Improving The Reliability Of Ship Machinery

A Step Towards Unmanned Shipping

E. M. Brocken

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by

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Abstract

Due to the increasing seaborne trade, shortage of officers, constant work of crew on machinery during voyage and the large contribution of human error to shipping accidents it is time for shipbuilding to take the next step in automation. Unmanned shipping is the way to move forward and since the engine room houses some of the most important machinery in the ship, this is the equipment which has to be made more reliable first. Improving the reliability of ship machinery is the goal of this thesis, and this will be done for ship types with a simple design and relatively simple equipment, namely general cargo ships, container ships, bulk carriers and oil and chemical tankers.

In order to increase the reliability of the machinery, it will first have to be determined which failures occur to the machinery. The main engine, steering gear, fuel system, electrical system, cooling water system, diesel generator, shafting and other have all been found to be responsible for fatal technical failures in the past. Since these first five systems are responsible for the largest part of the failures, the focus of this thesis will be on these systems. These systems are crucial for the actual sailing of the ship, so making these systems more reliable makes great effort regarding unmanned sailing.

With the failures known, solutions have been developed for each individual failure. These solutions should have an equal or higher reliability compared to the initial solution. For the found solutions it can then be determined what their reliability improvement is. Determining the reliability improvement is done by knowing the failure rate of the machinery, which has also been determined. A list can then be made to determine which solutions provide the most reliability improvement. The cost of the best solutions is calculated next. In order for the unmanned ship to sail the oceans in the near future, it has to be financially competitive to the manned ship.

When looking at the causes of the failures it was found that human error and improper maintenance are both responsible for almost 20% of the failures. Performing better maintenance was though not found to realize much reliability improvement, just as an alternative solution was not found to realize much reliability improvement. Solving the maintenance related failures or choosing an alternative system is thus not the best solution to the failures. The best type of solution was found to be a type of redundancy. Solutions to the main engine failures, steering gear failures and fuel system failures were found to achieve the most reliability improvement. This was to be expected since these systems are also responsible for the highest number of failures.

When making a ship unmanned, equipment such as accommodation, fresh water systems, HVAC and others do not have to be installed. Money that does not have to be spend on this equipment is the budget for the reliability solutions. The cost of the three solutions with the most reliability improvement was found to fit perfectly within the budget that is available. It can thus be concluded that it is possible to increase the reliability of ship machinery while staying financially competitive to the manned ship. Budget is then also still available to pay for other systems that are needed for unmanned shipping. Redundancy was found as being the best type of solution. If all the best solutions are applied, the machinery would have a mean time between failures of nine years. Finding solutions to the diesel generator failures, shafting failures and other failures is needed to increase the reliability even further.

In order to improve the reliability of the machinery even further, more detailed failure data has to be known. Of half of the failures there is currently not enough information. Better knowledge of the failure distribution will help to determine better solutions. It also helps to know to what ship types these failures occurred to. Failures in redundant systems are not within the failure data. Having this data really helps to get a better view of the problem. Knowing what failures the crew prevents during operation and knowing more precisely which failures they induce also helps to get more detailed knowledge of the machinery failures. If better failure data is available, a more detailed failure rate can be determined. When it also known which level of reliability is required, the more detailed failure rate can be used to determine whether this level of reliability can be reached. The here named advises would though all require extra research and are therefore recommendations for future work.

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E. M. Brocken
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Symbol	*Meaning*	*Unit*
e	Euler's number, mathematical constant, 2.71828	[-]
λ(t)	Failure rate	[-]
ρ	Density of the fluid	[kg/m^3]
c_1	Constant	[-]
k	The number of input events in the OR gate	[-]
n	The number of input events in the AND gate	[-]
t	Time interval. For instance the length of a ship journey	[h]
v	Ship speed	[m/s]
A	Rudder area	[m^2]
C_D	Drag coefficient	[-]
C_L	Lift coefficient	[-]
D	Drag force	[N]
L	Lift force	[N]
P	Unreliability or probability of failure	[-]
P_E	Effective towing power	[W]
$P(x_0)$	The probability of occurrence of the AND gate output event, x_0	[-]
$P(x_i)$	The probability of the input event in the AND gate, x_i	[-]
$P(y_0)$	The probability of occurrence of the OR gate output event, y_0	[-]
$P(y_i)$	The probability of the input event in the OR gate, y_i	[-]
V	The free stream incident velocity	[m/s]
CPP	Controllable Pitch Propeller	
MTBF	Mean Time Between Failures	
PTI	Power Take In	

1 Introduction

Over the past years the amount of tonnage moved by ships has been growing significantly. In the year 2000 a seaborne trade of 30,823 billions of ton-miles was shipped whereas in the year 2013 a total of 50,374 billions of ton-miles was transported [95]. According to the estimation for 2014 and the forecast for 2015 the amount of ton-miles to be transported will continue to rise. If more cargo will be shipped this means that the demand for skilled crew members will rise as well. This can be stated by assuming that ships will not get much bigger in size in order to fill this gap of skilled crew members. It can be found from the manpower study of 2010 by BIMCO (Baltic and International Maritime Council) et al. that the supply of skilled crew does not match the demand which causes a shortage of skilled crew members. In the year of 2010 the supply of crew members was estimated to be 624,000 officers and 747,000 ratings while the demand was estimated to be 637,000 officers and 747,000 ratings. This means an overall shortage of about 2% [10]. Looking at the benchmark estimates for the years 2015, 2020 and 2025 it can be found that there is a surplus of ratings, but a shortage of officers of 2.1%, 11.7% and 18.3% for respectively the years 2015, 2020 and 2025 [11].

The new generation of employees starting in the maritime sector are called generation Y or Millennials. Born between the 1980s and late 1990s they grew up with a constant access to technology [46]. They are more educated and better adapted to technology than their parents when entering the workforce. It is said that many of the new generation do not want to spend all their life at sea, but want to use their skills onshore [18]. This will create a shortage of young crew members, since the number of new seafarers will be lower than it used to be. The same can be said for the older generation of seafarers. When having a family they might want to have a regular 9 to 5 job in order to spend more time with their family. This causes extra manning problems since there already is a shortage.

Another problem related to manning is human error. About 80% of all accidents at sea are caused by human error [34]. There are several causes for human error such as fatigue, stress, health, communications and language and cultural variance.

In order to decrease the number of seafarers needed and to be able to give them a more regular job, automation can be used. This will help to limit the amount of human error. Having more automation might also lower the expenses of the ship owners if the cost of automation is less than the 'normal' expenses.

The engine room houses most of the important machinery in the ship. It is said that the machinery in the current engine rooms is error-prone and that crew has to do a lot of work to keep it running. The engineers for instance have to inspect the machinery, make sure that the machinery can operate properly and maintain and repair the equipment. This includes checking the level of lubrication oil, adapting the systems to the weather conditions, cleaning filters, cleaning turbochargers, pumping fuel from one tank to another and more. Having more automation or redundancy in an engine room might therefore be a good solution to the current problems. However, before solutions can be determined, it will have to be understood where the problems in the ship originate from. This will make it possible to determine which systems in the ship are the most error-prone. For each of these systems it can then also be determined what causes the failures. When the errors are known, a list of solutions can be developed. For all of these solutions it will then have to be determined whether they are feasible or not. This will be done by investigating whether a solution can realize a reliability improvement, although other factors may also determine the feasibility. The reliability improvement of all feasible solutions will then have to be calculated. Before this can be done, the failure rate of the ship will have to be determined. When the reliability improvements of all solutions are known it can be seen which solutions give the largest improvement. For these solutions it will then have to be determined what their financial impact is. If solutions are found that make the machinery more reliable and are financially viable at the same time this can help to make ships autonomous or remote operated in the future. Ships sailing without crew will not be affected by the shortage of skilled crew members. These ships will also not be prone to human error on board the vessel.

1.1. Thesis Outline

This thesis will focus on the problems that will occur when making an engine room unmanned for commercial ships trading at sea. During the voyage there will be no engineers on board to work on the machinery. Since this thesis is a step towards unmanned sailing it is chosen that no other crew members are present on the ship as well. An unmanned engine room[1] might be implemented first on a manned ship. If that is the case, the ship is still steered by humans but the machinery runs without interference of the crew. Implementing an unmanned engine room on a ship which also has crew might be chosen as a transit solution to the unmanned ship. The practicalities of implementing the unmanned engine room fall outside the scope of this thesis since these decisions will have to be made by operational experts of the shipowner. Every shipowner has to decide for themselves how far they want to go with the automation of the ship.

The machinery of a ship includes systems to sail the vessel, to generate electrical power, to condition cargo, to provide living conditions for the crew, and others [90]. Systems to sail the ship refers in this case to the propulsion of the ship. Systems on the bridge will get their power from the generation of electrical power. The machinery in this thesis will focus on the machinery which has led to technical failures in the past [30]. These machinery systems are; steering gear, main engine, diesel generator, shafting, electrical system, fuel system and cooling water system. This is roughly equal to the propulsion and auxiliary systems of the ship.

Other systems on the ship can also fail during operation, but the named systems are crucial for the transport from A to B. For the systems that are responsible for the actual sailing of the ship it is a must to be reliable since the ship is difficult to retrieve when a fatal error occurs. Other systems that might fail do not have such a drastic effect. For instance, if a ship has a crane installed which fails during voyage, the ship can still continue its route, if no disastrous things occurred to the crane. The ship is then not lost at sea without propulsion. For this type of specific equipment, increased reliability is nice to have but not vital for unmanned operation. Determining failures and solutions for the (ship) specific equipment is something that is nice for future work, but is too specific for this thesis. Other systems, such as bridge systems might be controlled from shore. When a failure occurs to these systems, a shore control centre might be able to reset those systems.

1.1.1. Ship Types Within Scope

The function of a ship determines the required level of auxiliary systems. The auxiliary systems therefore differ from ship type to ship type since one type of ship requires much more auxiliary systems for it to be operational than another ship type needs. For example, a bulker does not require much auxiliary systems whereas a pipe layer requires much more auxiliary systems due to the complexity of its operation. Merchant ships transporting cargo from A to B all have a roughly similar requirement for the auxiliary systems, which is rather small since these ships are not very complex. This means that they are very suitable for having an unmanned engine room because there is not much equipment for which failures have to be solved. Due to the complexity of the equipment for the ship types passenger ships, offshore vessels and service ships they do not fit within the scope of this project. Their machinery is too complex and specialized to belong to the first vessels to have an unmanned engine room. Although gas tankers are merchant ships, they are also excluded from the scope of this project due to their specialized systems such as pressurized and/or refrigeration systems.

[1] An unmanned engine room is defined as an engine room in which no engineers are present during voyage. These engineers are also not able to access the engine room via computers outside the engine room. If an engineer has to take action regarding machinery in the engine room, this has to be done from for example a shore control centre. Otherwise, the only option to access the engine room is when the ship is in port.

It can thus be said that there is no fundamental difference between the machinery plants of the most basic cargo vessels. The vast majority of these vessels have a similar layout with an accommodation in the back which has most of the machinery directly below it. In front of the accommodation are the cargo holds which differ from ship to ship. This thesis will focus on general cargo ships, container ships, bulk carriers and oil and chemical tankers. Ro-Ro cargo vessels usually have a ramp at both ends of the ship and a large cargo deck in between. This limits the engine height, which makes this ship less flexible for machinery changes. This ship type will therefore fall outside the scope of this project. Tugs will also fall outside the scope of this thesis since these are not cargo vessels. The ship types specialized cargo ships and other tankers are also not included in the scope since they only make up respectively 0.3% and 1.0% of the world fleet by number and these ships are also highly specialized. The chosen range of ships makes up 52.5% of the world fleet in total number of ships and 83.3% of the total tonnage [35]. If a solution is found for making engine rooms unmanned a big part of the world fleet is able to use it. Table 1.1 shows the distribution of the world fleet. The ship types that fit within the scope are in bold type. Some of the solutions that will be found in this thesis might also be applicable for the ship types which have been excluded from the scope. Due to the complexity of the machinery in the excluded ship types this would only mean a small reliability improvement. It is therefore questionable whether these solutions will be applied on these ships since there is still a lot of other error-prone equipment. The ship types that fall within the scope benefit the most from the found solutions since these ships have the least equipment.

Table 1.1: Distribution of world fleet by number and tonnage

Ship Type	% By Number	% By tonnage
General cargo ships	**19.1**	**5.0**
Specialized cargo ships	0.3	0.3
Container ships	**6.0**	**17.7**
Ro-Ro cargo ships	1.7	4.1
Bulk carrier	**12.9**	**35.1**
Oil and chemical tanker	**14.5**	**25.5**
Gas tankers	2.0	4.9
Other tankers	1.0	0.1
Passenger ships	7.8	3.1
Offshore vessels	9.4	3.0
Service ships	5.6	0.9
Tugs	19.4	0.4
Total	100	100
Total included within scope	**52.5**	**83.3**

1.1.2. Unmanned Ship Concepts

The idea of an unmanned ship has already been mentioned four decades ago [86]. Later on more research has been done and nowadays it is possible to distinguish three concepts of unmanned ships [9].

- **'Shore Captain'** The control system is transferred ashore. The ship retains only a largely self-regulating propulsion plant together with the equipment needed for reception, transmission, and decoding of the control signals received from the shore and supervision of onboard systems. This is also called remote operated.
- **'Captain Computer'** The ship is equipped with sufficient hardware and software to perform all tasks and decisions autonomously using Artificial Intelligence.
- **'Master/Slave'** Convoys of unmanned 'slave' ships sail remote-controlled from a manned and highly automated 'master' escort ship. The 'master' ship has to be highly automated since this concept is mainly thought to be used if explosives or other dangerous cargo have to be transported

away from the crew. All tasks for the 'slave' ships have to be performed from the 'master' ship so automation can help to keep the number of crew members down.

Since the terms of these three concepts are often used incorrectly they are shown here for better understanding. In this thesis, unmanned is used to describe all of these three concepts in one word. For the outline of this thesis it is namely not important which of these three concepts is used, as long as no engineer is on board for the machinery. With the Master/Slave configuration help is close by, this concept will therefore have to be excluded from the scope of this thesis. The ship will have to sail the journey without physical human interference during the voyage.

1.1.3. Research Questions

This section will show the research questions. First the main question will be mentioned after which the subquestions are determined. These subquestions are necessary to answer the main question.

Main question

- What are the machinery related problems regarding an unmanned engine room? How to solve these problems such that the reliability[2] is equal or better compared to the manned engine room while being financially competitive at the same time?

Sub-questions

- What are the current problems with machinery and where do they originate from?
  This question will determine the failures that are currently occurring to machinery in the engine room on board vessels. After it is determined what machinery the failures occur to, it has to be investigated in which components the causes of the problems are. This gives insight in what has to be solved and where to look for the solution.

- How many of the problems have non-human causes?
  What is the impact of human error in the failures to ship machinery? The problems caused by humans no longer occur on board the ship if it comes to operating the ship unmanned. Human error related to installing or maintaining machinery might still be present. This question has to be answered in order to be able to develop solutions for problems that still exist when there are no humans on board.

- What are possible solutions to the non-human problems?
  This question is set to develop a set of solutions for the non-human related problems. In this stage all options are "good" options, as long as they meet the reliability criterion. The best solution will be chosen in a later stage.

- What is the best solution for the non-human problems?
  It is case specific which solution is the best solution. This can be a function of speed of the ship, range of the ship, required maintenance interval or cost of the solution and will be investigated later on.

- Is the reliability of the unmanned engine room equal or better to the manned engine room?
  In order for an unmanned engine room to be implemented in a ship is has to be of equal quality as the current engine rooms. This can be determined by checking if the reliability is equal or better to a manned engine room.

[2]Reliability is defined as: "The ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure" [16].

1.2. Previous Work

This section will deal with some of the research that has already been conducted on unmanned ships. First, some relevant work on unmanned vessels will be shown after which previous work on ship machinery will be presented. Finally the literature on machinery failures will be dealt with.

1.2.1. On Unmanned Vessels

Over the past years the attention for ships without crew has grown significantly. Several companies have already made concepts for unmanned vessels. DNV-GL has developed a concept for an unmanned, zero emission, short sea ship of the future which will sail along the coast of Norway in order to decrease road transport [33]. Rolls-Royce has also shown their vision on the intelligent ship [69] and is currently leading an Autonomous Ship Research Project [82]. The MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) project was a research project for an unmanned merchant ship which checked its technical, economic and legal feasibility. It was co-funded by the European Commission and was a collaboration between different institutes [63]. There are more examples of crewless ships, such as the Autonomous Work Boat [87] and the US Navy Unmanned Surface Vehicle [71].

So far, there are no merchant ships which are operated without crew in an autonomous way but TNO has developed a shore support system so that less engineers can be aboard a vessel [76]. This means that for Dutch coasters the Chief Engineer is replaced with a beginning Maritime Officer. He has both navigational and engineering tasks. This means that the persons on board have less skills than they used to have. This is compensated by having support from shore, available every hour of the day.

1.2.2. On Ship Machinery

Regarding ship machinery there has not been much research yet. Two students of the Rotterdam Mainport University of Applied Sciences have done a study for Imtech Marine & Offshore to design the ship-shore information flow in order to control an engine room, but this did not involve any changes regarding the machinery [57].

The MUNIN project has done more research on actual redesign of the ship machinery in their deliverables 6.2 (Specification concept of the general technical system redesign) and 8.7 (Final Report: Autonomous Engine Room) [64] [66]. This research involved the redesign of a bulk carrier with the most commonly installed propulsion plant, a two-stroke low speed diesel engine directly coupled to a fixed pitch propeller.

Regarding the redesign of the machinery there were several changes. The most important design change is the change of fuel type, since switching between fuels is prone to errors. The fuel changed from a residual to distillate. This is quite a drastic change since the ship is sailing on open sea, so it is not financially competitive to ships who do switch between fuels. But since the ship also sails in emission control areas it is necessary to use the more expensive fuel type. Further on, more redundancy was added to the system. Deliverable 6.2 also describes the possibilities of operation with faulty systems. MUNIN deliverable 8.7 concludes by saying that an unmanned engine room is technically feasible. Since MUNIN did not do any financial calculations on their design it is not possible to directly implement their work on a ship. It was also not determined by MUNIN what the reliability improvement of their solutions is.

MUNIN has taken great effort in designing a maintenance strategy for the unmanned engine room [65]. It has investigated the current way of performing maintenance and has identified the gap between maintenance on a manned ship and the unmanned ship. With this information known it has determined a maintenance framework for the unmanned engine room which is run out of the shore support centre. The information on maintenance can be useful for this thesis, since machinery and maintenance are closely linked.

When designing the ReVolt, DNV-GL have also taken the fuel/engine type of the ship in consideration. After considering MGO, LNG, hydrogen and batteries they chose the batteries due to its well-to-propeller efficiency and zero emissions [33]. This was the best option for this design, but not necessarily for all unmanned vessels.

1.2.3. On Machinery Failure

The German Ship Safety Division has put together an article about technical failures in several of their annual reports [28] [29] [30]. Goal of the research was to analyse the potential danger to the shipping industry caused by technical failures in German waters on German or non-German ships. It is not known on which ship types the failures occurred and what the distribution is between these ships. The failures have been distributed over eight different system groups. No information is given about the system group 'other', which makes it impossible to determine what type of failures occurred and what caused them. The amount of failures and the percentage of failures can be seen in Table 1.2. Data for these failures is available for the years 2001 up to and including 2004, 2010 and 2011. The amount of failures per system group and their contribution to the total percentage wise are shown in Table 1.2. This table is a summary of the individual years 2001, 2002, 2003, 2004, 2010 and 2011. The failures for the individual years can be seen in Appendix A.

Table 1.2: Technical failures in the system groups

System group	Amount [-]	Percentage [%]
Main engine	139	38.7
Steering gear	75	20.9
Fuel system	40	11.1
Electrical system	32	8.9
Cooling water system	30	8.4
Shafting	24	6.7
Diesel generator	13	3.6
Other	6	1.7
Total	359	100.0

It can be seen from Table 1.2 that the main system groups main engine, fuel system, cooling water system, electrical system and steering gear are responsible for nearly 90% of the technical failures. For each of the main systems it is investigated where these problems originated from. For most of the failures a clear source was found.

Not all machinery failures that occurred in German waters are included in the shown research by the German Ship Safety Division. When for instance one out of two engines that are installed in a ship failed during operation, this is not registered as a failure in the statistics. This is because that particular failure did not lead to a fatal technical failure. Failures in machinery for which redundancy is available are therefore not registered. The number of failures to ship machinery is thus likely to be higher than the registered number. The percentages between the different systems are likely to be different when all failures are considered. Since the total number of failures in redundant systems are not available, those cannot be taken into account.

There are also other causes, such as foundering, collision, fire or wrecking, which would cause a ship to be completely inoperable [17]. Some examples of foundering are sinking due to rough weather, leaks and breaking into two. If one of the named failures occurs, but does not lead to a loss of the ship, the ship is likely to be (severely) damaged. It is therefore probably not able to continue its route and will have to be retrieved or salvaged. For unmanned shipping, solutions to prevent these failures might have to be developed in order to reduce the risk of an external failure or loss of the ship. This does however not fit within the scope of this thesis since this thesis solely focusses on ship machinery and not on for instance communications or route guidance.

Since crew is currently always present on the ship, they prevent failures that would otherwise have occurred in an unmanned situation. It is impossible to determine how much of a difference human presence makes within this thesis. Depending on the age of the system, a crew member has to take action more often. Filters, separators and bilge pumps are said to cause an alarm the most. It can thus be said that more failures to these particular parts will occur when the crew is taken of the ship. Using monitoring equipment would allow a computer, or crew onshore, to react in the same way as a crew member would do. For instance, RH Marine has automation systems that could act as a crew member [80]. Adapting the maintenance strategy such that it is known that particular parts survive another journey would also allow to prevent these failures. For instance the dynamic maintenance planning of Wärtsilä that uses condition based monitoring can be used [101]. This helps to reschedule maintenance in a maintenance window by predicting the actual condition of the equipment. When systems are installed that monitor the equipment and therefore substitute the crew it can be stated that the failures that are now prevented by the crew are being prevented by a monitoring system. No extra failures due to the absence of crew will thus occur.

In 1978 the failure of equipment on board airplanes was studied. It was found that the failures can be categorized in six different pattern groups which can be seen in Figure 1.1 [70]. Half of the patterns are age related and the other half are random. The age related groups are bathtub, wear out and fatigue. These are accountable for respectively 4%, 2% and 5% of the failures, making a total of 11% age related failures. The random failures were accountable for the other 89% with the groups break in period (7%), random (14%) and infant mortality (68%) [55].

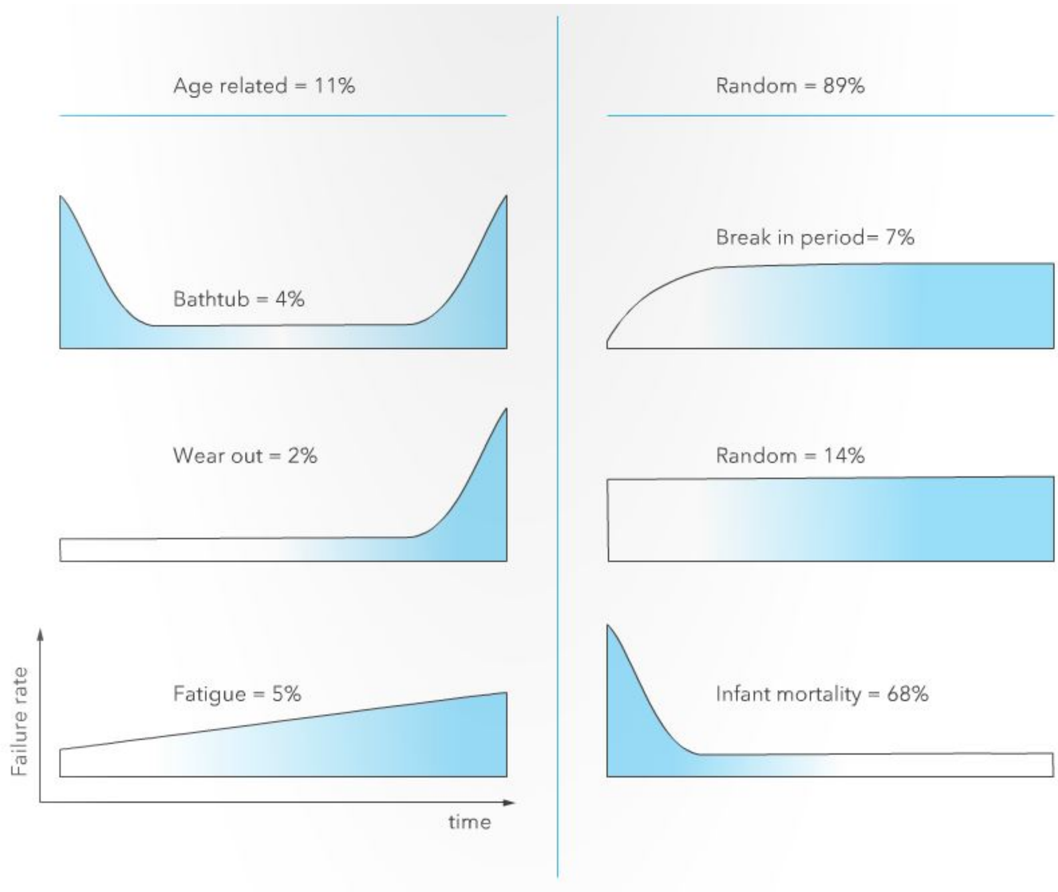


Figure 1.1: The six possible failure rate patterns

This study has also been repeated by the US Navy, to find out whether there were any differences for ships regarding these patterns. Both in 1982 and 2001 they discovered that the age related failures were higher compared to airplanes. In 1982 it was found that the age related failures made up 23% of the failures and the other 77% was random. In the study of 2001 on submarines it was found that 29% was age related and 71% was random [5]. The change in the ship failure distribution compared to the airplane distribution is said to come from the salinity in the environment of the ship, which causes an increase in corrosion. The failure patterns as shown in Figure 1.1 will not be taken into account in this thesis. For the found failures it is not known to which category they belong. It is therefore not possible to use these failure patterns in this research. They have though been named since it is interesting to know how a part can fail. For further research this might also be important.

2

Machinery Problems

This chapter will analyse the reports of the German Ship Safety Division regarding the failures of ship machinery in order to put the machinery faults into a fault tree to be able to give a better overview of the problems and their causes.

Firstly, the theory of the fault tree analysis will be dealt with in Section 2.1 after which a system overview is given in Section 2.2 and it is chosen on which systems this thesis will focus. Then for all considered systems, main engine, steering gear, fuel system, electrical system and cooling water system their failures will be dealt with on an individual basis in respectively Section 2.3, 2.4, 2.5, 2.6 and 2.7. It will also be determined what the effect of human error (Section 2.8) and improper maintenance (Section 2.9) is on the total number of failures. In Section 2.10 a conclusion regarding the cause of the failures will be drawn.

2.1. Fault Tree Analysis

Throughout the industrial sector a fault tree analysis is a widely used method to do reliability analysis of engineering systems. It was developed in the early 1960s by the Bell Telephone Laboratories. It is a logical representation of the relationship of basic fault events that may cause a specified undesirable event. This undesirable event (failure of the system, in which failure is well defined) is the top event of the tree and is the thing that should not happen [27]. From the top undesired event the fault tree graphically develops all potential causes of that event.

The fault tree analysis considers component failures, subassembly failures, normal conditions, human errors, and combinations of these items [8]. Systems are almost always made up of subsystems which on their part consist of components. In order to determine the reliability of a system it is necessary to determine the influence of the subsystems and components in the system. A fault tree is a logic diagram and by means of logic gates, such as AND and OR, indicate which subsystems and components lead to the undesirable top event.

2.1.1. Fault Tree Symbols

There are three categories of symbols used in the fault tree: events, gates and transfer symbols. Events are things that can happen, either in isolation or in combination with other events, and induce an undesired top event. Gates show the relationships between events. Transfer symbols are used for transferring portions of the fault tree from one sheet to another [8].

Event types

- **Command event** The rectangular shaped box is the top or intermediate event. It results from the combination of fault events in the tree below it. See Figure 2.1a, page 10.

- **Basic failure event** The basic event is the lowest part in the tree and shown in Figure 2.1b on page 10. A basic fault event or the failure of an elementary part or a component is shown by a circle.

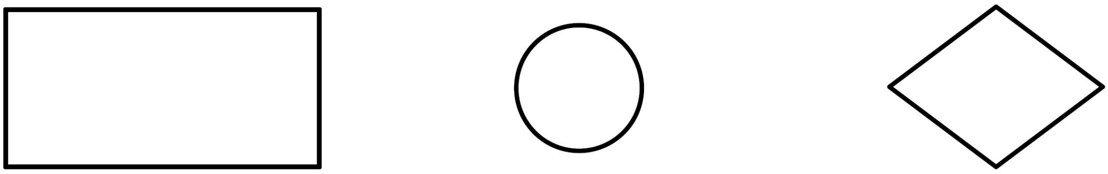
- **Human error or undeveloped event** A human error or an undeveloped event is represented by a diamond. An undeveloped event is one that requires no further development. This can for instance be events that are highly unlikely. These are shown as undeveloped events in order to show that they have been taken in consideration. It is shown in Figure 2.1c.

Gate types

- **OR gate** If any of the lower events occurs, an output fault event will occur. Its symbol is shown in Figure 2.2a.
- **AND gate** If all of the lower events occur this gate gives an output fault event. It can be seen in Figure 2.2b.
- **INHIBIT gate** An INHIBIT gate, Figure 2.2c, is a special version of the AND gate. It places a constraint on the event below the INHIBIT gate. If the condition is satisfied and the event below occurs, the event above the INHIBIT gate occurs.

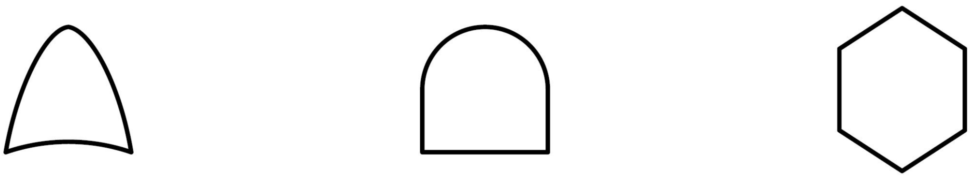
Transfer Symbols

The transfer symbol is a triangle. It has a number inside the triangle which indicates to which sheet, or from which sheet, the information is transferred. It can be seen in Figure 2.3. A transfer symbol which is shown on top of a command event shows to which sheet the tree transfers. If it continues to another sheet, it is shown at the bottom of a command event.



(a) Command event (b) Basic failure event (c) Human error or undeveloped event

Figure 2.1: Different events within a fault tree analysis



(a) OR gate (b) AND gate (c) INHIBIT gate

Figure 2.2: Different gates within a fault tree analysis

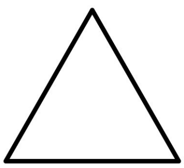


Figure 2.3: Transfer symbol

2.1.2. Rules For Setting Up The Fault Tree

There are several rules when it comes to setting up the fault tree and performing the analysis [51].

- Define the system and the assumptions pertaining to it.
- Identify the system top fault event (i.e., the system undesirable event to be investigated).
- Identify all possible causes that can cause the top event to occur, by using fault tree symbols and the logic tree format.
- Develop the fault tree to the lowest detail as per the requirements.
- Perform analysis of the completed fault tree in regard to factors such as understanding the proper logic and the interrelationships among various fault paths and gaining proper insight into the unique modes of product/item faults.
- Identify the most appropriate corrective measures.
- Document the analysis with care and follow up on the identified corrective measures.

2.1.3. Calculations Within A Fault Tree

When the fault tree is constructed it can be used to determine the probability of occurrence of the top event. For this, the probabilities of the basic events have to be known. With those known it is possible to calculate lower events while taking the multiple types of gates into account.

The probability of occurrence of a fault event output from the AND gate is given by the following formula [26].

$$P(x_0) = \prod_{i=1}^{n} P(x_i) \tag{2.1}$$

Where

$P(x_0)$	The probability of occurrence of the AND gate output event, x_0
n	The number of input events in the AND gate
$P(x_i)$	The probability of the input event in the AND gate. The input event is x_i for i = 1, 2, 3, ..., n

The probability of occurrence of the OR gate can be calculated with another formula [26].

$$P(y_0) = 1 - \prod_{i=1}^{k} \{1 - P(y_i)\} \tag{2.2}$$

In which

$P(y_0)$	The probability of occurrence of the OR gate output event, y_0
k	The number of input events in the OR gate
$P(y_i)$	The probability of the input event in the OR gate. The input event is y_i for i = 1, 2, 3, ..., k

Using both Formula 2.1 and Formula 2.2 makes it possible to determine the probability of occurrence of the top event. How the probability of occurrence of a basic event is determined will be discussed in Chapter 4.

2.2. System Overview

The failure reports of six years are available, namely 2001, 2002, 2003, 2004, 2010 and 2011. Over these years a total of 359 failures have occurred. The systems as mentioned in Chapter 1 will now be discussed on an individual basis. Since the main engine, steering gear, fuel system, electrical system and cooling water system make up 88.0% of all technical failures only these systems have been dealt with by the German Ship Safety Division. The causes of the failures in the systems diesel generator and shafting have not been explained. Since these two system groups, together with the group 'other', are accountable for only 12.0% of the failures these are not the groups that give the best chance for a reliability improvement. Therefore only the five failure groups for which the cause of failure have been named will be considered for this thesis. The other systems will be neglected.

The claims about the failure origins as made by the German Ship Safety Division will be checked with different sources in order to confirm the problem and get more information on their origin. Unfortunately not all origins of the machinery failures have been explained by the Ship Safety Division. Only if a failure occurred multiple times or has a very clear cause it has been named. Each system therefore shows a large group of failures with unknown distribution. It is sometimes known which failures are or are not part of this group but the failure distribution between them is never known.

Before a fault tree can be constructed of the ship machinery, the top event has to determined. The top event of the ship machinery fault tree is 'fatal technical failure'. This is the event that should not happen and has to be avoided. Each of the system groups can lead to a fatal technical failure, which makes that they are all connected to the top event with an OR gate. The percentage of failures for which an event responsible is shown in the fault tree, with the event above it being a 100%. If this information is not available, a question mark is shown.

The first five machinery systems are all dealt with in detail in later sections so these therefore transfer to other sheets. The fault tree with all basic events is also far too large to put on a single piece of paper. The top part of the fault tree can be seen in Figure 2.4. For visual representation the top event is located on the left side of the paper and the fault tree continues to the right side. This makes it possible to read the events without having to turn the page. All other fault trees in this chapter are constructed in the same way.

In Appendix B all fault trees of the individual systems are put together as close to each other as possible, which makes it possible to view the fault tree as a whole. In the appendix the fault tree is also constructed with the top event on top of the page and all other events below it.

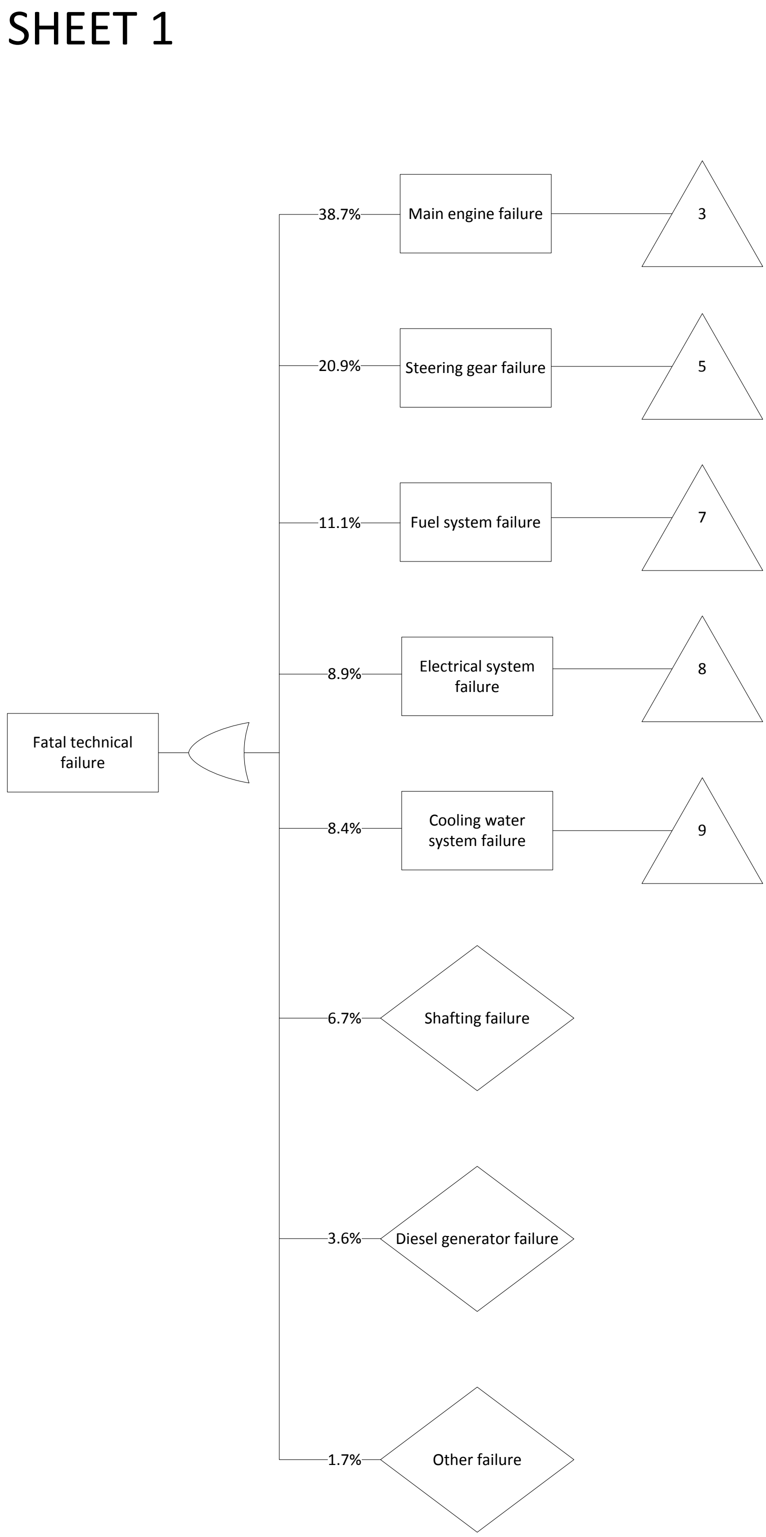


Figure 2.4: Fault tree with all system groups

2.3. Main Engine

The main engine is the primary cause of machinery failures with almost 40% of the total number of failures. A big part of the main engine failures, 36.7%, are caused by the starting, reversing and regulating device. Twelve of the total 41 failures in 2010 and 2011, 29.2%, have a cause that is described as 'standard failure'. For the years 2001/2002, 2010/2011 the turbocharger has failed eight times.

In Table 2.1 the distribution of the different failure types can be seen. For every failure type it is shown what its contribution is to the total number of failures of the main engine and to all systems. A failure of the starting, reversing and regulating device, a standard failure or a turbocharger failure are the only failures that are named explicitly. The German Ship Safety Division has not given a clear distribution of the cause of all failures for all years. Therefore, there is a big number of failures with unknown distribution. Part of these failures can still be standard failures or turbocharger failures since those were not named in all years. Other failures can also be part of this group, but then they probably have a small distribution.

Table 2.1: Distribution of the main engine failures

Failure type	% Main engine [%]	% All systems [%]
Failure in starting, reversing and regulating device	36.7	14.2
Standard failure	8.6	3.3
Turbocharger failure	5.8	2.2
Unknown distribution	48.9	18.9
Total	100.0	38.7

First the failures in starting, reversing and regulating device will be dealt with after which the standard failures will be explained and then finally the turbocharger failures are explained. All these failures together give the fault tree of the main engine, which can be seen in Figure 2.5, 2.6 and 2.7 on respectively page 16, 17 and 18.

2.3.1. Failures In Starting, Reversing And Regulating Device

The cause for the problems in the engine controller seem to come from bad maintenance of this complex and important equipment. The start control air systems, missing or defective air dryers in control air systems cause the main engine to lose reliability when fouled or corroded. During inspections of ships it was also found that air drying systems have not always been installed due to cost reasons. Other causes that have been given for the failure of the engine controller are the following.

- Failure of control equipment
- Regulating device of reversing gear system
- Electronic failure reversing gear system
- Starting air system

The fault tree of the engine controller can be seen in Figure 2.5. It is recognised by the UK P&I Club that the control equipment is responsible for a large portion of the main engine failures [61].

2.3.2. Standard Failures

The standard failures of the main engine are caused by the following problems.

- Defective intake or exhaust valve
- Fixed injection pump
- Cracked or leaking cylinder cover
- Cracked cylinder liner
- Broken or unsealed injection line

In the years 2001 to 2004 this group was not mentioned, but it can be assumed that standard failures also occurred in these years. The fault tree of the standard failures can be seen in Figure 2.5 and 2.6.

The German Ship Safety division stated that it can only be told from a detailed analysis of maintenance reports of these particular vessels how these problems have occurred. This can for instance come from a material failure or faulty maintenance, they stated. For this research these problems have been checked for possible causes in order to get a better insight in the problems. Unfortunately not for all failures a cause has been found.

Defective Intake Or Exhaust Valve

The flow and exchange of gas is controlled by valves, which seal the working space of the cylinder [79]. There are several causes for the failure of a valve. Wear failure, valve face recession, fatigue failure, thermal fatigue, erosion/corrosion, overheating and carbon deposits are some of the causes. Generally, valves fail due to fatigue.

The types of fatigue that occur most often are thermal fatigue, corrosion fatigue and low and high-cycle fatigue. The combination of high temperature and cyclic loading causes the valves to fail. A decrease in hardness and yield strength is also caused by high temperature which also causes corrosion of exhaust valves. Overheating causes surface oxidation and fretting. The fatigue strength is also lowered due to overheating.

Cracked Cylinder Cover

The thermal and pressure stresses of combustion cause that cylinder covers are subject to high levels of stress [39]. These stresses are imposed on the already existing stress by the initial head tensioning. The imposed stresses can be increased by excess cylinder combustion pressures, excess cylinder thermal stress or incorrect, for example over-tensioning of the cylinder cover, assembly. These can all lead to extra stress which can cause cracks.

Broken Cylinder Liner

Wear of the cylinder liner is one of the most important parameters when determining the time between overhaul of large diesel engines [90]. A crack in the cylinder liner can have multiple causes. Poor cooling, improper fit of pistons, incorrect installation, foreign bodies in the combustion space, or erosion and corrosion are all causes of a cracked cylinder liner [24].

2.3.3. Turbocharger Failures

For the years 2001/2002 and 2010/2011 the turbocharger of the main engine has failed eight times. A failure of the turbocharger leads to a big drop in the performance of the engine. This can cause thermal overheating or even complete failure.

A turbocharger is used to increase the efficiency of the engine. It compresses the intake air, so more fuel per stroke can be burned which makes that a cylinder produces more power output. It thus increases the power density [90]. Listed below are some of the problems that can occur to a turbo.

Exhaust Gas Temperature

Too high exhaust gas temperatures can cause problems with the turbo [99]. This can for instance be caused by faults in the engine fuel injection system or due to insufficient air in the combustion chamber for combustion. The latter causes the turbocharger filter to get blocked. If the compressor of the turbine or turbocharger is contaminated, the exhaust gas back pressure is too high or if the turbine blade is damaged or eroded this can also cause failures with the turbocharger.

Charge Air Pressure

If the charge air pressure is too low or too high this can also cause problems which can eventually lead to failures. A leakage in the exhaust gas duct or an incorrectly adjusted fuel injection may be causes of a too low charge air pressure. If the engine performance is higher than normal this can cause the charge air pressure to be too high. This can also be caused by an incorrectly adjusted fuel injection system or incorrect indication of the manometer.

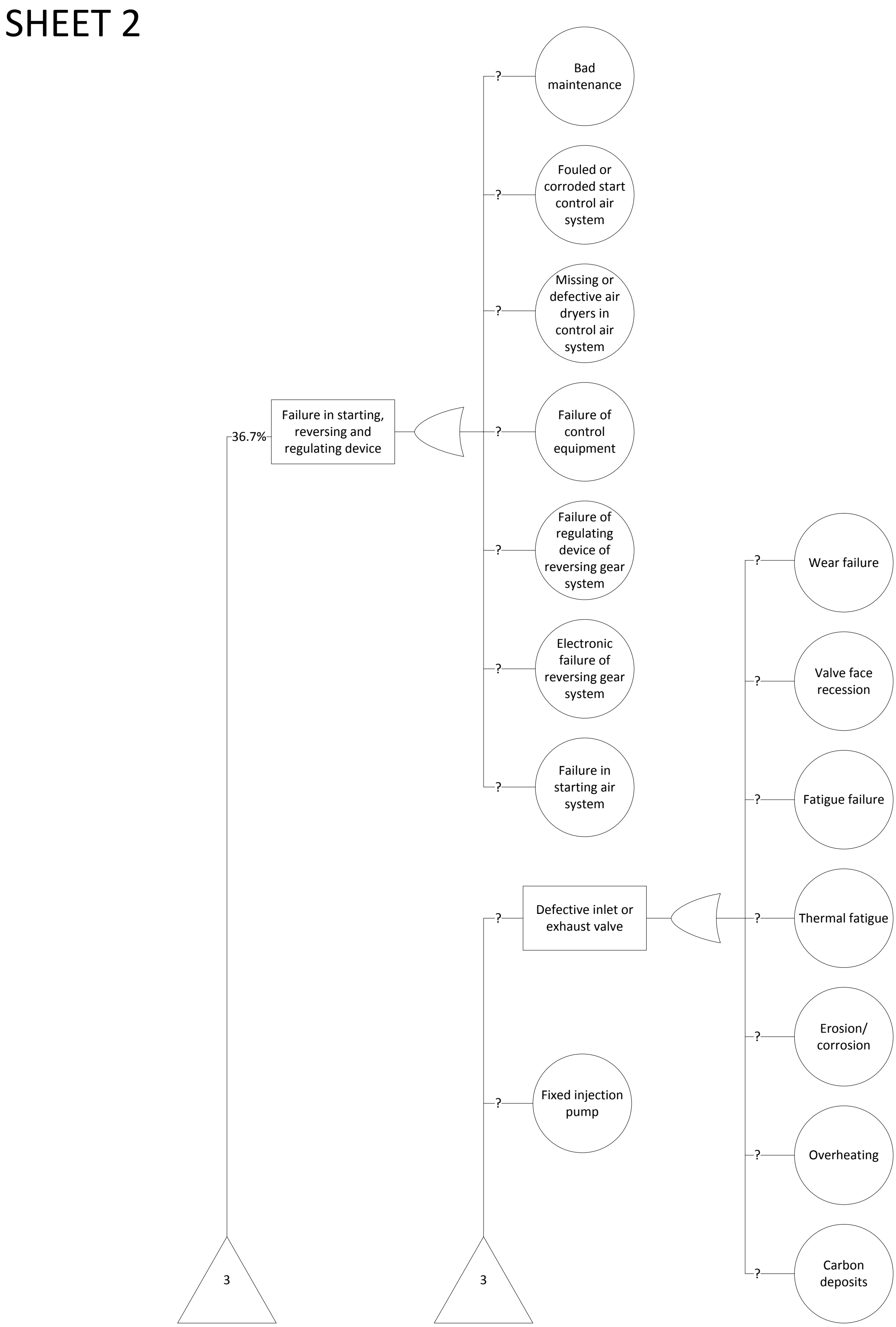


Figure 2.5: Fault tree of the main engine (1 of 3)

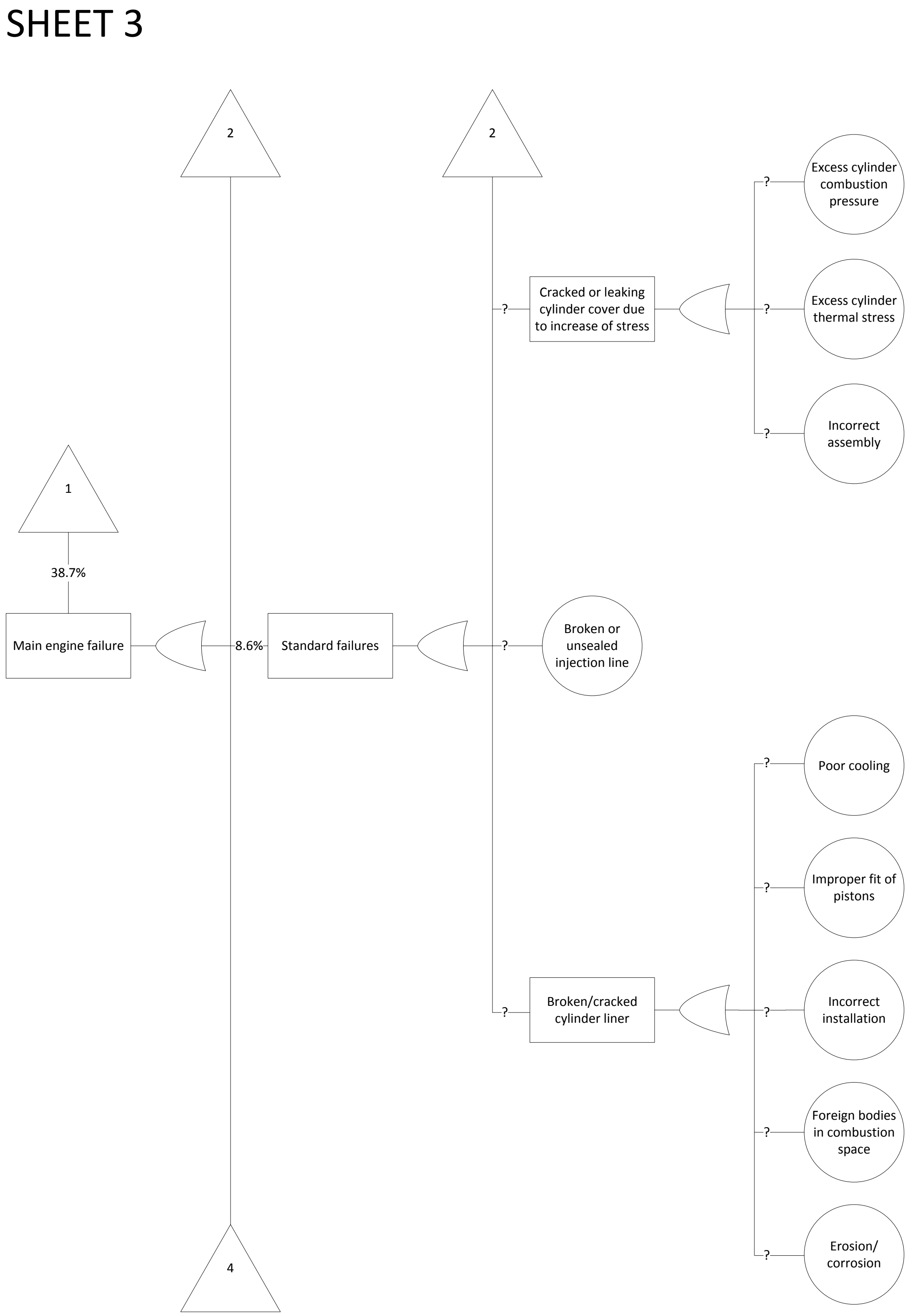


Figure 2.6: Fault tree of the main engine (2 of 3)

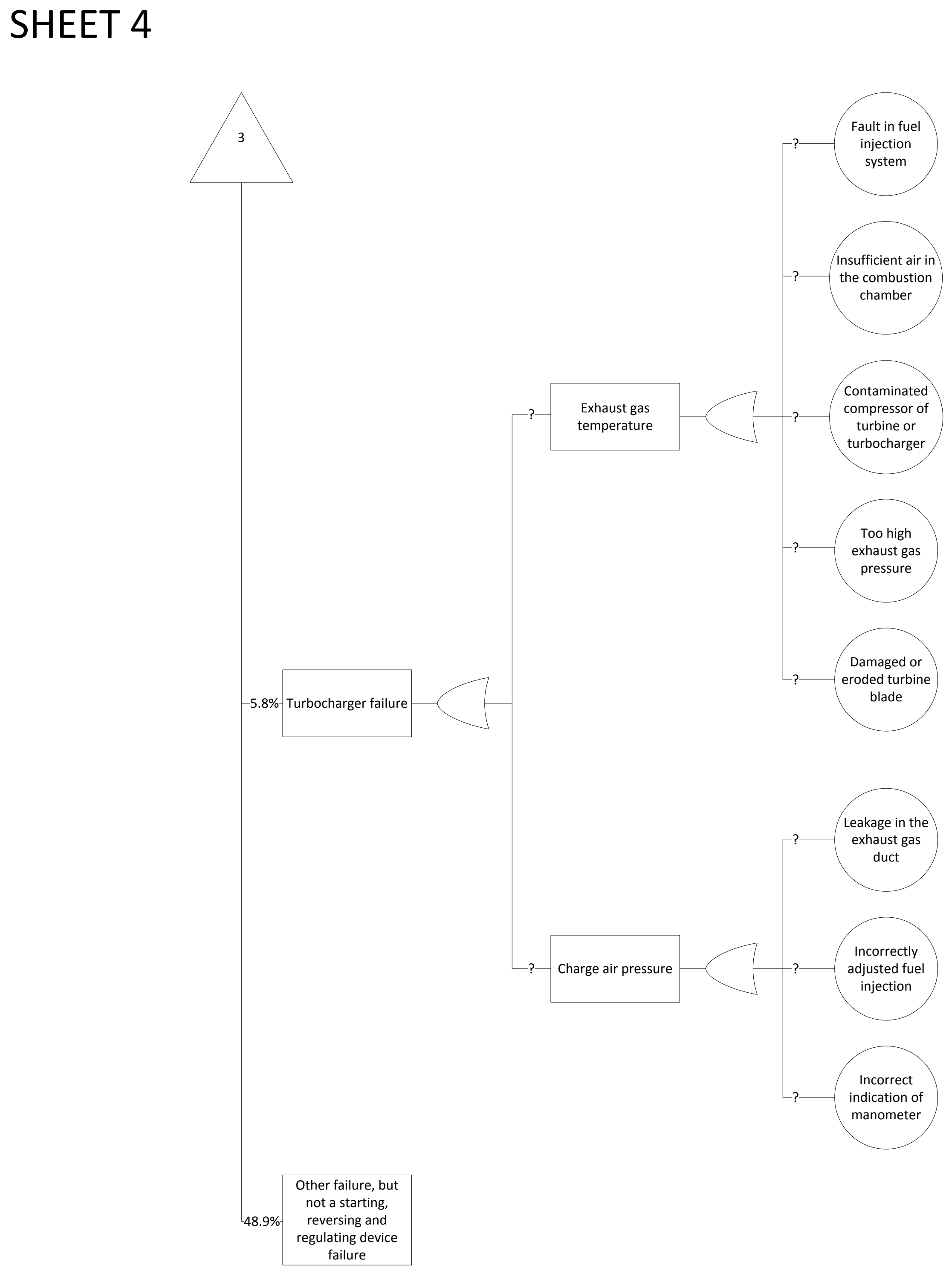


Figure 2.7: Fault tree of the main engine (3 of 3)

2.4. Steering Gear

The steering gear comes at the second place regarding the number of failures over the six years that are considered. A total of 75 failures, 20.9% of the total number, was registered. For the years 2010 and 2011 a significant lower number of failures was registered compared to the years 2001 up to 2004 but no clear cause for this reduction was found. The following reasons for failure of the steering gear were given in the reports.

- Failure of electrical supply and control devices
- Others, with unknown cause

The distribution of the different types of failures can be seen in Table 2.2. The two failures as stated above make up the biggest part of the number of failures. Their distribution of the steering gear failures can be seen in the second column, whereas their contribution to the failures in all systems can be seen in the third column. There is also a big portion of failures with unknown distribution. These failures can be part of the failure 'other failure' or can be of an entirely different kind. This cannot be determined from the reports by the German Ship Safety Division.

Table 2.2: Distribution of the steering gear failures

Failure type	% Steering gear [%]	% All systems [%]
Failure of electrical supply and control devices	45.3	9.5
Other failure	13.3	2.8
Unknown distribution	41.3	8.6
Total	100.0	20.9

There are two types of steering gear systems available: a hydraulic and an electrical system [40]. It is not known from the failure statistics whether one of the two is more vulnerable to failures than the other. Unfortunately no causes for the failure of control devices are given. No other sources have been found which explain this failure type. It is therefore not possible to determine the causes of the failure of control devices.

First, the failure of electrical supply will be dealt with after which short-term failure will be discussed. Finally other steering gear failure research will be discussed and all failures are put in a fault tree, see Figure 2.8 and 2.9 on respectively page 21 and page 22.

2.4.1. Failure Of Electrical Supply

A review of steering gear failures by The Washington State Department of Ecology shows that the electrical components of the steering gear are responsible for just over half (20 of 34) of the failures they recorded [93]. Of these twenty failures six are caused by loose or broken electrical connections. Other reasons for the breakdowns of either the steering gear or the electrical system are not given. Still, this report shows that a failure of electrical supply has a big impact and that part of the cause lies with loose or broken connections.

2.4.2. Short-Term Failures

The failure statistics show that human error is for a great part responsible for the failures to the steering gear. Terms such as 'short-term control failure', 'rudder did not respond' or 'short-term electrical supply failure' were given by crew members to describe failures, but these were often not reproducible by authorities and classification societies [30]. If these terms are stated it is clear that human error is in play.

2.4.3. Other Steering Gear Failure Research

A research on rudder failure on inland ships states that about every week a failure occurs that is caused by problems with the steering gear [54]. This failure rate applies to ships sailing on inland waterways that fall within the Dutch management area. It is not known how many ships are sailing in this area on average. Their research found out that 58% of the accidents related to steering gear failure are caused by an engineering failure, 27% due to human error and the other 15% due to the lack of an ergonomic arrangement and build up of the wheelhouse. These percentages are not included in Table 2.2 or the fault tree. This is because the numbers from two different researches should not be mixed. The placement of the steering lever led to failures relatively often. This research defined rudder failure as every situation where unintended an abnormality of the set course by the operator or the course set on the steering machine occurs. More information on this research and a more detailed explanation of the cause of the failures can be found in Appendix C.

Although this research was solely focused on inland shipping some of the outcomes can still be used for sea shipping. The causes of the failures will be the same for inland and sea shipping since the steering gear has the same function and is therefore composed of the same equipment. This research on the steering gear can thus provide insight on which failures might be part of the group 'other'. The number of failures cannot be used as a reference for sea shipping since inland ships have a lot more rudder movements due to the geometry of their waterway. It is therefore likely that more steering gear related problems occur on inland waterways.

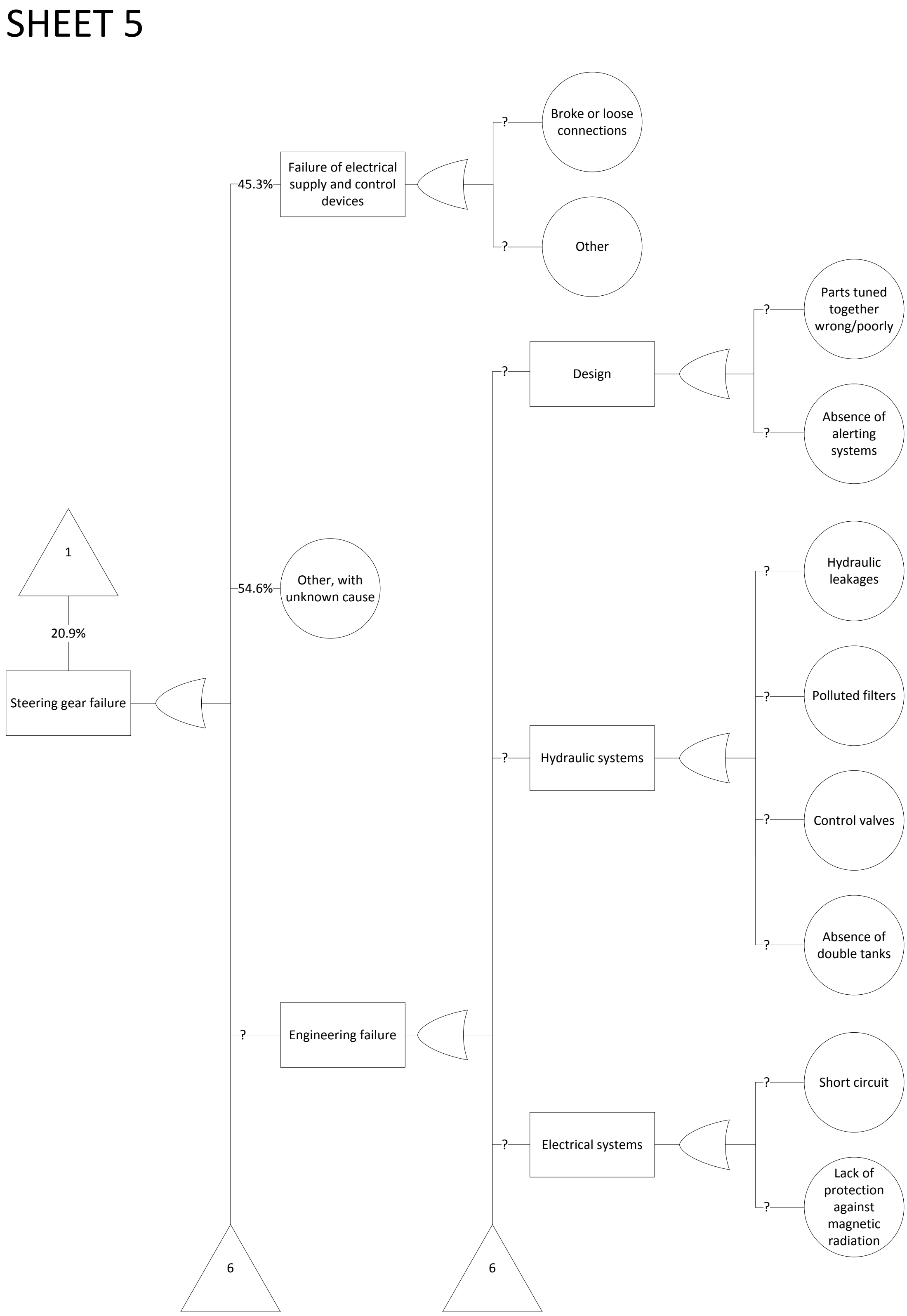


Figure 2.8: Fault tree of the steering gear (1 of 2)

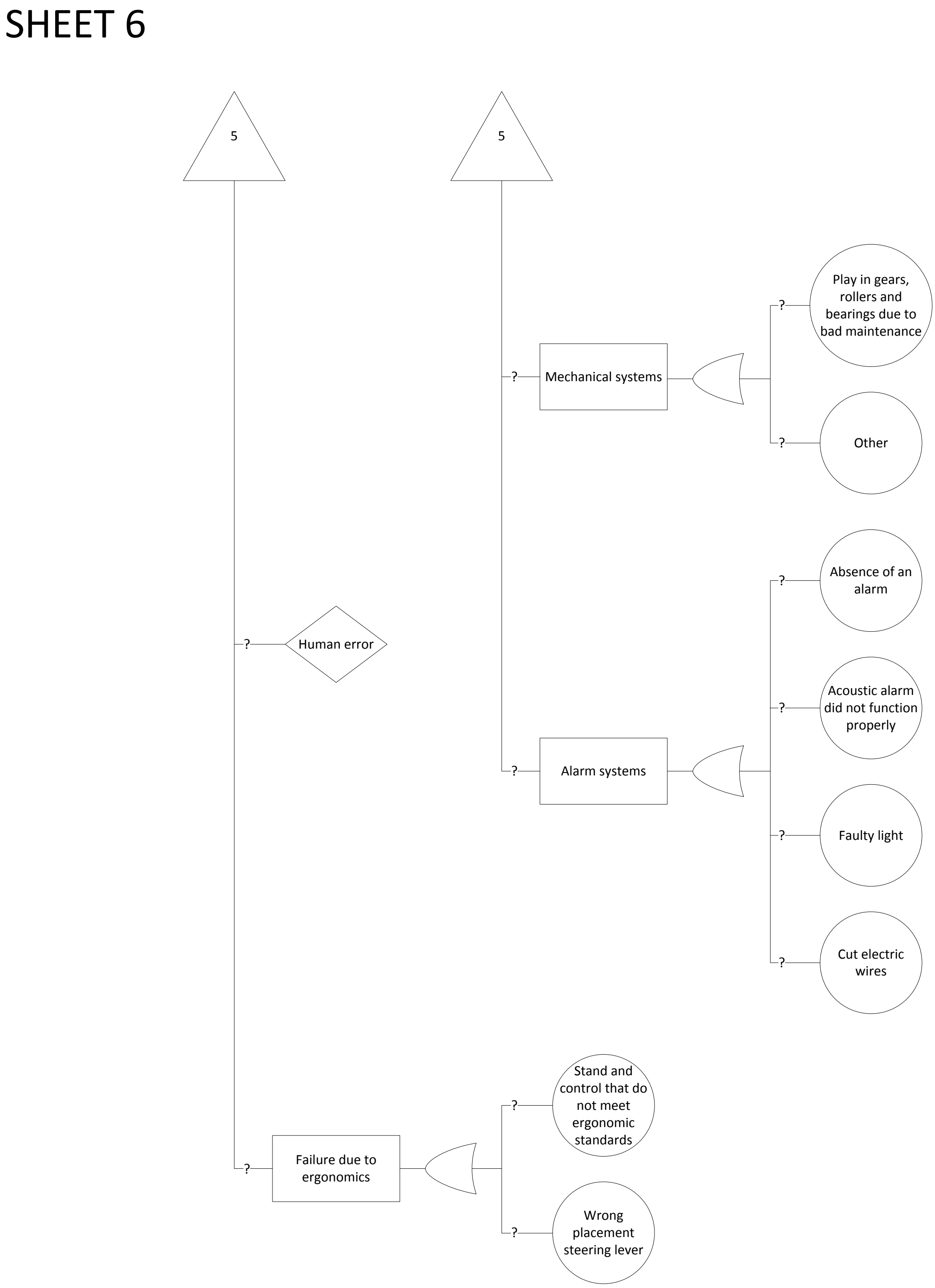


Figure 2.9: Fault tree of the steering gear (2 of 2)

2.5. Fuel System

A failure in the fuel system has serious consequences since it often leads to an abrupt loss of propulsion and manoeuvrability of the vessel due to the stop of main engine(s) and generator(s). For the years 2001 and 2002 some of the causes were: insufficient fuel care, fuel of poor quality and strong vibrations of fuel lines which causes material fatigue or fractures. A broken fuel line, air in the fuel system, fuel intolerance and the fuel filter were some of the other main causes.

Secondary causes to the fuel system failures are due to the interpretation of building codes. Cost savings for new build ships were achieved by combining the fuel systems for the main engine and auxiliary engines. A problem in the fuel system than affects both engines.

For the years 2010 and 2011 the fuel system is responsible for more failures compared to 2001 up to 2004. For the years 2001 up to 2004 the fuel system was responsible for 9.2% of the total failures whereas it was responsible for 15.5% of the failures for the later years. The biggest part of the failures with the fuel system in 2010/2011, 58.8%, have a direct link to the MARPOL rules regarding the use of low-sulphur fuels.

Only for the fuel intolerance some numbers are available to determine its contribution to the total number of failures of the fuel system and all systems. These percentages can be seen in Table 2.3. Of the failures in the fuel system 75.0% has a unknown distribution. This can come from all failures as mentioned earlier, insufficient fuel care, fuel of poor quality, strong vibrations of the fuel line, a broken fuel line, air in the fuel system and the fuel filter. It can also be that the influence of fuel intolerance is bigger, due to the fact that specific numbers were only given for one year. Since a big part of the failures has an unknown distribution it is difficult to use these number for further calculations.

Table 2.3: Distribution of the fuel system failures

Failure type	% Fuel system [%]	% All systems [%]
Fuel intolerance	25.0	2.8
Unknown distribution	75.0	8.4
Total	100.0	11.1

First insufficient fuel care will be dealt with, after which fuel of poor quality is discussed. Then the causes for a broken fuel pipe, air in the fuel system and fuel intolerance will be explained. At last, fuel filter failures are discussed. This all leads to the fault tree of the fuel system, which can be seen in Figure 2.10 on page 26.

2.5.1. Insufficient Fuel Care

Before fuel can be delivered to the engine for combustion it has to be transferred from the storage tanks through heaters, filters and purifiers in order to meet the specifications as set by the engine manufacturer. If the fuel is not taken care of in a sufficient way, problems can arise during this process. The need for low sulphur fuels has caused changes in the fuel refining process, which has resulted in lower quality HFO being delivered to ships [41]. Different oil components are mixed in order to optimise the sulphur content. This can create side effects such as instability, incompatibility, ignition and combustion difficulties.

When the fuel is according to the specifications, problems can still occur. Sediment can build up in the tanks, which causes new fuel to contaminate. The mixing of fuel from different bunker locations can lead to unstable fuel. Unstable fuels are subject to asphaltene settlement which can be whirled up during rough weather. This can cause blockages and engine failures [96].

2.5.2. Fuel Of Poor Quality

Fuel with poor properties has a negative effect on the reliability [7]. Marine diesel fuel is supposed to cool and lubricate the injection system. When this is not properly done it can lead to excessive wear and premature failure of either the injectors or the fuel pump. Some of the contaminants found in marine fuel oil are: water, Sodium, sediment, Alumina/Silica, sludge, fibres and oxidation products [6].

An example of the effect of poor fuel quality is given by Gard [42]. A ship had bunkered HFO in the Far East. It had received samples to test it, but none of them were analysed. It was scheduled to sail to Europe, therefore it was bunkered to almost full capacity. When the ship had just left port the new fuel was being used for the first time. Soon an abnormal sludge generation was experienced which resulted in excessive water-sludge content in settling and service tanks. This caused problems in the performance of the main engine. Due to this performance problem the speed was lowered. During the day they had to stop several times in order to replace fuel valves, fuel pumps and to clean filters and change exhaust valves. When arriving in port several days late, a lot of repairs had to be done. All the fuel bunkered in the Far East was pumped out and all pistons were dismantled and repaired, as well as the piston rings. Some piston top rings were broken or badly worn and one of the cylinder liners was cracked. The fuel system of the engine also had to be overhauled, as well as the turbocharger. If the fuel would have been tested they would have found that it did not meet specifications.

It is very clear that fuel of poor quality can have a very strong effect on the machinery. When the fuel is not within the limits as specified by the engine manufacturer it can result in a total overhaul of all components in the engine room. This is an expensive operation.

2.5.3. Broken Fuel Pipe

A broken fuel pipe obviously causes a problem since no fuel can be delivered to the engine. Corrosion-induced weakness is the most common cause of a pipe failure [67]. Pipes corrode both on the inside and on the outside. On the inside the pipes may be subject to erosion, fatigue and galvanic action, while they are mainly subject to corrosion due to atmospheric conditions on the outside. They can also corrode locally on the outside due to the dripping of liquids onto them. If clamps have loosened pipes can also erode if fretting occurs.

Some pipes are forced into alignment which causes stress in the pipe. This can cause a failure when other stresses are induced, for instance due to thermal expansion or impulse loading.

2.5.4. Air In The Fuel System

When fuel is stored and at rest air is not visible in the fuel. The air will separate from the fuel, as the fuel starts to move. The air collects at the high points along its path. If the air bubbles are not separated from the fuel it can reach the fuel injection system, causing an Interrupted Exhaust Beat (IEB) [72]. Depending on the amount of air that enters the engine this can cause the engine to shut down. This happens if multiple cylinders get a wrong mix of fuel to air.

Air can only come in the engine if the fuel is not properly filtered before reaching the engine. It can thus be said that this problem is caused due to a flaw in the design of the fuel system.

2.5.5. Fuel Intolerance

Switching between two fuels is a very delicate process, causing fuel intolerance to be the problem in ten out of seventeen failures for the years 2010/2011. For the years 2010 and 2011 fuel intolerance has a larger failure distribution than for the years 2001 through 2004 which is caused by MARPOL Annex VI since it limits the exhaust gasses. MARPOL Annex VI also named four areas to be emission control areas. More information on MARPOL Annex VI can be found in Appendix D. In emission control areas HFO cannot be used, if no exhaust gas treatment system is installed, since it contains too much Sulphur. Sailing on cleaner fuel is the most used solution for this problem. Since this is more expensive, the fuel type is changed only just before entering or directly after leaving the emission control area. Fuel intolerance often has serious consequences such as abrupt fatal technical failure, loss of manoeuvrability or even a blackout, in case of an auxiliary engine.

The California Office of Spill Prevention confirms that the MARPOL rule causes incidents regarding the fatal technical failure. They claim that a third of the total fatal technical failure cases have to do with this new MARPOL Annex VI rule [81].

Timing is crucial in a fuel change-over when mixing fuels with different sulphur contents. The temperature changes can cause problems when mixing is done incorrectly. Drastic temperature changes can result in thermal expansions which may result in irregular fuel pump operation, ultimately causing seizures in the worst case. MAN has recommended a 2 °C per minute increase during fuel change. The viscosity of the fuel also affects the process. Both lowering the temperature of HFO as well as raising the temperature of MGO are impractical. This can respectively risk overloading of the fuel pump or gassing of the system.

High temperature in both the fuel system and engine room cause a reduction of the viscosity of the MGO. This can have internal leakage in the engine fuel pump as a consequence, which can cause difficulties when starting the engine, astern operation or when the engine is used at low load. In the fuel system several pumps, such as the engine fuel pump, transfer pump, circulating pump and supply pumps require a minimum viscosity of 2 cSt for proper operation.

The State of California recognizes six categories when it comes to a fatal technical failure [92]. Three of these categories apply to the fuel system. One category is for all problems that occur with controlling the temperature of the distillate fuel. The heating of either MGO or MDO may cause the so called flashing, the vaporising of the lighter fuel. The fuel injectors do not work when the fuel has flashed. This flashing causes a loss of power in a cylinder. When this occurs in multiple cylinders this could result in a fatal technical failure.

Another fatal technical failure category involves incidents regarding the loss of fuel oil pressure. This can occur either to the fuel pumps or fuel injectors. The heavy fuel can only be used when it is heated to 150 °C in order to get it flowing. This expands the metal that the fuel runs through. When the fuel is switched to distillate there is a big temperature drop since these do not need to be heated and can be burned at about 40 °C. This causes the metal to contract, causing a loss of fuel pressure. It also causes a marginal spray pattern and leaks at the injector. Any leaks can cause external combustion, or even fire. The recommended interval for replacing O-rings is 10,000 hours according to the manufacturer, but has been found to be 2,000 hours in reality.

The last fuel related category involves the loss of fuel oil pressure or the loss of flow. HFO of a lower grade has high amounts of asphaltenes. These settle in the fuel lines and other components. When MGO is later run trough the system this releases the asphaltenes. This causes strainers and filters to clog.

2.5.6. Fuel Filter Failures

The problems from the fuel filter originate for a great part from the quality of the fuel. If there are a lot of sediments in the fuel those will be separated in the fuel filter. If the amount of contaminants in the fuel is higher than the specifications of the manufacturer allow, the filter is full within less hours of service. A clogged filter can stop the supply of fuel to the engine which causes it to stop.

Figure 2.10: Fault tree of the fuel system

2.6. Electrical System

A failure in the electrical system leads mostly to a blackout[3]. This was the case for both 2001/2002 and 2010/2011 with a total of 8.9% of the system failures. In the annual report of 2004 the electrical system was not dealt with, so the origin for the problems in these years cannot be found.

In Table 2.4 it can be seen for what percentage of failures a blackout is responsible. This is stated both as part of the electrical system failures as well as part of all system failures. A big number of failures with an unknown distribution is present. Some of these are very likely to also be a blackout, but other failures are involved as well. The fault tree can be seen in Figure 2.11, page 28.

Table 2.4: Distribution of the electrical system failures

Failure type	% Electrical system [%]	% All systems [%]
Blackout	53.1	4.7
Unknown distribution	46.9	4.2
Total	100.0	8.9

The cause of the blackout has to be identified in order to find the original problem. A blackout is often preceded by disturbances to the onboard power supply, frequency, load, fuel system or cooling water system. This can lead to a shut down of active safety systems to the auxiliary diesel. Apart from these disturbances some very clear causes preceded a blackout.

- Failure of the main computer of a large container ship, followed by a blackout and prolonged emergency anchoring
- A network overload due to switching on the bow thrusters. So this is a stronger consumer followed by a blackout.
- Failure of automatic power generator of sectors of the main switchboard.

Other research has given several other causes for a blackout. A total of 400 blackouts have been reviewed in this research. The following failure types have been found [61].

- Automation failure
  From the reported blackouts, 16% was caused due to an automation failure. No noteworthy reasons were given for these failures.
- Control equipment failure
  For this group, which was responsible for 20% of the failures, also no reasons were given.
- Electrical failure
  An electrical failure was responsible for 16% of all blackouts. Many of these blackouts were caused as a result of starting bow thrusters or deck machinery at a moment that insufficient power was available. It is often not thought of that when starting an electrical motor the starting current is several times higher than the full 'on load' current.
- Lack of fuel
  A lack of fuel is the cause of a blackout in 16% of the cases. It is mainly caused by a blocked fuel filter.
- Mechanical failure
  This type of failure was responsible for 7% of the failures. No reasons have been given.
- Human error
  A total of 23% of the reported blackouts was due to human error. This group is responsible for the most causes for a blackout. Some of the causes of human error were 'pressing the wrong button' or tripping an on-load generator.

[3]Blackout is to be understood to mean a "deadship" condition. "Deadship" condition is to be understood to mean a condition under which the main propulsion plant, boilers and auxiliaries are not in operation and in restoring the propulsion no stored energy for starting the propulsion plant, the main source of electrical power and other essential auxiliaries is to be assumed available [50].

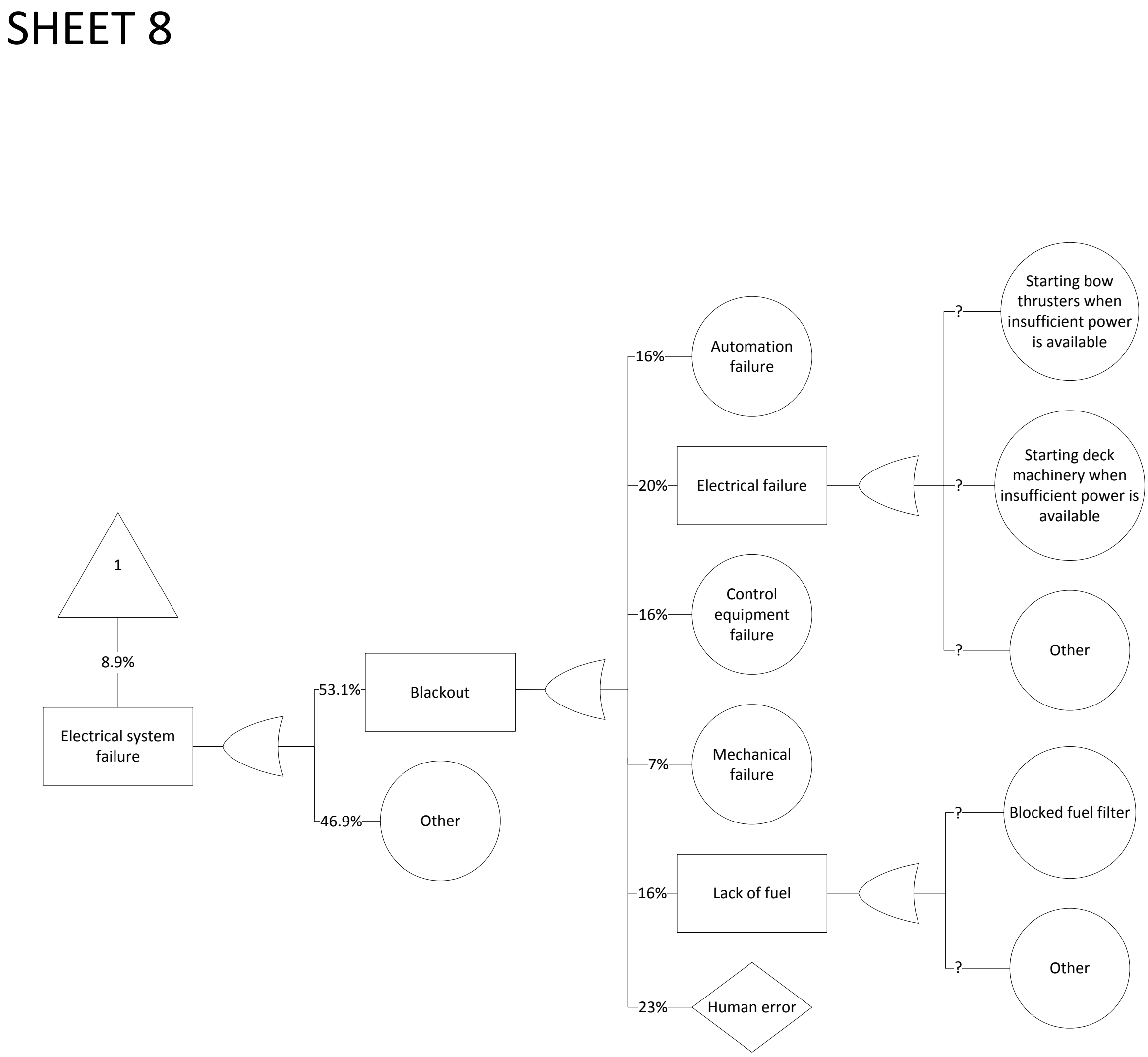


Figure 2.11: Fault tree of the electrical system

2.7. Cooling Water System

At the fifth place regarding the total number of failures, with 8.4%, is the cooling water system. Failures regarding this system include breakdowns of the following parts.

- Cooling water pumps
- Piping systems
- Controller and sensor failures of high-, low temperature- and seawater cooling system

The cooling system has a high and a low temperature system. The water in the high temperature system circulates in the main engine and can be used for heating of the evaporator if required. The low temperature system runs through the main engine air coolers, lubricating oil coolers and all heat exchangers [58].

For the years 2010/2011 six out of the fifteen failures were due to ice that was stuck in the seawater filter which caused a failure in the cooling water system. It was mentioned that this problem increased significantly compared to previous years. It also has to be stated that for new buildings often no clear separation between cooling systems of main and auxiliary systems is present due to cost reduction.

No numbers regarding the failure of the cooling water pumps, piping systems or controllers and sensors are known. It is therefore not possible to determine which of these failures is responsible for the biggest portion of the cooling water system failures. It is known what the contribution of ice in the seawater filter was in the years 2010/2011. This has therefore been shown in Table 2.5. It can be seen that the biggest portion of the failures have an unknown distribution. This group is most likely to consist of failures that have been named above.

Table 2.5: Distribution of the cooling water system failures

Failure type	% Cooling water system [%]	% All systems [%]
Ice in seawater filter	20.0	1.7
Unknown distribution	80.0	6.7
Total	100.0	8.4

The causes for a failure of a cooling water pump will now be investigated after which the problem of ice in the seawater filter will further be determined. In Figure 2.12, page 30, the fault tree of the cooling water system can be seen.

2.7.1. Failure Of Cooling Water Pumps

There are two main causes for the failure of a water pump. The first cause is leaking from the weep hole, while the second cause is a broken water pump housing and shaft [37].

The broken shafts result from excessive vibration and unbalance. The latter two are caused by bent, cracked or broken fans or a fan that is not squarely mounted on the shafts. A cracked or bent pulley or overtightened belt can also cause a broken shaft.

2.7.2. Ice In Seawater Filter

It is confirmed that ice in the inlet of the seawater cooling is a real danger when sailing in icy waters [94]. It has to be stated that for the majority of the year this problem cannot occur due to the absence of ice. If the ship is to operate in icy water, a solution to the problem has to be found. A blockage of the inlet causes the engines to not perform properly and can eventually lead to overheating of the engines and a potential shut-down.

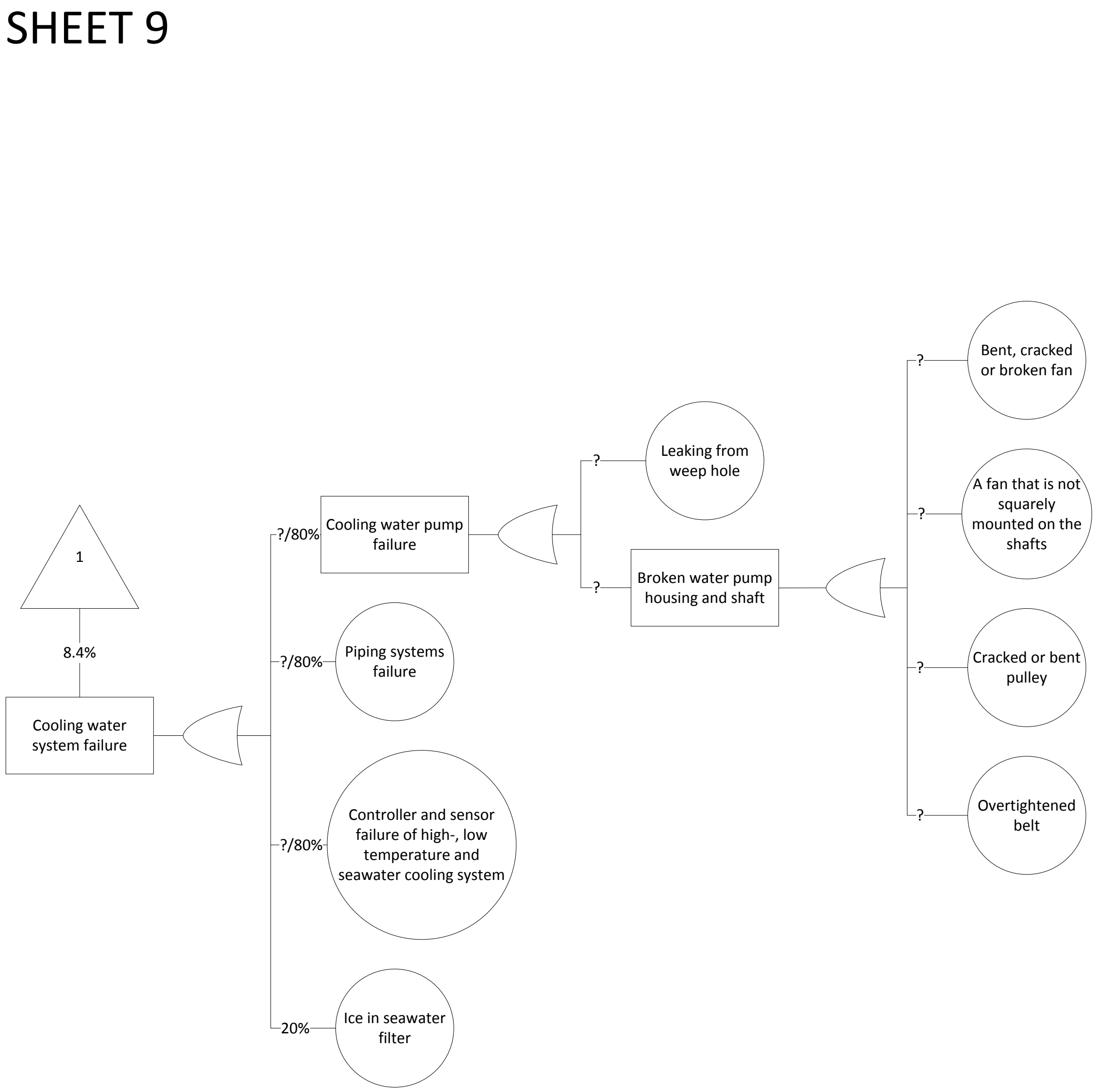


Figure 2.12: Fault tree of the cooling water system

2.8. Contribution Of Human Error To Machinery Failures

In Section 2.4 through Section 2.7 it was found that human error was the cause for multiple failures. This section will review the type of faults that are connected to human error to get an rough number on the percentage of machinery failures caused by humans. For the failures which occur due to man-made errors no solutions have to be found since these will no longer occur on board if the ship is made autonomous. If certain tasks are moved ashore, and done by humans, this might make that new human induced failures occur. However, that does not fall within the scope of this thesis.

For each of the five systems it will be reviewed what the impact of human error is. The calculations in this section are rough calculations since no accurate data is available for all specific failures. For some failures human error will be held totally responsible although it is only part of the cause. For other failures human error will have to be neglected since no numbers are available. It is assumed that this method is roughly correct and levels out over the systems. The number that is eventually determined should therefore be taken as a ballpark figure and not as an exact number. These human induced failures can be placed in a fault tree, for better understanding of the problem.

For each of the failures caused by human error it is determined what their contribution is to the total number of failures in a specific system group. This number is then multiplied with the contribution of that system to the total number of failures over all system groups. This way the contribution of a specific basic event as a part of the entire system can be determined.

$$P_{\text{Event as part of all failures}} = P_{\text{Contribution of event to system failures}} * P_{\text{Contribution of system failures to all failures}} \tag{2.3}$$

It was found that for the main engine and cooling water system no failures were caused by human error. Human error causes failures in the steering gear, fuel system and electrical system. For these three systems it will be explained what the influence of human error is.

2.8.1. Definitions

In order to work with the term human error it is necessary to state the definition. The definition of human error is found to be [27].

> *'This is the failure to carry out a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to property and equipment.'*

Another term that is often used in combination with human error is human factors. The definition of human factors is.

> *'This is a study of the interrelationships between humans, the tools they utilize, and the surrounding environment in which they live and work.'*

For this thesis it is both important to know how often human error occurs, but it is also important to know within which systems it occurs. Therefore both human error and human factors are relevant.

2.8.2. Steering Gear

It was found earlier that short-term failures in the steering gear are very likely to be caused by human error. These failures cannot be reproduced by authorities which showed that human error was in play. Other research confirmed that human error has a direct link with steering gear incidents in 27% of the cases. With the steering gear being responsible for 20.9% of the total number of failures it can be determined that human error in the steering gear is responsible for 5.6% of the total failures. This part of the failures will no longer occur on board if the ship is sailing autonomous, but can move ashore dependent on the automation form of the ship.

The failures due to ergonomics are also human error. These are responsible for 15% of the total number of rudder failures as determined by other rudder research. This makes that the failures due to ergonomics are responsible for 3.1% of the total number of failures.

2.8.3. Fuel System

Human error is not directly responsible for failures in the fuel system. Insufficient fuel care, fuel of poor quality, a broken fuel pipe and the fuel filter though all have a connection with human error either in the decision making process or maintenance wise. It is not known how much these failures contribute to all failures in the fuel system, so it is assumed that their contribution is 0.0%.

In case of fuel intolerance human error contributes to the failure. Switching between fuels is a very delicate process which is obviously affected by human interference. In 2010/2011 fuel intolerance was responsible for 58.8% of the failures. With the fuel system being responsible for 11.1% of the failures, this makes that fuel intolerance is responsible for 6.5% of the total number of failures over all system groups. This form of human error will no longer be present on board but might move ashore, if fuel switching can be used for unmanned sailing.

2.8.4. Electrical System

A blackout is the main cause for a failure in the electrical system. It is found that 23% of the blackouts are directly caused by human error. Since the electrical system is responsible for 8.9% of the failures it can be determined that human error in the electrical system is the cause for 2.1% of all failures. This group will no longer exist when the ship is sailing unmanned.

The electrical failures which led to a blackout were mostly caused by an overload of the net when switching on machinery. The decision to switch on machinery is made by humans, who also made the decision not to switch off other machinery or generate more power. It can thus be said that these failures are also caused by human error. With this failure type being responsible for 16% of the causes of the blackouts it is responsible for 1.4% of the total failures. Depending on the operating modus of the ship this failure will still be present in an unmanned modus.

2.8.5. Human Error In A Fault Tree

Adding the contribution of human error to failures in steering gear, fuel system and electrical system gives the total percentage of human error in all systems. It can thus be determined that human error is responsible for 18.7% of the total number of failures. In Figure 2.13 the fault tree of the entire system is shown, with all events that are caused by human error next to the corresponding systems.

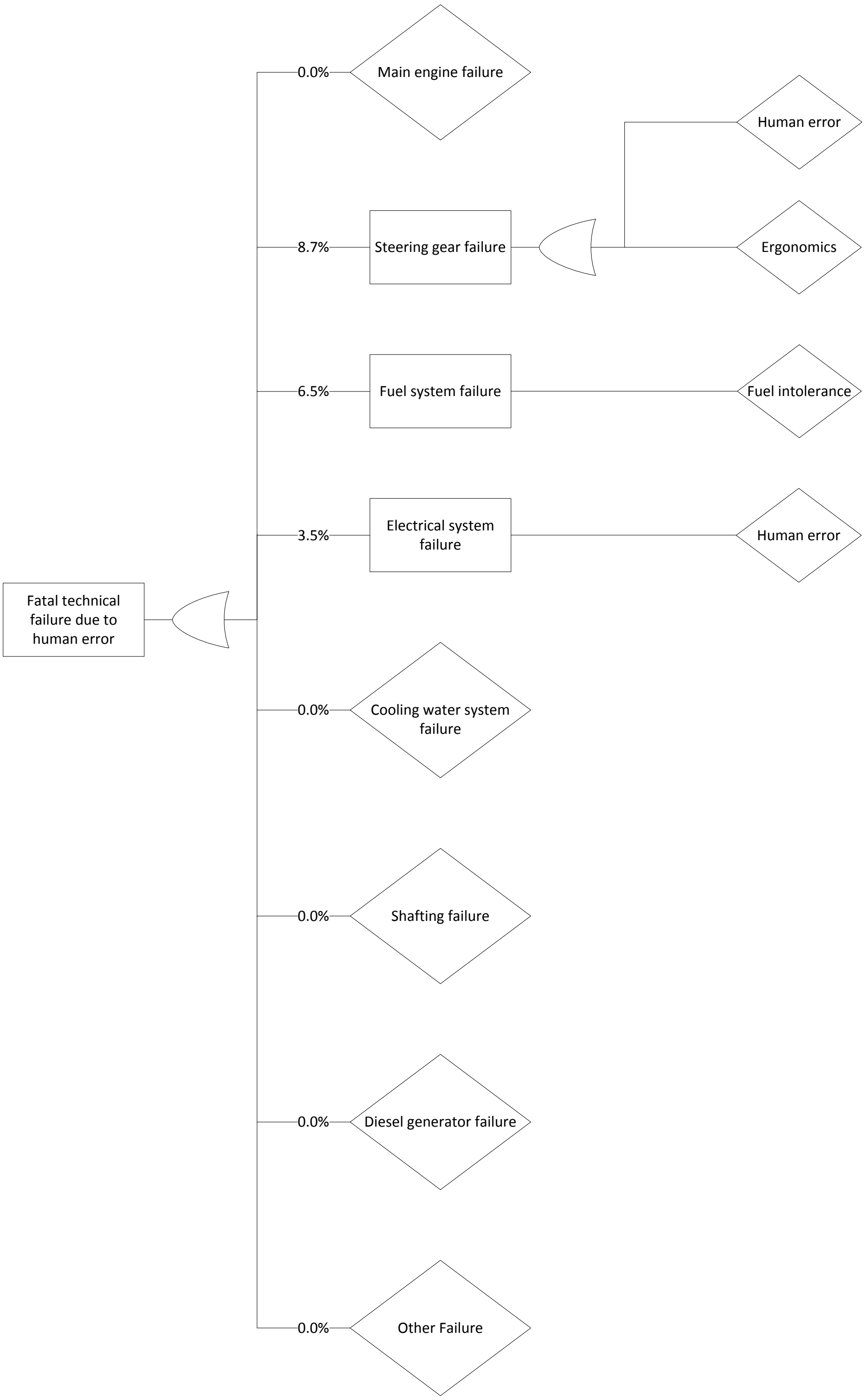


Figure 2.13: Fault tree of the failures due to human error

2.9. Contribution Of Improper Maintenance To Machinery Failures

For multiple failures it was said that improper maintenance was (partly) the cause of a failure. This was the case for multiple systems which means that improper maintenance has a high impact on causing failures.

Maintenance has a high vulnerability to errors since it can be complex and involves the frequent replacement of various parts. A high level of skills is necessary in order to detect faults that are difficult to spot or occur infrequently [75]. Human error in maintenance can occur in several ways.

- Omission error
  Component/part not installed or replaced
- Incorrect action error
  Wrong component/part installed or replaced; wrong check carried out
- Not restored to operational state error
  System not reactivated/deactivated
- Procedural error
  Failure to carry out inspection

In the past, maintenance errors have led to big incidents such as the Piper Alpha oil production platform explosion (maintenance error which led to a leak and eventually caused the explosion) and the Erika oil spill (a poor organisation of maintenance tasks and procedures caused one of the worst oil spills ever in Europe). Improper maintenance is also found to be the main cause of fires and explosions in ships [78].

Maintenance is a cost that ship owners want to minimize as much as possible. If a ship is being maintained it does not make money, in an unmanned setting. Unnecessary costs due to maintenance taking longer than expected or due to a lower maintenance interval have to be avoided. The push for maintenance to be done quickly and within budget can thus cause problems at a later moment.

The design of equipment and maintenance tasks influences the maintenance performance. Equipment that is difficult to maintain is likely to contribute to maintenance errors. A poor design of equipment is a causal factor in one-third of the marine casualties [100].

A study on maintenance manuals reviewed whether the manuals were good enough [21]. It was found that seafarers are estimated to be able to work quickly with different types of equipment and deliver high standards. They are often switched between ship types, so they have to be flexible. When switching from one ship type to another, they might encounter equipment they have not been specifically trained for. This has contributed to marine accidents in the past.

It was also found that the manuals provided to the seafarers are varying in quality considering specificity, content, language and presentation. The language provided is not always one that the crew has sufficient knowledge of. If the manual is of poor quality this leads to an increase of human error.

Since there is no standard for technical and/or operational documentation this is a process that costs money. Only a few owners and operators invest in reports since this is a costly option. The risk of human error would be reduced if standards for documentation are available.

The next subsection will determine what the impact of improper maintenance is on the total number of failures. It was found that improper maintenance has an effect on the main engine, steering gear, and electrical system, but not on the fuel system and cooling water system.

2.9.1. Main Engine

This system group is responsible for 38.7% of the total failures. The cause for the problems with the starting, reversing and regulating device seem to come from bad maintenance. Since 36.7% of the engine failures are caused by this device, this means that the starting, reversing and regulating device is responsible for 14.2% of the total number of failures. This failure might still occur when the ship is unmanned.

From the standard failures only the broken cylinder liner seems to be connected to a maintenance error. No numbers for this part are available though, so it is impossible to determine for what percentage of the total number of failures it is responsible. Since a broken cylinder liner is one of many standard failures it is likely that it has almost no contribution to the total number of failures.

2.9.2. Steering Gear

Loose or broken connections are partly the cause for the failure of electrical supply in the steering gear. The only reason given for this cause is a lack of maintenance. It is therefore assumed that all six of these twenty failures are caused by human error. According to this research, 20 out of 34 failures are due to electrical supply. This means that 58.8% of the steering gear failures are due to electrical supply. Of this 58.8%, 30% is caused by human error. As a part of the total failures, the contribution of human error in the electrical supply is therefore 3.7%. If the ship is unmanned, these failures can still occur since maintenance will still be done by humans.

2.9.3. Electrical System

A lack of fuel was the cause in 16% of the blackout failures. It was mainly caused by a blocked fuel filter. This was found to be caused by contaminants in the fuel which is greatly dependent on the fuel quality and level of maintenance. This failure can therefore either be caused by human error or improper maintenance. It is chosen to hold improper maintenance responsible for this error since low fuel quality does not have to be a problem if the filter is cleaned properly and regularly. This failure is responsible for 1.4% of the total failures. Since the contribution of this failure to the total number of failures is small, it is also not really important if this is a human error or an improper maintenance error, because the calculations are rough. This failure is probably still present when the ship is unmanned.

2.9.4. Fault Tree Improper Maintenance

When the individual contributions of improper maintenance are added, it can be found that it is responsible for 19.3% of all failures. This is almost equal to the contribution of human error. This clearly shows that improper maintenance is a large cause to the total number of failures and thus that improving maintenance has as much as an effect as removing the crew from the ship. It also shows that proper maintenance might be the first step to making the engine room unmanned. The fault tree in Figure 2.14 (page 36) shows the involved systems and events regarding improper maintenance.

2.10. Conclusion

In all of the system groups main engine, steering gear, fuel system, electrical system and cooling water system different technical failures occur. The fault trees for the individual systems can be seen in the corresponding section and the fault tree of the entire system can be seen in Appendix B.

Technical faults with the main engine (38.7%) occur to the starting, reversing and regulating device, are standard failures or are turbocharger related. Problems with the steering gear (20.9%) come from the failure of electrical supply, an engineering failure, human error or a failure due to ergonomics. Insufficient fuel care, fuel of poor quality, a broken fuel pipe, fuel intolerance and a clogged fuel filter are some of the causes of a fuel system failure (11.1%). Several causes for a blackout have been found, which is the main cause for an electrical system failure (8.9%). In the cooling water system (8.4%) a cooling water pump failure or ice in the seawater filter are some causes for a failure.

Human error and improper maintenance were both named as being responsible for multiple failures. It has been determined for both what their failure contribution is. It was found that human error is responsible for 18.7% of all failures, divided over the systems steering gear, fuel system and the electrical system. Improper maintenance was found to be responsible for 19.3% of all failures. The systems in which improper maintenance occurred are main engine, steering gear and the electrical system. The only system that is not affected by either human error or improper maintenance is the cooling water system.

With all failures known, solutions can be determined. For all failures on the first row of the fault tree of a system, solutions will be determined. This means that for for instance the main engine, solutions will only be found for the starting, reversing and regulating device, standard failures, turbocharger failures and the failures with unknown distribution. For these failures, the percentage to the total number of failures is known, so it can be determined how much of a reliability improvement can be gained with each individual solution. When only solutions to for instance the main engine failures as a whole are found, the solutions can become a bit to general. Solutions that solve for instance only two out of four failures would then no longer be taken into consideration although they might have a high reliability improvement. Developing solutions to the failures on the first row of the fault tree of a system will thus provide for more detailed solutions.

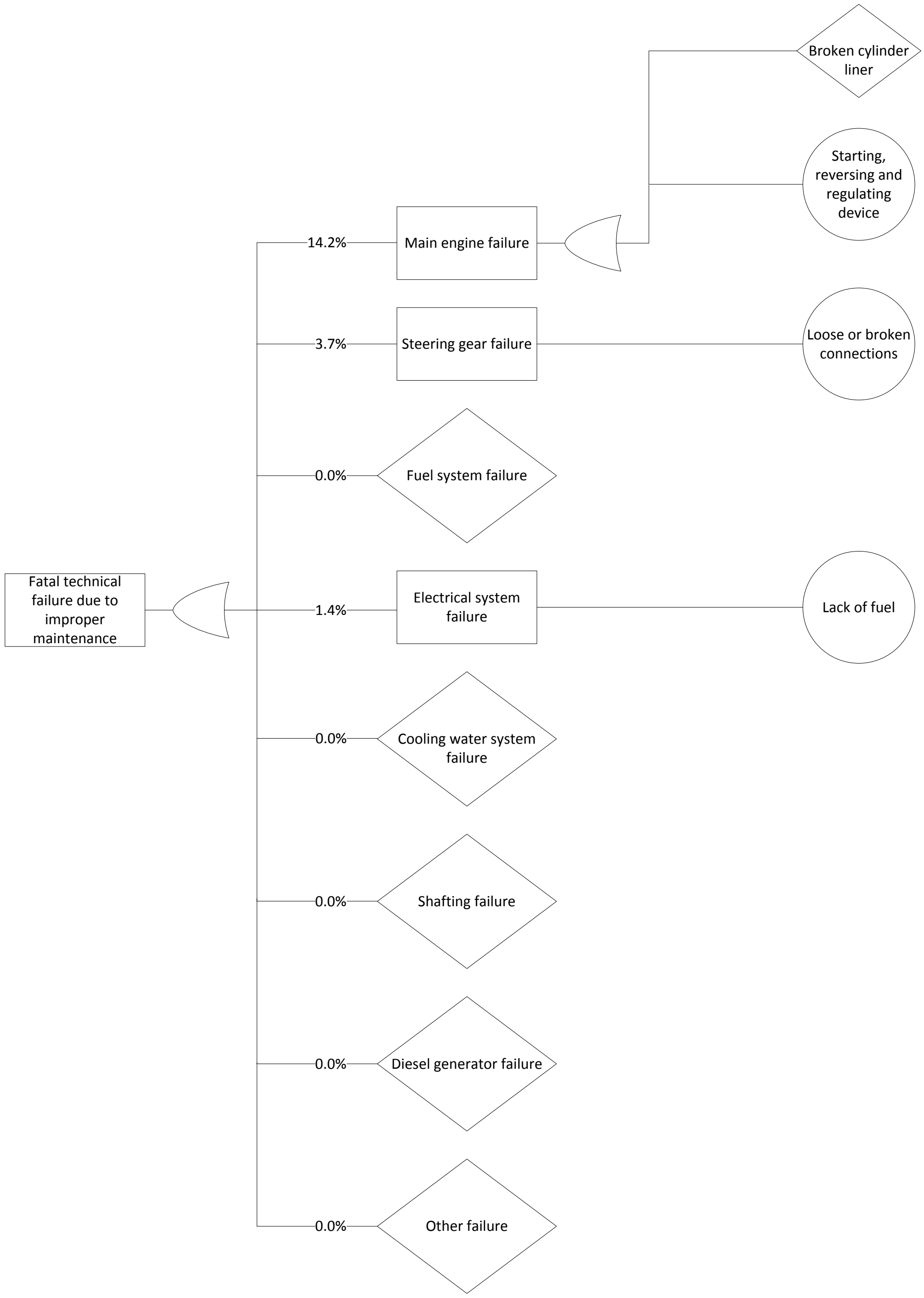


Figure 2.14: Fault tree of the failures due to improper maintenance

3

Generating Solutions

In this chapter solutions will be generated for the machinery failures determined in Chapter 2. Solving these failures increases the reliability of the machinery systems. That is a big step towards unmanned sailing, since having machinery that is more reliable is one way to make the ship able to sail crewless.

The failures that were defined in the previous chapter will first be sorted by their severity in Section 3.1. This makes it possible to see which failures have the largest impact on the total number of failures. Then it will be established what the requirements are for the possible solutions in Section 3.2 and Section 3.3 will state which types of redundancy there are. These requirements will have to be taken into account when generating solutions. After the requirements are set, solutions will be generated for each of the systems. This gives a better picture of what is going on in all systems and makes it possible to determine alternatives for an entire system at once, if necessary. It will be assessed for all systems what the influence of maintenance is on the reliability. Adding redundancy is the second point of attention and finally an alternative for (part of) the system will be investigated.

3.1. Failures By Severity

Developing solutions to failures with the highest contribution to the total number of failures has the largest impact. Making the systems in which these failures occur more reliable gives the highest improvement on the total reliability. It is also important to find solutions to the failures with a lower contribution, but these solutions might be expensive compared to the reliability improvement. Later on it will have to be determined what the cost is of the developed solutions. The ultimate goal is to meet the required level of reliability for the least amount of money. How much the required level of reliability is, will not be determined in this thesis. To determine what the required level of reliability has to be, it has to be known what the current reliability level is and how much extra reliability is required in order to have a sufficient level of reliability. This a task for future work. For some solutions it might be known that a solution meets a certain required level of reliability. For instance, when the mean time between failures is now found to be two years, this means that once every two years a failure occurs. When the mean time between failures is increased to for instance 50 years, it can be stated that this meets the required reliability. After all, the lifetime of the ship is 20 to 25 years, so having a mean time of 50 years between failures ensures that a failure only occurs to about half of the ships. This thus meets a required level of reliability.

This section states all failures found in Chapter 2 and lists them by severity. Table 2.1, 2.2, 2.3, 2.4 and 2.5 have been reorganised based on the severity of the failures. This list can be seen in Table 3.1. Thirteen failures represent the five main systems which together combine for 88.0% of the failures. Adding the failures for the systems 'shafting', 'diesel generator' and 'other' gives a total of a 100%. A list of all failures can be seen in Table 3.1, which is organized from high to low contribution to the total number of failures. The systems in which the failures occurred have been added to the table: ME stands for main engine, SG for steering gear, FS for the fuel system, ES for the electrical system, CW for the cooling water, SH for shafting, DG for the diesel generator system and OT is used for the failure that occurred in the system 'other'.

Table 3.1: Different failure types ordered by their severity

Failure type	System	% All systems [%]
Unknown distribution	ME	18.9
Starting, reversing and regulating device	ME	14.2
Electrical supply and control devices	SG	9.5
Unknown distribution	SG	8.6
Unknown distribution	FS	8.4
Unknown distribution	CW	6.7
Shafting	SH	6.7
Blackout	ES	4.7
Unknown distribution	ES	4.2
Diesel generator	DG	3.6
Standard failure	ME	3.3
Fuel intolerance	FS	2.8
Other	SG	2.8
Turbocharger failure	ME	2.2
Ice in seawater filter	CW	1.7
Failure in other, system	OT	1.7
Total		100.0

It can be noticed from Table 3.1 that failures with unknown distribution make up a big part of the failures, namely 46.8%. For some of these groups there is no information on which failures are part of this group. This makes it impossible to determine any specific solutions to failures in these groups since the exact cause is unknown. However, general solutions such as redundancy can be named because this would guarantee operation, even if an unknown failure has occurred. It is also found for most groups that improving maintenance leads to a higher reliability, this is probably also the case for the failure groups of which it is unknown what failures they contain. There is no reason to assume that improving maintenance would not improve reliability for a group with unknown failures in it. This way, solutions can be found for groups with unknown distributions. For other groups with an unknown distribution some of the failures are known. Solutions for these problems can therefore be generated, but how much of a reliability improvement this gives is unknown, since it is not known how the failure distribution within the group is. One of the failures in the group could for instance be responsible for 20% whereas the other failure might be responsible for 70%, but this is unknown. Assumptions will therefore have to be done to determine the reliability improvement due to these solutions.

3.2. Requirements To The Solutions

Determining which requirements are set for the solutions is very important. This sets the boundaries for the solutions and therefore limits them. For now, only one requirement is set. A possible solution will have to be better in terms of reliability than the current solution.

It has to be determined whether a possible solution has a higher reliability than the current situation. Otherwise this has a negative effect on the total reliability. In a later chapter the best solution will be chosen out of all possible solutions (if there are any). When choosing a solution other factors might also play a role, such as price, operational profile of the ship, maintainability and space requirement.

For each of the failures it will first be determined whether there is a solution to the problem that occurred. If there is no solution available, it will be determined whether adding more redundancy might increase reliability. Finally, alternatives for a system will be reviewed. If a system is replaced by another system, this might discard a failure. The alternative system will then have to be more reliable then the existing system in order to be a sufficient alternative.

3.3. Types Of Redundancy

Redundancy will be one of the solutions in this chapter that will be named as a solution to increase the overall reliability. Redundancy plays an important role when designing machinery plants. The need for redundancy is for a big part driven by economic and environmental damage. Having more redundancy ensures safety and at the same time ensures the availability to fulfil a mission [90]. There are several ways to gain more redundancy in a system.

- Full-backup redundancy. This ensures full availability of a function. A failure of a component does not cause a loss of performance. This is established by installing two components when only one is necessary for operation. The second component is called the cold spare.
- Two or more components are used to fulfil a function. If one of them fails, the function is still available. Losing one of the components might have degraded the performance. There are two levels of degradation.
  - Degradation of full capacity to a lower level. This is the case when one of several identical components fails. If for instance one out of four components fails, the other three will still perform their desired function, but their overall performance is of a lower level than before.
  - Degradation of capacity under extreme conditions only. This is when multiple components of a certain type are installed, but all of them are only operated under extreme conditions. Then, if one of the components fails, the ship is still operable under normal conditions, but no longer under extreme conditions.
- Two or more equivalent systems operating under different working principles, but still fulfilling one function. These systems work differently, so this will cause degradation in case one of these systems fail. This has to be accepted and this principle is called hot spare. An example of this is the generation of 24 volts DC with a converter being backed up by batteries.

All types of redundancy as stated above are examples of functional redundancy. Another form of redundancy, spatial redundancy, can be achieved when equipment is placed in separate compartments. For instance, machinery for twin propeller ships can be arranged this way [104]. The further away from each other, the better the spatial redundancy. When a ship is struck by an external factor the equipment is less likely to fail at the same time.

The downside of redundancy is that it is expensive and requires space and weight. It is one of the larger cost drivers for ships that require high levels of redundancy [90]. Since the unmanned engine room requires more redundancy it is an expensive design.

3.4. Determining Solutions

In the following sections, Section 3.5 through Section 3.9, solutions will be generated for the different subsystems. The subsystems will be dealt with in order of magnitude of their contribution to the failures. First, the main engine failures will be dealt with, then the steering gear failures, fuel system failures, electrical failures and finally the cooling water system failures. Each of the subsystems contains multiple failures. Those will also be dealt with in order of magnitude.

As stated previously, for each of the failures it will be determined whether a direct solution is available. Then, it will be checked whether more redundancy can be added and if there are any alternatives.

3.5. Solutions To The Main Engine Failures

This section will deal with the solutions to improve the reliability of the main engine. First, solutions will be generated for the failures with unknown distribution, after which solutions to the starting, reversing and regulating device failures will be generated. Solutions to the other failures can then be determined, namely the standard failures and the turbocharger failures. For all failures, individual solutions are generated. In reality, a combination of solutions might be applied, if this gives a better reliability. This will later be determined.

3.5.1. Solutions To Unknown, Main Engine

It is not known what type of failures are part of the group of main engine failures with unknown distribution. Generating solutions to these specific failures is thus impossible. It will therefore be determined whether improved maintenance is an option, how to gain more redundancy in the main engine and if there are any alternatives to it.

Improvement Of Maintenance
An improvement of maintenance is a solution to the failures with unknown distribution. For all other main engine failures, an improvement of the maintenance is named as a solution. Considering that it is a solution to all other main engine failures, it can be assumed that it also is a solution to the failures with unknown distribution, although this was not specifically mentioned.

Engine Redundancy
Redundancy in the main engines can be gained by installing more engines as a full-backup. Each of the engines should then be able to deliver the required power. One engine takes over for another in case of an engine failure. Installing an extra engine requires a lot of space and has a big impact on the machinery weight. This can cause the engine room to be bigger than usual. If this goes at the expense of the cargo space this option does not come cheap.

Dividing the required power over multiple engines is also an option to improve redundancy. When one of the engines fails there is still enough power left to sail the ship safely to its destination. After arriving in the desired port repairs can be performed to the broken engine. Having more engines available makes it possible to monitor them closely and to shut one off if it gives strange values from the sensors. This might prevent big failures.

A power take in (PTI) adds redundancy and is also a backup solution. A power take in can be used to propel the ship (with limited speed) by a generator or battery pack. The main engines are decoupled from the shafting, so the PTI has limited resistance.

The use of a PTI might only be a decent solution for ships sailing close to shore. When sailing on the PTI, the ship has limited power. So when it is halfway across the ocean between America and Europe, it takes longer for the ship to reach shore. A battery pack has to be big in order to get the ship to shore, although the third power relationship of speed and power works as an advantage. Sailing at half the speed only requires one eights of the power. The speed should not be decreased too much, since the wind and current will otherwise dominate the direction of the ship.

If the moment comes that one engine fails and another has to take over this has to be a smooth operation. An engine failure can take place at any time. In the heat of the moment the backup engine has to be operational instantly. Every second the ship is sailing on limited power it has less manoeuvrability and it becomes more vulnerable to accidents. This is of course mostly the case when sailing in port, locks or other areas with high traffic density.

Alternatives
There are several alternatives to the 'regular' diesel engine. These are listed below. For all of the alternatives it is determined whether they meet the requirement as set earlier. These alternatives have been taken into consideration since they might prove to be a better solution.

- **The gas turbine** There are several types of ships that are a candidate for using gas turbines: cruise ships, ferries, LNG carriers and fast container ships [107]. From this classical point of view a gas turbine might therefore not be a direct solution for all ships within the scope of this thesis.

  The gas turbine has a modular construction which means that repair by replacement is easy due to the multiple exchangeable sub-units. It has a high reliability and maintainability [90]. Unfortunately, no data was found to compare the reliability of a diesel engine and a gas turbine. Compared to a diesel engine, a gas turbine has a higher power density and is more environmental friendly but it has a lower efficiency, a higher fuel consumption and it needs fuel of a higher quality [107]. As gas turbines are highly reliable, they are an alternative to the diesel engine.

- **Steam turbine plant** Due to its low power density, lower fuel economy and high initial costs the steam turbine has lost ground. It is sometimes used together with a gas turbine. The thermal energy in the exhaust gases of the gas turbine is then used to generate steam for the steam turbine. This has a negative effect on the initial capital cost but also increases overall efficiency. They are said to have good operational reliability and only lost ground due to their lower efficiency [52]. Again, no information is available to compare the reliability of a diesel engine with that of a steam turbine plant. For now, the steam turbine is thus an alternative for the diesel engine.

- **Nuclear reactor** A nuclear reactor can be powered by a steam plant or an oil-fired boiler [19]. The reactors mostly use uranium as their fuel type, with Thorium being another option. During operation, a nuclear ship does not emit CO_2, NO_x, SO_x and particulate matter.

  Even if nuclear propulsion is a more reliable option than a diesel engine, this is not a feasible option. It will therefore not be taken into consideration. An unmanned ship on itself already starts the debate whether that is a good idea, let alone an unmanned ship sailing with nuclear fuel. This will simply not be accepted by the general public. A nuclear reactor will therefore no longer be an alternative.

- **Fuel cell** A fuel cell converts chemical energy into electric energy. No combustion engines or generators are required for this process. There are also no moving parts involved in the fuel cell, but only in the support systems such as pumps, fans and humidifiers. Since this system has less moving parts than a conventional propulsion system it is more quiet. The reactants hydrogen and oxygen are mostly used in a fuel cell. They react to form water and both electrical and thermal energy. Methane can also be used as an alternative to hydrogen. As long as the reactants are available, this system can run. In the medium to long term a fuel cell might be a possible way to propel the ship. They do not emit SO_x and NO_x. If hydrogen is used, it also does not emit CO_2.

  With hydrogen not being widely available, this is a huge disadvantage. First, this infrastructure has to be developed before ships can use hydrogen. Compared to diesel engines they also have lower specific powers and lower power densities. The long term reliability regarding the fuel cell has never been tested [77]. Since the reliability of a fuel cell is unknown, it cannot be considered as an alternative to the diesel engine. The fact that the infrastructure is not widely available is also a major disadvantage.

- **Batteries** There are three common types of batteries: lead acid, zinc-carbon and nickel cadmium. When DNV-GL designed the ReVolt they chose batteries as the propulsion system due to the low speed of their ship and its small size. If solely batteries are used they will have to be charged in port. When the ship is sailing on batteries, no emissions are emitted, which is useful when sailing in emission control areas. Downside of batteries is that they need replacement once every several years since they lose performance over time. Since the batteries are still being developed it might become a feasible solution in the mid or long term. Due to the size of these battery packs it might only be feasible for small ships sailing close to shore [19]. There are no moving parts in a battery so it is likely that the reliability is equal or better than a diesel engine. Batteries are therefore seen as an alternative to the diesel engine.

- **Diesel-Electric** Although not really being an alternative to the diesel engine, its concept is still different. It is therefore included in this list. When using a diesel-electric propulsion, generator sets are used to generate the required power, both for propulsion and auxiliary purposes. This propulsion concept therefore has two tasks which means that loading can be optimized, resulting in lower fuel consumption and emissions [59]. Due to the multiple engine redundancy this concept is said to have high reliability. When one of the generator sets malfunctions the other set will have enough power to sail the ship into port on a lower speed. The engines can be placed anywhere in the ship and be connected to the propulsors by cables. If this type of propulsion will be used the failures in the main engine and the diesel generators will overlap. Diesel-electric propulsion is thus an 'alternative' to the regular diesel engine.

3.5.2. Solutions To The Starting, Reversing And Regulating Device Failures

Engine redundancy is one solution to prevent a failure due to the starting, reversing and regulating device. Every engine is controlled by its own engine controller, so when engine redundancy is applied, two controllers have to fail before a fatal technical failure occurs. Engine redundancy can be gained by either having the availability of a full-backup engine or by dividing the power over multiple engines. A power take in as a backup is also an option.

The problems with the starting, reversing and regulating device mostly come from improper maintenance, as explained in Subsection 2.3.1. It has been stated by the German Ship Safety Division that only qualified personnel should carry out maintenance and repairs. While doing this they should use original parts from the manufacturer. A failure of the starting, reversing and regulating device is most likely to happen close to shore, since that is the moment that the motor controller is used most.

The quality of the parts can play a big role in the reliability of the machinery. A new part might be cheaper but if it breaks more often it becomes more expensive eventually, especially if it causes problems to other components at the same time. There are two types of spare parts: original equipment manufacturer parts (OEM) or non-OEM parts.

- The definition of OEM is not well defined within the maritime industry. Some companies state that OEM parts are parts that are supplied by the supplier of the equipment or by licensed companies. Other companies state that a supplier of a supplier is also an OEM. Sometimes even the supplier of the supplier of the supplier is stated as being an OEM [85]. Spare parts from an OEM will have similar serial numbers to the old parts. All schemes will therefore stay accurate, which prevents maintenance errors.

- Non-OEM parts (sometimes also referred to as ’pirate’ parts, replacement parts, after market parts or ’re-engineered’ parts) are parts that are not supplied by the original manufacturer of certain equipment. Since these parts come from a different supplier, a different serial numbering system is used. This can lead to difficulties when reading schemes.

According to Wärtsilä, OEM parts are the most competitive choice in the long run [102]. This is not really surprising considering that they are an OEM company. Wärtsilä states that non-OEM parts increase the risk of a breakdown due to a malfunction of a single part. This can also be the case for parts of a previous revision. Due to the possible unreliability of non-OEM parts they can lead to high repair costs. With the contribution of the spare parts being around 5-15% of the operational expenses depending on the ship type (the other operational expenses are crew, stores, insurance and administration [62]) it can therefore be discussed whether saving on OEM parts gives the biggest cost savings. Wärtsilä also states that inferior non-OEM parts might lead to an increase in costs due to an higher consumption of lube oil or fuel oil.

One reason for buying non-OEM parts instead of OEM parts is the after sales services of the OEM companies. Due to new-buildings their focus might shift to those ships instead of after sales service. This service is something the non-OEM companies are very good at, since that is their only business [85]. The quality of non-OEM parts is not necessarily of a lower quality than that of OEM parts.

It cannot be told from these sources whether OEM or non-OEM parts are better. It is clear that OEM parts are more expensive, but also come with guarantees regarding quality. Non-OEM parts are cheaper but it can only be told from experience whether these parts can guarantee the same level of reliability. It can take years to find out which non-OEM parts are perfectly compatible to OEM parts [13]. It is therefore advisable to only use OEM parts for the machinery of an unmanned ship, unless certain non-OEM parts have found to be suitable as well. This limits the chance of a failure due to improper maintenance or improper replacement parts.

A combination of the two named solutions is also an option, since this increases reliability. It will later be determined how much of an extra reliability this gives and whether combining two solutions is financially viable.

3.5.3. Solutions To The Standard Failures

The group of standard failures in the main engine is responsible for just 3.3% of the total number of failures. This group consists of parts that can fail on an engine such as valves, pumps, cylinder covers, injection lines and cylinder liners. According to the German Ship Safety Division a material failure or faulty maintenance are likely to have caused these failures. This can only be told from maintenance reports of the ships to which these failures occurred. But this statement shows that paying attention to the maintenance increases reliability.

The goal of this thesis is not to redesign an engine on the level of these failures. That is a task for engine manufacturers and someone with a better knowledge of engines. It is still questionable whether somebody with a detailed knowledge of engines is able to increase the reliability of the overall ship significantly by redesigning these parts. Faults will eventually always occur to one of these parts.

Using a different type of engine leads to other standard failures. These specific failures might be gone, but the new machinery will also be prone to failures. So switching to another type of main engine is not necessarily a solution to increase reliability.

For this failure, multiple solutions can be determined. Applying engine redundancy solves these problems. If one of the engines fails due to a standard failure, there is still enough power available to get to shore. Installing a power take in also increases the redundancy of the main engines.

3.5.4. Solutions To The Turbocharger Failures

A turbocharger is a delicate piece of machinery. Maintenance therefore has to be strictly performed based on the schedule provided by the turbocharger manufacturer [30]. Maintenance of it should only be carried out by qualified personnel and parts for it should also come from the original manufacturer in order to guarantee reliability of the system [28]. Proper maintenance is thus the first solution to the turbocharger failures.

It is not the goal of this thesis to redesign the engine or in specific the turbocharger. When engine redundancy is applied, or when a power take in is installed, a turbocharger failure will not lead to a fatal technical failure since the other engine still functions properly. As this solves the problem, no other, more detailed, solutions are suggested.

3.6. Solutions To The Steering Gear Failures

This section will determine solutions to the steering gear failures. These failures, being responsible for 20.9% of all failures, will be dealt with in order of magnitude. First the solutions to the failure of electrical supply and control devices will be generated, after which solutions to the failures with unknown distribution can be determined. Finally, solutions to the other failures will be generated.

3.6.1. Solutions To A Failure Of Electrical Supply And Control Devices

This steering gear failure is for a big part caused by broken or loose connections. There is also a large share of which the causes are unknown. For these failures it is difficult to find a solution. Loose or broken connections are stated to be caused by improper maintenance. It should therefore again be stated that maintenance should only be performed by qualified personnel. This keeps the maintenance at a known quality since people with decent knowledge are working on the ship. Compared to land based electrics a lot more rules are set regarding the material and methods due to the salinity of the water [74]. Only qualified personnel should therefore perform the maintenance.

Another solution for the loose or broken connections is to double all wires. This way, if one connection fails there is another connection which takes over. The vessel can thus continue its journey on the other wire. In the next port the failed connection can then be replaced or reconnected. Adding redundancy can also be done by splitting the steering gear into two systems. These will then both have to fail before this becomes fatal.

Any alternatives to electric wires are not available. For wireless communication, Bluetooth might be an option, since it is a replacement for wires and is able to transfer data at the same time. Although it might be an option to use Bluetooth, it is not yet used for this application in the marine industry. It should therefore first be properly tested before it can be implemented in an unmanned ship.

3.6.2. Solutions To Unknown, Steering Gear

For this group it is not known what the failures are. Solutions to the causes of these failures can thus not be found. It is very likely that better maintenance is a solution to these failures. This has already been proven to be a solution for multiple other failures so it can be assumed to be effective for this failure as well. The reliability of the steering gear can also be improved by adding redundancy. When having a steering gear installation with multiple rudders, these rudders can be separated into multiple systems. A failure in one of the steering gear systems then does not affect the other system. Splitting the steering gear into two separate systems would mean that everything has to be doubled.

Sailing the ship with one broken steering gear system limits the manoeuvrability of the ship, as long as the broken rudder is not stuck in a steering direction. If the broken rudder remains in the position in which it broke, it can still have a steering effect causing the ship to no longer be able to continue its route. A mechanism should thus be included to get the rudder in the zero degrees position. This can for instance be done by removing the hydraulic pressure of that rudder, such that the forces on the rudder bring it back in neutral position. Limited manoeuvrability can lead to difficulties when sailing in port or in other areas where high manoeuvrability is required. Extra manoeuvrability can be gained by installing a stern thruster or by making the rudders larger than required. Making the rudder area larger than required induces extra resistance, which leads to a higher fuel consumption. This is therefore a costly option. The stern thruster can be made retractable. This way it has no hydrodynamic disadvantages. When needed it can be lowered and used for extra manoeuvrability. The azimuthing thrusters can both be used with electric and diesel drive. According to Rolls Royce they have a high operational reliability and easy maintenance [83]. This azimuthing thruster can also be used as a 'get you home' device.

In case azipods are used for propulsion no rudders are required. The azipods provide the manoeuvrability of the ship. In order to power the azipods, an electric propulsion system is needed, so diesel-electric propulsion is usually chosen. Using azipods will require more wiring, which also has been proven prone to errors. If maintenance of these electrical connections is done correctly this should prevent these failures. Azipods have a high reliability, require low maintenance but are more capital intensive [3]. Compared to the traditional propulsion they are said to have a better fuel efficiency. Azipods seem to be a plausible alternative, although it cannot be stated how their reliability compares to that of regular steering gear. Regular steering gear has less parts, so therefore might be more reliable. Whether an azipod has an equal or better reliability than regular steering gear can thus not be stated. Installing one azipod is therefore a questionable solution, but installing two azipods would be a solution with a higher reliability. The option to install two azipods can therefore be taken into consideration.

3.6.3. Solutions To Other, Steering Gear

The group 'other' is responsible for 2.8% of all failures. But what is actually responsible for these failures is unknown. Options in order to improve the redundancy of the steering gear or possible alternatives for it have already been discussed in Subsection 3.6.2.

3.7. Solutions To The Fuel System Failures

This section will deal with the solutions to all fuel system failures. If necessary, also redundancy improvements and alternatives will be determined. First solutions to the failures with unknown distribution will be dealt with after which solutions to the fuel intolerance can be determined.

3.7.1. Solutions To Unknown, Fuel System

The failures in the fuel system with an unknown distribution are responsible for 8.4% of all failures. This group consists at least of the following failures; insufficient fuel care, fuel of poor quality, strong vibrations of fuel line, broken fuel pipe, no proper filtering of air in the fuel and a clogged fuel filter.

First, the failures insufficient fuel care, fuel of poor quality and the clogged fuel filter will be dealt with. Those have more or less the same cause and will therefore have the same solution. A solution will then be found for respectively the strong vibrations of the fuel line, a broken fuel pipe and the improper filtering of air in the fuel.

Fuel Quality

The failures insufficient fuel care, fuel of poor quality and the clogged fuel filter all seem to be caused mainly by the quality of the fuel and the mixing of fuel from different locations. Therefore a solution or plan of approach has to be developed in order to make sure that proper fuel is bunkered.

It is recommended to have the quality of the fuel checked before bunkering [29]. A sample of the fuel should be send to a laboratory and if the properties of the fuel are found to be in order, the fuel can be bunkered. It is then known that the fuel is of sufficient quality before entering the ship, which is of course the most ideal scenario. Since checking a sample of fuel in a lab takes a lot of time, fuel is mostly checked after bunkering, if it is checked. It is said that only one third of the fuels on internationally sailing ships are tested. A lot of improvement can thus be gained. If the fuel is checked after bunkering, enough fuel of a known and decent quality should still be available. The ship can then sail on this proper fuel until it knows the quality of the bunkered fuel [42]. If low quality fuel is bunkered this should be kept separate from the other fuel and the rest of the fuel system. It has to be off-loaded in the next port in order to bunker clean fuel instead [30]. If improper fuel is removed from the ship all parts that came in contact with the bad fuel have to be cleaned. No contaminants will then stay aboard.

The quality of fuel is different all over the world. One of the most basic parameters of fuel is the density. A difference between the given and measured density can be used to determine whether the behaviour of a supplier is good, medium or bad. Of course a measured difference in fuel density does not say anything about the quality of the fuel, but companies who are honest about their fuel are not likely to hide something. In order to know something about the quality of the fuel from a supplier, a fuel testing agency can be used, such as Veritas Petroleum Services (`http://www.v-p-s.com/index.html`).

It has been stated that a clear separation of fuels from different locations should be present. Mixing of fuels from different locations can potentially lead to a fuel system failure. Therefore each of the fuels should have its own settling tank and storage tank [30]. Fuel is still present in the ship both when fuel is checked before bunkering or checked before using since a ship cannot arrive in port with all tanks empty. Two fuel systems are therefore required to keep the fuel separated. It is advisable not to save any money by installing one fuel system, but spend the money on making these tanks separate. If it is possible to always bunker fuel on one location this is the best scenario. Fuel from one location will likely be of the same quality most of the times. When always bunkering on one location, the fuel should still be checked. Bunkering in one harbour is only possible for short sea shipping with a constant route and sufficient range to make their round trip.

Vibrating Fuel Line

Excessive vibrations in the fuel line can lead to a fuel system failure. These vibrations will therefore have to be avoided. The natural frequency of a fuel line should thus be outside of the range that can be expected from the machinery. No excessive vibrations will then be caused due to the natural frequency. The natural frequency of the fuel line can be changed by changing its stiffness, mass or by adding dampers or springs. This failure or its solution will not be reviewed any further in this thesis since it requires a detailed study and its failure distribution is expected to be small.

Broken Fuel Pipe

The most common problem that causes a broken fuel pipe is corrosion induced weakness either on the inside or outside of the pipe. When a pipe is forced into alignment this can also cause a failure of the pipe. There are multiple measures to prevent corrosion in pipelines and therefore extend its lifetime. Four common techniques are protective coatings and linings, cathodic protection, material selection and corrosion inhibitors [68]. A combination of protective coatings and linings in combination with cathodic protection is often found to be the most cost-effective solution.

An effective monitoring and maintenance program can be a very good insurance against preventable corrosion problems. Pipes should also be replaced when they are severely damaged by corrosion. Even if measures are applied to limit the speed of the corrosion a pipe will eventually corrode. Their thickness should be measured and checked with the rules on a regular basis, which would be very expensive since every part of the pipe would then have to be monitored. This way, if corrosion occurs this does not directly have a failure as a consequence when the pipe gets thinner.

Backup pipes can also be installed as a solution to a failure by a broken pipe. In case one of the pipes fails, a backup pipe can take over the task of the original pipe. The broken pipe will then be closed down. Having a backup pipe available means that all pipes have to be doubled in order for this option to work. Many valves will also have to be installed in order to shut off parts of the pipe that have broken. This is a costly and spacious option.

The fretting of loosened clamps can be prevented by checking these clamps on a regular basis. Clamps loosen over time so it is important to check whether they loosen or not, so they can be retightened if needed. If fretting has already occurred it is best to replace the pipe and make sure to check it more often. As mentioned earlier, forcing a pipe into alignment also caused failures. During the build, or when repairing a broken pipe this can occur. It is advisable not to force a pipe into alignment, but take the time to properly connect pipes to one another.

The broken fuel pipe will not be taken into consideration for the rest of this thesis. Monitoring every part of a pipe is simply too expensive and would require too many sensors. This failure is also expected to have a small contribution in the total number of failures. Installing pipes properly is given as an advice but will also not be taken into consideration any further.

Filtering Of Air From The Fuel
Air can only come in the engine if fuel is not properly filtered, which then leads to a failure. To prevent air from getting in the engine a simple solution can be used. A filter head should be used that has the outlet line directly on top of it. With the outlet line exiting directly above the filter there is no place for air bubbles to collect [72]. The filter will therefore take all the air out. The problem of improper filtering can thus be solved by making sure that a correct filter is installed and that there are no areas for air to collect in the fuel lines leading to the injection system.

To be absolutely sure that the air is filtered from the fuel, a second filter can be installed. If two filters are positioned close after another, this adds redundancy. Any air that accidentally got through the first filter will be separated in the second filter. In case of a failure of one of the filters, there is already a backup filter in place.

3.7.2. Solutions To Fuel Intolerance

The cause of fuel intolerance lies within the fuel change-over as a result of entering or leaving an emission control area. It should be noted that this failure only occurs to ships who sail both inside and outside emission control areas and use two or more types of fuel. Ships sailing outside these areas, for instance from Africa to South America or Australia to Asia do not have to switch fuel, since those are not sailing in ECAs. When sailing outside ECAs no solution to this problem has to be found since it simply does not exist. Those ships can just sail on one type of fuel, most likely HFO since it is the cheapest fuel. As long as this fuel type complies with the global limits no different fuel has to be used.

Ships sailing only in emission control areas are likely to sail on marine diesel. This way, they comply with the emission rules and use only one type of fuel at the same time. Fuel intolerance can therefore not occur, when the fuel is properly controlled. All ships in the emission control areas have to comply to the emission requirements, so there is no financial disadvantage with this solution.

When fuel switching is necessary the mixing of different fuels (and possibly from different locations) should be avoided, as stated already in Subsection 3.7.1. The systems for the heavy fuel oil and marine diesel oil should thus be separated as much as possible, which requires two fuel systems.

Ships sailing partly inside, partly outside the emission control areas can also go with only one type of fuel in order to solve fuel intolerance. But for these ships there is a big financial disadvantage when doing so. This might therefore not be the best solution for these vessels. For these ships another type of fuel might be an option. A selection of a new fuel is based on its advantages and disadvantages. For different ships and operational profiles another fuel might be the best alternative. DNV-GL has stated that for a possible alternative fuel to play an important role in the future it should meet the following conditions; affordability, sustainability and safety and reliability [22]. Affordability is the most important parameter, since low fuel prices give more room for profit than high fuel prices. New fuel types and fuel technologies tend to be more expensive than conventional fuel types. The fuels LNG, methanol and electricity will be discussed. This Subsection will end with information on the scrubber. This equipment cleans the exhaust gasses and can therefore also be used to be able to use one type of fuel.

- **Liquid Natural Gas** LNG (Liquid Natural Gas) is a possible fuel alternative. Using this fuel prevents SO_x in the emissions and heavily reduces NO_x and particulate matter. It does not reduce the emission of CO_2 [31]. It is currently available for bunkering in several ports in Europe, Incheon (Korea) and Buenos Aires in Argentina. LNG is a developing market, so more bunker locations will follow. Although being a developing market it is already a proven and available solution [22]. The extraction of schale gas in North America gives competitive natural gas prices while giving more energy security at the same time [22]. For LNG, a different type of engine is required, namely a gas engine or dual fuel engine.

  LNG fuelled engines are available for the full power range, with capacities ranging from 5 to 50 MW. Compared to a conventional machinery installation, a LNG installation is about 30% more expensive. This is due to another type of engine, tanks, new piping and other equipment. The size of the LNG tanks are about three to four times bigger compared to conventional tanks. This is due to energy density of LNG and the extra insulation. This has effect on the carrying capacity or range of the vessel. Compared to a diesel engine it might have a 1-3% higher efficiency.

  During the production, transportation and use of the natural gas methane slip may occur. This greenhouse gas has 25 times more impact compared to CO_2. This leakage would possibly cancel out the benefits from changing fuel. Calculations by DNV-GL estimate that there is a methane leakage of 5.5%, which would make the emissions of LNG and diesel fuel almost equivalent. The leakage of methane should therefore be reduced. Techniques are available to limit the methane slip in marine engines. For diesel cycle engines a high pressure injection, dual fuel concept can be used. This system produces a bit more NO_x, but it limits the methane slip to $0.2\ gCH_4/kWh$, which is about 0.1%. This eliminates the problem almost completely. In total, using LNG reduces the emissions by up to 25%, when no slip occurs. In reality, the reduction is more in the range of 10-20%. The use of LNG might be a bridge towards a further reduction of emissions. LNG is fossil-based, so it is not a sustainable fuel.

- **Methanol** Methanol is a biofuel. Biofuels are made by converting biomass, or biomass residues into a liquid fuel [22]. It is mainly produced from natural gas or coal. In a sustainable way, it can also be made from black liquor in pulp and paper mills. When produced from natural gas it has almost the same emissions as diesel. When generated from coal, it has two times as many emissions. If it is generated from the black liquor, the emissions are slightly higher than when it is generated from natural gas.

  Biofuels are currently generated in small factories. It is difficult to scale these up to the required level. This is partly due to technical issues and the availability of biomass. The market demand also plays a role. The investments and developing of this fuel will determine whether this fuel will be widely used. So far, only one ship is using methanol as a fuel [91]. For this thesis it will not be further investigated because it first needs to be further developed, in order to become a proven concept.

- **Electricity** There are two forms of electric propulsion: a pure electric and a hybrid propulsion system. The latter was already dealt with in 3.5.1. For a pure electric system, electricity is generated onshore and then stored on board until it is used for propulsion or auxiliary purposes. The most common way to store electricity are batteries. Ships powered by electricity do not produce direct emissions. These emissions are produced at shore, when the electricity is generated. Batteries are significantly more efficient than marine engines. With the maximum efficiency of a marine engine being 50%, batteries charge and discharge with an efficiency of 95% or higher [22]. This therefore decreases the efficiency losses and also the emissions. Dependent on the way the electricity is generated this actually limits the emissions significantly. If the electricity is generated in a sustainable way, this limits the emissions. Electricity generated with coal or oil produce the same level of emissions, apart from the efficiency difference.

  If the price of electricity is competitive with those of marine fuels, the cost of operation is similar. Before the ship can become operational, high capital costs have to be invested in batteries. This can be upwards of $1,000/kWh [32]. This can be recovered by lower maintenance requirements and operational savings. The initial costs might become lower when the production of batteries increases.

  The infrastructure in port has to develop in order to make electricity a widely used fuel. Electricity grids have to be upgraded, as well as storage systems on shore. When in port, electricity from shore can also be used to power the ship. This is called cold ironing. For cold ironing to be financially viable, fuel must be around $900/ton.

Scrubber
Exhaust Gas Cleaning Systems (EGCS), also called scrubbers are an option for removing SO_x from the exhaust gases. Instead of using an alternative and/or cleaner fuel, the exhaust gases are being washed. This means that HFO can still be used in ECAs, since the exhaust gases are treated after combustion. There are three types of scrubbers: open-loop, closed-loop and hybrid. The hybrid scrubber is a combination of the open-loop and closed-loop scrubber [60]. In scrubbers, the exhaust gas is cleaned on its way to the funnel. This is done by water which is injected in the exhaust gas stream. When the chemical reaction has occurred, the water will leave at the bottom of the scrubber. SO_2 and SO_3 react with H_2O to form respectively H_2SO_3 and H_2SO_4.

There is an increased capital cost when using a scrubber. A scrubber is cheaper with an increasing engine size. For engines with a power lower than 5,000 kW the scrubber system will cost around $370/kW. With an engine output of around 10,000 kW this cost will decrease to around $250/kW and for larger engines this can even drop to $120/kW [22]. A scrubber does not filter the NO_x out of the air.

In case the ship is sailing in ECA area 3 or 4 (North American Area or United States Caribbean Sea Area) an extra system is thus required to comply with the IMO emission rules.

In case the ship has a failed scrubber, it would not be allowed in the emission control areas. With a failed scrubber, the ship will have to sail in port and it will have to be explained why the ship did not meet the regulations. The scrubber will then have to be repaired in port before the ship can continue its operation. A backup scrubber can be installed to increase redundancy, but this requires a lot of space and is also an expensive solution. For this thesis, a scrubber is not seen as a feasible alternative. It is expensive and requires much space. It can also not be stated whether it is more reliable than decent fuel switching. With the global emission limits it would also mean that a scrubber might have to run during the entire voyage, which increases operational costs and challenges. Choosing one fuel type, or separating the two types sufficiently is thus a better solution, from a reliability, financial and space requirement standpoint

3.8. Solutions To The Failures In The Electrical System

In this section, solutions to the failures in the electrical system will be generated. The biggest failure in this system is the blackout, so this failure will be dealt with first. Then the failures with unknown distribution will be dealt with.

3.8.1. Solutions To A Blackout

For only two of the causes of a blackout a reason was given, these are an electrical failure and a lack of fuel. For the causes automation failure, control equipment failure and mechanical failure no causes were given. This makes it impossible to come up with solutions to these failures. For the other two failures it is possible to determine solutions. Human error was also responsible for some of the blackouts that occurred. With some of these causes being 'pressing the wrong button' or 'tripping an on-load' generator it is determined that these particular failures will no longer exist.

A blackout due to an electrical failure was caused by switching on machinery when insufficient power was available. This can easily be avoided by making sure that enough power is available. Before (heavy) machinery is switched on, it should be determined whether this is the case. If not, an extra generator has to be started in order to fulfil the power requirements. The impact of heavy equipment should be known in order to determine whether extra power is needed.

A lack of fuel has also lead to a blackout multiple times. It was mainly caused by a blocked fuel filter. Performing maintenance on the fuel filter more often can avoid this problem from occurring. A blocked fuel filter can also be caused by sediments in the fuel. Making sure that the fuel is clean therefore also helps to avoid a blocked fuel filter and thus a blackout. The quality of the fuel again seems to have an influence on the reliability.

3.8.2. Solutions To Unknown, Electrical System

It is not known which failures are present in this group. These are all the failures in the electrical system that were not caused by a blackout. What these failures are is not known. No specific solutions can therefore be developed. Some of these failures might be broken or loose connections, as seen previously. This failure group may therefore partly be caused by improper maintenance.

One way to increase the reliability of the electrical system is to increase the redundancy of the system. This means that the system will be doubled. This is a costly operation, but would be the only option in this case. Any alternatives for the entire system are just not available.

3.9. Solutions To The Cooling Water System Failures

This section will deal with all failures that occurred to the cooling water system. First, the failures with unknown distribution will be dealt with, after which solutions can be found for ice in the seawater filter.

3.9.1. Solutions To Unknown, Cooling Water System

The failures with unknown distribution consist at least of the following failures; cooling water pump failure, piping systems failure and controller and sensor failure of high-, low temperature and seawater cooling system. More types of failures might also be present in this group, but this is unknown. This group is this big because only data is known for the failure 'ice in seawater filter'.

For each of these individual failures in the unknown distribution some solutions, redundancy improvements and alternatives can be found. First the cooling water pump will be dealt with, then the piping system and finally the controllers and sensors.

Cooling Water Pump Failure
A broken water pump is caused when the pump is leaking from the weep hole or when it has a broken housing or shaft. A broken shaft can be caused by excessive vibration and unbalance. These are caused by a faulty fan or improper installation of the fan. A broken shaft can also be caused by a faulty pulley or overtightened belt. Correct installation and regular checks will remove part of the failures. The same goes for the pulley, this should also be checked regularly to prevent failures. The belt should be installed properly, in order to make sure that this failure does not occur. Improving the maintenance of the pump is likely to take away part of the problem. The installation of the pump is also considered under the term 'improvement of maintenance'

Once in a while, a pump will still fail. Therefore, installing an extra pump will give an extra level of redundancy. If one pump fails, the other can take over. It is also possible to have both pumps working at half the capacity. This means that they are both running at the same time, so there is no start up time required for the backup pump. Installing an extra pump of course costs money and requires more space, but that is acceptable when it also gives more reliability. Any alternatives for the pump are not available. This is therefore not an option to improve the reliability of the cooling water system.

Piping Systems Failure
For the piping systems failure it is not known what the cause is. If it has to do with a failure due to a breakage, the same precautions can be taken as with the broken fuel pipe, see 3.7.1. It is likely that this piping failure has something to do with the salinity of the seawater, since that is used to cool the engine. The thickness of the pipes should regularly be checked for their thickness and replaced if necessary. Protective coatings can be added to these pipes to lengthen their lifetime. As said previously, it is very expensive to measure every part of the pipe for its thickness. This failure will therefore no longer be taken into consideration since there is no solution which can solve this failure with small effort.

Controller And Sensor Failure
In case of a failure of the controller and sensor, it is not known what the cause is. This makes finding a solution for the problem nearly impossible. The easiest option to get rid of this error is therefore to install multiple controllers and sensors. Their values and behaviour can be monitored, so when it gives values that are not determined as normal, another data point can be used. When in port, the faulty controller and/or sensor can be replaced. Doubling the controllers and sensors has to be done for the high temperature water, low temperature water and seawater.

3.9.2. Solutions To Ice In Seawater Filter

Ice in the seawater filter caused several failures. A solution to this failure only has to be developed for ships which can expect ice on their route. For ships sailing in ice, the cooling system should be upgraded to a winter cooling system. A winter cooling system should have the inlets as far aft as possible, have sea boxes of specific characteristics and other specific measures [94]. These measures assure that ice is not likely to enter the inlet. If ice somehow enters the inlet, measures to melt the ice or flush it back out are available. Even if these measures do not solve the failure, the system can run by circulating cooling water. The winter cooling system thus adds redundancy and should prevent this failure from happening. This might not have been installed on several ships due to the cost of it. It is therefore necessary to determine whether this winter cooling water system is needed when designing a ship.

3.10. Conclusion

This section will summarize which solutions are actual possibilities for the different machinery failures. It will also conclude whether these solutions can be a solution to the determined failures. If the reliability of a generated solution is not equal, or better to the current solution, it is not an option.

Table 3.2 shows all solutions that have been developed in this chapter. For each system, all failures are shown in one column and the percentage that they contribute to the total number of failures is shown in the second column. For some of the failures with unknown distribution, it is known which failures are part of this group. These failures have therefore been named individually, with individual solutions. The possible solutions to these failures are shown in the third column. In the last column it can be seen whether a determined solution is a possible option or not. Two answers can be found; Yes and No. In case the answer is Yes, a derived solution is a possibility to increase reliability. These solutions will thus be taken into consideration in the next chapters. All solutions that get a No are not of at least equal reliability or they are no longer an option due to other reasons that have already been explained in this chapter. Those solutions will therefore no longer be taken into consideration.

Table 3.2: All failures and whether a generated solution is a possible option

Failure	%	Solution	Option
Main Engine	*38.7*		
Unknown distribution	18.9	Installing more engines as a full-backup	Yes
		Dividing the power over multiple engines	Yes
		Power Take In as a backup	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Alternative engine with better or equal reliability	
		• Gas turbine	Yes
		• Steam turbine	Yes
		• Nuclear reactor	No
		• Fuel cell	No
		• Batteries	Yes
		• Diesel-Electric	Yes
Starting, reversing and regulating device	14.2	Install more engines as a full-backup	Yes
		Dividing the power over multiple engines	Yes
		Power Take In as a backup	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
Standard failure	3.3	Install more engines as a full-backup	Yes
		Dividing the power over multiple engines	Yes
		Power Take In as a backup	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Combination of engine redundancy and proper maintenance	Yes
Turbocharger failure	2.2	Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install more engines as a full-backup	Yes
		Dividing the power over multiple engines	Yes

Failure	%	Solution	Option
Steering Gear	*20.9*		
Electrical supply and control devices	9.5	Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install more electrical wire as a full-backup	Yes
		Split steering gear in seperate systems	Yes
		Install a stern thruster as a full-backup	Yes
		Wireless alternatives, such as Bluetooth	No
Unknown distribution	8.6	Split steering gear in seperate systems	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install a stern thruster as a full-backup	Yes
		Increase rudder area	No
		Use azipods for propulsion, then no rudders are required	Yes
Other	2.8	See solutions to Steering gear, unknown distribution	
Fuel System	*11.1*		
Unknown distribution	8.4		
• Insufficient fuel care, Fuel of poor quality, Clogged fuel filter		Check the quality of new fuel before bunkering/using	Yes
		Keep fuels from different locations separated	Yes
		Always bunker fuel from the same location, if this fuel has proven to be of sufficient quality	No
• Strong vibrations of fuel line		Change natural frequency of fuel line	Yes
• Broken fuel pipe		Corrosion control of pipelines	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install extra pipes as a full-backup	Yes
• Air in fuel		Install the proper air filter	Yes
		Install an extra air filter as a full-backup	Yes
Fuel intolerance	2.8	Keep different types of fuel separate	Yes
		Keep fuels from different locations separate	Yes
		Alternative fuel	
		• Liquid Natural Gas	Yes
		• Methanol	No
		• Electricity	Yes
		• Scrubber	No

Failure	%	Solution	Option
Electrical System	*8.9*		
Blackout	4.7	Enough power should be available when starting equipment	Yes
		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Check the quality of fuel before bunkering/using	Yes
Unknown distribution	4.2	Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install an extra electrical system as a full-backup	Yes
Cooling Water System	*8.4*		
Unknown distribution	6.7		
• Cooling water pump		Use official replacement parts, installed and maintained by qualified personnel	Yes
		Install and extra pump as a full-backup	Yes
• Piping		See Fuel system, Unknown distribution, Broken fuel pipe	Yes
• Controller and sensor		Install extra controllers and sensors	Yes
Ice in seawater filter	1.7	Upgrade cooling water system to a winter cooling system	Yes

4

Reliability Improvement Of Solutions

This chapter will determine how much of a reliability improvement can be gained for all possible solutions as found in Chapter 3. Before this can be determined, the failure rate of the machinery has to be determined. This is needed to perform the reliability calculations and will be done in Section 4.1. When the reliability improvements of all possible solutions are known, a list can be made of the highest reliability improvements. Subsequently, the costs of these improvements can be calculated. This way, it can be determined how much of a reliability improvement can be gained for a certain amount of money. The financial aspect will eventually determine whether a solution will be implemented or not.

All solutions will be dealt with in order of magnitude of the failure distribution of the systems. So first the reliability improvement of the solutions to the main engine failures will be dealt with in Section 4.2. In Section 4.3 it will then be determined how much of a reliability improvement can be gained in the steering gear. This will also be determined for the fuel system, electrical system and cooling water system in respectively Section 4.4, 4.5 and 4.6. After the possible reliability improvements have been determined, this can be summarized for all systems and conclusions can be deducted in Section 4.7.

4.1. Failure Rate Machinery

In order to determine the reliability improvement of each individual solution, the failure rate of the machinery has to be determined. This will show how often the machinery fails as a function of time. With the failure rate known, it can also be determined what the mean time between failure is. The definitions of the failure rate and mean time between failure are the following.

- Failure rate, $\lambda(t)$, is the probability of failure per unit of time, wherein the probability refers to the situation where, up to and including time t, not a failure has occurred [53].
- Mean time between failure (MTBF), $\frac{1}{\lambda(t)}$, describes the amount of failures of a product as a function of time.

In order to determine the failure rate, it has to be determined how long a ship movement of a ship in German waters is. The original failure data consists of failures that occurred in German waters. It is therefore important to determine the duration of a ship movement in German waters. To determine this, the length of a ship movement and the speed during this movement have to be determined. This makes it possible to determine how long the ship has been in German waters. Both for the length of a ship movement and the speed during a ship movement, estimations will have to be done since there is no available data on the length or speed during a ship movement.

4.1.1. Length Of A Ship Movement

In order to be able to determine the failure rate of the ship machinery, the length of a ship movement within German waters has to be determined. It is considered a movement when a ship sails from or to a port in Germany or when a ship passes through German waters while both its port of departure and destination are located outside Germany. The waters in which the ship movements are counted is the territorial sea or 12 nm zone. Both the North Sea and the Baltic Sea run along the German coast. In both seas, ship movements can therefore be counted. In Figure 4.1 the edge of the German territorial of the North Sea and Baltic Sea is indicated with a dashed line [14] [15]. The solid line shows the Exclusive Economic Zone (EEZ) of Germany.

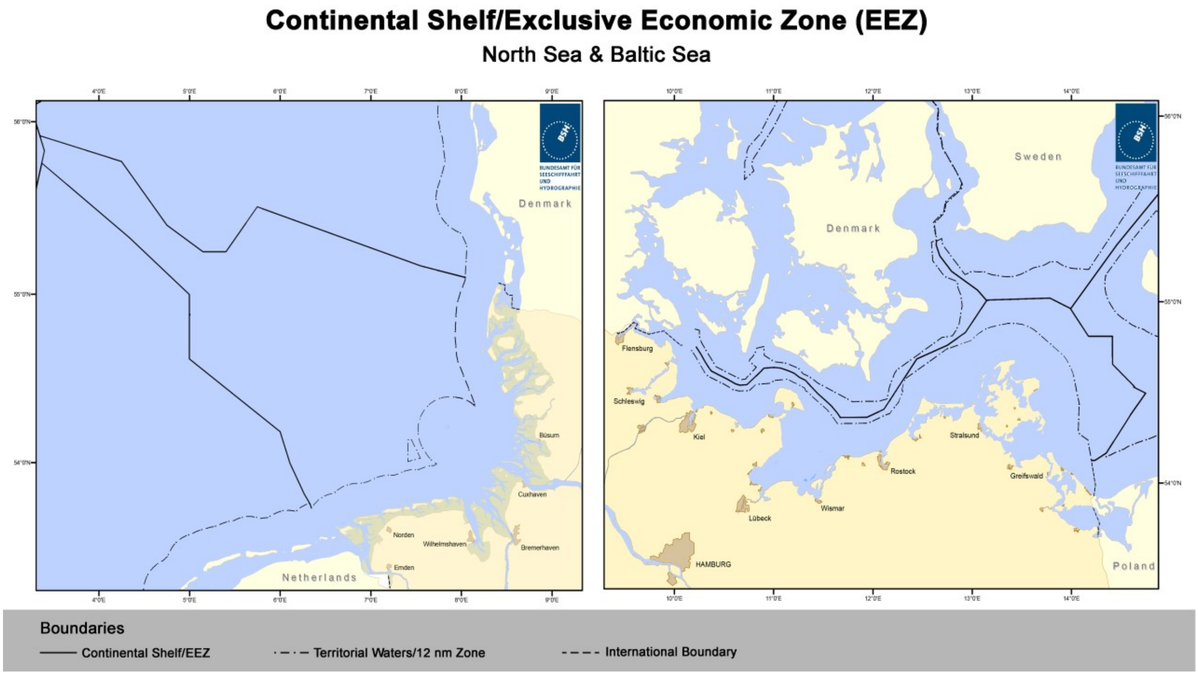


Figure 4.1: Exclusive Economic Zone (EEZ) of Germany in North and Baltic Sea

From Figure 4.1 it can be seen that the territorial sea is only a small part of the EEZ in the North Sea. In the Baltic Sea, the territorial sea is close to the EEZ since there a many countries around the sea, so the line of the EEZ lies close to the 12 nm line and shore.

Assuming that 12 nm is the average length that a ship sails in German waters is not correct. Ships sailing from or into port will have longer journeys since the ports are not located in the 12 nm zone but further inland. Sailing to a port is therefore a journey which is always longer than 12 nm, especially for a port such as Hamburg which is located far inshore. Ships sailing through German waters will likely sail through German waters in the Baltic Sea due to the geometry of Germany in the North Sea. Sailing through German waters is not the shortest route there. Probably only the Baltic Sea will thus be used by ships that are not coming from or going to a port in Germany.

The route that is assumed to be average is from the port of Hamburg to the outer edge of the German 12 nm zone or vice versa. The port of Hamburg is very important since it is Germany's largest seaport so a lot of traffic will sail from or to Hamburg [44]. With around 10,000 ships calling the port every year, the port of Hamburg is responsible for 20,000 movements. This is a quarter of the number of ship movements through German waters every year. With the port of Hamburg being located 120 km inshore, the average length of a ship movement can be determined [1]. A journey of 120 km equals to 64.8 nm, so when the 12 nm of the length of the territorial sea is added it can be found that an average trip through German waters is 76.8 nm, which is rounded to 77 nm. If the average trip is actually longer, relatively less failures occur. If the average ship movement is actually shorter, relatively more failures occur. It is assumed that the above assumptions are accurate, even though there is no data on the actual length of a ship movement. The accuracy of the assumptions is not important since the final failure rate is supposed to be a ballpark figure. It is needed to get a feeling of the actual problem and to be able to perform calculations in order to draw conclusions about the reliability improvement of each solution. The final failure rate is very small. When calculations are done which multiply these small values with themselves, the values become even less significant. Even if the determined failure rate is ten times as high in reality, these calculations still cause the failure rate after a solution to be very small. The same is the case when the failure rate is actually ten times as low.

4.1.2. Speed During A Ship Movement

When the speed during a ship movement is known, the time per ship movement can be determined. No data of the speed during a ship movement is available from the used research, so this will have to be estimated. Different types of ships are concerned in this thesis, which all sail on different speeds. For instance, a bulk carrier sails on low speed whereas a container ship sails on a high speed. Therefore an average for all these ships has to be determined.

The speed of the ships is estimated to be twelve knots on average. This value is chosen because both the North Sea and Baltic Sea are heavily trafficked. Ships are therefore not likely to sail on their maximum speed. Since the going to and coming from a port is a big part of the ship movements the lower speed in harbour has to be accounted for. The average speed at sea may be closer to fifteen knots but since manoeuvring in port is done at lower speeds and takes much time, the average speed is lower when this is taken into account. When the speeds of the ships that are sailing from or to the port of Hamburg are checked with MarineTraffic, it can be seen that these ships average around twelve knots. If the speed was found to be lower in reality, this would mean that relatively less failures per hour occur. A higher speed would lead to shorter ship movements which would lead to relatively more failures per hour. Again, the accuracy of the speed during a ship movement is of no importance. The gained result is accurate enough to perform calculations and get a feeling of the size of the problem.

4.1.3. Failure Rate Calculations

It is known for the years 2003 and 2004 that 107 failures have occurred during 160,000 ship movements. Assuming that the other years have the same number of failures per ship movement makes it possible to determine that the recorded 359 failures were caused in 537,000 movements during six years. It was previously stated in Chapter 1 that age has a significant influence on the failure rate. It is assumed that ships of all ages sail through German waters. Since 80,000 ships move through German waters every year, it can be expected that ships of all ages are represented in an equal manner. The determined failure rate will therefore be for a ship which is halfway through its lifetime and the failure rate is assumed to be constant. With the lifetime of a ship being around 20 to 25 years, the failure rate is thus determined for a ship that is around ten to twelve and a half years old.

Knowing that about 537,000 ship movements caused 359 failures makes it possible to determine, on average, how many movements are sailed per one failure. This can be determined by dividing the number of ship movements by the number of failures. For Equation 4.1, the ship movement and failure values for all six years are taken.

$$\text{Ship movements between failures} = \frac{537,000}{359} = 1,495 \approx 1,500\ movements \tag{4.1}$$

From the above equation it can be seen that roughly once every 1,500 movements a failure occurs. It can now also be determined how many movements are registered per day and what the interval is between two failures. First, the number of movements per day will be determined by dividing the number of movements by the number of days. For each year it is assumed that the ships sail 365 days. When the movements per day are known, it can be determined how many days are in between a failure by dividing the ship movements per failure by the ship movements per day.

$$\text{Ship movements per day} = \frac{537,000}{6 \times 365} = 245\ movements \tag{4.2}$$

$$\text{Days between failure} = \frac{1500}{245} = 6.1 \approx 6\ days \tag{4.3}$$

From Equation 4.2 it can be seen that 245 ship movements per day take place in German waters. Knowing that once every 1,500 ship movements a failure occurs, it can be seen from Equation 4.3 that once every six days a fatal technical failure occurs due to a failure in one of the systems.

It has previously been determined what the average length is of a ship movement as well as the average speed during this movement. Those were respectively found to be 77 nm and twelve knots. It can now be determined what the duration of a ship movement is. First, both the distance and the speed have to be translated to the metric system. The distance is therefore multiplied with 1,852, to get the amount of meters per ship movement. The speed is multiplied with 1,852/3,600 to get a speed in m/s.

$$\text{Distance of movement} = 77 \times 1,852 = 142,604\ m \approx 143,000\ m \tag{4.4}$$

$$\text{Speed during movement} = 12 \times \frac{1,852}{3,600} = 6.173\ m/s \approx 6.2\ m/s \tag{4.5}$$

With the distance and speed known, the time per ship movement can be determined by dividing the distance over speed, as can be seen in the following formula.

$$\text{Duration of movement} = \frac{143,000}{6.2} = 23,100\ s \approx 6.4\ h \tag{4.6}$$

With the duration of one individual movement known, it can be determined how many hours were sailed over the considered six years and what the mean time between failure is. With the mean time between failures known, the failure rate can be determined.

$$\text{MTBF} = \frac{6.4 \times 537,000}{359} = 9,595\ h \approx 9,600\ h \tag{4.7}$$

$$\text{Failure rate}, \lambda(t) = \frac{1}{MTBF} = \frac{1}{9,600} = 0.0001 = 1.0 \times 10^{-4} \tag{4.8}$$

From Equation 4.7 it can be seen that once every 9,600 operating hours a machinery failure occurs. This is a little over once a year based on continuous service of 24 hours a day, 365 days a year. During the lifetime of a ship, several fatal machinery failures will thus occur. A mean time between failure of 9,600 hours makes a failure rate of 1.0×10^{-4} for the entire system. Since the percentages of the different systems are known, the failure rate of each system can be determined by multiplying its failure percentage with the failure rate. The mean time between failure in years is also shown.

Table 4.1: Failure distribution, failure rate and mean time between failure per system

System	Failure distribution [%]	Failure rate	MTBF [yrs]
Main engine	38.7	4.0×10^{-5}	2.8
Steering gear	20.9	2.2×10^{-5}	5.2
Fuel system	11.1	1.2×10^{-5}	9.9
Electrical system	8.9	9.3×10^{-6}	12.3
Cooling water system	8.4	8.8×10^{-6}	13.0
Shafting	6.7	7.0×10^{-6}	16.3
Diesel generator	3.6	3.8×10^{-6}	30.4
Other	1.7	1.8×10^{-6}	64.4
Total	100.0	1.0×10^{-4}	1.1

With the failure rate known for each system, it can now be determined for all of the solutions, how much of a reliability improvement they give. Calculations within the fault tree use the probability of failure for its calculations. The following formula shows how the probability of failure can be determined [36] [98].

$$P(t) = 1 - \mathrm{e}^{-\lambda t} \approx \lambda t \tag{4.9}$$

In which

P Unreliability or probability of failure

e Euler's number, mathematical constant, 2.71828

t Time interval, in hours. For instance the length of a ship journey

Equation 4.9 shows that an approximation is available for the failure probability formula containing Euler's constant. This is valid for failure probabilities which are less than 0.1, meaning that with the calculated failure rate, the ship can sail 960 hours or about 40 days. It is assumed that the simplified formula can therefore be used. For the time interval t, a value of one hour is used. This way, the effect of time is isolated and only the effect of the changing failure rate is shown. All calculations therefore show the failure rate instead of the probability of failure.

4.2. Reliability Improvement Main Engine

There are four groups of failures in the main engine. For each of these failures, solutions have been developed which give a certain reliability improvement. These solutions have been shown in Chapter 3. A solution will have to give a significant reliability improvement before it will be with the first solutions to be applied. First, for all solutions that solve the failures with unknown distribution, the reliability improvement will be determined. This group has a failure rate of 2.0×10^{-5} and a MTBF of 5.8 years. Then, the same will be done for the solutions to the starting, reversing and regulating device failures (1.5×10^{-5} and 7.7 years), the standard failures (3.5×10^{-6}, 32.9 years) and turbocharger failures (2.3×10^{-6} and 48.8 years between failures). After the reliability improvements for all groups have been determined a conclusion can be drawn to which solutions give the best improvements for the main engine failures. The solution with the highest reliability improvement in the main engine is very likely to be investigated financially, since the main engine is responsible for the most failures. Therefore, this solution is very likely to be with the solutions with the highest reliability improvement.

4.2.1. Reliability Improvement Unknown Distribution

The first solution to increase the redundancy is by either installing more engines as a full-backup or to divide the power over multiple engines. It will first be determined for these solutions how much of a reliability improvement they give. Improving the maintenance also gives a reliability improvement. Then, the reliability improvement of the alternative engines will be determined. Finally, the improvement of the power take in will be dealt with.

Engine Redundancy

Engine redundancy involves another engine with equal power as the failed one, or multiple engines that have the total power divided over them. When an engine fails there is enough power available to continue the route of the ship in both cases. In case a full-backup engine is available, the ship can continue with the same speed since the same power will remain available. Cargo and ship are then not delayed. When the power is divided over more engines, the speed of the ship will drop. The ship will then continue its journey with a lower speed since less power is available and a delay of ship and cargo occurs. With a backup engine being available, or with multiple engines being available, a failure of one engine is not fatal. Failures to two engines are necessary before this leads to a fatal technical failure. If three or more engines are installed in the ship, a loss of two engines does not have to be fatal. It is though assumed that a failure of two engines will influence the performance of the ship to a level where it is no longer fully operational. A failure of two engines is thus assumed to be fatal.

Due to the failures with unknown distribution, engine number 1 has a failure rate of 2.0×10^{-5}. A second engine, engine number 2, which would serve as a full-backup or which would provide enough power at lower speed will also have a failure rate of 2.0×10^{-5} for the same failure. Multiplying these rates gives a value for a failure rate of both engines at the same time due to this particular failure. If this new failure rate is calculated, the improvement due to these two solutions can be determined.

$$\begin{aligned} \lambda_{\text{Both engines}} &= \lambda_{\text{Engine \#1}} \times \lambda_{\text{Engine \#2}} \\ &= 2.0 \times 10^{-5} \times 2.0 \times 10^{-5} = 3.9 \times 10^{-10} \end{aligned} \tag{4.10}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{3.9 \times 10^{-10}} - \frac{1}{2.0 \times 10^{-5}} \approx 293,500\ years \end{aligned} \tag{4.11}$$

The results of Equation 4.10 indicate that the failure rate of a main engine failure due to the failures with unknown distribution is reduced from 2.0×10^{-5} to only 3.9×10^{-10} with both engine redundancy solutions. As can be seen from Equation 4.11 this gives a MTBF improvement of 293,500 years for each of these solutions. It can thus be said that these solutions increase the reliability to a level which can be considered to be save.

Power Take In

A power take in has also been named as a solution to the failures with unknown distribution. The PTI will come into action when insufficient power is available from the main engines. It will then sail the ship home with a lower speed. It does thus not really solve the failure, but gives a reliable alternative. Since no official values for the failure rate of a PTI are known, it will be assumed that it has the same effect as a full-backup engine and dividing the power over multiple engines. This means that it is assumed that a PTI has the same failure rate as another second engine. It is thus assumed that a PTI gives a reliability improvement of 293,500 years.

Improvement Of Maintenance

Another solution that improves the redundancy of the engine, is to perform better maintenance. It was found that the level of maintenance is sometimes insufficient, which causes failures. Proper maintenance will reduce the occurrence of failures by 19.3%. The failure rate of a main engine due to a failure with unknown distribution, while being properly serviced can now be found.

$$\begin{aligned}\lambda_{\text{After proper maintenance}} &= \lambda_{\text{Before maitenance}} \times F_{\text{Reduction maintenance}} \\ &= 2.0 \times 10^{-5} \times 0.807 = 1.6 \times 10^{-5}\end{aligned} \tag{4.12}$$

$$\begin{aligned}\text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{1.6 \times 10^{-5}} - \frac{1}{2.0 \times 10^{-5}} = 1.4\, years\end{aligned} \tag{4.13}$$

Equation 4.12 shows that the failure rate reduces from 2.0×10^{-5} to 1.6×10^{-5}. This is a MTBF improvement of only 1.4 years, as shown in Equation 4.13. This is a significant smaller improvement than the one due to the redundancy solution. Only improving the maintenance thus does not seem to be the best solution for the failures with unknown distribution.

Engine Redundancy Plus Improvement Of Maintenance

The solutions as stated previously can also be combined to increase reliability. The new failure rate and the reliability improvement will be determined in the following equations. First, the effect of proper maintenance on one engine will be calculated. This value will then be used to determine the failure rate of a main engine failure, although engine redundancy has been applied and the engines have been properly maintained.

$$\begin{aligned}\lambda_{\text{After pm}} &= \lambda_{\text{Before maitenance}} \times F_{\text{Reduction maintenance}} \\ &= 2.0 \times 10^{-5} \times 0.807 = 1.6 \times 10^{-5}\end{aligned} \tag{4.14}$$

$$\begin{aligned}\lambda_{\text{Both engines after pm}} &= \lambda_{\text{Engine \#1}} \times \lambda_{\text{Engine \#2}} \\ &= 1.6 \times 10^{-5} \times 1.6 \times 10^{-5} = 2.5 \times 10^{-10}\end{aligned} \tag{4.15}$$

$$\begin{aligned}\text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{2.5 \times 10^{-10}} - \frac{1}{2.0 \times 10^{-5}} \approx 450,500\, years\end{aligned} \tag{4.16}$$

Combining the two measures reduces the failure rate to only 2.5×10^{-10}, so this solution is found to give a reliability improvement of 450,500 years. This is 157,000 years more than only applying engine redundancy as a solution. The combination of both solutions thus improves reliability even further. Since the engine redundancy solutions already increases the MTBF to 293,500 it can be said that combining the two measures is not necessary to increase reliability. A MTBF of 293,500 can be considered to be sufficient and the combination of the solutions is therefore no longer considered.

Alternative Engine

The alternative engines gas turbine, steam turbine, batteries and diesel-electric have all been stated to have a high reliability, although no data to compare them to the diesel engine was found. Since no failure rates of the alternative engines are known, it is impossible to determine the improvement gain. However, it can be determined whether installing another engine gives a reliability improvement that can compete with other solutions and is also a realistic improvement. If one of the proposed alternative engines is for instance 10% more reliable than the diesel engine, this only prevents 2.0×10^{-6} of the failures, which is a MTBF increase of 0.6 years. An improvement of only 0.6 years is very small compared to an engine redundancy solution. For an alternative engine to be a competitor to engine redundancy it has to give the same reliability improvement. This is an improvement of 293,500 years. For one type of alternative engine to give the same reliability improvement it has to be much more reliable, to a point which is no longer realistic. Using only one alternative engine as a solution to the failures with unknown distribution is thus not a realistic option.

For the previous statement, the effect of engine redundancy and proper maintenance have not been taken into account. If it is assumed that proper maintenance also has a positive influence on the reliability of the alternative engine, this will improve reliability of that engine with 19.3%. Two cases will be examined in order to determine whether alternative engines with a higher reliability show a significant lower failure rate than improving the engine redundancy of the diesel engine. First, the new failure rate of an alternative engine with a 10% failure rate reduction compared to the diesel engine will be determined. The second case is for an alternative engine with a failure rate reduction of 20%. For case one the failure rate of 2.0×10^{-5} is thus multiplied with 0.90 whereas the failure rate is multiplied with 0.80 for the second case. These factors compensate for the reduction of the failure rate. The same equations as used previously are being used. In order to shorten the equations, some of the terms have been abbreviated to their initials. This means that proper maintenance has been abbreviated to pm and reliability improvement has been reduced to ri. It has again to be stated for clarity that it is unknown whether there are engines available with the lower failure rates as chosen in both cases.

$$\begin{aligned} \lambda_{\text{After pm and ri}} &= \lambda_{\text{Before maitenance}} \times F_{\text{Reduction alternative engine}} \times F_{\text{Reduction maintenance}} \\ &= 2.0 \times 10^{-5} \times 0.90 \times 0.807 = 1.4 \times 10^{-5} \end{aligned} \tag{4.17}$$

$$\begin{aligned} \lambda_{\text{Both engines after pm and ri}} &= \lambda_{\text{Engine \#1}} \times \lambda_{\text{Engine \#2}} \\ &= 1.4 \times 10^{-5} \times 1.4 \times 10^{-5} = 2.1 \times 10^{-10} \end{aligned} \tag{4.18}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{2.1 \times 10^{-10}} - \frac{1}{2.0 \times 10^{-5}} \approx 556,500\ years \end{aligned} \tag{4.19}$$

For an alternative engine that is assumed to have a 10% lower failure rate, the reliability improvement is found to be 556,500 years. Compared to the reliability improvement gained by the diesel engine redundancy, this is an improvement of 262,500 years and an improvement of 106,000 years compared to the combination of engine redundancy and improved maintenance. This is a small improvement compared to what the other solutions already achieved.

Installing two alternative engines, which both have a reliability improvement of 20% compared to the diesel engine increases the MTBF with 704,000 years. Compared to engine redundancy, this is an improvement of 410,500 years and an improvement of 253,500 years compared to the combination of engine redundancy and improved maintenance. It is questionable whether there are engines available which can give a reliability improvement of 20%. If these are available, it is not necessarily worth it to install those. The engine redundancy measures already reduce the risk of this failure to a level where only one in about 11,750 ships will be struck with this failure during its lifetime of an assumed 25 years. Since those solutions already have such a significant impact, it can thus be said that installing a different engine is not chosen for improving reliability, but may be chosen for a different reason, such as maintainability or its space requirement. Installing an alternative engine, or multiple alternative engines, is thus not the best way to reduce the failures with unknown distribution. When the solutions that involve an alternative engine are beyond the solutions with the highest reliability improvement, those will not be taken into consideration financially. The reasons for this are: it is not clear whether these engines exist, they do not give a significant improvement and integrating another engine involves a lot of work, also in other systems.

4.2.2. Reliability Improvement Starting, Reversing And Regulating Device

This Subsection will deal with the reliability improvement calculations of the starting, reversing and regulating device. Two specific solutions have been found, namely engine redundancy and the improvement of maintenance. A combination of these two is also an option. The reliability improvements of all solutions will be determined, just as the remaining failure rate.

Engine Redundancy

The first solution to increase the reliability of the engine controller is to apply redundancy by either installing an engine as a full-backup or by dividing the power over multiple engines. Two engines would then have to fail due to a failure of the starting, reversing and regulating device before this becomes fatal. With both engine controllers having a failure rate of 1.5×10^{-5}, it can be determined that the failure rate of a fatal technical failure due to a failure of the engine controller for both engines is 2.2×10^{-10}. This is a reduction of 521,000 years compared to the initial failure rate, which is a significant reliability increase.

Improvement Of Maintenance

The second solution is to improve maintenance. The failure rate of the starting, reversing and regulating device after proper maintenance can be found with the equations as shown previously. It can be deducted that the reliability improvement due to proper maintenance is only 1.8 years. A failure rate of 1.2×10^{-5} will remain for this failure, which is still significant. This solution can thus already be said to have too little impact.

Combination Of Engine Redundancy Plus Improvement Of Maintenance

A combination of the engine redundancy solution and the improvement of maintenance improves the reliability even further. It can be calculated that the failure rate of two engines due to a engine controller failure, although those have been properly serviced is 1.4×10^{-10}. This is an improvement of 800,000 years compared to the initial failure rate, but only an improvement of 279,000 years to the sole solution of engine redundancy. It can thus be said that combining the two measures is financially not viable since the mean time between failures of the engine redundancy measure is already satisfying.

4.2.3. Reliability Improvement Standard Failure

In order to reduce the standard failures, several options are available. Installing more engines or dividing the power over multiple engines is one option. These engine redundancy options have previously also been seen as a solution to the engine failures with unknown distribution and will later also be seen for the turbocharger failures. These solutions thus benefit multiple failures. Another option is to improve the maintenance or accept that these failures occur, since it is only accountable for 3.3% of all failures. Accepting that this failure occurs is not a real solution though, as it does not improve the reliability.

If none of the proposed solutions proves to give a high reliability improvement, the solution to the standard failures will not be with the solutions to be applied. In that case, the possibility of occurrence of a failure will remain present and is thus accepted. Considering the acceptance of the failure on an individual basis is therefore no longer necessary.

This means that three options are left, engine redundancy, improving the maintenance and a combination of those. The reliability improvement gain due to engine redundancy solutions will first be determined. Then the effect of proper maintenance will be calculated. At last it will be assessed how much of an improvement the two solutions give combined.

Engine Redundancy

The first solution to be checked for its impact is the engine redundancy. As explained previously, this solution will either install a full-backup engine or divide the power over multiple engines. In both solutions, in case a failure occurs due to a standard failure, enough power is available so that the ship can continue its route.

It has been calculated that 1.2×10^{-11} of the initial failure rate of 3.5×10^{-6} will remain. This means that engine redundancy reduces the failure rate due to a standard failure from once every 32.9 years to once every 9,488,000 years. Applying engine redundancy thus has a significant effect.

Improvement Of Maintenance

As seen previously, improving the maintenance gives a reliability improvement of 19.3%. This makes it possible to determine how much of a reliability improvement can be gained by performing better maintenance. The failure rate of 3.5×10^{-6} will be multiplied with the failure reduction to determine the new failure rate.

With the previously shown equations, it has been determined that the failure rate due to a standard failure, although the engine has been properly maintained, reduces from 3.5×10^{-6} to 2.8×10^{-6}, which is an increase of the MTBF of only 7.9 years.

Engine Redundancy Plus Improvement Of Maintenance

A combination of the previously stated solutions reduces the remaining failure rate of the standard failures even further. This means that an engine redundancy measure is applied, while these engines are also properly maintained.

When engine redundancy is applied and both engines are well maintained, it can be found that the reliability improvement is 14,568,500 years. Compared to only applying the measure of engine redundancy, an extra reliability improvement of 5,080,500 years is gained. Since this is no necessary improvement compared to the engine redundancy measure, it is not worth it to combine both measures. Paying for two measures while one measure already gives enough reliability improvement is not viable.

4.2.4. Reliability Improvement Turbocharger Failure

There are two options to increase the reliability of the turbocharger. The first option is to increase the engine redundancy by either installing a backup engine or by dividing the power over multiple engines. Although a turbocharger failure will then still lead to an engine failure in case of the engine redundancy solution, it does not cause a fatal technical failure since enough power is still available. The second option is to use official parts and to have maintenance done by qualified personnel. A combination of both solutions is not considered since it is already found multiple times that this is not financially viable.

Engine Redundancy

When engine redundancy is applied, two engines have to fail before this is considered to be fatal. Using the equations that already have been used multiple times, shows that the failure rate is reduced from 2.3×10^{-6} to 5.5×10^{-12}. This is an improvement of the mean time between failure of 20,859,500 years.

Improvement Of Maintenance

It was found previously that improper maintenance is directly responsible for machinery failures in 19.3% of the cases. Doing proper maintenance thus reduces the failures such that 80.7% of the failures are still present. The new failure rate of the turbocharger failures can now be found to be 1.9×10^{-6}, which is an improvement of only twelve years. Since this reliability improvement is so small, this solution will probably not be one of the solutions with the highest improvement.

4.2.5. Summary Main Engine Reliability Improvement

With the reliability improvements of all solutions known, a list can be made to summarize the results of the reliability improvements and the remaining failure rate. Then, the maximum reliability improvement can be determined as well as the remaining failure rate. In a later chapter it will be calculated whether the maximum reliability improvement is also financially feasible. Table 4.2 will show the failure on the left and the solution to the failure next to it. The other two columns are for the reliability improvement and the remaining failure rate.

For each failure group it can be determined which solution realizes the highest reliability improvement. For the failures with unknown distribution, it is found that the engine redundancy solution has the largest reliability improvement. The combination of an engine redundancy measure with the maintenance solution gives a higher reliability improvement, but the level that is achieved with the engine redundancy measure is assumed to be sufficient. The engines with a 10% and 20% higher reliability have also been found to give higher reliability improvements, but it is not known whether these engines are available and changing between engines has a large impact on the machinery. The reliability improvement of 293,500 years is thus chosen to be the best. For the starting, reversing and regulating device, the engine redundancy solutions gives the highest reliability improvement, namely

Table 4.2: Reliability improvement and new failure rate for each of the solutions of the main engine failures

Failure	Solution	Reliability improvement [yrs]	New failure rate
Unknown distribution	Installing more engines as a full backup	293,500	3.9×10^{-10}
	Dividing the power over multiple engines	293,500	3.9×10^{-10}
	Power take in as a backup	293,500	3.9×10^{-10}
	Use official replacement parts, installed and maintained by qualified personnel	1	1.6×10^{-5}
	Combination of an engine redundancy solution and maintenance improvement	450,500	2.5×10^{-10}
	Alternative engine plus redundancy and proper maintenance		
	• 10% more reliable engine	556,500	2.1×10^{-10}
	• 20% more reliable engine	704,000	1.6×10^{-10}
Starting, reversing and regulating device	Installing more engines as a full backup	521,000	2.2×10^{-10}
	Dividing the power over multiple engines	521,000	2.2×10^{-10}
	Use official replacement parts, installed and maintained by qualified personnel	2	1.2×10^{-5}
	Combination of engine redundancy and maintenance improvement	800,000	1.4×10^{-10}
Standard failure	Installing more engines as a full backup	9,488,000	1.2×10^{-11}
	Dividing the power over multiple engines	9,488,000	1.2×10^{-11}
	Use official replacement parts, installed and maintained by qualified personnel	8	2.8×10^{-6}
	Combination of an engine redundancy solution and maintenance improvement	14,568,500	7.8×10^{-12}
Turbocharger failure	Installing more engines as a full backup	20,859,500	5.5×10^{-12}
	Dividing the power over multiple engines	20,859,500	5.5×10^{-12}
	Use official replacement parts, installed and maintained by qualified personnel	12	1.9×10^{-6}

521,000 years. For the standard failures, this is also the case, 9,488,000 years. The same goes for the turbocharger, where the engine redundancy solutions provide an improvement of 20,859,500 years.

When the reliability improvements for the best solutions to each failure are combined, it can be found that a reliability improvement of 4.0×10^{-5} can be gained. With these four measures applied, this leaves a failure rate of 6.3×10^{-10} of the initial 4.0×10^{-5}. A total of 100.0% of the failure rate can thus be prevented by applying these four measures. From the remaining failure rate it can be determined that the new MTBF is 182,500 years, which is an improvement of 182,500 years compared to the initial 2.8 years. Assuming a lifetime of 25 years it can be deducted that once during the lifetime of 7,300 ships a fatal error will occur caused by the main engines.

At the end of this chapter it will be determined which solutions give the highest reliability improvement overall, these will be examined further by calculating their costs. It can already be seen from the above table that the maintenance solutions are not likely to be investigated since they are found to only have a small effect on the MTBF. The redundancy options all give a very decent and satisfying reliability improvement. The combination of solutions has a large reliability improvement although it can be questioned whether the extra reliability improvement compared to a redundancy measure is required.

4.3. Reliability Improvement Steering Gear

The steering gear failures are responsible for 20.9% of all machinery failures (a failure rate of 2.2×10^{-5} and a MTBF of 5.2 years). Being the second largest group of failures, there are two main groups of failures that cause a steering gear failure. The largest group is the group which contains the group 'other' and the failures with unknown distribution. Since it is not known which failures are present in both the failures with unknown distribution as in the failure group other, their solutions are equal. They combine for 54.6% of all failures and have a failure rate of 1.2×10^{-5} and a MTBF of 9.6 years. A failure in the electrical supply and control devices is the second failure group (9.5%, 9.9×10^{-6} and 11.6 years). For each of the failure groups it will be determined how much of a reliability improvement is achieved by their solutions. This makes it possible to determine which solutions are the best from the standpoint of reliability improvement. It will also be determined how much of the failure rate remains after a solution has been applied. This section ends with a summary of all solutions and their reliability improvements and new failure rates.

4.3.1. Reliability Improvement Unknown Distribution And Other

This Subsection will deal with both the reliability improvement for the failures with unknown distribution and the failure group other since they have the same solutions. Together, these groups have a higher initial failure distribution and failure rate than the failures due to the electrical supply and control devices.

The solutions to these failures will be dealt with in the following order. First, it will be determined what the effect of splitting the steering gear is after which the effects of proper maintenance will be dealt with. Then, the instalment of a stern thruster as a full-backup will be discussed. At last, the reliability effects due to the switching from rudders to redundant azipods will be discussed. It will also be determined whether a combination of solutions might prove to give even higher reliability improvements.

Steering Gear Redundancy

When the steering gear is divided into separate systems, two systems have to fail before a steering gear failure becomes fatal. This will thus significantly increase the reliability of the steering gear. The remaining failure rate and the reliability improvement of this solution will be determined in the following two equations. It is assumed that one steering gear system is sufficient to continue the route of the ship or return it to port. The steering gear systems will then have to be designed in such a way that a failed steering gear system does not influence the manoeuvrability in a negative way.

$$\begin{aligned} \lambda_{\text{Both steering gear sets}} &= \lambda_{\text{Steering gear set \#1}} \times \lambda_{\text{Steering gear set \#2}} \\ &= 1.2 \times 10^{-5} \times 1.2 \times 10^{-5} = 1.4 \times 10^{-10} \end{aligned} \tag{4.20}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{1.4 \times 10^{-10}} - \frac{1}{1.2 \times 10^{-5}} \approx 807,000\ years \end{aligned} \tag{4.21}$$

When two separate systems are installed it is found from Equation 4.20 that only 1.4×10^{-10} of the failure rate remains. This means that an improvement of 807,000 years can be gained by installing multiple systems.

Improvement Of Maintenance

The effect of maintenance has already be seen for multiple other failures. It is thus very likely that this will also have an effect on the failure groups with unknown distribution. The reliability improvement due to the proper maintenance can be determined with the following equations.

$$\begin{aligned} \lambda_{\text{After proper maintenance}} &= \lambda_{\text{Before maitenance}} \times F_{\text{Reduction maintenance}} \\ &= 1.2 \times 10^{-5} \times 0.807 = 9.6 \times 10^{-6} \end{aligned} \tag{4.22}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{9.6 \times 10^{-6}} - \frac{1}{1.2 \times 10^{-5}} = 2.3\ years \end{aligned} \tag{4.23}$$

After proper maintenance has been performed, the failure rate lowers with 2.3×10^{-6} to 9.6×10^{-6}. The mean time between failures is extended with only 2.3 years. When only better maintenance is performed, there is still a high failure rate present. This was to be expected, since improper maintenance is only responsible for 19.3% of all failures. More measures are thus needed to lower the failure rate of the unknown distribution more significantly. The steering gear redundancy solution was already found to have much more improvement and is thus a better solution.

Install A Stern Thruster

When a stern thruster is installed, this serves as a full-backup of the steering gear. In case the steering gear fails, the stern thruster is lowered. This will then provide the steering capacity of the ship (if necessary together with a bow thruster). In order to determine the effect of adding a stern thruster, the failure rate of the stern thruster has to be estimated, since it is unavailable.

When the influence of a power take in was investigated, also no failure rate was present. It was then chosen to assume that the PTI had the same failure rate as the failure it was trying to solve. For the stern thruster, the same method will be used. It is thus assumed that the stern thruster has a failure rate of 1.2×10^{-5}. With this value known, the new failure rate can be calculated with the formulas as seen previously. From these formulas it can be found that installing a stern thruster has a positive effect on the failure rate. Only 1.4×10^{-10} of the initial 1.2×10^{-5} remains after the stern thruster has been installed. This means that a reliability improvement of 807,000 years can be gained.

Install Redundant Azipods

Of the azipods, also no failure rate is available. It will therefore be assumed, just as with the stern thruster, that its failure rate is the same as the failure rate of the unknown and other steering gear failures. This means that the reliability improvement due to the azipods is also 807,000 years and that it has a remaining failure rate of 1.4×10^{-10}. The effects of the steering gear redundancy, stern thruster and the instalment of a redundant set of azipods are thus all the same.

Combination Of Multiple Solutions

Since several different solutions have been found, multiple combinations of solutions can be made. Four solutions are present, of which three have the same effect. Proper maintenance has the least effect of the four solutions. The maintenance solution can thus be combined with one of the other solutions, for instance the engine redundancy. The measures with the same result can also be combined. For instance engine redundancy and the stern thruster can be combined to achieve a higher improvement. Compared to their sole improvement each of these combinations will improve reliability even further. First the results of the combination of maintenance and steering gear redundancy will be determined. After that, the results of the other combination will be calculated. The chosen measures in the combinations are examples, those have not been determined as being the best solution.

It can be found that a combination of proper maintenance and one of the other solutions lowers the failure rate to only 9.2×10^{-11}. This is an improvement of 1,239,500 years. Compared to the reliability improvement of the engine redundancy, this is an improvement of 432,500 years. Applying both measures thus has an effect, but this extra reliability is not necessary since the reliability improvement of the steering gear redundancy already is sufficient.

The effect of applying both the steering gear redundancy solution as well as installing a stern thruster can now be determined by calculating the failure rate of the steering gear to the power of three. It is then found that only 1.7×10^{-15} of the failure rate remains, which means that the reliability improvement is 67,860,360,000 years. This is 67,859,553,000 years more than one of these measures did individually. This new reliability improvement is very high and not necessary. This solution will thus not be financially investigated when it is found to be with the best solutions.

4.3.2. Reliability Improvement Electrical Supply And Control Devices

The failures in the electrical supply and control devices are found to be responsible for 9.5% of all failures. Two solutions can be found to the failures of the electrical supply and control devices. The first solution is to duplicate all wires and thus create more steering gear redundancy. The other solution is to perform better maintenance, as has also been seen for many other failures. A combination of the two solutions might also prove to be an alternative. This will also be calculated.

Wire Redundancy
When two sets of wires are installed for the steering gear, both sets have to fail before a steering gear failure occurs resulting in a fatal technical failure. Having wire redundancy thus reduces the possibility of occurrence of a failure. Since each set has a failure rate of 9.9×10^{-6}, it can be determined that their combined failure rate is 9.7×10^{-11} after two sets of wires are installed. This means that a reliability improvement of 1,172,500 years is realised.

Steering Gear Redundancy
When the steering gear is split into two different systems, this increases the reliability significant. Both steering gear systems then have to fail before this becomes fatal. With each set having a failure rate of 9.9×10^{-6} it can be found that only 9.7×10^{-11} of the initial failure rate remains which is an improvement of 1,172,500 years. These are the same values as were found for the wire redundancy.

Install A Stern Thruster
The effects of installing a stern thruster are the same as were found for the wire redundancy and the steering gear redundancy, namely an improvement of 1,172,500 years.

Improvement Of Maintenance
When proper maintenance is performed, this will result in a 19.3% lower failure rate. Knowing this makes it possible to determine the failure rate of the electrical supply and control devices after they have been properly maintained. It has been calculated that 8.0×10^{-6} is the remaining failure rate once proper maintenance has been performed. This is an improvement of only 2.8 years. This solution thus has a positive effect, but since a large failure rate is still present it is not very effective.

Combination Of Wire Redundancy And Improvement Of Maintenance
Although wire redundancy has proven to give a higher reliability improvement than better maintenance has, the two solutions together will give an even higher improvement. The failure rate and reliability improvement of two sets of wires while both being properly serviced can now be determined. The following results are also valid for a combination of either the steering gear redundancy or stern thruster solution together with the improved maintenance.

The failure rate after both solutions have been applied is found to be 6.3×10^{-11} and the reliability improvement is therefore 1,800,500 years. When both measures are applied, an extra improvement of 628,00 years is gained, compared to the wire redundancy measure. From a financial standpoint it can thus be stated that applying both measures is not worth it. The extra improvement that can be gained is not necessary in order to guarantee sufficient reliability.

4.3.3. Summary Steering Gear Reliability Improvement

With the effects of all individual solutions to the steering gear problems known, a list can be made to compare them. Table 4.3 lists all solutions for each failure. It shows the reliability improvement that can be gained when this solution is chosen and how much of the initial failure rate remains.

The maximum reliability improvement that can be gained for the steering gear can be found by summing up the highest reliability improvements for each of the individual failures. For the failures with the unknown distribution and the group other, the best improvement comes from the combination of two measures with 807,000 years of improvement. This is for instance the combination of the splitting of the steering gear in two separate systems and the instalment of a stern thruster. Since the individual solutions already realize enough reliability improvement, those solutions are chosen as being the best. An increase of the MTBF of 807,000 years can thus be realized for the failures with unknown distribution and the group other.

For the failures in the electrical supply and control devices, it can be found that a combination of proper maintenance and a redundancy solution gives the highest reliability improvement. Again, the extra improvement is not necessary. The redundancy solution is thus chosen as having the highest reliability improvement, namely 1,172,500 years.

When the overall reliability improvement of the steering gear is determined, it can be found that an improvement of 2.2×10^{-5} is possible. This leaves only 2.2×10^{-8} of the initial failure rate of 2.2×10^{-5}, which is a good result. The best solutions in the steering gear can thus prevent a total of 99.9% of the steering gear failure rate. The new mean time between failures is found to be 5,184 years which means that only one out of 207 ships will be struck by this failure during its lifetime.

Table 4.3: Reliability improvement and new failure rate for each of the solutions of the steering gear failures

Failure	Solution	Reliability improvement [yrs]	New failure rate
Unknown distribution plus Other	Split steering gear into separate systems	807,000	1.4×10^{-10}
	Install a stern thruster as a full backup	807,000	1.4×10^{-10}
	Use azipods for propulsion, then no rudders are required	807,000	1.4×10^{-10}
	Use official replacement parts, installed and maintained by qualified personnel	2	9.6×10^{-6}
	Combination of maintenance improvement and one of the measures with a 1.2×10^{-5} improvement	1,239,500	9.2×10^{-11}
	Combination of two measures with a 1.2×10^{-5} improvement	67.9×10^{9}	1.7×10^{-15}
Electrical supply and control devices	Install more electrical wire as a full backup	1,172,500	9.7×10^{-11}
	Split steering gear in separate systems	1,172,500	9.7×10^{-11}
	Install a stern thruster as a full-backup	1,172,500	9.7×10^{-11}
	Use official replacement parts, installed and maintained by qualified personnel	3	8.0×10^{-6}
	Combination of maintenance improvement and a measure with a 9.9×10^{-6} improvement	1,800,500	6.3×10^{-11}

4.4. Reliability Improvement Fuel System

The fuel system is the system that is responsible for the third most number of failures, namely 11.1% (1.2×10^{-5} and a MTBF of 9.9 years). Two groups of failures can be distinguished within the fuel system failures. The first group is a group of failures with unknown distribution. This group is responsible for 8.4% (8.7×10^{-6} and a MTBF of 13 years) of all failures and includes the following failures: insufficient fuel care, fuel of poor quality, clogged fuel filter, strong vibrations of fuel line, broken fuel pipe and air in the fuel. Fuel intolerance is the second group of fuel system failures and is responsible for 2.8% of all failures (2.9×10^{-6} and 39 years MTBF). The failures and their solutions will be dealt with in order of their failure contribution, so first the failures with unknown distribution will be dealt with after which the fuel intolerance solutions will be discussed. For all solutions it will be determined how much of a reliability improvement they give. It will also be determined how much of the initial failure rate remains after a solution has been applied. At the end of this section a list will be presented which shows the results for each of the solutions.

4.4.1. Reliability Improvement Unknown Distribution

The failures with unknown distribution are responsible for most of the fuel system failures. There are multiple causes for the failures in this group. For most of the solutions to these failures, no failure rate is available. Only for the maintenance related solutions, an effect is known. The absence of failure rates makes it impossible to determine the reliability improvement of every solution in detail. Therefore these failure rates have to be estimated. For every solution, it is estimated that they have the same failure rate as the failure that they are trying to solve. This means that all solutions that are not maintenance related are estimated to have a failure rate of 8.7×10^{-6}. First, all these failures will be dealt with. The given example is to check the quality of the fuel. After the effects of these solutions have been determined, the effect of all maintenance related solutions will be examined.

Check Quality Of Fuel Before Bunkering And Others

The quality of the fuel has to be checked before bunkering. Only when the fuel is found to be of sufficient quality it should be used, or in the best case bunkered. When low quality fuel is used, this can have a disastrous effect on the machinery. Knowing the quality of the fuel is thus an absolute must. The group of failures with unknown distribution has a failure rate of 8.7×10^{-6}. This failure rate will also be assumed to be representative for the solution to check the fuel. The failure rate of a fuel quality failure although it has been checked can now be determined with the following equations.

$$\begin{aligned} \lambda_{\text{Fuel system due to fuel quality and failed check}} &= \lambda_{\text{Fuel quality}} \times \lambda_{\text{Fuel check}} \\ &= 8.7 \times 10^{-6} \times 8.7 \times 10^{-6} = 7.5 \times 10^{-11} \end{aligned} \tag{4.24}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{7.5 \times 10^{-11}} - \frac{1}{8.7 \times 10^{-6}} \approx 1,516,500\ years \end{aligned} \tag{4.25}$$

Although this solution is calculated to give a reliability improvement of 1,516,500 years, as can be seen from Equation 4.25, this solution does not solve all failures in the group with unknown distribution. Six failures are found in the group with unknown distribution and five non maintenance related solutions have been proven to be a solution. The six failures are thus responsible for all of the failures in this group. When determining the best solutions based on their reliability improvement, this should be taken into account. There are a lot of uncertainties regarding the failure rate of the failures and its solutions. Spending money on solutions with a slightly lower reliability improvement might therefore be favourable over investing money in a reliability improvement with a high uncertainty.

The solutions to most other failures in this group give exactly the same failure reduction. This is because the failure rate of their solutions is also not known. The same failure rate will thus be assumed, which results in the same failure reduction. The solutions that have the same failure reduction are the following: 'keep fuel from different locations separate', 'proper instalment', 'proper filter' and 'air filter redundancy'.

Improvement Of Maintenance

One of the mentioned solutions is that the fuel system should be better maintained as a whole. This would mean a reduction in the failure rate of 19.3%. The reliability improvement that is gained by performing better maintenance can now be calculated.

$$\begin{aligned} \lambda_{\text{After proper maintenance}} &= \lambda_{\text{Before maitenance}} \times F_{\text{Reduction maintenance}} \\ &= 8.7 \times 10^{-6} \times 0.807 = 7.0 \times 10^{-6} \end{aligned} \tag{4.26}$$

$$\begin{aligned} \text{Reliability improvement} &= MTBF_{\text{After solution}} - MTBF_{\text{Before solution}} \\ &= \frac{1}{7.0 \times 10^{-6}} - \frac{1}{8.7 \times 10^{-6}} = 3\ years \end{aligned} \tag{4.27}$$

From the above two equations it can be found that improving the maintenance results in a 1.7×10^{-6} smaller failure rate, which is an improvement of 3.1 years. When the maintenance of the entire fuel system is performed better, this reliability improvement might be more realistic than the reliability improvements for the failures in the previous part, but the reliability improvement is not sufficient.

4.4.2. Reliability Improvement Fuel Intolerance

Fuel intolerance is responsible for 2.8% of all failures and has a failure rate of 2.9×10^{-6}. Two solutions have been found to cure this problem. The first solution is to keep different types of fuel separate and/or to keep fuel(s) from different locations separate. The last solution that was found is to switch to an alternative fuel. The two fuels that have been found as an alternative are liquid natural gas and electricity.

Keep Different Types Of Fuel Or Fuel From Different Locations Separate

The solution to keep different fuel types separately and the solution to keep fuels from different locations separately is practically the same. In both cases, two fuel systems have to be installed. Then, it is not important what fuel is used for the first and second system. It also does not matter where these fuels come from.

If a ship sails only on one type of fuel, fuel intolerance due to the mixing of two types of fuel cannot occur. When different types of fuel are used in the ship, they should be kept separate at all times. As long as this is the case, no failures should occur. When these measures are taken, part of the fuel intolerance failures will no longer be present. But even when the fuels are kept separate, there will be a small chance that a failure occurs. Therefore, the reduction of the failure rate due to separation of the fuels will have to be determined.

It is difficult to determine the reduction in the failure rate due to appliance of this solution. Therefore, an assumption has to be done. Just as with other solutions for which the failure rate was not known, it will be assumed that it has the same failure rate as the failure that it tries to cure. The failure rate of two different types of fuel or fuel from two different locations coming in contact and causing a failure while they are stored separately can now be determined. It can be deducted that 8.4×10^{-12} of the failure rate remains after this solution is applied, which is a negligible value since the reliability improvement is 13,647,500 years.

Alternative Fuel

When an alternative fuel is used, also an alternative engine has to be used. It was found in section 4.2 that an alternative engine does not give a high reliability improvement compared to a regular diesel engine. An alternative engine which is for instance 10% more reliable only realizes 4.8×10^{-11} more reliability, while a 20% more reliable engine only realizes 9.1×10^{-11} more reliability. When an alternative fuel in combination with an alternative engine proves to give more reliability in multiple facets, the alternative engine might prove to be an interesting option. Otherwise it is questionable whether an alternative engine is a good option.

Two fuels were found that can be used as an alternative. The first one is liquid natural gas. If this fuel is used, one type of fuel is sufficient to sail in all areas. Therefore fuel intolerance failures that occur because multiple types of fuel mix will not occur with LNG. Failures that occur because fuel is bunkered at multiple locations can still occur. When new fuel is bunkered, this should thus be kept separate from the already bunkered fuel. For LNG, this can have a significant negative effect on the space requirement, since LNG requires a lot of extra equipment. When the fuels from different locations are kept separately, both diesel and LNG have the same reliability improvement. Using LNG can thus be said to increase the reliability with 13,647,500 years, but only when the fuels are kept in separate locations.

The second fuel that proved to be an alternative is electricity. If electricity is generated on board, this is done with generators. These are most likely to run on diesel. Therefore, the possibility of fuel intolerance is still present. The generators will only run on one type of fuel, so only the failure rate of the mixing of fuel from different locations remains. If electricity is generated on board and the fuel from different locations is kept separately, a reliability improvement of 13,647,500 years is gained. When the electricity is loaded from shore when in port, the electricity is stored on board. The risk of a fuel intolerance failure is then transferred to the company who generates the electricity onshore. In case the energy is bunkered from shore, there is no chance of a fuel intolerance failure. A 0.0 failure rate is then left and the entire initial failure rate of 2.9×10^{-6} is prevented. This causes the mean time between failure to be infinity.

4.4.3. Summary Fuel System Reliability Improvement

With the reliability improvements known for all solutions, a list can be made to summarize them. It can then be determined which of the solutions realizes the highest reliability improvement. For each of the solutions, a reliability improvement was calculated and it has been determined how much of the initial failure rate remains after a solution has been applied. Table 4.4 shows the failure or group of failures that occurred in the fuel system in the first column, the second column shows the solution to these failures, whereas the third and fourth column show respectively the reliability improvement and the new failure rate.

Table 4.4: Reliability improvement and new failure rate for each of the solutions of the fuel system failures

Failure	Solution	Reliability improvement [hrs]	New failure rate
Unknown distribution	Use official replacement parts, installed and maintained by qualified personnel	3	7.0×10^{-6}
• Insufficient fuel care, Fuel of poor quality, Clogged fuel filter	Check the quality of new fuel before bunkering/using	1,516,500	7.5×10^{-11}
	Keep fuels from different locations separated	1,516,500	7.5×10^{-11}
• Air in fuel	Install the proper air filter	1,516,500	7.5×10^{-11}
	Install an extra filter as a full backup	1,516,500	7.5×10^{-11}
Fuel intolerance	Keep different types of fuel separate and/or keep fuels from different locations separate	13,647,500	8.4×10^{-12}
	Alternative fuel		
	• Liquid Natural Gas	13,647,500	8.4×10^{-12}
	• Electricity		
	- Generated on board	13,647,500	8.4×10^{-12}
	- Generated onshore	∞	0.0

From Table 4.4 it can be seen that most solutions to the fuel system failures realize the same reliability improvement. This is the case since there are a lot of uncertainties regarding the failure rates and how much of an impact a particular solution has. When the solutions to the failures with unknown distribution are beyond the solutions that have the best reliability improvement, these solutions have to be taken into consideration carefully. Spending money on solutions with a known effect can be chosen over solutions with an uncertain effect, although the known effect might be lower.

For the failures with unknown distribution, at least 7.5×10^{-11} of the failure rate will remain. This means that a maximum of 8.7×10^{-6} can be prevented. For the fuel intolerance, 2.9×10^{-6} of the failures can be prevented. This leaves 8.4×10^{-12} of the fuel intolerance failures. The solutions to the fuel intolerance failures thus have a significant effect. When the reliability improvements of the two failure groups are combined, 1.2×10^{-5} of the failures can be removed from the initial 1.2×10^{-5}. A negligible failure rate of 8.4×10^{-11} remains. The two best solutions combined thus prevent 100.0% of all fuel system failures. When the mean time between failure is calculated for the new failure rate, it can be determined that a fuel system failure will cause a failure once every 1,365,000 years. One out of every 54,600 ships will thus be struck with this failure during its lifetime of 25 years.

Both for the failures with unknown distribution and the fuel intolerance failures it was found that keeping different types of fuel separately and keeping fuels from different locations separate is a solution to the problem. These solutions are thus effective for both failure groups within the fuel system. Those can be assumed to be the best solutions for all fuel system related failures.

4.5. Reliability Improvement Electrical System

All the failures in the electrical system combine together for 8.9% of all failures (a failure rate of 9.3×10^{-6} and a MTBF of 12 years). Of this 8.9%, 4.7% is caused by a blackout (4.9×10^{-6} and a MTBF of 23 years) while the other 4.2% has an unknown distribution (4.4×10^{-6} and 26 years). In this section the reliability improvements of these solutions will be determined. First, the solutions to the blackout will be dealt with, after which the solutions to the failures with unknown distribution will be shown. When the reliability improvements of all solutions to both failures are known, it can be determined which solutions give the highest reliability improvement. This also makes it possible to determine the decrease in the initial failure rate as well as the new mean time between failures.

4.5.1. Reliability Improvement Blackout

There are three possible solutions to prevent a blackout from happening. The first solution is to improve the maintenance. Making sure that enough power is available when new equipment is started is the second way to get a higher reliability. The last measure is to check the quality of the fuel before bunkering or using. In this order, the solutions will be dealt with. Possible combinations of solutions will be dealt with at the very end.

Improvement Of Maintenance

The effects of proper maintenance can quite easily be determined since it is known that 19.3% of all failures are caused by improper maintenance. Multiplying the failure rate of the blackout with the failure reduction due to the better maintenance determines how much of the initial failure rate will remain present. It is determined that the failure rate lowers from 4.9×10^{-6} to 4.0×10^{-6}. This is a reliability improvement of only 5.5 years.

Availability Of Power

Before new equipment is started, it has to be made sure that enough power is available. When this is always the case, this failure will no longer occur. Since this will never be the case in reality, there will be a (small) chance that this condition is somehow not satisfied. A small failure rate will thus remain present when this solution is applied.

Since the lack of availability of power is only one of many failures that cause a blackout, it is not entirely responsible for the failure rate of 4.9×10^{-6}. It is responsible for this rate together with all other failures that cause a blackout. This means that when the solution is applied to solve the availability of power, this does not solve any of the other failures. Although this solution might reduce the failure rate of a blackout heavily, the other failures that cause a blackout might still be present.

In previous cases when no failure rate was available, the failure rate of a measure which has no available data was assumed to be equal to the failure rate of the failure it has to solve. This would mean, that the failure rate of the software that has to check whether enough power is available is assumed to be 4.9×10^{-6}. When this measure is installed, two failures have to occur before this leads to a fatal technical failure in the electrical system. The failure rate will thus decrease sharply. With the new failure rate of this solution determined, it can be determined how much of the failure rate will remain after it is applied. It is found that the new failure rate is 2.4×10^{-11}, which is an improvement of 4,705,500 years.

In case the failure rate of the availability of power is found to be responsible for, for example, only half of the blackout failures, a different answer is found. In this example, the remaining failure rate would reduce to 6.1×10^{-11} since the failure rate of the power availability failure would be reduced to 2.5×10^{-6}.

Although the exact failure rates of the failures leading to a blackout are unknown, it can be seen that a 50% difference in the failure rate has a negligible influence on the reliability improvement. This proves that although the chosen values of the failure rates are rough, the solutions can be said to be accurate since the values do not differ much when different failure rates are used.

Fuel Quality

The quality of the fuel is partially responsible for the cause of a blackout. Just as for the unavailability of power it is not solely responsible for all blackout failures, but the combination of all failures is responsible for the failure rate. For the reliability calculations though, the entire blackout failure rate will be used since no detailed failure rates are known.

The failure rate of the fuel quality is thus assumed to be 4.9×10^{-6}. The new failure rate of a failure that occurs although the fuel is being tested before bunkering or using will now have to be calculated. When the fuel is tested before bunkering and when only fuel that has the decent properties is used, a smaller amount of failures will occur. There is always a chance that something goes wrong, so this has to be accounted for. When the failure rate of a failure despite checking the fuel is assumed to be equal to the failure rate of a blackout, the reliability improvement can be determined, in case the fuel quality is always verified. With this failure rate, the reliability improvement due to this solution can be calculated.

The new failure rate is found to be 2.4×10^{-11}, which is an improvement of 4,705,500 years compared to the initial 23 years. These values are the same as for the availability of power since the calculations use the same values.

Combination Of Multiple Solutions

Although both the solution to the availability of power and the lack of fuel quality have the same effect, their effect can still be increased by combining them with the proper maintenance solution. While this solution might not be financially competitive, it is still good to know how much of a reliability improvement can be gained. The results from these equations are both for the combination maintenance plus availability of power and the combination maintenance plus fuel quality.

It can be found that the combination of two measures give a reliability improvement of 7,225,500 years. This means that a failure rate of only 1.6×10^{-11} is left after both measures have been applied. This is an increase of 2,520,000 years compared to the best individual solutions. Combining both measures thus increases the reliability even further. A single measure reduces the failure rate to a level which is almost negligible and can be considered sufficient. Combining two measures is thus not required from a reliability standpoint and is definitely not financially viable.

4.5.2. Reliability Improvement Unknown Distibution

For this group of failures with a failure rate of 4.4×10^{-6}, two solutions were determined. The first solution is to improve the quality of the maintenance. The second option is to install an extra electrical system as a full-backup. A combination of the two solutions is also an option. First, the impact of the proper maintenance will be reviewed, then the improvement due to the electrical system redundancy. Finally, the impact of a combination of the two solutions will be determined.

Improvement Of Maintenance

The maintenance can be improved by making sure that official replacement parts are used, which are installed by qualified personnel. This will lower the failure rate with 19.3%. The new failure rate and the reliability improvement can easily be determined as respectively 3.5×10^{-6} and 6.3 years. It can again be seen that improving the maintenance does not have a significant effect on the reliability improvement.

Electrical System Redundancy

When the entire electrical system is doubled, it has a full-backup. Both systems then have to fail before this becomes fatal. Doubling the entire electrical system is a costly operation that will also require space. If this proves to be the solution with the most improvement, it will have to be determined whether this is also a good solution from a financial standpoint. Though first it has to be determined how much of a reliability improvement can be gained when this solution is applied.

It can be found from the previous shown equations that installing an extra electrical system has a significant beneficial effect on the new failure rate. The failure rate is reduced to only 1.9×10^{-11}, which is an improvement of 6,032,000 years for the MTBF.

Combination Of Improvement Of Maintenance And Electrical System Redundancy

The reliability improvements for the two individual solutions improvement of maintenance and electrical system redundancy have been found. When the two solutions to the failures with unknown distribution are applied, an even higher reliability improvement can be gained. If the reliability improvement of the combined solution is known, it can be determined whether this extra reliability improvement is significant and necessary compared to the improvement of a sole solution.

When both measures are applied, a very small and negligible failure rate of 1.2×10^{-11} remains. This means that the MTBF is increased with 9,262,000 years. Although the remaining failure rate is already negligible when the electrical system redundancy is applied, this failure rate is 6.6×10^{-12} lower. It can already be stated though that this extra improvement of 3,230,000 is financially not worth the effort. Only applying the electrical system redundancy is thus sufficient.

4.5.3. Summary Electrical System Reliability Improvement

With the reliability improvements of all solutions determined a list can be made which will show for each individual failure the available solutions as well as the reliability improvement in years. It is also shown how much of the failure rate remains after the solution has been applied. In the left column of the table, the failures are shown, the second column shows the solutions to these failures. The third column shows the reliability improvement and the last column shows the remaining failure rate.

Table 4.5: Reliability improvement and new failure rate for each of the solutions of the electrical system failures

Failure	Solution	Reliability improvement [yrs]	New failure rate
Blackout	Use official replacement parts, installed and maintained by qualified personnel	6	4.0×10^{-6}
	Enough power should be available when starting equipment	4,705,500	2.4×10^{-11}
	Check the quality of fuel before bunkering/using	4,705,500	2.4×10^{-11}
	Combination of proper maintenance and one of the other solutions	7,225,500	1.6×10^{-11}
Unknown distribution	Use official replacement parts, installed and maintained by qualified personnel	6	3.5×10^{-6}
	Install an extra electrical system as a full backup	6,032,000	1.9×10^{-11}
	Combination of maintenance improvement and system redundancy	9,262,000	1.2×10^{-11}

Table 4.5 shows that both failures have solutions that prevent almost the entire failure rate and thus have a significant effect. For the blackout it can be seen that the solution to improve the maintenance and apply power availability or the fuel quality solution have the same influence. Both solutions prevent 4.9×10^{-6} of the initial 4.9×10^{-6}. The individual solutions of the power availability and fuel quality give an improvement of 4.9×10^{-6} and are definitely cheaper, since they are individual solutions. Applying both measures is therefore not necessary and definitely not worth it.

When the solutions to the blackout failures are with the solutions that give the highest reliability improvement it has to be determined whether this failure should be solved. Since the failure rates of the different causes to a blackout are not known, it is difficult to tell whether the shown reliability improvement is actually accurate. There are a lot of uncertainties in the distribution of the causes of a blackout. Spending money on a reliability improvement of a different failure that certainly takes away that failure might prove to be a better option.

For the failures with unknown distribution, the combination of maintenance and the improvement of the system redundancy gives the highest failure reduction. They combine for a reduction of 9,262,000 years. This is thus the best solution, based on the reliability improvement. The solution to only install an extra electrical system is though definitely cheaper than the combination of the two solutions and since it provides significant reliability improvement this solution is chosen as being the best.

When the reliability improvement of the best solutions to both failures is added, it can be found that 4.9×10^{-6} of the failure rate can be prevented for the blackout failures and 4.4×10^{-6} for the failures with unknown distribution. The remaining failure rate is found to be only 4.3×10^{-11}. The corresponding MTBF is 2,643,500 years. When the solutions with the highest reliability improvements are installed in the ship, 100.0% of the failures in the electrical system will no longer occur.

4.6. Reliability Improvement Cooling Water System

The cooling water system is the last group of failures for which the reliability improvements have to be determined. The failures in the cooling water system are responsible for 8.4% of all machinery failures (a failure rate of 8.8×10^{-6} and a MTBF of 13 years). This percentage is divided over two groups of failures. The first group of failures is a large group of which the failure distribution is unknown. This group is responsible for 6.7% (7.0×10^{-6} and a MTBF of 16 years) of all failures and will be dealt with first. The second group of failures is caused by ice in the seawater filter. This group is responsible for only 1.7% (1.8×10^{-6}, 65 years) of all failures and will be dealt with after the group with unknown distribution has been dealt with. Finally, a summary of all reliability improvements and remaining failure rates will be made. This will show all different solutions and their impact on the failure rate.

4.6.1. Reliability Improvement Unknown Distribution

The failures in the group with unknown distribution come from the cooling water pump(s), the piping and the controllers and sensors. Two solutions have been determined to solve the cooling water pump failures and only one solution has been determined for the controller and sensor related failures. In the named order, these solutions will be dealt with.

Cooling Pump - Improvement Of Maintenance

Improving the maintenance of the pumps has a positive effect on their reliability. Since the failure rate of the cooling water pumps is unknown, the failure rate of the entire failure group with unknown distribution will be taken for the calculations. For the piping and controllers and sensors, an improved maintenance is also likely to have a positive effect. Improving the maintenance prevents 19.3% of all failures. How much of a reliability improvement this gives can now be determined. The new failure rate will also be determined.

The new failure rate of a cooling water system failure, although it has been properly serviced is 5.7×10^{-6}. This is an improvement of 4 years. Since proper maintenance has a positive effect on the entire cooling water system, this reliability improvement can be realized with a greater certainty than some of the other reliability improvements in this section. Though, the MTBF is still of a level that is not satisfying.

Cooling Pump - Pump Redundancy

When more cooling water pumps are installed than required, pump redundancy is gained. This means that when a pump fails, another one is available to take over so that no performance is lost. At least two pumps will then have to fail before this becomes fatal. With the second pump having the same failure rate as the first one, the reliability improvement can be determined.

Only 4.9×10^{-11} of the failure rate remains after pump redundancy is applied. This means that a reliability improvement of 2,327,500 years is gained by installing an extra pump. This value might be slightly exaggerated, since a cooling water pump is only one of many failures in this group. Solving only one of these failures can thus not take away such a big portion of the total number of failures.

Controller And Sensor Redundancy

When extra controllers and sensors are installed, this provides redundancy. When one of the sensors fails, another can take over. The same goes for the controllers. In case a sensor seems to give strange values, these values can be verified with the other sensor. This makes it possible to better determine whether a failure occurs to the system or to a sensor. The failure rate of a second controller or sensor is equal to that of the first one, namely 7.0×10^{-6}. With it having the same value as a second cooling water pump, the new failure rate and reliability improvement are equal. These are thus found to be respectively 4.9×10^{-11} and 2,327,500 years. Again it has to be stated that this solution only solves one of many failures in this group.

4.6.2. Reliability Improvement Ice In Seawater Filter

Ice in the seawater filter is responsible for 1.7% of all failures. The only solution that has been found to solve this is installing a winter cooling system instead of a regular system. A winter cooling system prevents ice from coming into the cooling system. If ice somehow does get in the seawater inlet, the system has measures to get rid of the ice. The winter cooling system is only necessary for ships that sail often in ice invested waters. For ships that do not sail in ice invested waters, the failure rate due to ice in the seawater filter is not present.

For the winter cooling system, a failure rate will have to be determined in order to calculate the failure reduction that can be achieved. It will be assumed that the failure rate of the winter cooling water system is 1.8×10^{-6}, equal to the failure rate of the failure that it tries to solve. With the failure rate of the cooling water system known, it can now be determined how much of a reliability improvement can be gained. A failure reduction of 37,236,500 years can be gained, such that a failure rate of only 3.1×10^{-12} remains.

4.6.3. Summary Cooling Water System Reliability Improvement

With the reliability improvements determined for each individual solution, they can now be put into a table. This table will show which solutions are available to a particular failure. It will also show how much of a reliability improvement can be gained when this solution is applied and how much of the initial failure rate remains.

Table 4.6: Reliability improvement and new failure rate for each of the solutions of the cooling water system failures

Failure	Solution	Reliability improvement [yrs]	New failure rate
Unknown distribution			
• Cooling water pump	Use official replacement parts, installed and maintained by qualified personnel	4	5.7×10^{-6}
	Install an extra pump as a full backup	2,327,500	4.9×10^{-11}
• Controller and sensor	Install extra controller and sensors	2,327,500	4.9×10^{-11}
Ice in seawater filter	Upgrade cooling water system to a winter cooling system	37,236,500	3.1×10^{-11}

Table 4.6 shows that multiple solutions to the failures with unknown distribution have an equal reliability improvement. This is because there is a lot of uncertainty regarding the failure distributions of this failure group and its solutions. The maximum reliability improvement of a single solution is thus found to be 2,327,500 years. This much of a reliability improvement is not likely to be generated from one single solution, since there are so many failures in this group. The lower value of a 4 years improvement for the maintenance solutions seems more realistic, since these deal with the entire group.

The solution to ice in the seawater filter prevents 1.8×10^{-6} of these failures. Although it removes almost the entire failure rate of this failure, this solution is not likely to be with the best solutions based on reliability improvement since the initial failure rate is small.

It can be found that 7.0×10^{-6} of the failures with unknown distribution can be prevented and 1.8×10^{-6} of the ice related failure rate. Adding the failure rates gives a reliability improvement of 2,190,500 years. Only 5.2×10^{-11} of the initial failure rate remains when the best measures to both failure groups are applied. This means that a failure reduction of 100% can be gained for the failures related to the cooling water system.

4.7. Conclusion

For all systems, it has been determined what the reduction in failure rate is for each of their solutions. In the previous sections, the results of these reductions were shown for each individual system, based on the magnitude of the initial failure rate of a specific failure. This made it possible for each system to determine which solution realizes the highest reliability improvement. In order to determine which solutions give the highest reliability improvement overall, the solutions to all failures have to be compared.

When all solutions are organized based on their reliability improvement, this gives a long table, which can be seen in Appendix E. Table E.1 shows the system in which the failure occurred, the failure that occurred and its solution. This is followed by the reliability improvement and the remaining failure rate for the specific failure. The reliability improvement in Table E.1 is expressed as the prevented failure rate. This way, the solutions which prevent the most failures can best be deducted. Otherwise, a solution such as the upgrade of the cooling water system to a winter cooling water system would be placed very high since its reliability improvement is over 37 million years. It is though only responsible for 1.7% of all failures and therefore little failures are prevented. Showing the prevented failure rate thus shows the best solution based on the initial failure distribution of all failures. The solutions are arranged by their reliability improvement so the solution with the highest improvement is shown first and the solution with the least improvement is shown last.

With all reliability improvements known, the maximum prevented and minimal remaining failure rate can be determined. Table 4.7 shows the initial failure rate, the maximum prevented failure rate and the remaining failure rate for each system. The maximum prevented and minimal remaining rate in total can now be determined. Note that the failure rates for the systems shafting, diesel generator and other have not been included in the table. No solutions for these systems have been determined, so these failure rates did not change. They have though been included in the calculations for the row 'total'.

Table 4.7: The initial, maximum prevented and minimal remaining failure rate for each system

System	Initial failure rate	Maximum prevented failure rate	Minimal remaining failure rate
Main engine	4.0×10^{-5}	4.0×10^{-5}	6.3×10^{-10}
Steering gear	2.2×10^{-5}	2.2×10^{-5}	2.2×10^{-8}
Fuel system	1.2×10^{-5}	1.2×10^{-5}	8.4×10^{-11}
Electrical system	9.3×10^{-6}	9.3×10^{-6}	2.8×10^{-11}
Cooling water system	8.8×10^{-6}	8.8×10^{-6}	5.2×10^{-11}
Total	1.0×10^{-4}	9.2×10^{-5}	1.3×10^{-5}

From Table 4.7 it can be seen that a maximum of 9.2×10^{-5} of the failure rate can be prevented. A minimum of 1.3×10^{-5} will remain, even if all solutions with the highest improvement are applied. The initial failure rate can thus be reduced by 88.0% and the new failure rate has a corresponding mean time between failures of 9 years. This value is still significant and would mean that a ship will be struck by a failure almost three times during its lifetime of 25 years. Although this is a large improvement compared to the initial MTBF of a little over a year, this new value might not be sufficient. What level should be considered sufficient is though not known and has to be determined in future research.

For this research, only solutions for the main engine, steering gear, fuel system, electrical system and cooling water system have been found. The remaining failure rates for these systems are therefore very low. When solutions for the other three systems are found as well, the failure rate that can be prevented can be increased. The three systems for which no solutions have been determined are responsible for 1.3×10^{-5} of the remaining failure rate. This clearly shows that the found solutions for the five systems have a significant effect, since their remaining failure rates are negligible to the total remaining failure rate. It can be expected that when solutions are determined for the three neglected systems, their remaining failure rate will follow the trend of the first five systems and will become negligible as well. Excluding the failure rates of the systems for which no solutions have been determined, the mean time between failures would be 5,000 years. It can thus be seen that the remaining failure rate has a significant effect on the mean time between failures. Solutions for the other systems might also be necessary in order to come to a level of reliability which can be said to be sufficient.

Some solutions have been named as a solution for multiple failures. The individual reliability improvements for all solutions therefore have to be added in order to determine which solutions give the highest reliability improvement. The solutions with the highest reliability improvement are the ones that will be investigated financially. Since these solutions show the highest improvements they have the largest impact, but for these solutions to be applied, they have to be financially viable.

For multiple failures, a combination of two solutions was found as an extra solution. This was usually a combination of a maintenance and redundancy measure. Combining the solutions gained even more reliability improvement compared to the best of the sole measures. However, the solution to only apply the redundancy solution was in all cases already found to be a solution with a very significant effect. It can therefore be said that the small improvement from the combination of solutions is not necessary from a reliability standpoint. From a financial standpoint it is definitely not worth it to apply a combination of measures. Investing money in measures which are not required is not profitable. When determining the best solutions, the combination of measures will therefore no longer be taken into consideration.

For all failures in the main engine a solution to apply engine redundancy by either installing more engines as a full-backup, dividing the power over more engines or by installing a power take in as a backup was found. The failure rates for the failures with unknown distribution, starting, reversing and regulating device failures, standard failures and turbocharger failures can thus be combined. Applying engine redundancy will solve all these problems. Together, the engine redundancy solutions combine for an improvement of 4.0×10^{-5} while only 6.3×10^{-10} of the initial failure rate remains. Engine redundancy is the solution with the highest reliability improvement overall and will therefore be financially investigated.

For the steering gear, it can be found that the redundancy option is a solution to both the failures with unknown distribution as well as to the failures in the electrical supply and control devices. Splitting the steering gear into separate systems or installing a stern thruster as a backup can be found as a solution. Together, they combine for an improvement of 2.2×10^{-5}. The remaining failure rate when one of these solutions is applied is 2.4×10^{-10}. Redundancy of the steering gear is found to be the solution with the second highest improvement. The cost of this solution will therefore also be determined later on.

In the fuel system, redundancy is also a solution for both failures, namely the failures with unknown distribution and the fuel intolerance. Fuel system redundancy prevents 1.2×10^{-5} of the failure rate, with only 8.4×10^{-11} of the initial failure rate remaining. This solution is the third best when it comes to reliability improvement and will therefore also be considered for its financial aspect. In the failures with unknown distribution, other failures such as air in the fuel are also present. These are not solved by applying redundancy. The calculations of the failure rate prevention might therefore be a little on the positive side. However, it is still a valid solution for the fuel intolerance and most of the failures with unknown distribution. There is also no other solution that comes close to the reliability improvement of this solution. It is therefore assumed that this solution, even if the actual reliability improvement is a little lower, still comes at the third place regarding the total reliability improvement.

The three redundancy options can now be placed into one table as a small summary. Table 4.8 shows the system in which the failure occurred and also names the failure. It then shows the redundancy solutions and their reliability improvement. It ends with the failure rate that remains after a solutions has been applied. The solutions in this table are the ones of which the costs will be determined in the next chapter.

Table 4.8: The three best solutions based on reliability improvement

System	Failure	Solution	Reliability improvement [yrs]	New failure rate
ME	Unknown distribution, starting, reversing and regulating device, standard failures and turbocharger failures	’Installing more engines as a full-backup’ or ’Dividing the power over multiple engines’ or ’Power take in as a backup’	182,450	6.3×10^{-10}
SG	Unknown distribution plus other and electrical supply and control devices	’Split steering gear into separate systems’ or ’Install a stern thruster as a backup’	5,200	2.4×10^{-10}
FS	Unknown distribution and fuel intolerance	Keep different types of fuel separate and/or keep fuels from different locations separate	1,364,800	8.4×10^{-11}

Table 4.8 shows the three best solutions based on their reliability improvement. It can be seen that for all three systems, the failure rate is heavily reduced. Since the main engine, steering gear and fuel system are the three systems that are responsible for the highest failure rate, it was to be expected that the solutions in these systems would be with the best solutions.

It is interesting to notice that the improvement of maintenance has not been named in Table 4.8 as a solution with one of the highest reliability improvements. Although improper maintenance was found responsible for 19.3% of all failures, the solution to do proper maintenance only has a small effect on all solutions instead of much impact on a few solutions. When all improvements due to the improvement of maintenance are added, it can be found to reduce the failure rate by 1.7×10^{-5}, but it also has a remaining failure rate of 7.0×10^{-5}, which is an improvement of the MTBF of only half a year. Maintenance is thus found to be responsible for a big portion of the failures, but only solving maintenance is not the solution to increase the reliability of ship machinery significant.

Another interesting conclusion is that an alternative engine or an alternative fuel are not beyond the best solutions. Since these solutions only prevent very specific failures, they do not have a significant effect overall. Other solutions to the engines or fuel have effect to multiple failures and therefore achieve a higher reliability improvement overall. MUNIN also concluded that the diesel engine can still be used, but then with a distillate fuel [64]. In this thesis, it has not yet been determined whether a residual fuel or distillate fuel is better. For the ReVolt, batteries were chosen as their propulsion type, but this also was a small ship, sailing close to shore and with limited speed which creates a different business case [33].

For the electrical system and the cooling water system a redundancy solution is also found as having the largest reliability improvement. Although a value was found for the reliability improvement, the accuracy of this value can be questioned. A solution to one of the failures in these systems was used as the basis for the calculations. It is not known what the distribution between the failures in the failures with unknown distribution is. It is therefore necessary to have a better insight into the failures in these groups before solutions are installed. Additional reliability calculations are therefore required to know the actual impact of a solution.

Overall, it was found that solutions in the main engine, steering gear and fuel system have the largest reliability improvement. The costs of these solutions will therefore be investigated in the next chapter. Table 3.1 in Chapter 3 showed the different failure types ordered by their severity. Knowing which solutions give the highest reliability improvement, it can now be stated for each of these failures whether it will be solved with one of these three solutions. The first column in Table 4.9 shows the failure type, the second column the system in which the failure occurred, the third column whether a solution is solved or not and the last column shows for how much of the total number of failures a particular failure is responsible. The bottom row of the table shows how many of the failure types are solved with these solutions as well as which part of the failure distribution this is.

Table 4.9: Different failure types ordered by their severity and whether they are solved or not

Failure type	System	Solved [Yes/No]	% All systems [%]
Unknown distribution	ME	Yes	18.9
Starting, reversing and regulating device	ME	Yes	14.2
Electrical supply and control devices	SG	Yes	9.5
Unknown distribution	SG	Yes	8.6
Unknown distribution	FS	Yes	8.4
Unknown distribution	CW	No	6.7
Shafting	SH	No	6.7
Blackout	ES	No	4.7
Unknown distribution	ES	No	4.2
Diesel generator	DG	No	3.6
Standard failure	ME	Yes	3.3
Fuel intolerance	FS	Yes	2.8
Other	SG	Yes	2.8
Turbocharger failure	ME	Yes	2.2
Ice in seawater filter	CW	No	1.7
Failure in other, system	OT	No	1.7
Total		9/16	70.7/100.0

From Table 4.9 it can be seen that nine out of sixteen failures are solved with the three solutions with the highest reliability improvement. The five failures with the highest individual failure distribution are solved with these solutions, as well as some of the failures with a lower failure distribution. Together, these nine failures combine for 70.7% of all failures. The effect of these three solutions is thus substantial.

5

Cost Of Solutions With Highest Reliability Improvement

In Chapter 4 three groups of failures were found of which the solutions give the highest reliability improvement overall. In this chapter, it will be determined which of these solutions is the cheapest and which of the solutions is the best. For each solution it will have to be determined what it costs and it will also be determined what the effect of this solution is on the design of the ship. Before both the cost and design change(s) can be determined, a reference ship and route have to be chosen. With the cost of all solutions known, it is easy to determine which solutions are the cheapest. From other research, it is known how much money becomes available when the ship is made unmanned. With the cost of the machinery solutions known, it can thus be determined whether an unmanned ship can remain financially competitive after applying these solutions.

First, the reference ship and reference route will be introduced in Section 5.1 after which the available money for solutions is discussed in Section 5.2. Then, the solutions to the main engine failures, steering gear failures and fuel system failures will be financially investigated in respectively Section 5.3, 5.4 and 5.5. In Section 5.6 conclusions will be drawn to which solutions are the best and how much of the available budget is used for these solutions.

5.1. Reference Ship And Route

In order to determine the cost of the solutions, a reference ship has to be chosen. With a known reference ship, a value for for instance the needed power is available. This makes it possible to determine the cost of the engines. Without a reference ship this would not have been possible. The route of the ship is necessary to determine for instance the fuel cost or the required range of the batteries when the ship fails halfway during its voyage.

The ship that will be chosen as a reference ship comes from another research regarding unmanned shipping. A general cargo ship, type M-Borg and designed by Conoship, is taken as a reference [38]. This ship was chosen in the other thesis since it was believed that small ships are more suitable for unmanned shipping. For this particular ship it has been determined how much money becomes available when the ship is made unmanned. Using this ship therefore makes it possible to state whether the cost of the solutions are within the budget or far outside the budget. A route from Rotterdam to Halifax (Canada) was chosen in the other research to include both the heavily trafficked North Sea as well as the open Atlantic Ocean. The route has a length of 3,150 nautical miles [38]. The reference ship can be seen in Figure 5.1. It has a length of 134.5 meters, a breadth of 16.5 meters, a draught of 7.0 meters, a displacement of 11,986 tonnes and a deadweight of 8,950 tonnes.

5.2. Available Money For Solutions

When a ship is sailing unmanned, apart from not needing crew, some equipment is no longer required. Accommodation, fresh water systems, sanitary systems, HVAC, deck equipment such as the free-fall lifeboat and other equipment can be removed [38]. With these systems not being needed, money be-

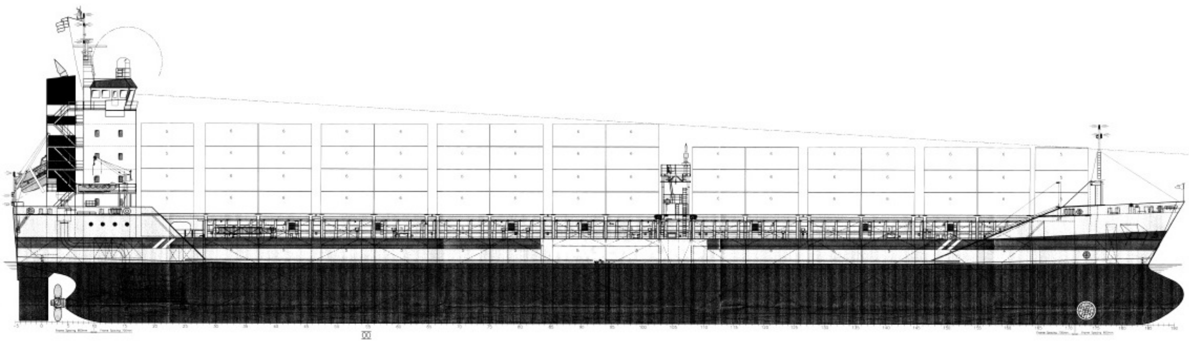


Figure 5.1: The reference ship, type M-Borg, sailing from Rotterdam to Halifax

comes available to invest in solutions to increase the reliability of the machinery. Research showed that making a ship unmanned affects half of the steps in the design spiral [38]. For the steps total deadweight, lightweight, powering, machinery selection and general arrangement cost calculations have been performed. It was found in that research that for the reference ship, approximately €2,000,000 can be saved when the ship is made unmanned.

There are three types of costs related to a possible solution: capital costs, voyage related costs and operational costs [97]. The capital cost of the machinery is the money that is initially required to buy the machinery that is installed. Operational costs are those that are actually needed to run the ship. It is part of the costs that are independent of the voyage, which are for instance the following: crew salaries, maintenance, repair and insurance. The voyage related costs are different from the operational costs. Operational costs take care of the running of the vessel, whereas the voyage related costs are costs that are induced by the voyage. These voyage related costs are: fuel, port fees, canal fees, pilots and cargo handling.

When the same amount of money is spend on an unmanned ship as on a manned ship, the ships are financially competitive. The operational and voyage related costs are likely to be different for the unmanned ship, especially since crew costs will change significantly. Costs such as repair, insurance, port fees, canal fees, pilots and cargo handling are though very likely to remain the same. The total benefit of the change of these costs is not known, but since owners do not want high investment costs, it can be said that when the same amount of money is spend on an unmanned ship as on a manned ship they are financially competitive. The found two million euro is though not solely available for machinery solutions. Other equipment is also required when the ship is made unmanned. Equipment to create situational awareness, equipment that replaces the duties of the crew and a shore control station are all necessary for the unmanned ship [38]. Some of the two million euro therefore has to go to these systems. It is not precisely known how much of the available money can be spend on machinery solutions, but the ballpark figure is known. When the costs of all solutions are determined, it can easily be seen whether the cost of the solutions is close to the budget or that they are far too expensive.

When comparing the cost of the solutions, this will mostly be done by comparing the capital cost. The capital costs will be determined by rule of thumb equations and are therefore not an exact value. Only when necessary will the operational and voyage related cost be taken into consideration.

5.3. Cost Of Main Engine Solutions

The found main engine solutions apply to all main engine failures. Three solutions have been found as a possibility to solve the failures with unknown distribution, starting, reversing and regulating device failures, standard failures and turbocharger failures. Installing more engines as a full-backup, dividing the power over multiple engines or installing a power take in as a backup have all been found increase the MTBF by 182,450 years. First, the cost of installing an extra engine will be determined, then the cost of dividing the power over multiple engines and then, the cost of a power take in as a backup is determined. Finally, it will be concluded which main engine solution is the cheapest and if this also is the best solution. The power in the reference ship is provided by a Wärtsilä 8L32 engine, which generates 5,280 kW of power.

5.3.1. Cost Of Full-Backup Solution

The full-backup solution involves installing a second Wärtsilä 8L32 engine. In this case, more power is installed than is required for normal operation. When one of the engines fails, the backup engine will be started to take over for the first one. The speed of the ship will then not have to be reduced and service can be resumed as before the engine failure.

When two engines are placed in the ship instead of one, this will have an effect on the layout of the engine room. The drive train of the reference ship consists of one engine which is connected, through a gearbox, to a controllable pitch propeller (CPP). All these components are in line with one another. When two engines are installed, those will need to be placed next to each other, with sufficient spacing to allow maintenance. Placing them in line would require a longer engine room, which costs cargo space and is therefore not an option. When the engines are placed next to one another, it is likely that they need to be installed higher in the ship than the single engine. This is due to the geometry of the aft body of the ship. The shape of the ship could also be changed in order to accommodate for two engines. Extra engine foundation is necessary to support both engines. They will still be connected with the CPP through a gearbox. Two shafts will thus enter the gearbox and one shaft will leave the gearbox. Because only one of the engines will be running at all times, the size of the gears can remain the same since the maximum power to be transferred through the gearbox is the same at all times. The only design change to the gearbox is therefore the change from one to two entry shafts. From the gearbox to the CPP, the shafting will remain the same in case two engines are installed. Extra piping and wiring is needed when installing a second engine since the original piping and wiring is only suitable for one engine. More piping and wiring thus have to be installed in order to guarantee that both engines have access to for instance fuel, lubrication and cooling water. This increases the need for space in the engine room. The changes to the engine room are only stated here to get an impression of the design changes but are not put into new drawings of the engine room. For this thesis, it is interesting to know the cost of the solution and the changes that occur due to this solution, but the detailed design of these changes falls outside the scope.

The extra engine costs money, as well as the extra structural foundation and the required extra piping and wiring. The gearbox might also be a little bit more expensive due to the extra inlet shaft. If all these costs are determined, it can be found what the cost of this solution is. It can be found that $\$4,700 \times P^{0.79}$ is a rule of thumb for the entire power generation system, in which P is the installed power in kW. This rule of thumb also includes the cost of the fuel system, lubricating system, cooling system, air system and exhaust system [2]. A substantial part of the cost of the power generation come from these named auxiliary systems. The provided rule of thumb of $\$4,700 \times P^{0.79}$ can thus not be used directly since only the cost of the main engine has to be known. The same research also provides another rule of thumb, namely \$200 to \$300 per kW of power [2]. For a first quote of the engine price, the average of \$200/kW and \$300/kW can be used, \$250/kW. This does however not take into account the price of equipment that also changes and the found relationship of engine power to the power of 0.79. The other costs that are induced due to the change of the engines are estimated at \$50/kW, so the engine cost combined with the cost of the changes equals the upper limit of the engines, \$300/kW. For a 5,280 kW engine, this would mean a cost of \$1,584,000. Using this value, the coefficient of 4,700 in the power generation cost formula can be recalculated for only the main engine and its changes. The formula that includes the power 0.79 is thought to be more precise since this accounts for the fact that large engines are relatively cheaper. Knowing that the engine has a size of 5,280 kW and costs \$1,584,000 with the simple rule of thumb it can be found that the new coefficient is 1,618, which is rounded to 1,600. The formula that will be used to determine the cost of the engine plus the cost of the design change is thus $\$1,600 \times P^{0.79}$. It is not known in which year these rule of thumbs have been determined, so inflation cannot be taken into account.

Having determined a rule of thumb, the cost of the full-backup solution can be determined. Two engines of 5,280 kW are installed. For each of these engines it can be found that they cost \$1,396,371, so together they combine for a cost of \$2,792,742. It is not known for which year these numbers have been established, so the corresponding exchange rate is not known. The exchange rate of today[4] is therefore taken in order to find that €1,244,865 is the extra cost due to the second engine. The budget for solutions is €2,000,000 so this solution falls within the budget, although it already uses 62% of it.

[4] 23 September 2016, \$1.00 = €0.8915 [106]

5.3.2. Cost Of Dividing Of Power

When the power is divided, two smaller engines are installed which combine for 5,280 kW of power. Each engine thus delivers 2,640 kW. When one of the engines fails, enough power is available to continue the route of the ship. Since the power is reduced, the speed will drop. Due to the third power relation of speed and power, the speed will still be significant when 50% of the power remains, which can be calculated with the following formula [90]. A reduction of the power to 50% is the result of one engine failure, when two engines are installed.

$$P_E = c_1 * v_s^3 \tag{5.1}$$

In which

P_E Effective towing power [W]

c_1 Constant

v Ship speed [m/s]

When the power in Equation 5.1 is chosen to be a 100% and a speed of a 100% is assumed for v, it can be determined that c_1 is equal to 1.0. If the power is reduced to 50%, it can be determined with the known value of c_1 that the new v is 79.4%. This means that when the ship only has 50% of the power remaining, it can still sail on 79.4% of its initial speed. A speed of 79.4% of the initial speed should be sufficient to proceed with the service of the ship.

The same equipment changes when the power is divided as would when the full-backup solution is applied. Since the engines with less power are smaller, their position in the engine room might be a little different compared to the backup solution, however this is only a minor detail. It was previously determined that the cost of an engine is $\$1,600 \times P^{0.79}$. The price of two 2,640 kW engines can thus be found as $1,615,166 or €1,439,920. This is an extra €195,056 on top of the original installation. Since this solution only uses 10% of the budget, it fits perfectly into the budget.

5.3.3. Cost Of Power Take In

In this Subsection, it will be determined what the cost of the power take in solution is. The power for the power take in can come from either a diesel engine or a battery pack. First, the cost of a diesel engine as a PTI will be determined, after which the cost of a battery pack will be calculated. Before this can be done, it will have to be determined what size the power take in will have to be in order to get the ship to shore. For the dividing of power it was determined that 50% of the power would lead to a speed of 79.4% of the initial speed. For the power take in it is assumed that it has to be of sufficient power in order to realize a speed which is 50% of the original speed, namely 7 knots. It is assumed that with this speed, the ship is still able to continue its route and sail to shore, though with a significant delay, or sail to the nearest port in order to get the problem fixed. For further research it might be advisable to determine whether 50% of the speed is enough to reach shore. The solution of a PTI is one in which the ship is not always at the desired port after a failure has occurred. The corresponding power with a speed of 50% is found to be 12.5%, which is 660 kW.

Diesel Engine As PTI

The cost of an extra engine of 660 kW can now be determined with the previously shown equations. A 660 kW engine is small, so this engine might be placed a little off centre on the side of the shaft that leaves the gearbox. This would mean that the main engine can still be placed on the centreline and that the change in the engine room is rather small. With the previously shown rate for the engine price it can be found that a PTI has an additional cost of €240,814, or 12% of the budget of €2,000,000. This solution thus fits within the set budget but it is more expensive than the previously solution and its result is less satisfactory.

Battery Pack As PTI

The power take in can also be powered from a battery pack. In order to determine the cost of this solution, the needed capacity of the battery pack has to be determined. Knowing the time to get to the nearest port and the required power to do so makes it possible to determine the capacity of the battery pack. When sailing on the PTI, the ship sails at half the initial speed. The reference journey was found to be 3,150 nm. A failure can occur at any time during this journey. The worst case scenario is when the ship is around halfway during the voyage. At this point the distance to shore is the longest, namely 1,575 nm. When the ship has not yet sailed 1,575 nm it is closest to the port of departure and will therefore return to this port. If the ship has already sailed over 1,575 nm, it will continue its route to the port of arrival. The moment of the failure thus dictates whether the cargo will only be slightly delayed, or if the delay is significant. Returning to the port of departure after a failure is the worst case scenario.

A trip of 1,575 nm at 7 knots takes 225 hours. Knowing that 660 kW is required for propulsion, it can be found that 148,500 kWh is required when the main engine fails halfway during the voyage. In 2015, Tesla predicted its lithium-ion batteries could have a price of $100/kWh by 2020 [23]. The current prices of batteries are higher, but for now this value is assumed. Although being the price for the battery in a car, this number is workable in order to determine whether the cost of a battery pack is financially feasible. At a cost of $100/kWh, it can be found that the battery pack would cost $14,850,000 or €13,238,775. The cost of a battery pack obviously does not fit within the budget of three million. The solution of a PTI being powered by a battery pack is thus not a competitive solution. The price of batteries has to decrease drastically before the price of a battery pack comes close to the budget. Since the price of the battery pack is so far out of the budget, it has not been determined how much weight the batteries would add to the ship. Another type of battery than the lithium-ion batteries might also be used, for instance a lead-acid battery. But even if this proves to be a little cheaper, it is still far too expensive as a solution.

5.3.4. Conclusions On Cost Of Main Engine Solutions

With the costs of the individual solutions known, it can now be determined what the cheapest solution is and which solution is the best. Table 5.1 shows for each solution what it costs and what the speed of the ship after a main engine failure is as a percentage of the initial speed.

Table 5.1: Main engine solutions: cost and speed after failure

Solution	Cost of solution [€]	Speed after failure [%]
Full-backup engine	1,244,485	100.0
Divide power	195,056	79.4
Power take in		
• Diesel engine	240,814	50.0
• Battery pack	13,238,775	50.0

From Table 5.1 it can be seen that the cost of a battery pack as a PTI is by far the most expensive solution. Being the only solution that does not fit within the budget it should not be chosen. It can also be seen that the cost of the full-backup solution is the highest of the solutions that do fit within the budget. This was to be expected since the required power is installed twice and one of the engines is only used in case of emergency. This solution though guarantees that the speed of the ship does not have to be lowered after a failure. The option to divide the required power over two engines can be found as the cheapest solution, only €195,056. It also guarantees a speed of 79.4% of the initial speed. This solution can therefore be concluded to be the best solution to prevent a fatality. The PTI would achieve a speed that is lowest of all solutions and it is also comes second regarding cost, when choosing the diesel engine option, and is thus not a better solution than to divide power over the engines.

Since the result of the cost of the solutions is highly dependent on the assumed formula, it will have to be investigated how the results of the cost calculation differ if a different value in the formula is used. If the determined value of 1,600 for the formula is actually twice as high, 3,200, a different result will be found. With a formula of $\$3,200 \times P^{0.79}$ it can be found that dividing the power over two engines is still the cheapest, but now costs an extra €390,111. This solution then costs 20% of the budget, instead of the previous 10%. It can thus be seen that although the formula is changed significantly, the cost of this solution still fits within the budget. Even when the original rule of thumb of $\$4,700 \times P^{0.79}$ is used, only 19% of the budget is required to install this solution. From the two scenarios in which the parameter in the cost formula was increased it can be found that the parameter does not influence whether a solution fits within the budget or not. In case the cost of the entire power generation system is used as the cost for the main engine solutions, the best solution is still only 29% of the budget.

If the considered ship would have a different engine size, the result of the cost calculation would be different. The drawn conclusion would though be the same. When a ship with a smaller engine size was to be considered, the cost of the solutions would lie closer to one another and the differences will thus be smaller. For a ship with a larger engine, the costs of all solutions would be higher and the differences between them larger. In all cases, the full-backup engine will be the most expensive, followed by the power take in. The option to divide the power over multiple engines will always be the cheapest. Since it only costs 10% of the budget in this case, it can be said that this solution can be applied.

Before the 195 thousand euro is invested in the ship, a fatal main engine failure will occur once almost every three years. After the investment, a fatal technical failure due to two engine failures during the same voyage is once every 182,450 years. So this is just over an euro per extra year between failures.

5.4. Cost Of Steering Gear Solutions

For the steering gear failures, the solutions to split the steering gear into separate systems or to install a stern thruster as a backup have both been found as a solution with a high reliability improvement. The cost of these solutions will therefore be investigated in the following subsections. First, the cost of two steering gear systems is calculated after which the cost of a stern thruster will be determined. Then, it can be concluded which solution is the best solution to increase the steering gear reliability.

5.4.1. Cost Of Splitting The Steering Gear Into Separate Systems

When two steering gear systems are installed, this will have a significant effect on the design of the ship. In the design of the reference vessel one controllable pitch propeller (CPP) is installed, together with one rudder. If two sets of steering gear are installed, this means that two rudders are installed, while only one propeller is present. Both rudders will thus be placed off centre in order to guarantee a symmetrical steering. Placing both rudders off centre causes them to no longer be in the direct wake of the propeller, which lowers their steering capacity. This is because the speed of the water behind the propeller is higher than outside the slipstream. When a ship owner decides to apply this measure, it will have to be calculated how large the rudder area will have to be when they are placed in water with a lower velocity. Using the following formula, the rudder area for a configuration with two steering gears can be determined [20]. The lift of the rudders has to be same for both configurations in order to have the same manoeuvrability.

$$L = \frac{1}{2} C_L \rho A V^2 \tag{5.2}$$

In which

L	Lift force [N]
C_L	Lift coefficient [-]
ρ	Density of the fluid, 1,025 for sea water [kg/m^3]
A	Rudder area [m^2]
V	The free stream incident velocity [m/s]

It can be seen from Equation 5.2 that when the speed of the water is for instance half of the speed as in the initial configuration, the rudder area has to be four times as high in order to have the same lift. Since the drag formula for the rudder is $D = \frac{1}{2} C_D \rho A V^2$, with D the drag force [N] and C_D the drag coefficient [-] it can be seen that the drag of the rudder will remain the same. Increasing the size of the rudders therefore does not have a negative effect.

It is not known what the speed of the water is after the propeller in the reference configuration. Since it is also unknown what the speed of the water at the rudder will be in the new arrangement, the new size of the rudders cannot be determined. The speed of the water at the rudder will have to be determined for both configurations with a hydrodynamical analysis, which falls outside the scope of this thesis.

Knowing what the effect of a second set of steering gear is makes it possible to determine the cost of the second steering gear. Based on an actual quotation, it is found that the cost of one set of steering gear, including rudders, is found to be €50,000 in 2012 for a ship sailing on inland waters [45]. A quotation for a steering gear of an ocean going vessel is likely to be different, but a better number is not available. With a price of €50,000 it is only 2.5% of the budget, so if the actual price is twice as high, it would still only be 5% of the budget. The working principle of the steering gear is the same for inland ships as for ocean going ships so that is not a problem. Since the forces on the rudders of ocean going ships are likely to be larger, the steering gear is likely to be larger and therefore more expensive for ocean going ships. The first set of steering gear will also become a little more expensive in a two rudder configuration since the rudder will be larger. It is though assumed that the extra cost due to the increase of rudder area is negligible compared to the cost of the steering gear. The total cost of an extra steering gear is thus found to be €50,000 although it has to be stated that this is probably on the low side.

5.4.2. Cost Of Installing A Retractable Stern Thruster As A Backup

Installing a stern thruster is done next to the controllable pitch propeller that is already present. With the CPP placed on the centreline, the stern thruster can only be placed on the centreline with great difficulty. There is hardly any space to install it since it cannot be placed in front of the CPP, and installing it in between the propeller and the rudder is also not an option, due to the limited space. The only option to place the stern thruster on centreline is by placing it behind the rudder. This might be challenging in the design of the machinery though since the rudder will then have to be placed forward in order to allow this design.

Another option is to place the stern thruster off centre. It would then be placed either on port or starboard side of the ship. When the steering gear fails, the stern thruster is lowered and this will then provide steering by turning the thruster. With it being placed off centre, it will constantly have a steering effect, when in the zero position. In order to neutralize this steering effect, the stern thruster can be placed at an angle or the bow thruster can be used to compensate the yaw effect that is created by an off centre stern thruster.

When the steering gear fails, the stern thruster will not have to deliver the full 5,280 kW of propulsion power. After all, the propeller remains functional in case of a steering gear failure and is therefore still able to perform its task. The stern thruster only needs to deliver the power that is required to be able to manoeuvre the ship. The required power is assumed to be equal to the size of the bow thruster, 650 kW [84]. Since the stern thruster is located almost at the very end of the ship, it has large leverage and therefore much steering effect. Especially since the stern thruster can be placed at -90/90 degrees, which a rudder would not be able to do. When the full power of the stern thruster is used, this power is no longer available for propulsion. A total of 4,630 kW would thus remain available for propulsion, assuming that the bow thruster and stern thruster always combine for a maximum of 650 kW. With 4,630 kW of power being available for propulsion, a speed of 95.7% of the initial speed can be sailed, so steering with a stern thruster only has a small influence on the performance of the vessel.

For the price of a propeller (and shafting), several rules of thumb are available. These rules of thumb depend on the type of propeller and the required operating speed of the propeller. For a fixed pitch propeller, €55/kW can be used for propellers operating at a 100 rpm, whereas €65/kW should be used for propellers with a speed of 250 rpm. For controllable pitch propellers, which are more complicated, values of €70/kW for 100 rpm propellers and €110/kW for propellers of 250 rpm can be used [25]. A stern thruster, especially one that is retractable is a complicated piece of machinery. The stern thruster is most likely to be of a fixed pitch configuration. Due to the complexity of the equipment to make the stern thruster retractable it is chosen to assume the average value of the CPP propeller cost. These propellers are most sophisticated and their rules of thumb are therefore more likely to represent the actual cost. An average value of €90/kW makes that the cost of the stern thruster is €58,500, a value that falls inside the budget. These rule of thumb values do not include the electric motor of the stern thruster. The previously determined price will therefore be doubled in order to accommodate for the cost of the electric motor. This brings the total cost to €117,000, still only 6% of the available budget. The cost calculation of both steering gear solutions can thus be found to be relatively rough.

5.4.3. Conclusions On Cost Of Steering Gear Solutions

For both individual steering gear solutions it has now been determined what their cost is. The cost and impact on the design can now be compared for both solutions in order to determine what the best solution is. Splitting the steering gear into two separate systems results in an additional cost of at least €50,000. It also dictates that the rudders will become larger, but this does not have extra drag as a consequence. Installing a stern thruster has a more drastic effect on the design, due to its placement. The cost of the stern thruster was estimated at €117,000.

The cost of both solutions fall perfectly into the set budget of €2,000,000 so both of them are an option within this budget. Even when the costs are twice as high in reality they are well within budget. It can be seen that the cost of two steering gear systems is smaller than the cost of installing a stern thruster. Due to the rule of thumb calculations and the quote of the steering gear, it is difficult to say how accurate these calculations are. Choosing the best solution based only on the calculated cost would therefore not be wise, especially due to the small difference. Also taking other arguments into account, such as the operational practicalities, may therefore be the better option. Splitting the steering gear involves two rudders, which are both operational at all times. Both sets therefore need to be maintained at the same interval. This solution thus requires extra maintenance compared to the stern thruster. The stern thruster is namely only lowered when the steering gear has failed. With fewer operating hours, it needs little maintenance. On the other hand, the placement of the stern thruster is difficult. For a Wärtsilä thruster it is found that ten minutes are needed to retract the thruster [103]. Depending on the case, this might be too long in order to get the ship operational again.

Considering that the stern thruster can be placed behind the rudder, so on the centreline, it is chosen as the best solution. Although it is a little more expensive, it has the least effect on the ship design. Installing two sets of steering gear requires two larger rudders, which are operational at all times. With a stern thruster installed, one small rudder can still be used in high velocity water instead of two large rudders in low velocity water. The time to retract the stern thruster is the only real downside of the stern thruster, but this can be considered acceptable. In cooperation with a manufacturer it is maybe possible to design a stern thruster with a shorter retraction time.

One of the other reasons to choose for the stern thruster instead of two steering gears is that the stern thruster also provides a backup solution if the shafting fails. If the shafting fails, the ship is no longer able to propel itself since it cannot use the installed CPP. The stern thruster was estimated at 650 kW, which is enough to propel the ship at almost 50% of its initial speed, as was found when designing the PTI. So choosing the stern thruster instead of two steering gear systems solves an extra failure.

5.5. Cost Of Fuel System Solutions

The solutions to keep fuels from different locations separate and/or to keep different types of fuel separate were found to be the third best solution reliability wise and are therefore investigated financially. These solutions can be seen as one solution since they both require two separate fuel systems. The cost of an extra fuel system is thus the additional cost for these solutions.

When two fuel systems are being installed, they can both have half the capacity of the initial fuel system. This means that the volume of the fuel bunker tanks does not have to be altered. After all, they still have the same capacity together. One of the only changes is that there should be two places where fuel can enter the ship. This way, fuel from different locations enters different bunker tanks. When in the tanks, the fuel should not come in contact with the other fuel before entering the engine. It was found that splitting the power of the engine over two engines increases reliability. The engine solution and the fuel solution can therefore be combined. Each engine can have its own fuel system. The only remark to this is that there has to be a valve that somehow connects both systems. This would allow one fuel system to fuel both engines in case of a fuel system failure. A failure in the fuel system should not lead to a 'loss' of a main engine and therefore speed. This valve would also allow that the system with the least fuel is emptied first and that then the fully bunkered fuel system can be used. The empty system could then be cleaned in order to get ready for new bunkers. Although one would not want to have a connection between both fuel systems, it is necessary for practicalities. Placing this valve as close to the engines as possible reduces the risk of a failure due to the mixing of fuel.

The cost difference within the fuel system is found to be piping, separators, filters and pumps. No changes to the tanks are needed. Extra separators, filters and pumps are needed in order to make those redundant. Since so little adaptations are needed it can be said that the additional cost of two fuel systems compared to one fuel system is very small. The cost of the extra separators, filters and pumps will be accounted for in the cost of the piping. It has to be estimated how much extra piping is needed in order to determine the cost of this solution.

The material cost of one meter of pipe is found to be €25 [56]. It is unknown how much length of pipe needs to be added in order to make two individual systems. As a first assumption it is assumed that twice the length of the ship is needed on top of the already existing piping infrastructure. With the ship having an overall length of 134.5 meters, this would mean that 269 meters of piping is added. Assuming that the cost of man-hours is the same as the material cost means that one meter of pipe costs €50, which would make that €13,450 is the cost of the extra 269 meters of pipe.

Since the cost of €13,450 is highly susceptible to the assumption of the length of the extra piping and the cost of man-hours, it will have to be determined what the cost would be if these factors change significantly. If the required piping would actually be five times as high as assumed, a higher cost for this solution would be found. This solution would then cost 67,250 euro, which still fits perfectly within the set budget of €2,000,000 since it is only just over 3% of the budget. If the cost of the man-hours would be doubled as well, it would cost €100,875 for this solution to be installed. This is still only just over 5% of the original budget and therefore acceptable. Because the cost in case of the extreme conditions are still safely within the budget it can be said that the made assumptions do not influence the conclusion that can be drawn regarding implementing this solution.

The entire reliability improvement due to these solutions can though only be gained when one type of fuel is used. When two types of fuel are used, they can be separated in different systems, but fuel from different locations will then still have to be stored together. Keeping fuel from different locations separate was found to give a higher reliability improvement than keeping different types of fuel separate. It is therefore needed to sail on one type of fuel, unless four fuel systems are installed, but this would make the total fuel system unnecessarily complex and expensive. Having one type of fuel in order to increase reliability will also increase voyage related costs. A cleaner and more expensive fuel has to be used, otherwise the sulphur limits for the emission control areas cannot be met. The reference route for this ship is Rotterdam - Halifax. Both ports lie in an emission control area, so clean fuel needs to be used. Since the voyage related costs will increase due to sailing on the more expensive fuel, it will have to be investigated what the additional voyage related costs of this solution are.

The current price of heavy fuel, IFO380, is found to be \$246.50/mt [88]. IFO380 is a fuel with a maximum of 3.5% sulphur content. The cleaner ultra low sulphur fuel oil (ULSFO), is found to cost \$383.00/mt and has a maximum of 0.1% sulphur content [89]. The price for both fuels has been based on the price of a metric ton of fuel in the Port of Rotterdam, as of 27-09-2016. In order to determine the price difference for a journey from Rotterdam to Halifax, the fuel costs for both types of fuel has to be determined.

The reference ship has a speed of fourteen knots [84]. With the known distance of 3,150 nm it can be determined that the journey takes 810,000 seconds (225 hours). The required energy for a one way trip from Rotterdam to Halifax can then be found by multiplying the engine power with the duration of the journey.

$$E = P \times t \tag{5.3}$$

In which

- E Required energy [kJ]
- P Engine power [kW]
- t Duration of the journey [s]

The required energy is found to be 4,276.8 GJ, with Equation 5.3 for an engine running at 100% efficiency. Since an engine operates at an efficiency of around 50%, the actual required energy can be found to be 8,553.6 GJ. Dividing the required energy by the calorific value of the specific fuels makes it possible to determine the weight of the required fuel.

$$m_f = \frac{E}{h^L} \tag{5.4}$$

In which

m_f Required fuel [kg]

E Required energy [kJ]

h^L Calorific value of fuel [kJ/kg]

For IFO380, a calorific value of 40,000 kJ/kg is found [105]. A value of 44,094 kJ/kg is stated for ULSFO [12] It can thus be found that for a one way trip Rotterdam - Halifax respectively 214 tonnes and 194 tonnes of IFO380 and ULSFO are needed. This brings the cost for the heavy fuel to $52,712 or €46,992 and $74,298 or €66,236 for the cleaner fuel. It can thus be seen that using ULSFO leads to about 40% extra voyage related costs, when sailing outside an emission control area. Inside the emission control area, they have the same cost. The heavy fuel is found to cost €14.9 per mile whereas the low sulphur fuel is found to cost €21.0 per mile at a speed of fourteen knots.

It is determined that the cost of the solution to keep fuels from different locations separate and to keep different types of fuel separated is €13,450. Since this solution dictates that only one type of fuel is used, namely the more expensive ULSFO, it is found that the ship will have 40% higher voyage related costs when sailing outside an emission control area. If the ship were to sail 24/7 all year long, it runs 8,760 hours a year, which are 39 journeys from Rotterdam to Halifax or vice versa. At 40% higher voyage related costs, this would mean that operating solely on the cleaner fuel costs €750,516.

5.6. Conclusion

For each group of failures, the best solution has been determined. For the main engine failures, this was the solution to divide the power over multiple engines, for the steering gear failures it was found that installing a stern thruster is the best solution. Keeping fuel from different locations separate was found to be the best solution for the fuel system failures. The cost of these solutions can now be checked as a whole within the available budget. Knowing which failures are prevented within the budget makes it possible to determine what the reliability improvement of these solutions is and what the new failure rate of the system is. For the shown values in Table 5.2 all systems have been taken into consideration. Since the steering gear solution to install a stern thruster also helps to reduce the failure rate of the shafting, this has also been taken into account. Ice can be expected on the route of Rotterdam - Halifax, so the failure rate of ice that gets stuck in the seawater inlet cannot be assumed not to be present [73].

Table 5.2: Best solutions per system, together with their price, reliability improvement and new failure rate

System	Best solution	Price [€]	Reliability improvement [yrs]	New failure rate
ME	Dividing the power over multiple engines	195,056	182,450	6.3×10^{-10}
SG	Install a stern thruster as a backup	117,000	5,200	2.4×10^{-10}
FS	Keep fuels from different locations separate	13,450	1,364,800	8.4×10^{-11}
Total		325,506	3.7	2.4×10^{-5}

From Table 5.2 it can be seen that for 326 thousand euro an increase of the mean time between failures of 3.7 years is achieved. Before the solutions are applied, the ship has a MTBF of 1.1 years. With the solutions, this is increased to 4.8 years. A MTBF of 4.8 years still means that during a lifetime of 25 years a ship will be struck by a fatal technical failure a little over five times. So although the mean time between failures is significantly improved, more solutions are necessary in order to have ships with a higher MTBF. The achieved 3.7 years cost €325,506 so a one year increase of the MTBF costs just under 88 thousand euro. If the cost of all solutions is assumed to be equal this means that for the initial budget of two million, the MTBF can be increased by almost 23 years. This can though not be realized in reality since some money also has to go to the other equipment that is needed to make the ship unmanned. It was also found that the price per MTBF for the different solutions was quite different, varying from €0.01/yr to €22.5/yr. The calculation of 88 thousand euro per year of MTBF increase though shows that with the available budget it is possible to create a ship that is much more reliable than is currently sailing the oceans.

The price of €325,506 is found to be only 16.3% of the budget of €2,000,000 so the price of the solutions stays well within budget. If the price of the solutions was in reality found to be for instance twice as high the costs are still well within budget. This shows that although there are a lot of assumptions made regarding the cost of the solutions, their price will always fall within budget. Even when the cost of the solutions are five times as high in reality, the costs fall within budget. This shows that the best solutions can always be applied and depending on the cost of the other solutions, more solutions might be installed.

6 Conclusion

It has been investigated whether it is possible to increase the reliability of ship machinery, since more reliable machinery is a step towards unmanned shipping. Solutions to machinery failures have been generated in order to answer the following research question '*What are the machinery related problems regarding an unmanned engine room? How to solve these problems such that the reliability is equal or better compared to the manned engine room while being financially competitive at the same time?*'. In order to answer this research question it has been investigated what type of machinery failures occur and how those should be solved such that the reliability of the machinery increases. Although it has to invest in these solutions, the unmanned ship has to stay competitive with the manned ship.

It was found that the fatal technical failures occur to the main engine (38.7%), steering gear (20.9%), fuel system (11.1%), electrical system (8.9%) and cooling water system (8.4%). Failures also occurred to the shafting (6.7%), diesel generator (6.7%) and other systems (1.7%), but the failures in these three systems have not been taken into consideration since the five systems with the highest failure distribution are responsible for nearly 90% of all failures. Solving these failures first therefore has the largest effect. The failures were recorded in German waters during six years and all lead to a fatal technical error. When investigating the causes of the failures, it was found that human error and improper maintenance were both named as the cause of a failure multiple times. Human error was found to be responsible for 18.7% of all failures and improper maintenance for 19.3% of all failures.

With the failures known, solutions could be developed. Three types of solutions were generated: maintenance, redundancy or an alternative. Since maintenance was found to be responsible for almost 20% of all failures, performing better maintenance therefore might increase reliability. Adding redundancy ensures that the ship is still operational (although possibly with limited performance) such that it can reach shore on its own. Alternative solutions were generated if those seemed to have a higher reliability. Combinations of solutions were also found as possibilities. All solutions that were found to have a higher reliability than the initial solutions were determined to be a possible solution in order to increase the reliability of the machinery.

Of the possible solutions, it has been determined what the reliability improvement is. In order to do so, the failure rate of the ship and the mean time between failures (MTBF) had to be determined. It was found that the failure rate of the ship is 1.0×10^{-5} and that it has a corresponding MTBF of 1.1 years. With the failure rate known it could be determined what the reliability improvement of all solutions is. Three groups of solutions were found as having the highest reliability improvement, namely main engine solutions, steering gear solutions and fuel system solutions. It was found from the reliability improvements of all solutions that only doing better maintenance has very little effect on the mean time between failures. The MTBF would only increase with half a year if better maintenance is performed. Combining two solutions in order to increase reliability is also not necessary. The redundancy solution already has significant impact for most solutions. Applying another measure upon the redundancy measure is therefore not required.

In order to determine which of the solutions with the highest reliability has to be chosen it has to be determined what they cost. Knowing what the cost of the solutions is helps to determine whether applying the solutions keeps the unmanned ship financially competitive to the manned ship. From previous research it was found that €2,000,000 is available to install measures on an unmanned ship.

For the failures in the main engine it was found that dividing the power over two engines is the best solution, costing €195,000. Installing a stern thruster as a backup was found as the best solution to solve the steering gear failures, at €117,000. The third best solution reliability wise is in the fuel system. Keeping fuels from different locations separate was found to cost €13,450. Only downside of this fuel system solution is that the voyage related costs increase with 40% when sailing outside an emission control area since only one type of fuel is used. For a year of continuous sailing, this would mean an added cost of €750,516. The three solutions together increase the mean time between failure with 3.7 years (from 1.1 years to 4.8 years). Their price of €325,506 stays well within the budget of two million euro. This shows that there is still enough money left to invest in other machinery solutions or to buy other required equipment.

It was found that it is possible to increase the reliability of the ship machinery, redundancy measures are found to have most impact. For the five considered systems almost all failures can be prevented since there is only a very small remaining failure rate. In order to increase the reliability of the ship further, solutions to the systems with the least failure distribution though also have to be developed. For the solutions with the largest reliability improvement it was found that the cost of their solutions would keep the ship competitive with the manned ships when looking at the capital costs. Improving the reliability of the ship is therefore possible without interfering with the competitiveness of the ship.

6.1. Recommendations

Failure Data

This thesis is mostly based on the recorded machinery failures in German waters, of which the data of six years is known. For future work it is interesting to get more knowledge of the failures that occurred. Failures with unknown distribution are responsible for 46.8% of all failures. Since no exact numbers of these failures are known, it is difficult to determine the reliability improvement of their solutions. Sometimes it is not even known which failures are part of these groups. The failures with unknown distribution might come from human error, but it can also be a large group of failures which has been unrecognised. Having more detailed data, preferably from more years and more locations, will help to better identify which failure causes are the largest. The availability of maintenance reports for these vessels might help to determine the age related causes of the failures.

It is also not known to what type of ships these failures occurred. Some ship types have been excluded from this research, but their failures might be beyond the recorded failures. Therefore, for future research, it is interesting to know to which ship types these failures occur . When it is also known what the machinery configuration of these ships is, this will provide better insight in the failures. It might be the case that a four-stroke engine is much more reliable than a two-stroke engine, but this cannot be told from the available data. More details on the ship type, configuration of the machinery, machinery redundancy and specific cause of failure are necessary to come up with more accurate solutions and therefore reliability calculations. Determining ship specific failures is also something that might be interesting for future work. Only the ship types which all are roughly equal and have little machinery have been included. Other ships such as gas tankers or Ro-Ro cargo ships can also sail unmanned in the future, but in order to increase their reliability more has to be known about their specific failures.

Job Of Crew

For future work it is also interesting to know what the crew actually does on board the vessel and how often they have to react to a possible cause of failure. Knowing what type of failures they prevent, or which failures they induce, will help to get a better insight in what the effect is of removing the crew.

Failure Rate

The failure rate in this thesis is also based on the reports by the German Ship Safety Division. If more accurate data is known of the failures, a more accurate failure rate can be determined. Knowing the failures that occurred in redundant systems will help to improve the accuracy of the failure rate. When the reports do not help to increase the accuracy of the failure rate, other data to increase the accuracy of the failure rate can be used. Failure rate databases such as the military handbook (MIL-HDBK), offshore & onshore reliability data (OREDA) or FIDES can be used to get a more accurate failure rate and mean time between failures. When a more accurate failure rate of the ship machinery is determined, it might also be possible to have a second view at whether there are more reliable main engines.

Required Level Of Reliability
In future work, it will also have to be determined what the required level of reliability is that one would want to achieve for an unmanned ship. This way, it would be easier to check whether a determined solution is a possibility or not. If it can easier be told whether a solution meets the required reliability, this limits the amount of work that has to be done.

6.1.1. If A Fatal Technical Failure Occurs

Although precautions have been taken to increase machinery reliability, a fatal technical failure can still occur. If this is the case, this will have a large impact on the operation of the ship. Due to this failure, the ship will no longer be able to sail to port using its own machinery. In order to realize unmanned shipping it has to be determined what the impact of a fatal technical failure is and how a ship can be retrieved after a failure has occurred.

The impact of a technical failure differs from area to area. Ships sailing close to shore usually sail in highly trafficked areas. There, a failure can thus have more impact than it would have if the failure occurred far offshore. The risk of an accident due to a fatal technical failure is much larger when close to shore than would be when far offshore. The rescue scenarios can therefore be put into two categories. The first category is a failure close to shore, the second one is a failure far offshore. The boundaries of an EEZ can for instance be chosen as the line between close to shore and far offshore. In all cases, the ship will have to send out a signal to notify surrounding ships of its new 'condition'. By notifying the nearby ships these can take extra care when passing the ship with failed machinery.

A Failure Close To Shore
When a failure occurs close to shore, the ship is likely to sail in a highly trafficked area. The risk of an accident is therefore high. If a ship suddenly has a technical failure, the other ships in that area might not have enough time to adapt to the new situation of this ship. Courses of ships intersect a lot in heavily trafficked area, so the chance of an accident is high. Especially a ship adrift in port would have disastrous effects due to the geometry of the port and the presence of many ships. When a failure occurs, the ship would have to drop anchor. Otherwise, it might run aground such that it becomes a salvage operation to rescue it. The location where the anchor is dropped is though not always an ideal location, but since the failure has occurred, it cannot sail to a different location. Its only two options are therefore to drop anchor or go adrift.

Since the ship is close to shore, the response time of a rescue team is small. When a failure has occurred, the ship can for instance be towed back to harbour, where the failure will be repaired. Another option is to put a repair crew on board the failed ship, either by ship or by helicopter. This repair crew can then fix the failure (if possible) and have the ship resume its business. Another option is to have a set of controls available on the ship for the repair crew. After they have fixed the failure, they can then sail the ship to shore. If a failure occurs close to shore, the impact of the failure can be large, but the ship can easily be retrieved. Different types of failures may require separate repair strategies. Not all failures may be possible to repair at sea.

A Failure Far Offshore
If a failure strikes the machinery of the ship, the ship will not be able to finish its route. It will be left adrift in the middle of the ocean, subject to wind and current. Anchoring is not an option in this case due to the depth of the water. Until help arrives, the ship will thus be subject to nature's influences. Due to the waves, the ship may start rolling, which might cause it to loose some cargo. The probability of an accident in the middle of the ocean is smaller when compared to coastal waters. On the wide ocean, there is more room to change the route. If a ship was to fail, the other ships can simply sail past it at a safe distance.

Ships close to shore can potentially be rescued with the help of a helicopter. The range of an Airbus H225® helicopter for instance has a range of 613 nm [4]. Since the helicopter might have to fly back to shore, for instance because no helicopter pad is available on the ship or if the weather is too rough to drop crew on board, only half of this range is available. So if a ship is more than 300 nm offshore, it can no longer be rescued with a helicopter. If the machinery has failed far offshore, a helicopter is therefore not a rescue solution. In order to rescue the ship, a ship would have to sail to the unmanned ship in order to perform a repair or to tow it to shore. This is an operation that requires a lot of time and will therefore be expensive.

Another option might be for the ship to be towed by another cargo ship sailing almost the same route. One ship should then be able to connect to the other ship. This can for instance be done by shooting a line from one ship to another, which can then be connected. Naval vessels already use systems to connect to one another when bunkering fuel at sea, so a small adaptation of this system may give it another application. This manned cargo ship that would sail in the direction of the failed ship could also be used to take a repair crew to the ship. This manned ship will already sail this route, so this solution is much cheaper than sending a vessel solely to rescue the unmanned ship. The impact of a failure of the machinery when far offshore can thus be said to be very small, but it is difficult to retrieve the ship. This can take days or maybe even weeks.

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A

Technical Failures in System Groups

Table A.1: Technical failures in the system groups for the years 2001 and 2002 [28]

System Group	Amount [-]		Percentage [%]		Both Years	
	2001	2002	2001	2002	Together	In %
Steering Gear	20	11	22.5	20.8	31	21.8
Main Engine	36	20	40.4	37.7	56	39.4
Diesel Generator	2	1	2.2	1.9	3	2.1
Shafting	8	3	9.0	5.7	11	7.7
Electrical System	8	4	9.0	7.5	12	8.5
Fuel System	7	10	7.9	18.9	17	12.0
Cooling Water System	3	4	3.4	7.5	7	4.9
Other	5	0	5.6	0	5	3.6
Total	89	53	100	100	142	100

Table A.2: Technical failures in the system groups for the years 2003 and 2004 [29]

System Group	Amount [-]		Percentage [%]		Both Years	
	2003	2004	2003	2004	Together	In %
Steering Gear	15	16	27.8	30.2	31	29.0
Main Engine	23	19	42.6	35.8	42	39.3
Diesel Generator	1	5	1.9	9.4	6	5.6
Shafting	3	4	5.6	7.6	7	6.5
Electrical System	4	2	7.4	3.8	6	5.6
Fuel System	3	3	5.6	5.7	6	5.6
Cooling Water System	4	4	7.4	7.5	8	7.5
Other	1	0	1.7	0	1	0.9
Total	54	53	100	100	107	100

Table A.3: Technical failures in the system groups for the years 2010 and 2011 [30]

System Group	Amount [-]		Percentage [%]		Both Years	
	2010	2011	2010	2011	Together	In %
Steering Gear	10	3	15	7	13	11.8
Main Engine	22	19	34	44	41	37.3
Diesel Generator	1	3	1	7	4	3.6
Shafting	4	2	6	5	6	5.5
Electrical System	7	7	10	16	14	12.7
Fuel System	12	5	18	12	17	15.5
Cooling Water System	11	4	16	9	15	13.6
Other	0	0	0	0	0	0
Total	67	43	100	100	110	100

B

Complete Initial Fault Tree

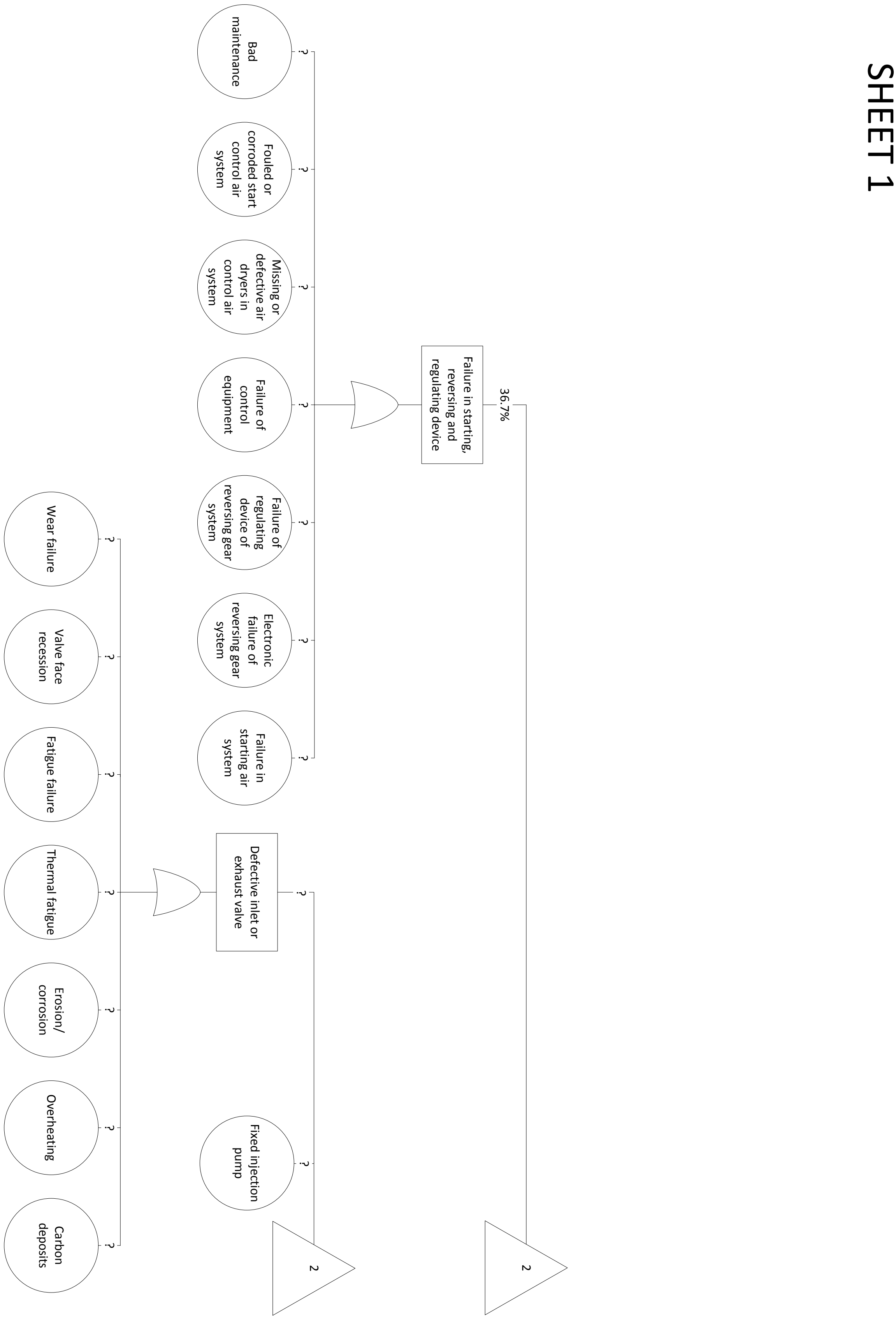

Figure B.1: Sheet 1 of 8 from the initial fault tree

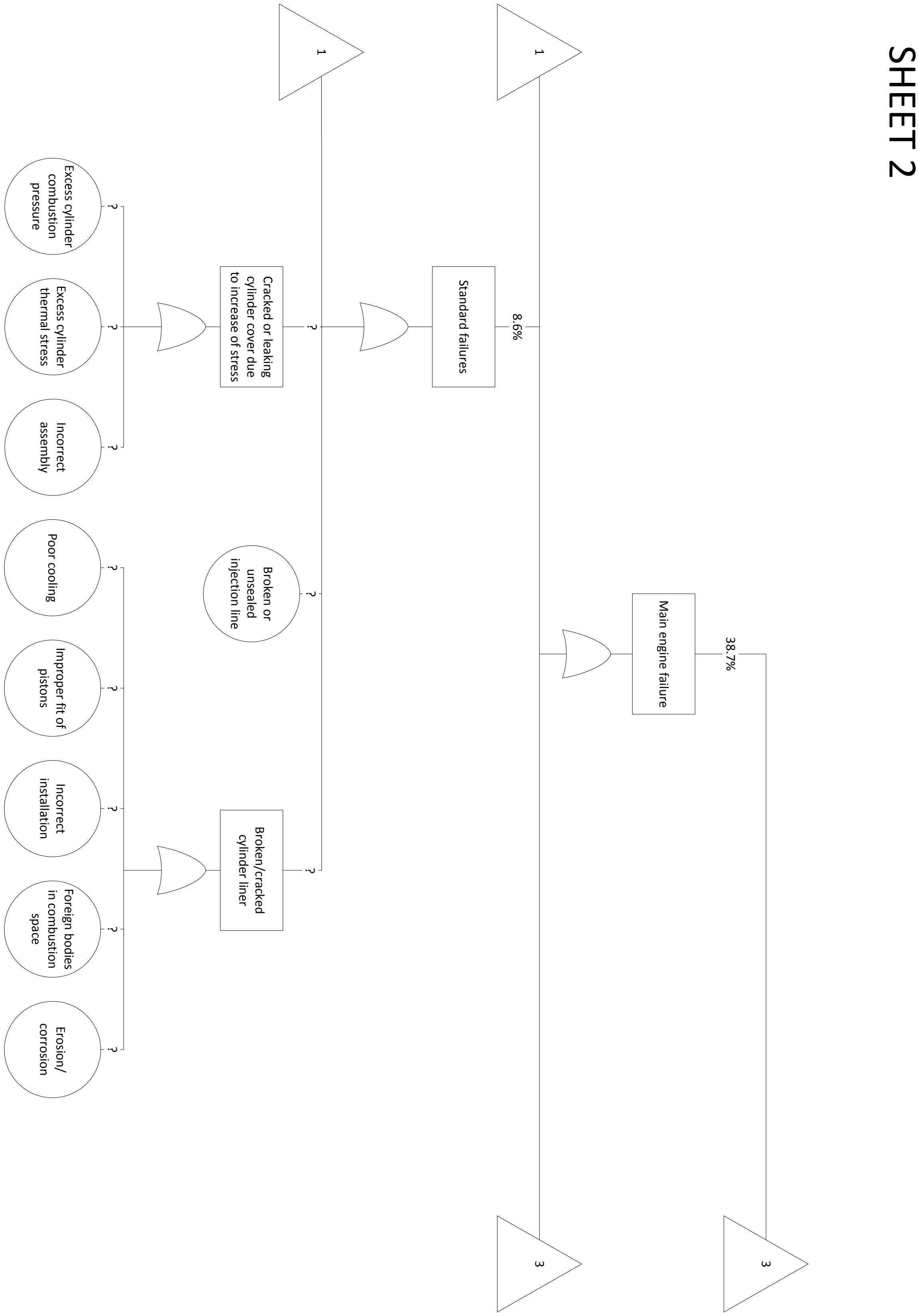

Figure B.2: Sheet 2 of 8 from the initial fault tree

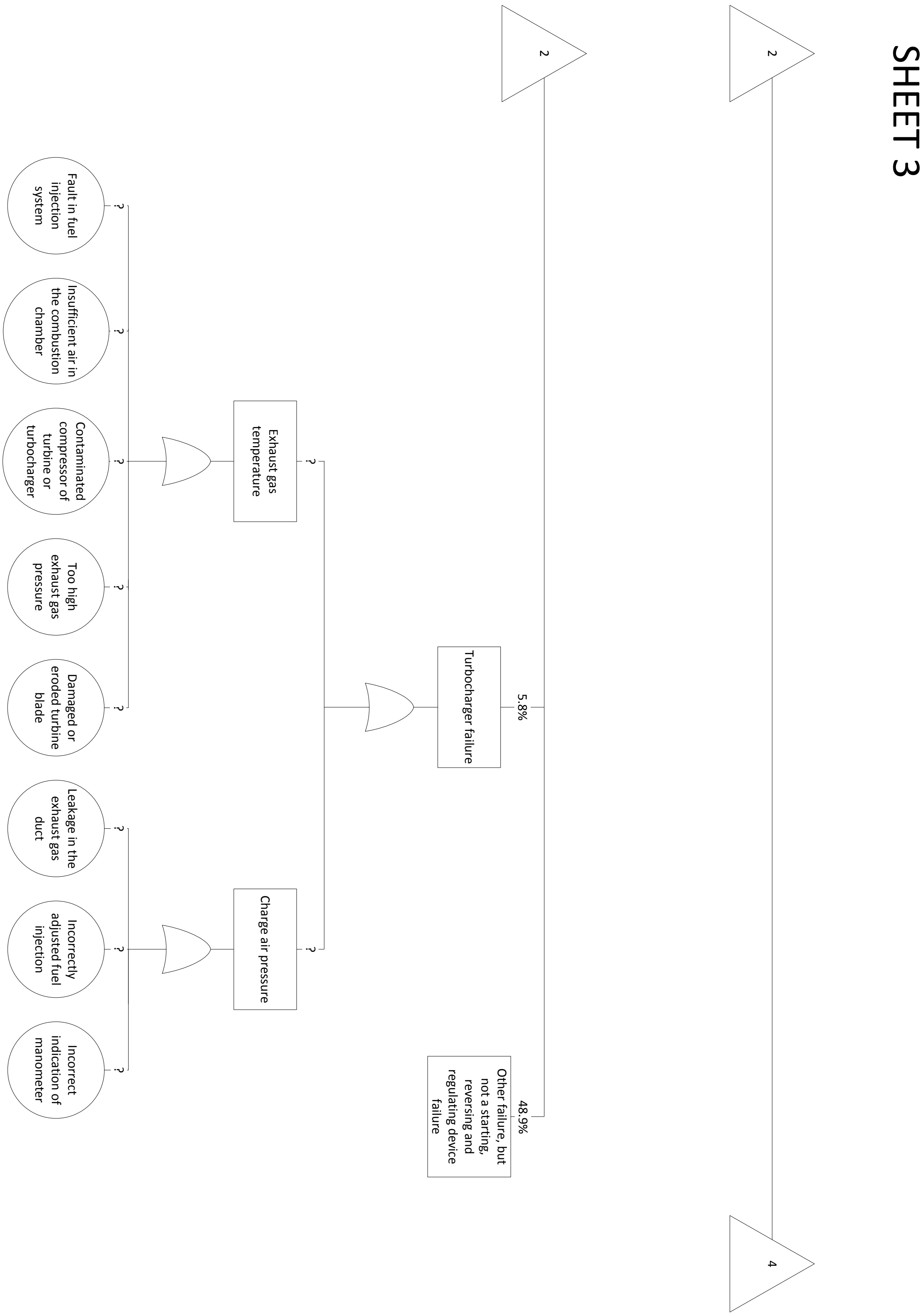

Figure B.3: Sheet 3 of 8 from the initial fault tree

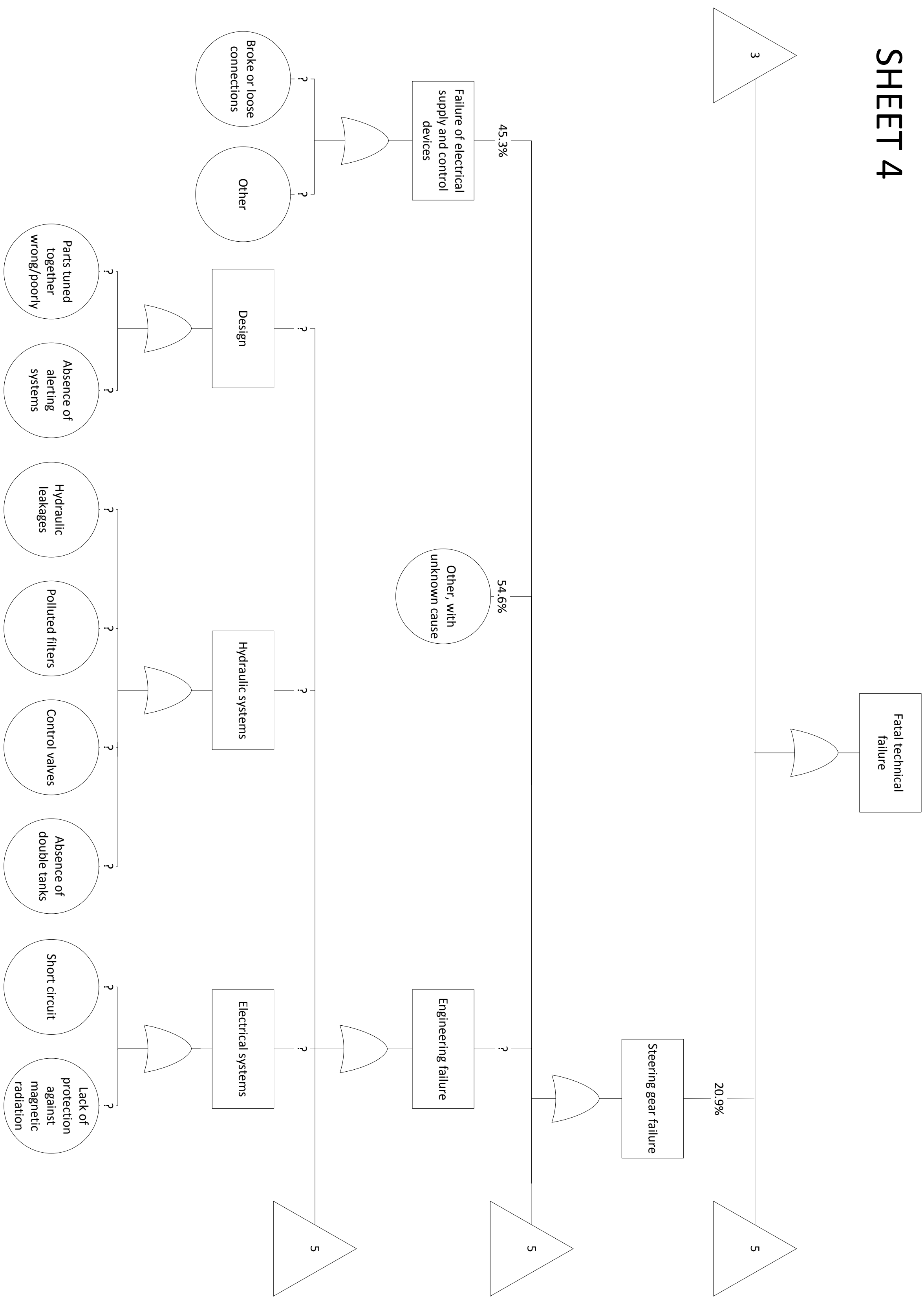

Figure B.4: Sheet 4 of 8 from the initial fault tree

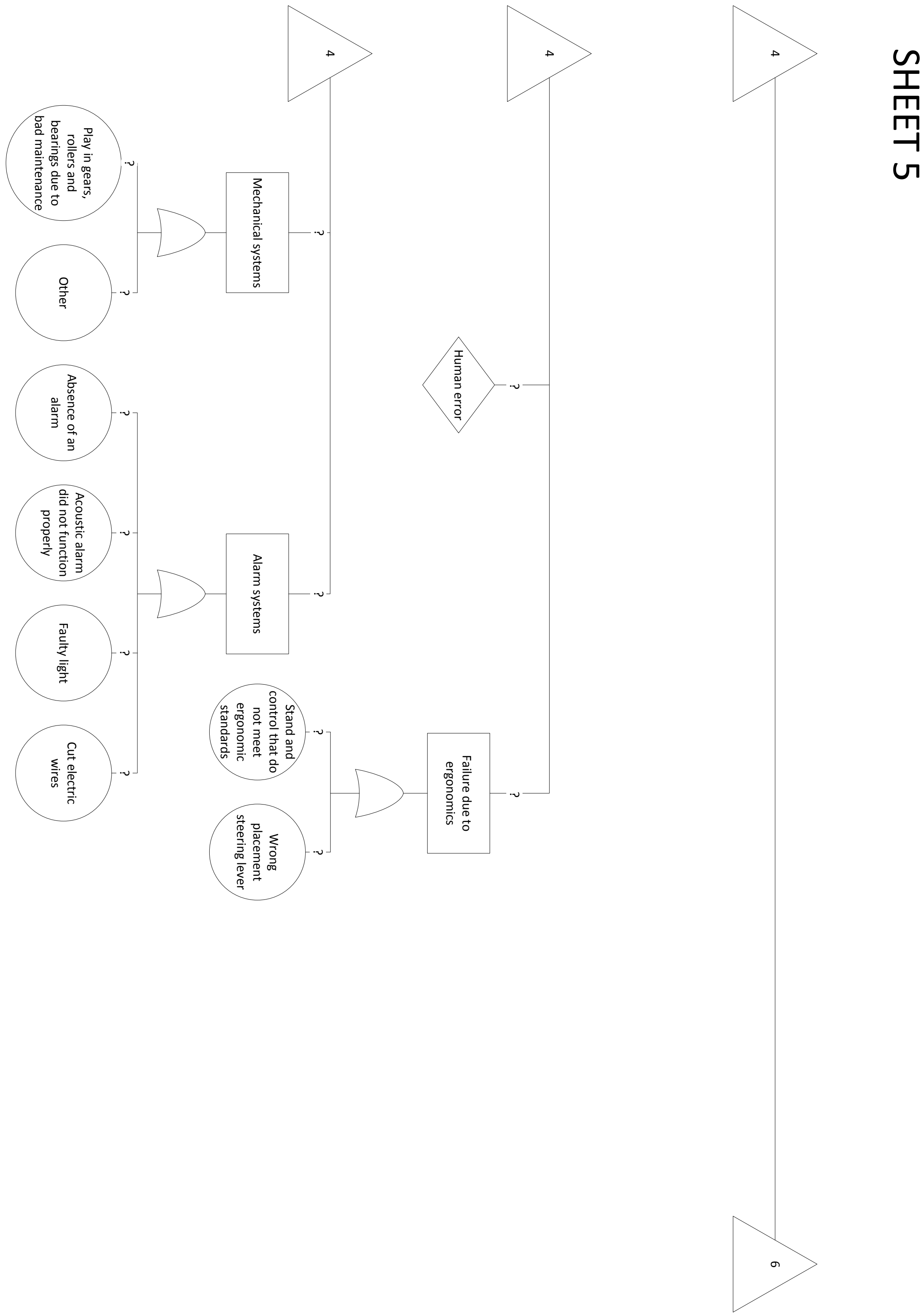

Figure B.5: Sheet 5 of 8 from the initial fault tree

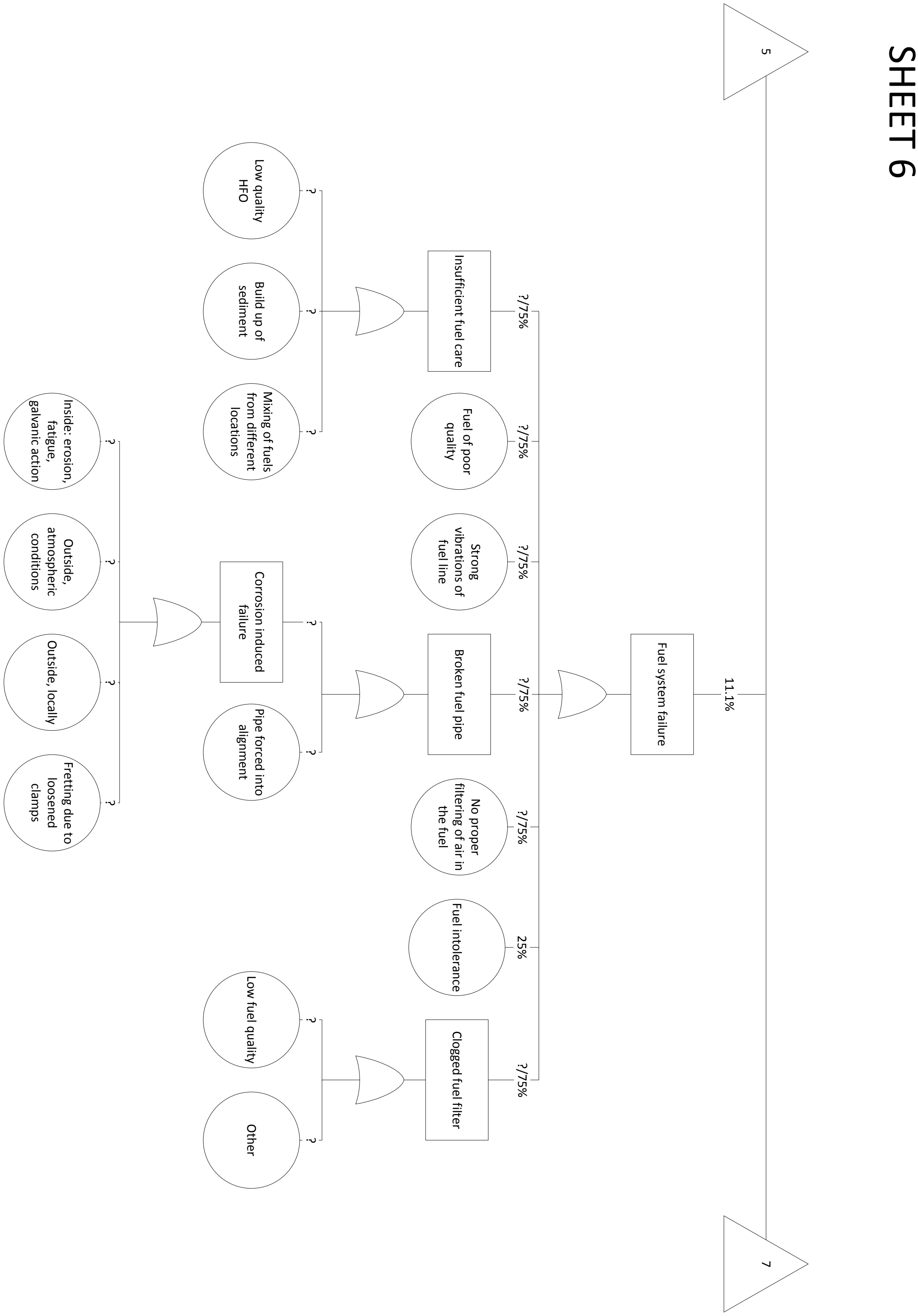

Figure B.6: Sheet 6 of 8 from the initial fault tree

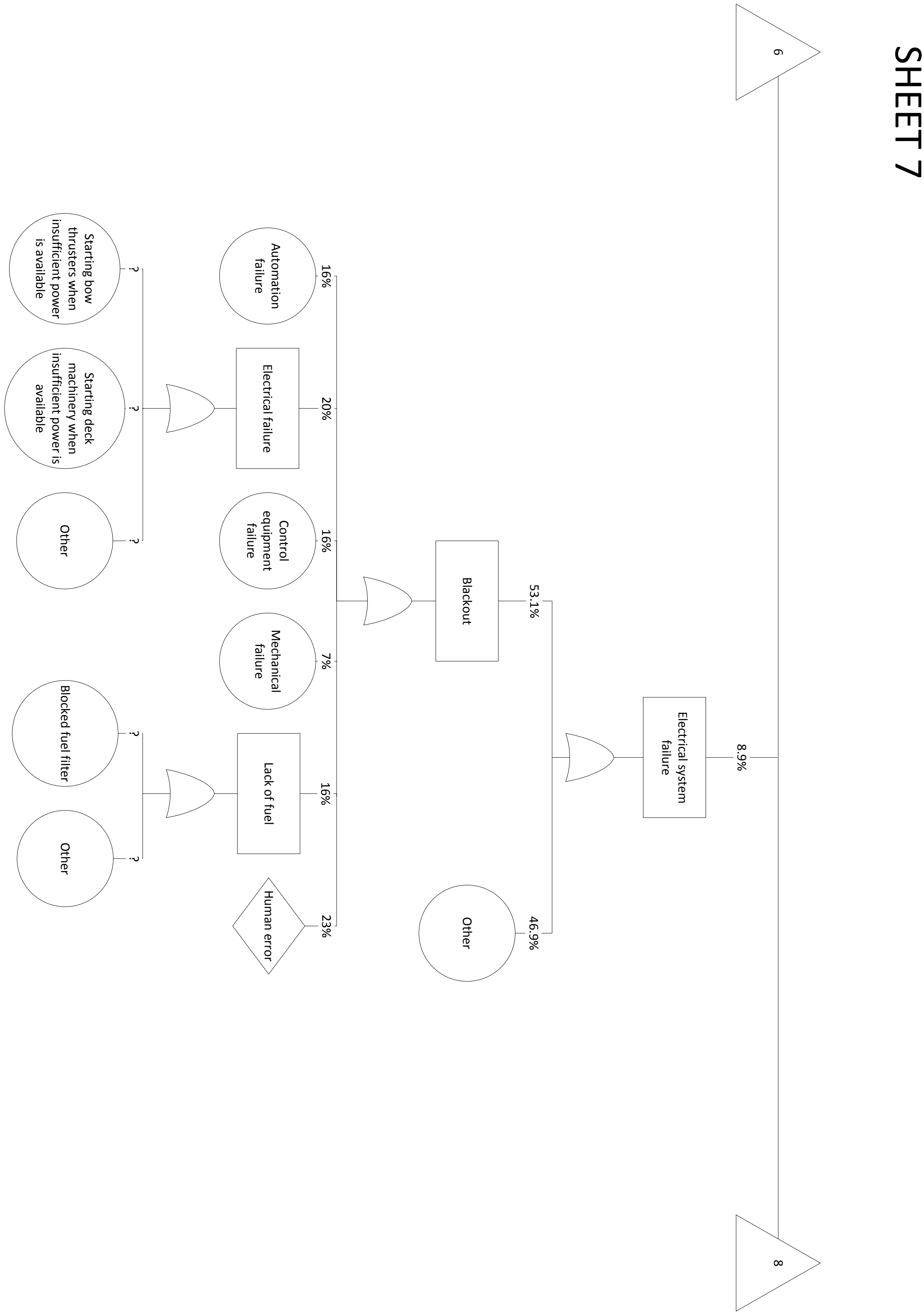

Figure B.7: Sheet 7 of 8 from the initial fault tree

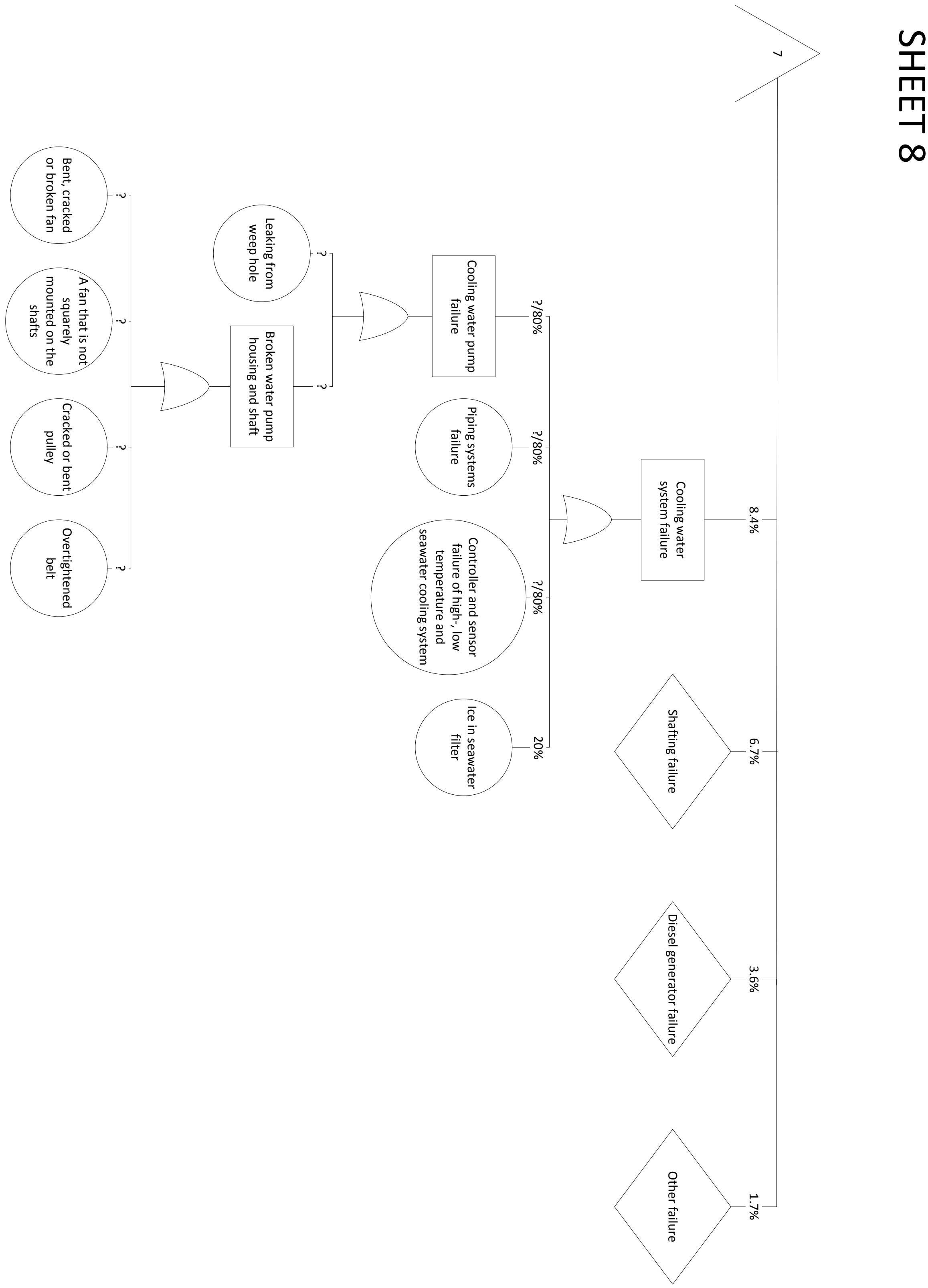

Figure B.8: Sheet 8 of 8 from the initial fault tree

C

Other Steering Gear Research

Over the course of the year 2001, 33 rudder related accidents were registered. Four main categories have been reviewed for a factual research. These have all been reviewed on an individual basis.

- Engineering
- Issues with the infrastructure
- Ergonomics
- Human error

Engineering
This part of the research focused on the technical aspects of the steering gear, such as quality of used material, maintenance and failure sensitivity. The faults in the engineering category have been divided into five subcategories. For each of these categories it is determined how much they directly contributed to a failure. Note that the total amount goes over a 100%. This is because multiple problems have been found in some ships.

1. Design
   For a number of vessels the existing old installation has been renewed partly or entirely during its lifetime. This caused multiple components to no longer be properly tuned to one another. Part of the system gave up by a power that was too high or too low. Parts of the alerting systems were absent on multiple ships. It is determined that in 43% of the cases the design has directly contributed to the failure.

2. Hydraulic systems
   In ten ships hydraulic leakages of at least one litre per twelve hours was found. Another frequent problem are polluted filters. The control valves and absence of double tanks have contributed to rudder failures respectively three and two times. The hydraulic systems has directly contributed to a failure in 19% of the time.

3. Electrical systems
   In several cases a short circuit caused a rudder failure. It was also found that protection against electromagnetic radiation was lacking both between mutual devices and external devices. In one case the rudder indicator was five degrees off due to this electromagnetic radiation. This system contributed in 62% of the cases directly to the rudder failure.

4. Mechanical systems
   Play in gears, chains, rollers and bearings was in certain cases substantial enough to cause failure of the rudder. From the state of these parts it was found that maintenance to these parts was not done, or not properly. In 29% of the cases the mechanical systems were directly responsible for the failure.

5. Alarm systems
   The absence of an alarm was the cause of a rudder failure in three cases. In one case no alarm was given to indicate that the steering gear was not responding to the given rudder commando. The skipper only noticed the malfunction from the behaviour of his ship, after which he turned on the second set of operating devices. Due to this rudder failure the ship caused a collision. In the other cases it occurred that the acoustic alarm did not function properly or that faulty lights and cut electric wires were found. The alarm systems are responsible for 16% of the failures.

Issues With The Infrastructure

The infrastructure was found to only be involved as a secondary factor in the rudder failure. The accidents have been divided into categories, based on where they were caused, on open water, river or canal. It was also noted whether or not the failure occurred when passing a bridge, lock or other engineered structure. It was found to be responsible for 0% of all rudder failures.

Ergonomics

On board ships it has often been found that stands and controls did not meet the ergonomic standards and were either the primary or secondary cause to the rudder failure. The working environment is, from an ergonomic view, determined by how the wheelhouse is divided and where equipment is located. The placement of the steering lever has caused multiple problems because it was placed in such a way that it was accidentally changed when officers hit it when walking by. The ergonomics are responsible for 15% of the total rudder failures. Since failures due to ergonomics are not technical failures they are a human error of some sort. It can be argued whether the error is made in the design or that accidentally walking into equipment is more an operational type of human error.

Human Error

In 27% of the cases there is a direct link between human error and an incident with the ship. Falling asleep, misjudgement, black-out and being on the phone are the given causes for these accidents with a human related cause.

D

MARPOL Annex VI

It is said that the biggest part of the fuel system failures in the years 2010 and 2011 are due to the new MARPOL rules. Therefore, this subsection will explain the new MARPOL rules. MARPOL[5] Annex VI came into force on the 19^{th} of May 2005 and is called 'Prevention of Air Pollution from Ships'. It has set limits to Sulphur Oxide (SO_x), Nitrogen Oxide (NO_x) and particulate matter (PM) [49]. Several emission control areas (ECAs) have been created with even stricter rules. There are four emission control areas [47]. These can also be seen in Figure D.1 in dark blue. The possible future ECAs are shown in light blue [43].

1. Baltic Sea Area
2. North Sea Area
3. North American Area
4. United States Caribbean Sea Area

Figure D.1: Existing emission control areas and possible future ECAs

Both emission control area 1 and 2 only restrict the SO_x emission, whereas the other two areas have restrictions for SO_x, NO_x and PM. The following restrictions have been placed for these emissions.

[5]MARPOL is the abbreviation of International Convention for the Prevention of Pollution from Ships [49].

D.1. Sulphur Oxide

Table D.1 shows the limits of SO_x both inside and outside the ECA zones [47]. The emission limit of 0.50% m/m outside ECAs will only come into force if a review in 2018 shows that there is enough fuel which complies with this rule. Otherwise the date can be postponed to 1 January 2025.

Table D.1: Sulphur Oxide limits

Outside ECA	Inside ECA
4.50% m/m prior to 1 January 2012	1.50% m/m prior to July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020	0.10% m/m on and after 1 January 2015

D.2. Nitrous Oxide

The NO_x emissions limit is divided into three tiers [48]. Ships constructed on or after 1 January 2000 have to comply with Tier I requirements, ships constructed on or after 1 January 2011 have to comply with Tier II. Ships constructed on or after 1 January 2016 have to comply with the Tier III requirements in the ECA zones and with the Tier II requirements outside the ECAs. The requirements set a limit to the emission of NO_x as a function of the engine speed, in g/kWh.

D.3. Particulate Matter

The emissions of particulate matter are directly related to the SO_x emissions [43]. No explicit PM limits have been set, since SO_x is already limited.

E

Solutions By Reliability Improvement

Table E.1: Reliability improvement for all solutions listed from high to low

System	Failure	Solution	Reliability improvement	New failure rate
ME	Unknown distribution	Alternative engine		
		• 20% more reliable engine	2.0×10^{-5}	1.6×10^{-10}
		• 10% more reliable engine	2.0×10^{-5}	2.1×10^{-10}
		Combination of an engine redundancy solution and maintenance improvement	2.0×10^{-5}	2.5×10^{-10}
		’Installing more engines as a full backup’ or ’Dividing the power over multiple engines’ or ’Power take in as a backup’	2.0×10^{-5}	3.9×10^{-10}
ME	Starting, reversing and regulating device	Combination of engine redundancy and maintenance improvement	1.5×10^{-5}	1.4×10^{-10}
		’Installing more engines as a full backup’ or ’Dividing the power over multiple engines’	1.5×10^{-5}	2.2×10^{-10}
SG	Unknown distribution plus other	Combination of two measures with a 1.2×10^{-5} improvement	1.2×10^{-5}	1.7×10^{-15}
		Combination of maintenance improvement and one of the measures with a 1.2×10^{-5} improvement	1.2×10^{-5}	9.2×10^{-11}
		’Split steering gear into seperate systems’ or ’Install a stern thruster as a full backup’ or ’Use azipods for propulsion, then no rudders are required’	1.2×10^{-5}	1.4×10^{-10}

System	Failure	Solution	Reliability improvement	New failure rate
SG	Electrical supply and control devices	Combination of maintenance improvement and a measure with a 9.9×10^{-6} improvement	9.9×10^{-6}	6.3×10^{-11}
		’Install more electrical wire as a full backup’ or ’Split steering gear in separate systems’ or ’Install a stern thruster as a full-backup’	9.9×10^{-6}	9.7×10^{-11}
FS	Unknown distribution			
	• Insufficient fuel care, Fuel of poor quality, Clogged fuel filter	’Check the quality of new fuel before bunkering/using’ or ’Keep fuels from different locations separated’	8.7×10^{-6}	7.5×10^{-11}
	• Air in fuel	’Install the proper air filter’ or ’Install an extra filter as a full backup’	8.7×10^{-6}	7.5×10^{-11}
CW	Unknown distribution			
	• Cooling water pump	Install an extra pump as a full backup	7.0×10^{-6}	4.9×10^{-11}
	• Controller and sensor	Install extra controller and sensors	7.0×10^{-6}	4.9×10^{-11}
ES	Blackout	Combination of proper maintenance and one of the other solutions	4.9×10^{-6}	1.6×10^{-11}
		’Enough power should be available when starting equipment’ or ’Check the quality of fuel before bunkering/using’	4.9×10^{-6}	2.4×10^{-11}
ES	Unknown distribution	Combination of maintenance improvement and system redundancy	4.4×10^{-6}	1.2×10^{-11}
		Install an extra electrical system as a full backup	4.4×10^{-6}	1.9×10^{-11}
ME	Unknown distribution	Use official replacement parts, installed and maintained by qualified personnel	3.8×10^{-6}	1.6×10^{-5}
ME	Standard failure	Combination of an engine redundancy solution and maintenance improvement	3.5×10^{-6}	7.8×10^{-12}
		’Installing more engines as a full backup’ or ’Dividing the power over multiple engines’	3.5×10^{-6}	1.2×10^{-11}
FS	Fuel intolerance	’Keep different types of fuel separate and/or Keep fuels from different locations separate’ or ’Alternative fuel, LNG’ or ’Alternative fuel, electricity generated on board’ or ’Alternative fuel, electricity generated onshore’	2.9×10^{-6}	8.4×10^{-12}

System	Failure	Solution	Reliability improvement	New failure rate
ME	Starting, reversing and regulating device	Use official replacement parts, installed and maintained by qualified personnel	2.9×10^{-6}	1.2×10^{-5}
ME	Turbocharger failure	’Installing more engines as a full backup’ or ’Dividing the power over multiple engines’	2.3×10^{-6}	5.5×10^{-12}
SG	Unknown distribution plus other	Use official replacement parts, installed and maintained by qualified personnel	2.3×10^{-6}	9.6×10^{-6}
SG	Electrical supply and control devices	Use official replacement parts, installed and maintained by qualified personnel	1.9×10^{-6}	8.0×10^{-6}
CW	Ice in seawater filter	Upgrade cooling water system to a winter cooling system	1.8×10^{-6}	3.1×10^{-11}
FS	Unknown distribution	Use official replacement parts, installed and maintained by qualified personnel	1.7×10^{-6}	7.0×10^{-6}
CW	Unknown distribution, cooling water pump	Use official replacement parts, installed and maintained by qualified personnel	1.4×10^{-6}	5.7×10^{-6}
ES	Blackout	Use official replacement parts, installed and maintained by qualified personnel	9.5×10^{-7}	4.0×10^{-6}
ES	Unknown distribution	Use official replacement parts, installed and maintained by qualified personnel	8.4×10^{-7}	3.5×10^{-6}
ME	Standard failure	Use official replacement parts, installed and maintained by qualified personnel	6.7×10^{-7}	2.8×10^{-6}
ME	Turbocharger failure	Use official replacement parts, installed and maintained by qualified personnel	4.5×10^{-7}	1.9×10^{-6}