylinder liner	1	2	1	5	1	1	7	0	7
Driving gear	2	2	1	5	1	1	7	1	6
Attached pumps	3	3	1	5	1	1	8	1	7
Manoeuvring system	4	2	1	1	3	1	7	0	7
Gearbox	3	2	1	5	3	1	8	0	8
Clutch	2	2	2	5	5	1	7	0	7
Stern tube seal cover	5	3	3	5	3	5	10	2	8
Basic diesel engine	4	2	2	1	3	3	7	2	5
Fuel oil pump	4	2	2	1	1	3	7	2	5
Lubricating oil pump	4	2	2	1	1	3	7	2	5
Cooling water pump	4	2	2	1	1	3	7	2	5
Starting air system	3	2	2	1	1	3	7	2	5
Alternator	2	1	1	1	1	5	7	2	5
Bunker tank	3	1	1	3	1	3	5	2	3
Settling tank	4	1	1	3	1	3	7	0	7
Day tank	4	1	1	3	1	3	7	0	7
Fuel oil centrifuges	4	3	2	3	1	3	7	1	6
Fuel oil supply pump	2	2	1	3	1	3	5	0	5
Fuel oil circulating pump	2	2	1	3	1	3	5	0	5
Fuel oil filter	4	4	3	5	1	5	9	2	7
Lubricating oil transfer pump	1	1	1	2	1	1	3	0	3
Lubricating oil full flow filter	4	3	1	3	1	1	7	0	7
Lubricating oil tank	1	1	1	2	1	1	3	0	3
Cylinder lubricators	2	2	1	5	1	1	7	1	6
Lubricating oil service tank	3	1	1	4	1	1	7	0	7

LO centrifuge	3	2	1	3	1	1	6	0	6
Sump tank	5	2	1	4	1	1	9	0	9
Seawater cooling pumps	4	2	2	5	1	5	9	1	8
Central cooling water pumps	4	2	2	5	1	5	9	1	8
Jacket water cooling pump	4	2	1	5	1	1	9	1	8
Deaerating tank	2	1	1	2	1	2	4	0	4
Expansion tank	4	1	1	2	1	2	6	0	6
Fresh water treatment	3	4	2	2	1	1	6	0	6
Starting air compressors	3	3	2	4	1	4	7	2	5
Main switchboard	3	3	2	1	5	5	8	2	6
Transformers	3	1	1	2	2	2	5	0	5
Cabling	2	1	3	2	2	2	5	0	5
Breakers	3	1	4	2	2	2	6	0	6
Actuator	2	2	1	1	4	1	6	0	6
Safety relief valve	2	2	1	1	3	1	5	1	4
Pump unit	2	2	1	1	4	1	6	1	5
Main control valve	2	2	1	1	4	1	6	1	5
Electric motor	2	2	1	1	4	1	6	1	5
Oil tank	3	1	1	1	3	1	6	1	5
Exhaust turbocharger	4	4	1	4	1	1	8	0	8
Economizer	4	4	2	1	1	3	7	0	7
Smokestack	3	2	1	1	1	1	4	0	4