Power and Propulsion Systems on Board Unmanned Naval Vessels

Study Into the Impact and Feasibility of Removing Maintenance Tasks on Board Naval Vessels

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by

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Summary

With the growing shortage of seafaring personnel, on-board systems need to be more reliable to be able to sail without. Multiple efforts are done to be able to sail with unmanned systems (systems that don't need maintenance while sailing), but for large unmanned surface vehicles, the P&P system is one of the systems that is not reliable enough. The goal of this thesis research was to study the possibilities of adjusting an existing P&P system to make it reliable enough for unmanned sailing. The research resulted in creating a reliability model that gives insight in the direct impact maintenance has on reliability to study the possibilities of removing maintenance personnel from board. Therefore, the main research question of this thesis is:

What adjustments to the power and propulsion system of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any on-board maintenance personnel?

To answer this research question, a study regarding the current system was done first with an functional and physical decomposition. This gave insight in what functions the P&P system needs to fulfill to provide the ship with power and propulsion, what systems the P&P system contains and what preventive maintenance actions are currently done to prevent failure. With the data and knowledge acquired by studying the system, performing a failure mode and effect analysis (FMEA) showed that data currently available is not able to show the impact of maintenance and thus it is unclear how reliable an unmanned system would be.

To be able to do so, a fault tree analysis (FTA) model was created to calculate the reliability and show the direct impact of maintenance for the P&P system on board a Holland class ocean going patrol vessel of the Royal Netherlands Navy. The model made use of an exponential distribution that was implemented with a time-dependent Weibull failure rate function while only using the mean time between failure (MTBF) and the maintenance frequency for preventive maintenance actions.

As a result, it has been found that either making the 20 weakest components of the P&P system redundant, or changing the maintenance strategy from condition based to predictive and making the 5 weakest components redundant, the reliability of a P&P system that receives no maintenance during 50-day missions can be as reliable as a manned P&P system. Furthermore, several sensory equipment is added to replace inspections currently done by maintenance personnel on board.

However, even though the reliability of a 50-day unmanned system can be as reliable as a manned system mathematically, the model does not take into account corrective maintenance. An expansion to this model including corrective maintenance should be researched to show the opportunities of an unmanned hybrid propulsion system. Other recommendations for further research include identifying failure mechanisms to adjust the failure rate progression and implementing repair times and cost to study the feasibility of adjusting the current P&P system and maintenance strategy for unmanned sailing.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AL	Autonomy Level
BE	Basic Event
DFT	Dynamic Fault Tree
DFTA	Dynamic Fault Tree Analysis
DMO	Defence Material Organisation
EBE	Extended Basic Event
FMEA	Failure Mode and Effect Analysis
FMTA	Maintenance Fault Tree Analysis
FRT	Failure Rate Threshold
FT	Fault Tree
FTA	Fault Tree Analysis
DFTA	Dynamic Fault Tree Analysis
GNC	Guidance, Navigation and Control
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LUSV	Large Unmanned Surface vehicle
MPT	Multinomial Process Tree
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
MUSV	Medium Unmanned Surface Vehicle
PTI	Power Take-in
PTO	Power Take-off
P&P	Power and Propulsion
RBD	Reliability Block Diagram
RPN	Risk Priority Number
USV	Unmanned Surface Vehicles
UUV	Unmanned Underwater Vessel

Symbols

Symbol	Definition	Unit
V (...)	Velocity	[m/s]
ρ (...)	Density	[kg/m^3]

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Introduction

Automation is in many ways part of our daily lives. Computers that help humanity living faster and more efficient, traffic lights that guide you through traffic, and cruise control on cars are just a few examples of automatic systems people come across on a regular basis. An automatic system can be defined as a system that is monitoring and performing tasks without any human intervention. When these systems are expanded with the capability to analyse the situation and are able to make independent decisions based on sensory data, the system can be recognised as an autonomous system [25].
In other words, autonomous systems are eliminating the human factor and can lower the amount of personnel required to fulfil tasks. The development of implementing autonomous systems is also the case on board of ships. Autopilots that are able to keep course without human interference and a dynamic positioning system that maintains a ship's position are just mere examples of autonomous systems in the shipping industry. This technology is being developed with the goal to completely remove the human operator on board of ships.

In the merchant sector, ships that are able to sail without human operator would significantly cut costs of personnel and other operational expenses making this one of the main drivers behind the development of this technology. This would make it possible for shipowners to lower the prices of their services or collect super-normal profits in the short run. In addition, unmanned vessels offer a solution for the growing on-board staff shortage on ships [17].

Unmanned vessels also significantly alter the possibilities of war-fighting. Unmanned vessels are able to operate in high-threat areas without the risk of losing human life and at the same time maintaining a high level of availability. As a result, unmanned vessels are of high interest to the Royal Netherlands Navy as well.

However, next to the technology needed for sailing without human operator, other aspects that enable ships to sail without humans on board are not as developed. The reliability of systems on board ships that is required for unmanned operations have not been researched as extensively [3] and appears to be one of the important areas that withhold ships from becoming unmanned. To be more specific, the power and propulsion system on board of ships receive frequent maintenance and inspections, and failures within the systems that provide the ship with power and propulsion are at the moment not reliable enough for unmanned operations for larger vessels, such as the Holland Class Offshore Patrol Vessel (OPV) of the Royal Netherlands Navy [20].

This thesis research will give insight in the reliability of the power and propulsion (P&P) system on board of the Holland Class OPV of the Royal Netherlands Navy by the use of a probabilistic reliability model. It will do this by answering the main research question of this thesis: *"What adjustments to the power and propulsion system of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any onboard maintenance personnel?"*

It will simulate the system's reliability as such that, with the data provided by DMO, the direct impact of maintenance becomes visible and will show how reliability is influenced when no humans will be on board to perform maintenance. The model does this by replacing the constant failure rate used for calculating reliability with a time dependant failure rate by making use of the Mean Time Between Failures (MTBF) and the planned maintenance frequency. This gives the possibility to understand what has to be done to make unmanned operations possible for Large Unmanned Surface Vehicles (LUSVs) and remove humans from the P&P system, making it reliable enough for unmanned operation.

The structure of this thesis is as follows: First, in Chapter 2, a literature review regarding Unmanned Surface Vehicles (USVs) and unmanned machinery systems is done to provide an overview of the current state of the art. The reliability of unmanned machinery and the methods for assessing and improving reliability from previous work is studied here. As on-board maintenance prohibits the the P&P system from being unmanned, section 2.2.5 will look at relevant efforts that studied the relationship between reliability and maintenance.
After the literature review, in section 2.3, the knowledge gaps found are mentioned and a problem definition including research questions is presented. A follow up on this chapter, chapter 3, will discuss how the research questions are answered by a methodology and will elaborate on the assessment method chosen to monitor reliability with the data that has been made available by DMO. With a proper methodology, answering the research questions by carrying out the methodology will be done accordingly. Chapter 4 will give more information regarding the studied P&P system and all activities that hinder an unmanned P&P system and chapter 5 will present a Failure Mode and Effect Analysis (FMEA) that will indicate the most critical components and give data inputs for the reliability model. This will lead to Chapter 6 and 7, that present the theory behind the reliability model and assessing the reliability of an unmanned P&P system. Finally, Chapter 7, 8 and 9 will present the discussion, conclusions and recommendations coming from this research.

2

Literature Review

Before research can be done on unmanned P&P systems on board Navy vessels, sufficient knowledge of current research areas has to be collected by means of a literature review. This will help understanding the problem and point out knowledge gaps. This chapter will therefore first name the difference between Unmanned and Autonomous, and will continue by discussing the Unmanned Surface Vehicle (USV) and USVs for defence purposes. The Chapter will continue to zoom in further to unmanned machinery systems to indicate important research ares within this topic and problems faced by previous research. This will provide background information regarding the main topic of this thesis.
Next, section 2.2 will look at how to assess reliability and suited methods to do so. Section 2.3 will discuss the importance of maintenance and how reliability and failures are influenced by maintenance. Finally, section will summarize the knowledge gaps found during the literature review and will present the research questions that will help filling these gaps.

2.1. Unmanned Systems

This section serves to give a more in depth view of this thesis. In this section, the unmanned vessel is defined, the relevancy and drive behind the development of Unmanned Surface Vehicles (USVs) is appointed, and the current state of the art is presented.

Unmanned & Autonomous

The terms unmanned and autonomous have been used by various literature in different ways [32]. This makes it necessary to first properly define these terms for this thesis before continuing to USVs:

Unmanned is defined as the physical absence of a human operator. An unmanned ship is thus defined as a vessel that is completely free of human operators on board. Whether or not a human operator is needed to operate the vessel or not is not included in this definition.

Autonomous is defined as a ship that is able to perform tasks without a human operator. It does not say anything regarding people on board of the vessel. The more operations a vessel can perform without human operator, the higher the level of autonomy. Classification societies, such as Loyd's Register, have defined the levels of autonomy ranging from AL0 to AL6. These are presented in table 2.1.

Level	Description
AL0	No autonomous functions. Humans control all actions
AL1	On-ship decision support system can presents options to human operator
AL2	On- and Off-ship decision support. All actions taken by human operator.
AL3	'Active' human in the loop. Decisions and actions are performed by the system under human supervision.
AL4	Human-on-the-loop. Ship operates autonomously with human supervision. High impact decisions are presented to be interceded and overwritten by the supervisor.
AL5	Fully autonomous. Ship is under less supervision, only occasionally.
AL6	Fully autonomous unsupervised ship.

Table 2.1: Levels of Autonomy defined by [42]

These definitions also state that an autonomous vessel does not necessarily have something to do with unmanned. So, the focus of this thesis is on unmanned vessels as defined in this section.

2.1.1. Unmanned Surface Vehicle

A frequently used term for unmanned vessel is Unmanned Surface Vehicle (USV). It is defined as a vessel that can operate and perform tasks without an on-board crew [67] and thus is fully excluded from on-board human operators. USVs are mostly studied because of the growing interest in the merchant sector, but it also offers a lot of potential advantages over human-operated vessels for multiple other maritime sectors. This is due to several reasons, with increasing safety and cutting operational expenses being the main drivers of this development [17].

Other benefits include the increasing shortage of skilled seafarers, bringing down the number of accidents caused by human error and increasing availability ([12], [63]).
Many efforts have been taken to develop unmanned shipping to a state where it is able to deploy commercial vessels with this technology and sail without any personnel on board.

Even though every different field of deployment for USV's has their own specific characteristics, they consist of the following main elements [41]:

- **Hull and Structure**
  In the maritime industry, several hull shapes are used for different purposes. The same holds for USV's. Depending on the application of the USV a different hull shape will be convenient.
- **Power and propulsion system**
  Most ships in the maritime industry are powered by a conventional diesel engine and a propeller. Other options are for example: fuel cells or batteries for power and water jets or Voith-Schneider propellers for propulsion. As for the hull, the type of Power and Propulsion (P&P) system also depends on the type of use. But, most importantly, the system has to be reliable.
- **GNC System**
  The Guidance, Navigation and Control (GNC) system connects all elements on board so it can control and monitor the entire vessel.
- **Sensors**
  A USV operates using many different sensors, tailored to its intended use. These sensors will always include an Inertial Measurement Unit (IMU) to measure the motions of the vessel, and a Global Positioning System (GPS) to monitor its location.
- **Communication systems**
  Communication systems are used to communicate with ground control, other vessels and between elements on board.

A visual layout is presented in the figure below.

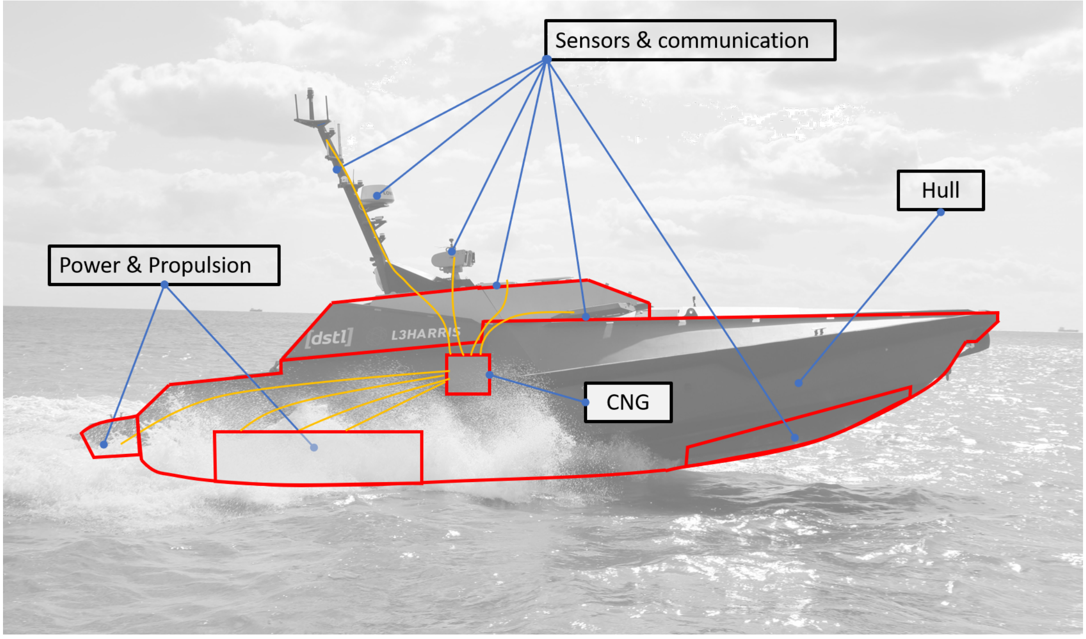

Figure 2.1: General Layout of a USV [30]

Several projects have studied the possibilities of autonomous and unmanned vessels. The MUNIN project [53] as well as the ReVolt-Project [62] and the Advanced Autonomous Waterborne Applications Initiative [1] are projects that studied a variety of areas in unmanned shipping. The most recent project is the AUTOSHIP project [8], which carried out analyzes regarding autonomous shipping such as safety, regulation, and economic factors and developed a framework including methods for the design of autonomous vessels.

USVs for Defence Purposes

Even though these projects and their developments are relevant, this thesis will have a focus which is more related USVs for defence purposes. USVs are capable to operate in high threat areas which expand the capabilities of the Navy, especially where putting human lives at risk is unacceptable.
In the field of unmanned vessels, the research was mainly on Unmanned Underwater Vessels (UUV), but USVs have been catching up for the past years [44] and have been more of interest since successful operations of USVs during the second gulf war [67]. Although most of the progress made is on smaller equipment vessels consisting mostly high speed crafts, the US Navy is planning to extend their budget to research and produce large unmanned surface and underwater vehicles for the coming years [20]. With recent developments, L3Harris is awarded a contract to produce a Medium Unmanned Surface Vehicle (13.7 m to 57.9 m long) for the US Navy as the first program for producing unmanned surface vehicles [40]. Another program called the Ghost Fleet Overlord program of the US Navy has recently added a vessel to the fleet now consisting of two Medium Unmanned Surface Vehicles that are capable of sailing unmanned and autonomously for more that 4,000 nautical miles [28]. Large Unmanned Surface vehicles (LUSVs) of 61 m to 91.4 m long are intended to be built in 2021, but there are concerns these types of vessels need more development [20], especially on the reliability side [39].

2.1.2. Unmanned Marine Machinery Systems

As indicated earlier, even though a lot of efforts are taken to make unmanned shipping possible, the reliability of the machinery on board still needs development.

The MUNIN project indicates that one of the major challenges for unmanned ships is to improve the reliability of the systems on board [31]. It indicates important research areas being:

- Looking at critical system design to improve and avoid single points of failures.

- Improving maintenance strategies to update weak components that are designed to be replaceable during voyage.
- Expanding the sensory equipment to detect and monitor the state of components in more detail.
- Developing fail-to-safe procedures in case of major system failure.

The US Navy, who takes the lead in producing USVs for defence purposes, also indicates reliability is of major concern and one of the challenges that holds back production, in particular for LUSVs [20]. This means that, compared to smaller ships that have an operational time which is in the range of hours, bigger ships face reliability problems due to their bigger and more complicated systems and longer operating times that can varying from a single week to several months. Studies have tried to improve reliability through failure data [11], make improvements through a redundancy reduced risk index [17] and have aught to predict the performance of failure sensitive components with the use of a Multinomial Process Tree (MPT) [2]. The problem these studies faced, was the lack of maintenance and failure data which made it necessary to make rough approximations and estimations. Therefore, this study will investigate the possibilities of leaving the power and propulsion system unmanned with the use of failure and maintenance data. The data made available by DMO consists of maintenance schedules, failure data and other data like mean time between failures of several components. However, the data available is still not sufficient to study reliability of unmanned systems through data analysis and thus to study the possibilities of unmanned power and propulsion systems a probabilistic approach is still desirable. The data available will be used to provide the probabilistic approach with inputs.

Previous studies done on unmanned machinery came up with several solutions to overcome reliability issues. Colon [17] indicated several solutions for weaknesses within the system. These included small alterations in the design of a single component, sailing on a different type of fuel, and installing a second drive train for redundancy. It was concluded all the improvements together made the engine room sufficiently reliable for unmanned operation. In another master thesis, Brocken [11] indicated that improving maintenance activities does improve reliability, but that its significance was too small to have a substantial impact. He therefore resolved the issue with expanding the weaknesses of the systems with redundancy, which resulted in adding a second drive train. A more recent study, performed by Edge et al. [23], designed an optionally manned trimaran concept for defence purposes. It tested both a Fully Electric Propulsion and a Hybrid system including a diesel generator and a PTO/PTI. Fault tree analysis concluded the hybrid option was the most reliable.
Other initiatives like the ReVolt Project [62] tried to avoid rotating equipment inside the hull as much as possible. This was realised by integrating a battery powered, fully electric P&P system and making sailing a maintenance free operation.

2.2. Reliability of Unmanned Machinery Systems

Reliability is one of the most important factors when it comes to unmanned machinery. Bourouni defines reliability as the ability to perform its function under specified conditions during a given period [10]. A not-reliable system has a high probability of failure and brings unnecessary risk to the performance of the vessel. Without personnel to perform on-board maintenance, knowledge regarding reliability whether or not systems are able to perform their function for a certain mission is extremely important.

In order to draw conclusions regarding the reliability of unmanned machinery in Power and Propulsion systems, it is necessary to apply engineering knowledge that can monitor the likelihood and frequency of failures. This section first discusses what a failure is and what type of failures can be defined. Next, the term reliability will be discussed briefly and how reliability is calculated, followed by the possibilities of modelling and improving the reliability of the P&P systems on board of Navy vessels.
Finally, the section will discuss how maintenance impacts reliability.

2.2.1. Failures

When assessing reliability, knowing the failure rates of components is essential. A failure can be defined as the event a component can no longer perform its function [35]. The probability of failure is an input parameter when studying the reliability of the system and it therefore is necessary to know the likelihood of failure for every component and their progression as a failure variable over time.

Repairable, non-repairable, mechanical and electronic components all fail according to six patterns that can be presented by curves [48]. These curves are visualised in figure 2.2.
Failures can usually be divided into two sorts of failures: failures that occur randomly and failures that occur due to degradation/deterioration, known as time-related failures.

Random Failures
Even though there is a correlation between usage, age and failure of components, [4] states that most failures occur randomly. It is therefore important that random failures are included into the reliability assessment. A random failure can be modelled in several ways:

- **Constant**
  The failure rate is constant over its entire lifetime.
- **Initial Break-in**
  The Failure rate is very low when new, but will quickly rise to a failure rate which will be constant for the rest of its lifetime.
- **Infant Mortality**
  The infant mortality is defined as a failure rate curve with a very high failure rate at the beginning of it's lifetime which will convert to a lower, constant rate of failure for the rest of it's lifetime.

Al these curves are insensitive to maintenance, meaning their failure rate will not change when preventive maintenance is performed.

Time-Related Failures
The time related failure curves change over the time they are used. This is due to degradation and occur because of aging, wear and other factors such as damage to supporting systems or external factors like temperature changes.
The patterns of time-related failures can be modelled by a continuous function that goes through several degradation stages before it fails.
There are mainly 3 different time-related failure patterns:

- **Bath tub**
  This pattern shows there is an initial break in period with a higher failure rate which converges to a constant rate for longer period. Due to degradation a wear out period raises the failure rate again.
- **Wear out**
  This failure pattern is characterised by a constant rate over it's entire lifetime until the end, where it significantly increases due to wear and tear.
- **Fatigue** The fatigue failure pattern is characterised by it's increasing failure rate over time.

All failure curves for time-related and random failures can be found in figure 2.2.

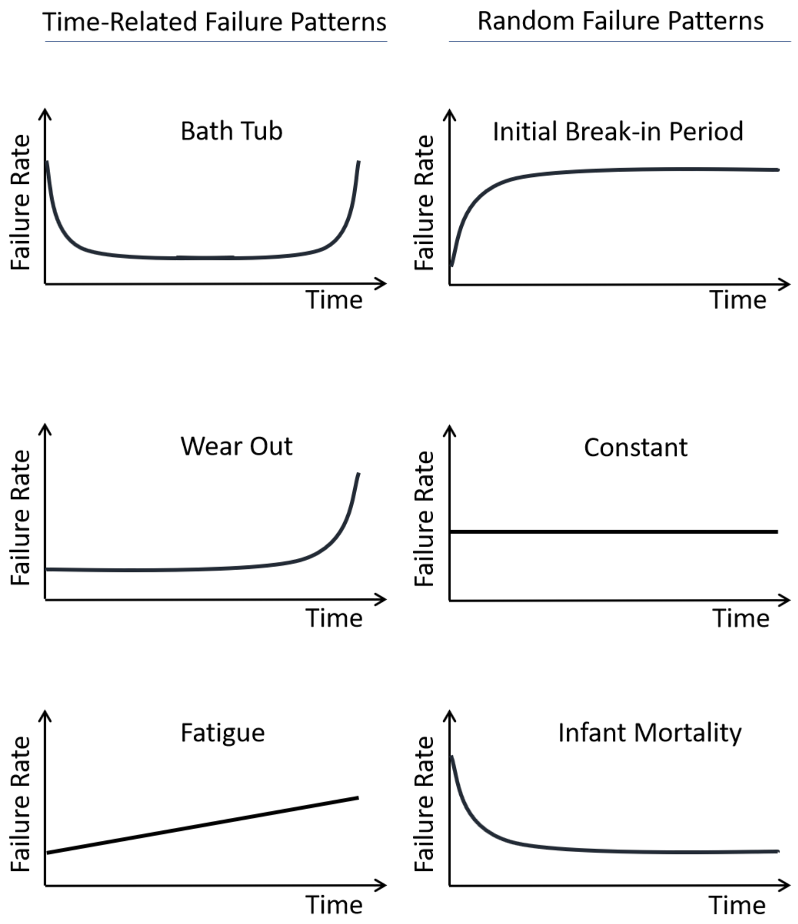

Figure 2.2: The six failure patterns

According to Endrenyi et al. [24], the degradation stage can be defined by either duration, indicating the stages with respect to time, or by physical signs like wear and corrosion and giving each level and kind of wear a degradation state.

In practical applications there is a preference for the second strategy, but because of the complexity and amount of components that make up the P&P system, both are intended of being used for the purpose of this thesis. Other reasons for this are the lack of data and because wear may simply be impossible to spot or link to it's performance or degradation stage.

Determining the Failure Pattern

To determine which failure pattern a component follows, statistical failure data is needed. When plotted over time, the failure pattern becomes visible. When the failure pattern is known, the failure mode of the component can determine where the failure occurred.
This is only an option when there is a significant amount of failure data that can plot the curve. Without sufficient data, statistical analysis is not possible. As the amount, nature and detail of maintenance and failure data available is not sufficient for determining the failure pattern, a probabilistic approach is desirable.

2.2.2. Reliability

Reliability can be seen as the probability a component or system will perform its function for a specified period of time and can be described by a function R(t) [35]. This probability can be either estimated through data analysis or calculated using a probabilistic approach, and, because reliability is a probability, it has a value which varies between 0 and 1. When using a statistical approach, a number of identical products are being tested or monitored. After time t, the number of failed products $n_f(t)$ and the number of products that survived $n_s(t)$ are used to calculate the reliability according to equation 2.1.

$$R(t) = \frac{n_s(t)}{n_s(t) + n_f(t)} \tag{2.1}$$

When using a probabilistic approach, the reliability function can be calculated with the use of a probability density function and is calculated according to equation 2.2.

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)dt \tag{2.2}$$

How these approaches are used in combination with failures and how this is used to assess reliability will be discussed in depth in chapter 6.

2.2.3. Assessing Reliability

The components in the considered systems have to be reliable to make sure the probability of failure is small enough to accept the risk it presents to the functioning of the entire system. Analysing Reliability can give insights in if the system is reliable enough.

Reliability analysis is defined as an approach that identifies and assesses the causes and frequency of failures. It gives the possibility to counter or mitigate the effect of failure to improve system performance [10]. Previous research has used several methods to assess reliability such as fault tree analysis (FTA), Failure mode and effect analysis (FMEA), and reliability block diagrams (RBD) [36]. Each has their pros and cons [5] and several methods should be studied to find one suitable for this thesis.
They all can be identified as a bottom-up method, like a FMEA where a failure of a component is studied and what effect that will have on the systems it is part of, or a top-down method like an FTA that studies the failure of a system and the possible causes down to component level. If possible, these methods can apply probability mathematics in order to give results regarding the reliability of the system. FTAs, FMEAs and RBDs are the most widely used methods to analyse the reliability of systems ([10],[19]) and therefore these methods are studied within this literature review.

Failure Mode and Effect Analysis (FMEA)

According to Arabian-Hoseynabadi, Oraee, and Tavner, the FMEA is a technique frequently used for reliability analysis [6]. It is seen as an essential tool used by several industries including the automotive, aerospace and nuclear industry Kabir et al. ([34] as cited in Kabir [33]). It was even stated that this technique is required by US government agencies like the Navy and Air Force in order to guarantee a certain safety and reliability [16]. It is an inductive method that uses expert estimations of causes that lead to events of system failure. It identifies failure modes i.e. a potential cause of failure, and studies the effect it has on the performance of the system [46]. Even though this is a widely used method for reliability analysis, it does not give a lot of insight in the probabilistic representation of system reliability [46]. It can however be of particular value to study what systems and components deprive the reliability most.
According to Mohammad [46] , the following steps are performed for the FMEA procedure:

- The system and the level at which the FMEA is performed is identified.
- A block diagram of the system is constructed. This could be on component level as well as functional level or combined.
- All failure modes and their potential effects on every level it propagates through are identified.
- Every failure is analysed and the severity of their consequence is assigned to a value.
- The methods for finding the failure modes have to be identified. For instance through sensors and inspections.
- Actions to mitigate or eliminate the failure are identified.

An example of an FMEA for a single component is presented below.

System	Sub-System	Part	Failure Mode	Effect Component	Effect System	MTBF
MDE	Engine	Piston	Piston Cracked	Component Failure	MDE Failure	50000

Table 2.2: Example of an FMEA of a piston

Fault Tree Analysis (FTA)

Most research done on reliability of machinery systems use Fault Tree Analysis (FTA) as an assessment tool [61]. Fault trees are directed a-cyclic graphs that describe the combinations of components failure that lead to system failures. FTA is focused on system failures and finding the cause of the failure. Furthermore can this method be used to identify possibilities for improvements and their impact on the reliability of the P&P system. It shows how a single component failure can propagate through the entire system causing it to fail. Edge et al.used fault tree analysis to get insight in what failures risked the successful execution of a mission and helped in determining and identifying what elements could lead to possible failure of the system [23].

FTA is a top-down method consisting of events and gates. Events can be seen as occurrences of failures and gates as a visualization of how events are connected to each other and under what circumstances an event can propagate through the fault tree. The events can be divided into the top event, which is the undesired event that is being analysed, intermediate events that depend on several basic events, and basic events representing the event that starts the propagation through the fault tree which can result in the occurrence of the intermediate event and finally the top event. All events have a probability of failure which are calculated by how the FTA is structured.

To visualise the different type of events, they all have their own shape. Basic events are represented as circles and an intermediate event as a rectangle. Because complex or large systems often require a lot of space, transfer events are created with a triangle to keep the fault tree structured and clear.

Gates

Basic events are attached to the rest of the events through gates. Just as discussed in 2.2, how these basic events are connected to the top event e.i. what gates these basic events have to pass to reach the top event depends how much influence the probability of failure of that particular event has on the total probability of failure of losing propulsion.

Next to the basic events being defined mathematically, the gates that connect the basic events to other events and finally to the top event have to be defined. To connect the Basic Events to a sub-system and what impact the failure a component would have on the functioning of the entire the P&P system AND and OR-gates.

AND-Gates

And gates are, as mentioned in 2.2.3 indicating that all connecting events have to occur in order to let the signal continue. Mathematically, a AND-gate is represented by the following formula with R_1, R_2 and R_n representing the reliability of the event at time t [54]:

$$R(t) = R_1(t) * R_2(t) * .R_n(t) \tag{2.3}$$

OR-Gates

OR-gates are indicating that either one of the connected events to the gate will result in a failure. This can be described mathematically by formula [54]:

$$R(t) = 1 - (1 - R_1(t)) * (1 - R_2(t)) * ..(1 - R_n(t)) \tag{2.4}$$

k\N gates

A k\N gate indicates that k of the N events connected have to occur in order to let the failure propagate further through the fault tree. A 2/3 Gate (2 of the 3 basic events have to occur) can be described mathematically by the formula below [59]:

$$R(t) = -2 * R_1(t) * R_2(t) * R_3(t) + R_1(t) * R_2(t) + R_1(t) * R_3(t) + R_2(t) * R_3(t) \tag{2.5}$$

The events and gates that can be used in FTA are presented in figure 2.3. Several gates are used in extensions to the Fault Tree, but these will be discussed when relevant. An example for a basic FTA of a ship propulsion system is presented in figure 2.4.

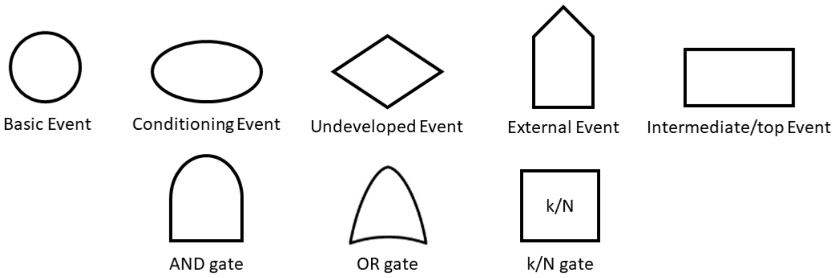

Figure 2.3: Events and gates of the FTA

By considering various outcomes and possible failures by monitoring system reliability, Edge et al. were able to identify weak spots in the system. Making fault trees of the possible failure events for these scenarios made it possible to identify where redundancy of systems or components was necessary.

Other studies like [11] and [2] both used the fault tree analysis methodology to point out weaknesses or study the reliability of a machinery system on board vessels. However, none of these models note how probabilities of failure within these systems are influenced by maintenance.
It is possible to add maintenance and repairs to Fault trees. But, including more complex components like degradation and maintenance makes the use of a basic FTA cumbersome [55]. It it thereby likely not suitable for the intended use. FTA can thus mainly provide insight in the most likely causes of failure, but not ideal to use as an assessment tool to monitor reliability when the inspection and maintenance interval is changed for a possible unmanned operation of the P&P systems. This means that in this case, an extended version like a Dynamic Fault Tree, or a Fault Maintenance Tree described by [55] can maybe offer a solution.

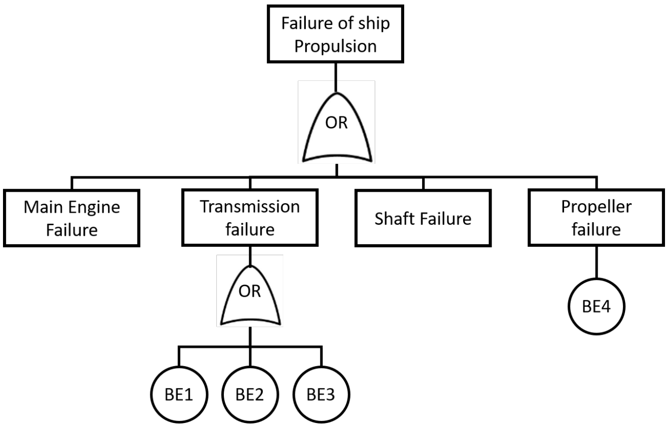

Figure 2.4: FTA of a ship propulsion system ([21] as cited in [23])

Dynamic Fault Tree Analysis (DFTA)

The Dynamic Fault tree (DFT) is an extended fault tree analysis method. It is a method widely used to asses reliability and safety of complex systems, because it allows to implement component interactions [9]. This is done by adding dynamic gates that make it possible to model and analyse interactions like

sequence dependant failures [22]. A P&P system has components whose reliability depends on each other. So a dynamic fault tree could be more suitable than the standard FTA.
The following gate additions make the DFT different from the standard FT:

- PAND gates propagate the failure if all inputs occur from left to right.
- FDEP gates indicate dependancy between events. If the input event of the gate occurs, all the connected events also occur.
- The SPARE gate represents a component that can be replaced by one or more components. When the first component fails, the spare component takes over its function until there are no spares left. The spares can be connected to several other gates, but when it is used as a spare for one event it cannot be used by another.

Basic events of the DFT method have an additional α, that complements the SPARE gate. When the basic event is an inactive input to the SPARE gate, α (also called the dormancy factor) is lower than 1, indicating a slower rate of degradation of the component represented by the BE.

Fault Maintenance Tree Analysis (FMTA)

The fault maintenance tree (FMT) is based on the dynamic fault tree. While the Dynamic fault tree added the dynamic behaviour of a degradation model by adding PAND, FDEP and SPARE gates, the maintenance fault tree adds the maintenance scheme for both preventive and corrective maintenance to the fault analysis. This is visualised in figure 2.6. This makes it possible to analyse the failure behaviour of the top event in a more dynamic way and in a longer time frame because the current state of components that haven't failed yet keep their current degradation state.
The Fault Maintenance tree is described as proposed by [55] and used by [13].
As an addition to the DFT, the FMT is including maintenance by introducing the following:

- **Extended Basic events (EBE)**
  Extended Basic events are Basic events that have been modified to incorporate degradation into the event it represents. Before a EBE occurs, it has to go through several levels of degradation, following the degradation curve it has been assigned to. When it reaches the end of the degradation level, the degradation curve resets and starts at the next level. The degradation scheme of the EBE is visualised in figure 2.5.

- **Rate Dependency Events**
  Some failures that occur in a mechanical system like the P&P system on board of Navy Vessels influence the failure and degradation of other components and/or sub-systems. For instance, if the oil pressure of the governor for the diesel engine fails, the lack of oil inside the diesel engine makes the engine to degrade at a significantly faster rate than in normal circumstances. Rate Dependency Events (RDEP) are representing these interactions between events. When a event occurs, the RDEP alters the degradation rate the EBEs connected to the RDEP accelerating the occurrence of that particular event.

- **Repair and Inspection modules**
  Another addition made by the FMT is the repair and inspection module (RM and IM) that will interact with the degradation of EBEs. The inspection module will act periodically, inspecting the degradation of an EBE. When the degradation reached a certain degradation level, the IM will initiate the RM. This can be either preventive or corrective maintenance. When not activated by the RM, the module will also perform maintenance periodically. When the IM decides to perform cleaning, the EBE is restored to its previous degradation level, while when replacement will reset the entire degradation progression.

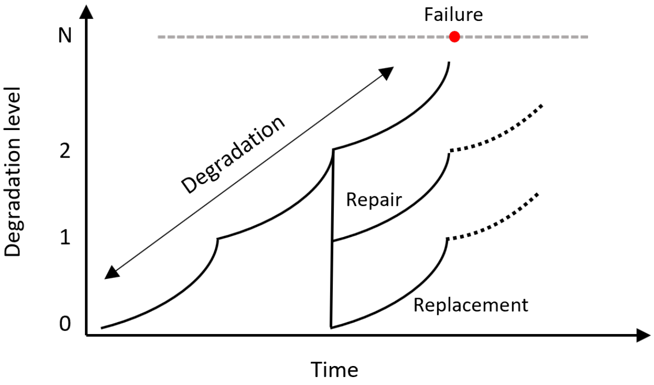

Figure 2.5: Sketches of degradation advancement scenarios [13]

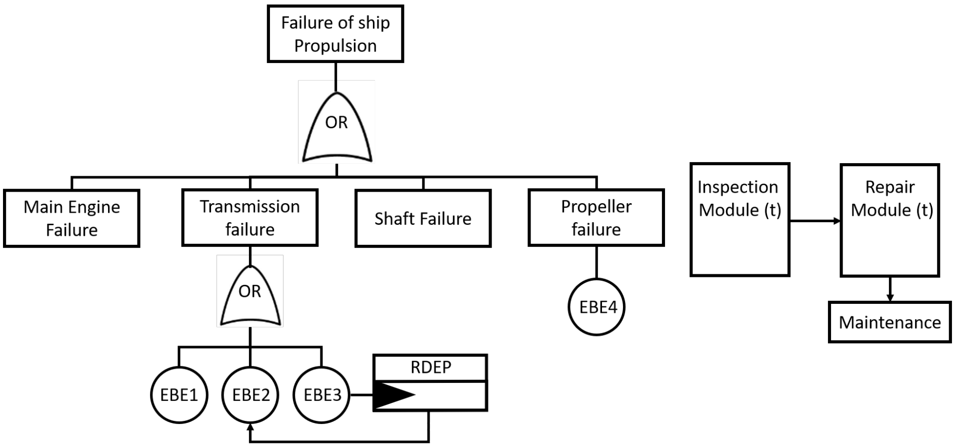

Figure 2.6: Example of a Fault Maintenance tree [13]

Reliability Block Diagram (RBD)

The Reliability Block Diagram (RBD) is based on blocks connected in parallel and series that indicate their dependency with respect to each other. This can be scaled down to systems, subsystems and if necessary to components to assess the reliability of the entire functioning of the system.

If the components are connected in series, the failure of any one of the components causes the next connected component to fail and so on, until the system fails. This makes it possible, just like a with an FTA, to monitor the failure propagation through the system if a failure occurs. Calculating reliability is presented as proposed by [14]. Reliability for components in series is calculated with formula 2.6, where n stands for the number of blocks.

$$R = P\left[E_1 * E_2, \ldots, E_i, \ldots, E_n\right] \tag{2.6}$$

When all blocks are independent, the reliability is calculated as:

$$R = \prod_{i=1}^{n} P\left[E_i\right] \tag{2.7}$$

An RBD with blocks in series is shown in figure 2.7.
Components connected in parallel are indicating redundancy. Parallel components are indicated as shown in figure 2.8, where only one of the components needs to work in order to avoid failure.

The reliability of such a system can be calculated through:

$$R = P\left[E_1 + E_2 + \cdots + E_i + \cdots + E_n\right]$$

or

$$R = 1 - P\left[\overline{E_1} + E_2 + \cdots + E_i + \cdots + E_n\right]$$

where $\overline{E_i}$ represents the complement of E_i, indicating that the component i has failed at time t. If all events are independent, the reliability may be defined as:

$$R = 1 - \prod_{i=1}^{n} P\left[\overline{E_i}\right]$$

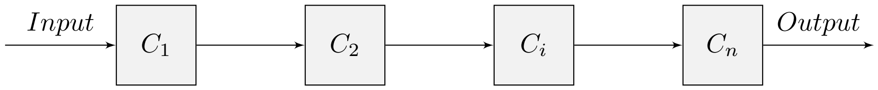

Figure 2.7: RBD in series

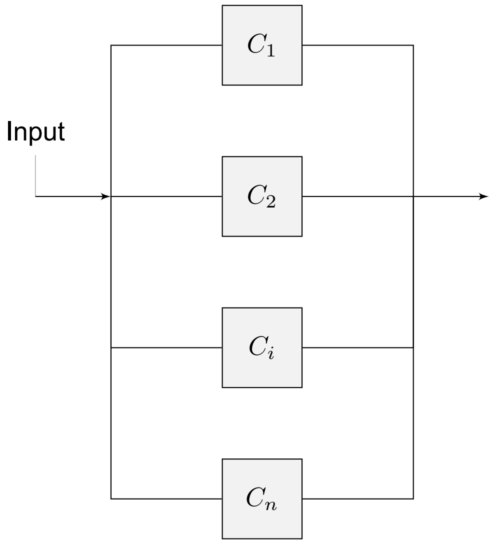

Figure 2.8: RBD in Parallel

2.2.4. Improving Reliability

When looking at current P&P systems, it shows that there are several tasks done by maintenance personnel that needs to be addressed otherwise when the possibility of on-board maintenance is no longer an option. According to Kooij, Colling, and Benson [38], there are 3 approaches that can help to make systems on board less dependent on maintenance during a mission:

Improving Current Technologies

Although [38] indicate that current technology needed for unmanned operation of USV's is mature and reliable enough, improving the current technology of components or systems is still considered to be an important factor. Improving technologies makes systems more reliable and results in a higher Mean Time Between Failure (MTBF). This gives a bigger probability of successful operation for the intended use of the system. Kooij, Colling, and Benson also indicated that the presence of maintenance personnel prevented the current systems from failing. In this case the machinery is working appropriately resulting in incentive to innovate these systems being smaller. This can make options that still have a high technological improvement rate attractive for unmanned systems in the future.

Removing Reciprocating Parts

The more components a system has, the less reliable it is going to be. It is therefore desirable to keep the number of parts used as low as possible, making the machinery more robust and reliable. This makes investigating options like fuel cells, batteries and electric motors more attractive for propulsion. However, most of these technologies are still under development, and ships sailing solely on batteries will be unlikely due to the scale issues [29]. Even though new technologies are less mature than the conventional systems used on board, their technological improvement rate is much higher, making them more attractive for future P&P systems [38].

Increasing Redundancy

Another possibility is to increase redundancy. This was suggested by Colon [17] and Brocken [11]. Systems that have single point failures are carrying a high risk with respect to the functioning of the entire system and thus is it desirable to equip these parts redundantly. Trying to remove reciprocating parts, trimming down the number of parts and adding redundancy to the on board systems to reach the goal of removing on-board maintenance personnel are obvious and logical choices to consider. They are effective and require relatively little resources for development and integration. However, [23] indicated that it is important not to rely solely on adding redundancy since that can result in space related problems, forcing the ship to me more voluminous compared to its manned counterpart.

2.2.5. Reliability & Maintenance

Maintenance is an important aspect when considering reliability. Mostly preventive maintenance is being done on a regular basis to ensure continuous operation, extend equipment lifetime, and to reduce costs. Especially too little maintenance is undesirable because this will affect vessel availability, which is a priority when it comes to Navy vessels. Thus, cleaning, replacement and other forms of maintenance all have their influence on the reliability of the machinery they are performed on. When looking at unmanned machinery, it is extremely important to be able to tell how the machinery is going to degrade and affect its reliability when no maintenance is done during sailing. But, the failure and reliability data made available by DMO is all affected by preventive maintenance. Thus the impact of maintenance needs to be known.

Influence of Maintenance on Reliability

As earlier stated, maintenance plays an important role in preventing degradation-related failures. Its goal is to increase the mean time to failure. In order to model failures when no on-board maintenance is performed, it has to be clear how maintenance influences the failure rate and the degradation of the system components. Both Cauchi et al. [13] and Endrenyi et al. [24] indicate that it can be assumed maintenance will at least bring the the component to its previous degradation stage. This can only be assumed for failure rates that change over time. Processes that have a constant failure rate and can be considered random will not be influenced by maintenance [24].

Preventive maintenance is done when the probability to failure of the considered component has an increasing probability to failure with respect to time. Maintenance done for a decreasing rate will increase the probability to failure and maintenance to components with a constant rate is useless.

Maintenance with a fixed time frame is the most commonly used method of maintenance, but reliability-centered maintenance is becoming more popular as it can further reduce the frequency of interruptions, making this economically an attractive option.
Maintenance thus increases component lifetime and system reliability. Other factors that can positively impact the system reliability are increasing system capacity, implementing redundancy and changing components of sub-systems for more reliable ones. These other options are possible solutions for removing on-board maintenance personnel and will be considered later in this thesis.

Most of the maintenance policies, including the one from DMO are not based on mathematics, but are based on instructions from manuals and experience. In the case of this thesis, it is necessary to make such a model in order to represent the effects of maintenance on reliability.

2.3. Problem Definition

With having elaborated on the relevant topics for this thesis in the previous sections, the knowledge gap and the research problem will be discussed below.

The reliability of the power and propulsion system needed for LUSVs is not sufficient enough, but the technology for this is available. Because this hasn't been studied as thorough as other elements present in a USV, there lies an opportunity to study this in this thesis. The challenge here is to come up with suitable solutions to improve the reliability as such the P&P system can operate without on-board maintenance.

Improving reliability has been done by others, but data of failure and maintenance was absent or not comprehensive enough. The only sources for data were failures of ships in German waters that needed help [11] and expert opinions [17]. Here lies a gap of knowledge regarding failure and maintenance. The challenge here lies in finding enough data to make a proper data analysis. Or, if the data is still insufficient, making more precise probability calculations.

Furthermore, the studies that did improve reliability did this without the consideration of the impact of maintenance activities on the reliability of the system. The knowledge gap here is that is it unknown what the direct impact of maintenance is on the reliability of the P&P system.

In short, this thesis has the opportunity to improve reliability for Large Unmanned Surface Vehicles through reliability assessment that incorporates preventive and corrective maintenance. It will do so by using data made available by DMO consisting maintenance and failure data, which is more comprehensive than the data used in previous studies.

To address these knowledge gaps found in literature, this thesis will try to:

- Acquire sufficient data to make failure rate development calculations
- Model the reliability of the unmanned power and propulsion system
- Analyse and point out the components that reduce the reliability of an unmanned power and propulsion system
- Make an effort to come up with improvements on these weaknesses through one of the methods mentioned in 2.2.4

Then, it becomes possible to draw conclusions regarding the feasibility of making these systems unmanned on board of Navy Vessels.
This translates the goal of this thesis as: Understanding of the implications of removing maintenance personnel from the Power and Propulsion system by the use of a reliability model and using this knowledge to make removing of personnel on these systems possible by introducing improvements.

2.3.1. Research Questions

As discussed earlier, little is known about the possible implications regarding reliability of not maintained machinery. In order to make it possible for Navy vessels to sail with an unmanned P&P system, research in these systems is needed.

Main Research Question

To reach the intended goal for this thesis, it is attempted to answer the following main research question:

What adjustments to the power and propulsion system of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any on-board maintenance personnel?

Sub-questions

Some sub-questions are needed to be answered first in order to come up with a substantiated answer for the main research question.

1. What system components make up the power and propulsion system of the Holland Class Patrol Vessels of the Royal Netherlands Navy?

Answering the first sub-question will give a clear understanding of what the current situation on board of Navy vessels is regarding maintenance, machinery on board and the circumstances the machinery is intended to operate in. This tells us what the systems looks like and how it operates. It shows every component that contributes to the main functions of the two systems: providing power, and providing propulsion.

2. What maintenance activities hinder maintenance free sailing and how can they be mitigated?

A second step in answering the main question is looking at the maintenance that is being done on board of the vessel in its current state. Answering this question gives an idea of which tasks can no longer be performed while sailing and makes it possible to determine if these activities can be easily omitted by adjustments to the system and if maintenance is really essential for successful operation.

3. What are the weaknesses of the power and propulsion system when not maintained during sailing?

After looking at what activities hinder maintenance free operation of the power and propulsion system, the next step in answering the main question is identifying weaknesses of these systems when they would be unmanned. A weakness can either be machinery that fails when no personnel is allowed to perform preventative maintenance, or to look at every component separately and mapping their failure behaviour, signals of failure and lifetime. The definition of weakness used in this thesis is: Components of the system that have a higher likelihood of failure when no preventative maintenance is being done while at sea.

4. What are the risks of the weakest components in the power and propulsion system?

Third, the importance of the components have to be considered. Is there for instance a loss of propulsion or power when a specific component fails or has this other, less severe consequences that can be solved when back in port?

5. What can be done to reduce the risk and improve the reliability of weak components of the power and propulsion system?

The risks regarding failure can be lowered by improving reliability which will improve overall performance of these unattended systems. It is therefore important to study possibilities in redundancy and approaches like changing components for alternatives that have a smaller likelihood of failure or have a less severe impact when failure does occur. Even a different maintenance interval for these components can be an option if the intended time of use is known.

6. How do improvements/alterations influence the reliability of the power and propulsion system and make the P&P system suitable for unmanned sailing?

Knowing what possible improvements can enhance the reliability of a system doesn't say anything about the impact the improvement has on the overall system. In order to answer the main research question, it is necessary to able to tell how the improvement influences the reliability of the systems. After answering this sub-question it should be possible to say something regarding the reliability of the unmanned energy and propulsion system for a mission.

2.4. Ethical Aspects of Unmanned Systems

The benefits of implementing unmanned technologies are vast and undeniable, but they do raise some interesting ethical questions of significant importance.

When there is no personnel on board, regulations have to be added or adjusted according to this development. Responsibility and safety in this case are of importance. What happens when a load starts moving and there is no personnel to restrain it again? Or what happens when freight is lost? Other safety aspects are situations where surrounding ships are in trouble. There are no sea fares to answer a mayday call because there is nobody to help in such a situation.

Technical Aspects

Advanced technology asks for highly trained personnel to engineer, maintain and repair such technology. Highly trained personnel is more scarce and thus this factor needs to be considered by companies and organizations that would like to implement these technologies. People have to be trained and that knowledge has to be kept up to date.

Regulations

With Unmanned technologies gaining ground in several fields within the maritime spectrum, laws and regulations have to be changed, adjusted or added. The IMO is at this moment assessing existing IMO instruments to conclude if these can be applied to autonomous ships with varying autonomy, including unmanned ships [37].

Distribution of Responsibility

Technologies like these are designed, developed and implemented with a lot of effort and includes a lot of people to make it possible. This makes it difficult to indicate the responsibilities of individuals or even companies and institutions. Codes of conduct can in some way provide guidelines to responsibility, but with new technologies it can be difficult to implement to specific cases. Furthermore, most codes of conduct are advisory and thus can only exercise responsibility on the individual as far as the reader understands.

Safety and Security

Safety and security are important aspects when considering unmanned systems and thus have to be thoroughly integrated into the operations of ships to avoid possible risks and problems as much as possible. For instance, regulations regarding collision and search and rescue have to be addressed before autonomous and unmanned ships can be part of the shipping industry. Another issue is the safety of cargo and the ship itself. With no-one on board, ships can easily be a target for stealing cargo and for stealing the entire vessel. Furthermore, they must be safe to operate and maintain. Ships that have no humans on board while sailing will undoubtedly change the design of such vessels. Finally, a system that is controlled from a distance can be hacked. This means that the control of a vessel is lost and controlled by someone else. This can cause serious harm to environment and people, especially when the vessel is Naval.

Unmanned Warfare

For unmanned warfare, UAVs and drones have already raised the ethical issues regarding unmanned and autonomous vessels. This does not mean these have been addressed, but research into unmanned warfare is therefore done in several occasions ([26], [7], [60]). Specific issues for warfare are that they have to safe to fight alongside humans [60]. It has to be possible to clearly and reliably make a distinction between friend and foe. Other issues that can be thought of are if unmanned systems make it easier to declare war when no human lives are at stake, but merely financial resources. For instance, drones are being used more frequently every year, causing more concerns regarding ethical issues [65].

Social Acceptance

When ships are unmanned of even possibly autonomous, they interact with their environment continuously. Ships and other structures will come across regularly and have to be addressed appropriate and correctly. The question asked when looking at social aspects of Unmanned Technologies is if USVs can be designed and operated in such a way they abide the ethical principles of the society.

Conclusion

It can be concluded that USVs can be beneficial in a vast spectrum of maritime activities and the demand for unmanned possibilities drives several initiatives in developing this technology. However, there are still several elements that require more research and development to successfully deploy USVs of larger size. The reliability of P&P systems is one of these elements [39]. At this point, it is not clear whether vessels with a size and operational profile above 61m are reliable enough to sail unmanned and thus there lies an opportunity to study whether it may be possible to integrate current technologies to make the P&P system reliable enough for large unmanned vessels.

Therefore, in this chapter, the state of the art in USVs is studied and several assessment methods that are commonly used to calculate reliability as well as the impact maintenance has on reliability were presented. From this information, it was clear that previous studies did not have enough data for proper reliability calculations and the absence of maintenance is not taken into consideration when looking at unmanned systems. With the main research question ”What adjustments to the power and propulsion systems of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any on board maintenance personnel?” and several sub-questions, it is considered possible to fill the knowledge gaps defined in 2.3.

3

Methodology

Now that the knowledge gaps, the goal of this thesis and the research questions to close the knowledge gaps are clear, the methodology to solve the research questions is presented below. This section will describe how the research questions are answered and why this particular method is chosen. It furthermore will briefly discuss what assumptions are made to come up with a conclusion regarding the main research question of this thesis.

3.1. Methodology Overview

Before going into detail, a flow chart will give an overview of the methodology that will finally answer the main research question:” What adjustments to the power and propulsion system of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any on-board maintenance personnel?”. First, the current P&P system is analysed. A functional decomposition, physical decomposition and a maintenance schedule are realised to get acquainted with the current system and to find out what maintenance tasks hinder the realization of an unmanned P&P system. Next, a failure mode and effect analysis is done to show what components and/or systems are needed to be improved when maintenance while at sea is no longer possible. With this information it is possible to do a reliability assessment. This assessment will use the data and will apply theory adopted from literature regarding reliability and failure rate to show what components or systems are the weakest when the current P&P system is unmanned and what risk they oppose, what can be done to mitigate those weaknesses. Finally, the actual reliability assessment by using the reliability model will show how improvements will influence the reliability of the P&P system. After the reliability assessment it is possible to come back and answer the main research question of this thesis. figure 3.1 gives an overview of the methodology used for answering the research questions.

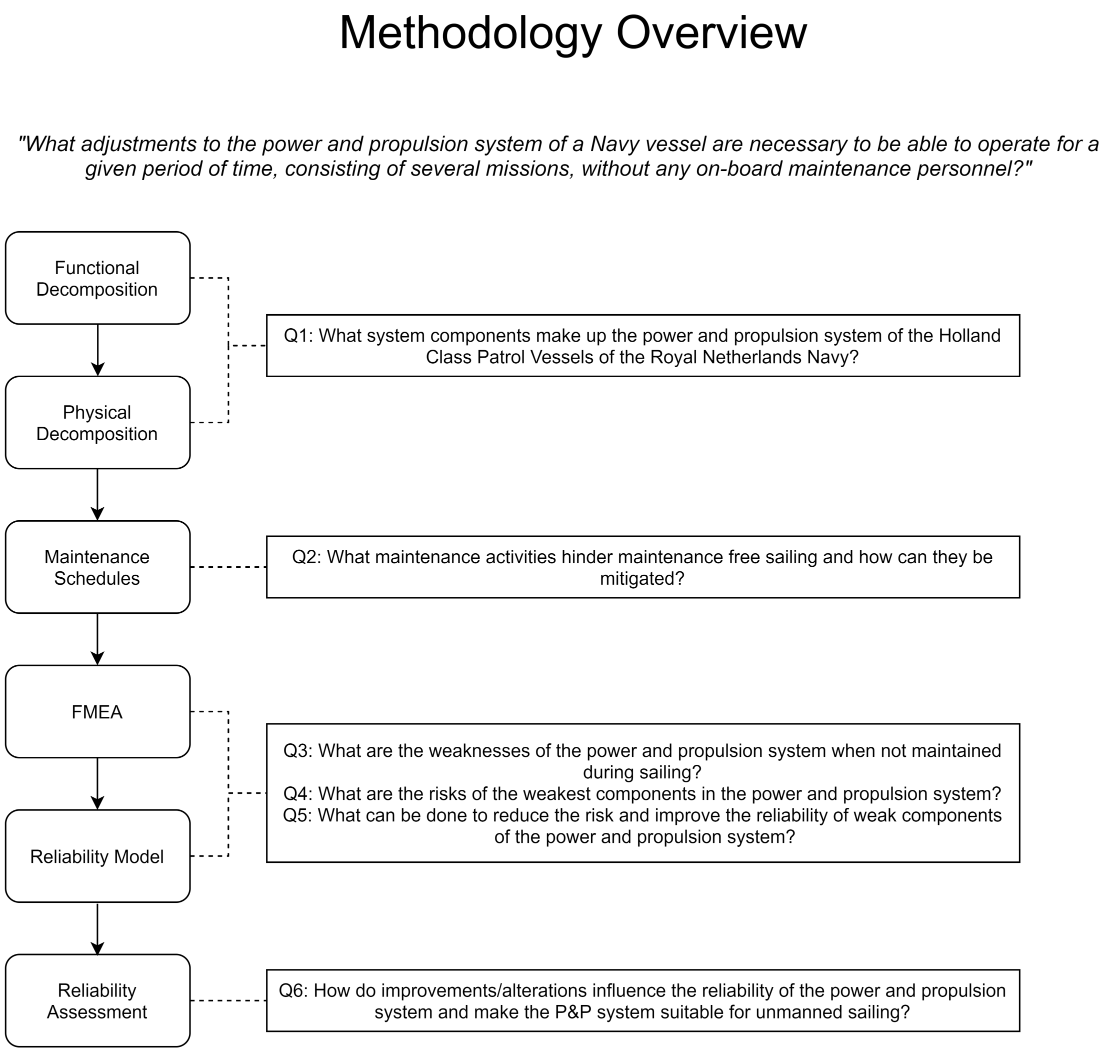

Figure 3.1: Overview Methodology

3.2. Analysis of the Current P&P System

Information regarding the current systems is essential to make an assessment of the P&P system. With the data available, it is possible to make a sufficient decomposition of the P&P system to get a better insight in what systems are responsible for what function and what maintenance activities are hindering maintenance free sailing and thus answering the

Functional Decomposition

One of the first pieces of information in order to be able to make a reliability assessment is to know what is implemented in the P&P system and what functions are fulfilled to provide the ship with power and propulsion. A functional decomposition is used to gain insight in the current situation by decomposing each function into relating functions in such a way that when combined it comprises the following function. The functional decomposition is essential when after the reliability assessment a redesign of the system is desirable. The functional decomposition can then be used to check whether redesigned system will actually fulfill all functions that are fulfilled by the current P&P system. Even though this thesis research eventually did not studied a system redesign, this still helped understanding and getting insight in the P&P system and further study could still make use of this decomposition.

Physical Decomposition

After the functional decomposition, the next step is to get an overview of the systems on board of the vessel that fulfill the functions found earlier. This will result in a decomposition that will be the backbone of the reliability analysis due to the breakdown in components. It will give understanding of the most important components within a system. With both the functional and the physical decomposition done, it is possible to answer the first research question:”What system components make up the power and propulsion system of the Holland Class Oceangoing Patrol Vessels of the Royal Netherlands Navy?”.

Maintenance Schedules

For answering the second research question: *”What Maintenance Activities hinder maintenance free sailing?”*, the physical decomposition is complemented with maintenance schedules to see what components need frequent maintenance and what other activities need to be addressed when no maintenance personnel is on board.

For all maintainable components on board there is a maintenance schedule which is based on manufacturer maintenance guides, or from own experience of experts. All these separate schedules are merged into a system called SAP that contains all the maintenance that has to be performed and in what frequency. It furthermore presents what institution is responsible for the maintenance, how many hours are reserved for the task and how much staff is needed. Systems maintained solely while in port are apparently reliable enough to not need any maintenance at sea. Leaving these out of the equation would make this study significantly easier, but these systems are still posing a risk of failing and thus are still taken into account during the reliability assessment. And, including these systems and components becomes even more important when sailing without maintenance personnel. The situation will most certainly occur the vessel is still at sea when one of those maintenance tasks has to be performed, which will increase the probability of failure for components that need less frequent maintenance.

Furthermore, the maintenance schedule can tell something regarding the failure patterns that are needed for the reliability assessment. Because maintenance is only performed when it drops the degradation state and lowering the probability of failure, it can be assumed there is a failure probability threshold at which the maintenance is being performed. By making an assumption of the threshold if necessary and plotting the rest of the curve, a failure pattern is constructed which can be used for the assessment. Expert knowledge regarding the research topic is desirable [51] and thus experts are consulted when possible to verify assumptions and to complement the data with interpretation.

FMEA

To answer the 3rd, 4th research question: *”What are the weaknesses of the power and propulsion system when not maintained during sailing?”* and *”What are the risks of the weakest components in the power and propulsion system and how can they be mitigated?”* a failure mode and effect analysis is composed. With the FMEA it should be clear what components are causing system failure when they fail and thus making the systems less reliable. This will use the physical decomposition made earlier and define possible failure modes for each component, its possibility of occurring and the effect it could have on the functioning of the systems it is part of, defining the risk a possible failure could have. With this information it should be possible to answer the 5th research question *”What can be done to reduce the risk and improve the reliability of weak components of the power and propulsion system?”* to structurally identify possible solutions to mitigate the risk and making the system more reliable. The FMEA will together with the maintenance schedules be the source of information for the reliability assessment. This gives a better insight in what weaknesses will most likely have to be addressed to make the biggest impact on improving the reliability of the P&P system and thus will help in both making the reliability model and making improvements when assessing the reliability of an unmanned P&P system.

3.3. Reliability Assessment

The 6th sub-question *”How do improvements/alterations influence the reliability of the power and propulsion system and make the P&P system suitable for unmanned sailing?”* and the main research question will be answered by a reliability assessment. This will substantiate the answer of the previous questions and will give a concrete answer to the reliability of the current system, if the unmanned system will be reliable enough, what the impact of possible improvements would be, and what improvements would result in a P&P system which is reliable enough for unmanned sailing.

For selecting an assessment method, there are several factors that can influence this decision.
First of all, it has to be possible to successfully use the desired method. Static and Dynamic fault tree analysis are methods widely known and used by the academic community ([52] as cited in [43]). Fault Maintenance trees have been developed only recent, and thus the guidance that can be provided and literature available when implementing this method will be limited. The Reliability Block Diagram-method is also a widely used method discussed in several books and papers, and thus should not lead to any issues regarding applicability.

3.3.1. Complexity

One important aspect of the assessment method should be that it is understandable and thus the method itself shouldn't be more complex than needed. Where the Fault Trees can complicate their clarity of the analysis when a large number of failure modes is studied component, the RBD is more clear because is looks simpler and should give the reader a better overview of the entire system.

However, the most important aspect of choosing an assessment tool is the complexity of the system that is studied. But, what is considered a complex system? [47] states that systems that do not have simple interconnections are called complex. Another definition found on [18] states ”Complex systems are systems where the collective behavior of their parts entails emergence of properties that can hardly, if not at all, be inferred from properties of the parts”. On the basis of these two definitions, it is assumed the P&P system is a complex system. A P&P system of the OPV studied does not have simple connections, meaning the inter dependency between components within and between systems is not entirely clear. This means the effect on every component and system of a failure mode of a single component cannot always be exactly predicted. To investigate complex repairable systems, an RBD does not exist or cannot be easily found. And thus a RBD is not suited for this research. This leaves the Dynamic Fault Tree and Fault Maintenance tree left for this research.

3.3.2. Maintenance

As this thesis is trying to make an assessment if it is possible to only do maintenance in port, it is important that the reliability assessment is done for a longer period of time. Studying a longer time frame means that not all components are new and have various levels of degradation, influencing the P&P reliability. Including maintenance and degradation gives the model the possibility to calculate whether in the long run sailing without on-board personnel is possible. This points to a fault tree analysis that includes maintenance in its reliability calculations. This concludes the fault maintenance tree is more suitable than the use of a dynamic fault tree.

3.3.3. Simplifications

Due to the complexity of the systems and the demand that maintenance has to be taken into the reliability calculations, the option most suitable would be the fault maintenance tree. It can implement dependencies among events, inspections and both preventive as corrective maintenance which makes this the most comprehensible approach.
However, the complexity of the studied system is in all its complexity too comprehensive for a master thesis of which the writer is no expert in any of the considered fields, and thus simplifications have to be made considering the available time and skill and needed research within these fields. From the FMEA done, which is discussed later in this thesis, impacts of all failure modes that have limited impact on the performance of a component or system were difficult to define and made the research for this thesis too cumbersome and complex and thus not taken into consideration.
Because the lack of this knowledge and time, a basic Fault Tree Analysis was finally chosen to be the most suitable solution to this problem. The basic events of the FTA will be extended by time dependant basic events that are dependent on operating hours and maintenance. Inter dependencies between events like the RDEP-gate are not implemented in the reliability assessment model. With this model it is still possible to answer all the research questions, because it will still be possible to calculate the reliability of the P&P system and include the impact maintenance has on reliability.

3.4. Conclusion

From the literature review it can be stated there are some knowledge gaps when looking at unmanned Power and propulsion systems. These include that LUSVs are deemed not reliable enough for unmanned sailing, sufficient data to study this opportunity is not available and the impact of maintenance on the performance and reliability of unmanned surface vehicles is unknown. Efforts have been made to close the gap and resulted in various solutions. But, insufficient data has mostly hindered concrete results. The data made available by the Defence Material Organisation can change this and this thesis will try to exploit the opportunity.

By setting up a problem statement complemented by research questions the direction of this thesis has been identified: Studying the impact of maintenance activities to conclude if it is possible for the P&P system of a Navy vessel to sail without on-board maintenance. This is an essential step towards Large Unmanned Surface Vessels when these are desired in the future.

A Functional decomposition will give sufficient information on current P&P systems on board of Navy Vessels. With this information it is possible to carry out an FMEA that can then be used to find weaknesses that oppose the highest risk in an unmanned power and propulsion system.

A fault tree analysis complemented with extended Basic events dependent on time of usage and maintenance will assess the reliability of the system for unmanned operation. The impact on the overall reliability of the P&P system will be analysed. It is deemed possible this methodology will eventually lead to a Power and propulsion system that is reliable enough for unmanned operation.

4

The Power & Propulsion System

A first step in answering the main research question is to collect information regarding the current P&P system. This will be done by answering the first research question: *"What system components make up the power and propulsion system of the Holland Class Patrol Vessels of the Royal Netherlands Navy?"*. To answer this research question, the first section will present a functional decomposition. This decomposition will be used to understand what functions are performed by the P&P system. It will also help when the system needs to be redesigned to check whether all functions are fulfilled. After the functional decomposition, a physical decomposition will be made with the use of the functional decomposition to connect the functions defined to systems and components this is presented in the 4.2. After this section it will be possible to answer the first research question. To get more information regarding the current situation of the power and propulsion system on board the OPV, the maintenance activities are studied in section 4.3 to answer the second research question "What maintenance activities hinder maintenance free sailing?".

4.1. Functional Decomposition

In order to make a functional decomposition, the main function of the P&P system has to be defined. The main function of the P&P system is defined as: Providing Mobility. The main function will be divided up into several other functions that have to be fulfilled in order to provide the ship with mobility. Every part of the decomposition consists of one single function. If the function can only be defined with "and" it means there are more functions than one and thus these have to be treated as separate functions. The first three levels of the functional decomposition can be found in figure 4.1.

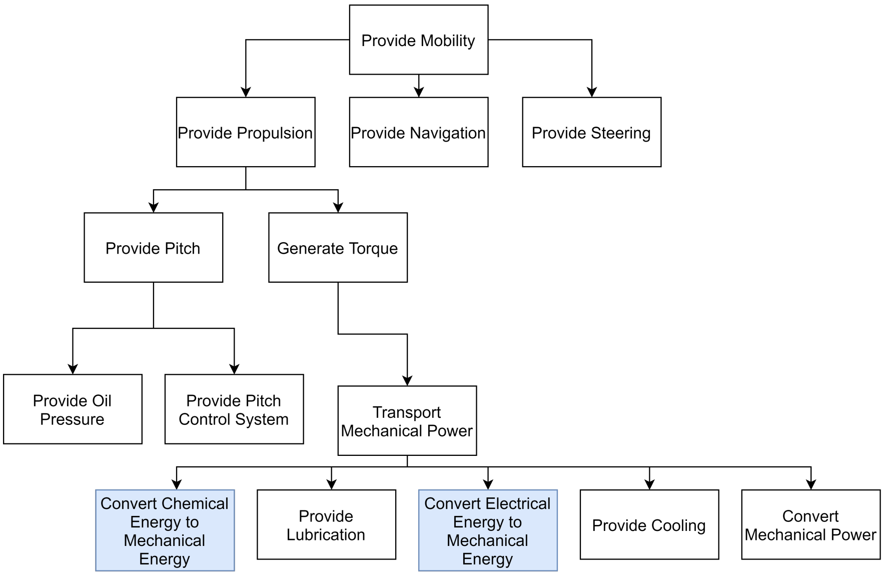

Figure 4.1: Part of Functional Breakdown Mobility Function

A total functional decomposition of the power and propulsion system for providing mobility can be found in appendix A. For this thesis, the functions highlighted in blue will be studied for this thesis. This is because, when looking forward to the physical decomposition, the systems that need the most frequent maintenance are the most interesting when studying the reliability of a power and propulsion system. In order to transport the mechanical power to generate torque for thrust and eventually mobility, the mechanical power first has to be generated and converted to the right magnitude, and for sufficient transport cooling and lubrication is needed. It furthermore can be seen that in the current situation, the OPV can provide the mechanical energy needed either by converting chemical energy to mechanical energy, or by converting electrical energy to mechanical energy. This means the propulsion system on board the Holland Class OPV of the Royal Netherlands Navy can be defined as a hybrid propulsion system [66]. This decomposition shows next to functions that have to be fulfilled how redundancy can improve reliability and where bottlenecks could possibly prevent removing maintenance personnel to shore. For instance, the decomposition shows that transporting mechanical power is essential, but generating that power can be done either by converting chemical or electrical energy and thus, if the system responsible for transporting mechanical power is subjected to frequent maintenance, adding redundancy might be a desirable option. How the functions distinguished are fulfilled is discussed below in the physical decomposition.

4.2. Physical Decomposition

To see what functions are fulfilled by what systems, more knowledge of the current situation on board of the OPVs is needed. This is done by looking at every function that has to be fulfilled and then looking into every system that fulfills that function. To see how the functions are linked to physical systems and components, this information was collected from multiple sources like platform handbooks, maintenance manuals, system breakdowns and maintenance schedules. With this information, relevant components regarding reliability and maintenance tasks are merged into a list of systems and then further divided to relevant components. Relevant components are components that are significant enough to mention regarding their importance for the functioning of the system they represent and the failure frequency of those components.

4.2.1. General Overview

To get a broad view of what the P&P system on board of the OPVs looks like, figure 4.2 presents a general overview of the propulsion architecture. It shows there are 4 diesel generators that provides all the loads and the Permanent Magnet Motor (PEM) with electrical power. In reality, one of these is a emergency generator, but in this case it is assumed there are 4 similar generators for simplification. It furthermore shows an electrical load distribution that is connected to the loads and the PEM motors through frequency converters and transformers to provide the electrical components with the right magnitude and frequency of electric energy. The main source of power comes from the two main diesel engines (MDE) that are connected, to a gear gearbox together with the PEM. A torn motor (TM) is connected to make sure the Diesel engine is able to start after is has been shut down. Finally, the gearbox is connected to the propeller shaft, which has a controllable pitch Propeller for propulsion.

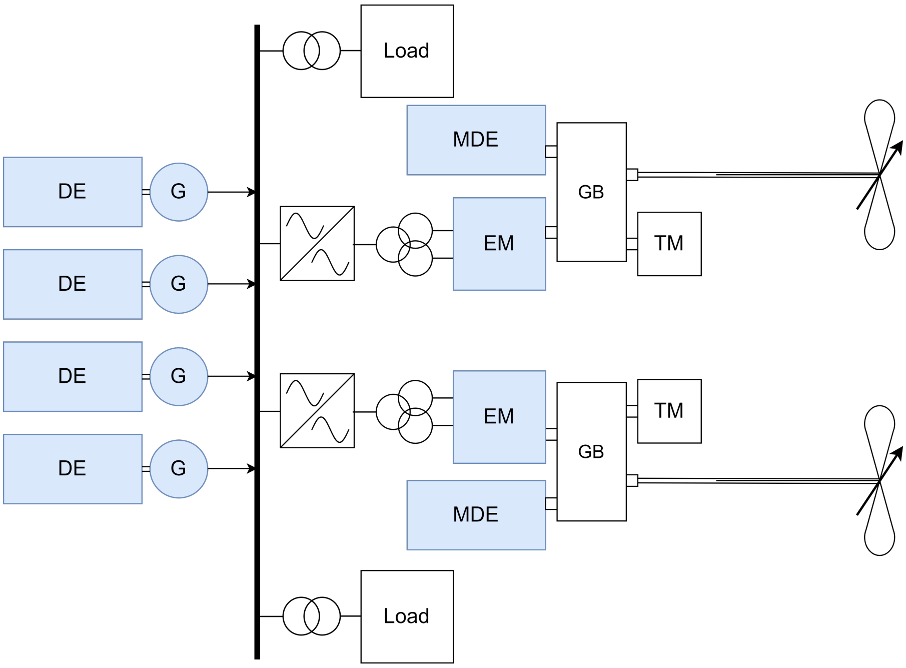

Figure 4.2: Schematic Presentation of General Propulsion Arrangement

Systems presented in blue are the systems within the power and propulsion system that are studied. This is because the other systems did not have enough information for a reliability study or the possibility of failure was small enough to be assumed as negligible. How this general arrangement fulfils the functions presented in appendix A is discussed below and complemented by the systems and the components that are relevant. Some information is left out or changed due to confidential reasons or because they make the analysis unnecessarily complicated, but this does not influence the readability or final results of this thesis. A list of all systems broken down to component level discussed in this section can be found in appendix A.2.

4.2.2. Convert Chemical Energy to Mechanical Energy

The Main Diesel Engine (MDE) is responsible for directly converting chemical energy to mechanical energy which is needed for the mobility function. Without proper functioning of the main diesel engine, the vessel is unable to sail at top speed or, depending on the functioning of the second MDE and the electrical propulsion system, not at all. The OPV houses two main diesel engines and therefore this system is already somewhat redundant when one of these fails. This function is further divided into several other functions that are visualised in a schematic overview of the main diesel engine system in figure 4.3. As can be seen from the figure, in order to convert chemical to mechanical energy the functions ”provide waste treatment”,”provide chemical energy”, ”control conversion” and ”provide lubrication” have to be fulfilled. These functions are discussed in more detail below.

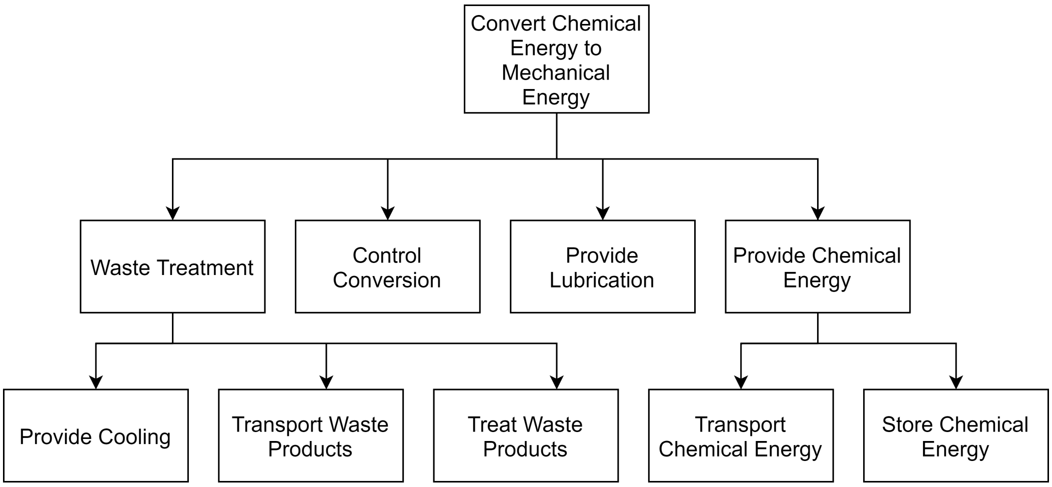

Figure 4.3: Functional decomposition for converting chemical energy to mechanical energy

Provide Chemical Energy
To provide chemical Energy, or in this case marine diesel oil (MDO), the two functions ”Transport Chemical Energy and Store Chemical Energy have to be realised. This is done by the fueling system in figure 4.4.

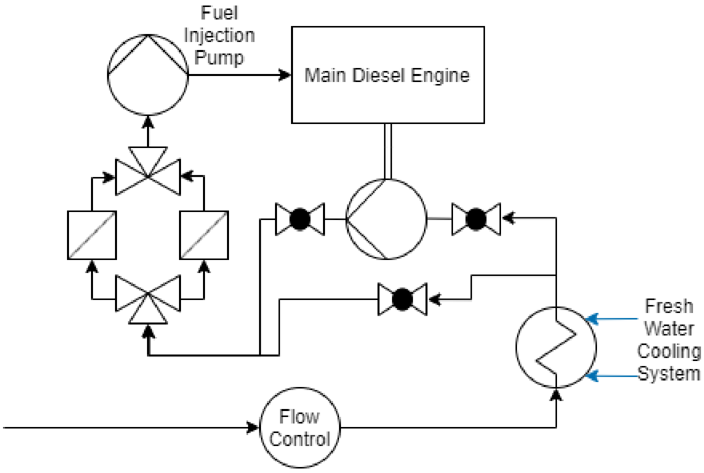

Figure 4.4: Main Diesel Engine Fueling System

The figure shows there are several filters, valves, a heat exchanger and two fuel pumps needed to transport the fuel to the main diesel Engine. Next to fuel, air is needed as chemical energy. This is done by the inlet air system and is visualised together with the exhaust system in figure 4.5. The Air inlet system consist a air filter to filter the incoming air from the environment, a turbocharger to compress the air and a two stage cooling system consisting of the HT and LT cooling system to further compress the air. Several sensors monitor the inlet air.

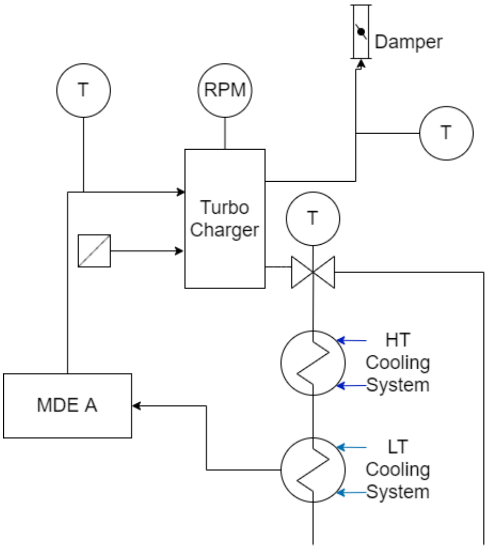

Figure 4.5: In- and outlet air system of the MDE

Control Conversion

To be able to control the conversion, a control system has to be implemented as well. This control system has been visualised by figure 4.6 and consists of several systems that make it possible to control the power conversion and mobility function from several locations on the ship.

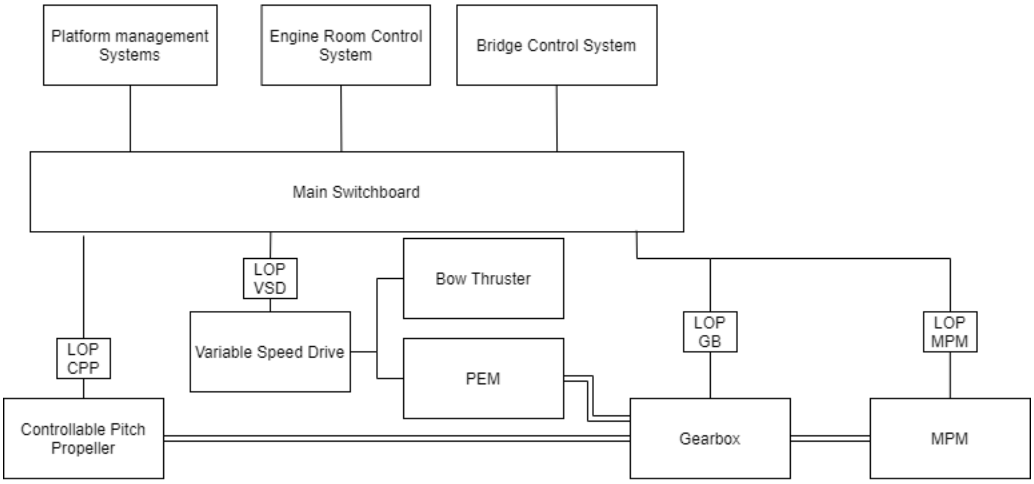

Figure 4.6: Propulsion Control System

Another form of control is starting the conversion. This is done by a starting Air system visualised in figure 4.7. The system consists of a pressurised starting air tank, which gets pressurised by a compressor. The pressurised air is then transported through several valves and filters and a depressurising unit to lower its pressure so it can be used to drive the connected devices which are the starter motor, the starter air amplification valve and the torn motor.

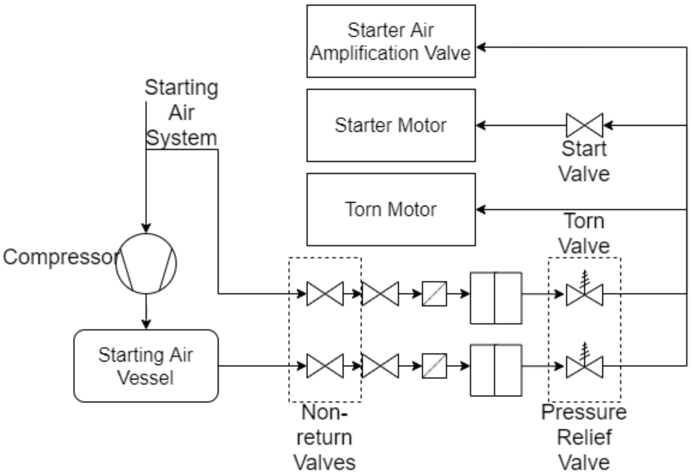

Figure 4.7: Starting air sytem of the MDE

Provide Lubrication

Because mechanical energy has motion, lubrication has to make sure this happens as smoothly as possible. The lubrication system dedicated to the main diesel engine is visualised in figure 4.4. As can be seen in the schematic overview, the lubrication system consists of two loops. The first loop is consisting the heating system and a electrically driven lubrication pump. The second loop is bigger and is consisting the engine powered lubrication pump, a parallel lubrication pump that adds redundancy, a heat exchanger connected to the cooling system and a duplex filter.

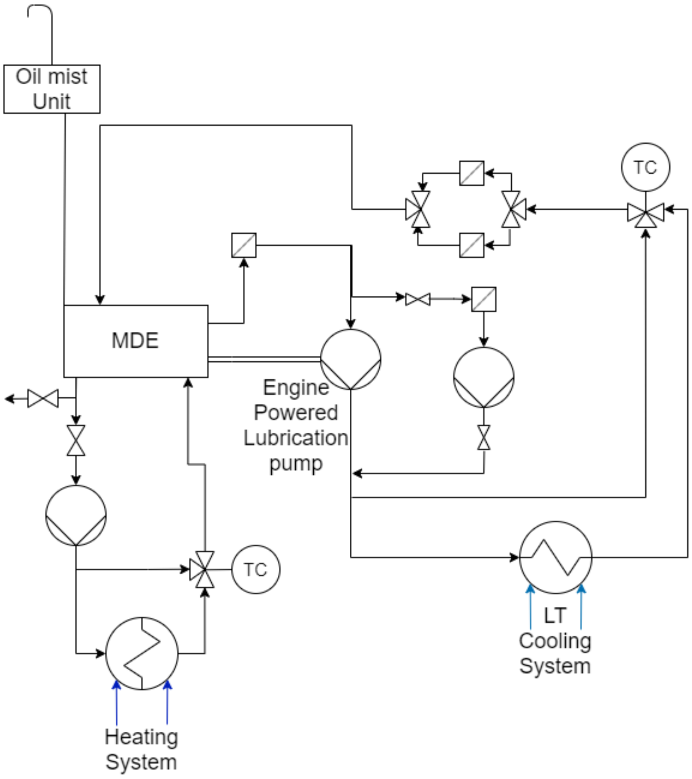

Figure 4.8: Main Diesel Engine Lubrication System

Provide Waste Treatment
The function waste treatment covers everything that has to do with byproducts. In the case of a diesel engine these are excess heat and exhaust gasses that have to be transported away from the conversion and treated if necessary. The exhaust system, or air outlet system, has already been visualised in figure 4.5.
To treat the excess heat, a cooling system is used. The Cooling system for the diesel engine is divided into a High Temperature Fresh Water Cooling System, a Low Temperature Fresh water Cooling system, and a seawater cooling system.
The HT Cooling System is the first step in cooling the MDEs. Coolant runs through the cylinder block to provide cooling. It furthermore heats up the inlet air before it continues to provides the heating installation and warms up lubrication oil. It then continues to the seawater heat exchanger where it gives of its heat to the seawater cooling system. Both diesel engines have their own HT cooling system. A schematic overview is given in figure 4.9.

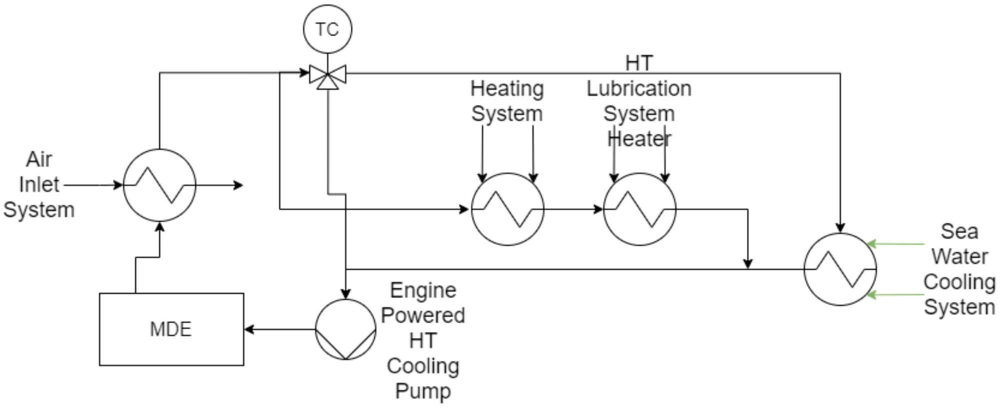

Figure 4.9: MDE HT Cooling System

The LT cooling system does not directly run though the MDE, but the cooling pump driving the system is powered by the MDE. The system extracts heat from the inlet air system after is has been exposed to the HT heat exchanger and then continues to the LT cooling water heat exchanger connected to the seawater cooling system. Finally, the coolant heats up the fuel oil used by the MDE. A schematic overview is given in figure 4.10.

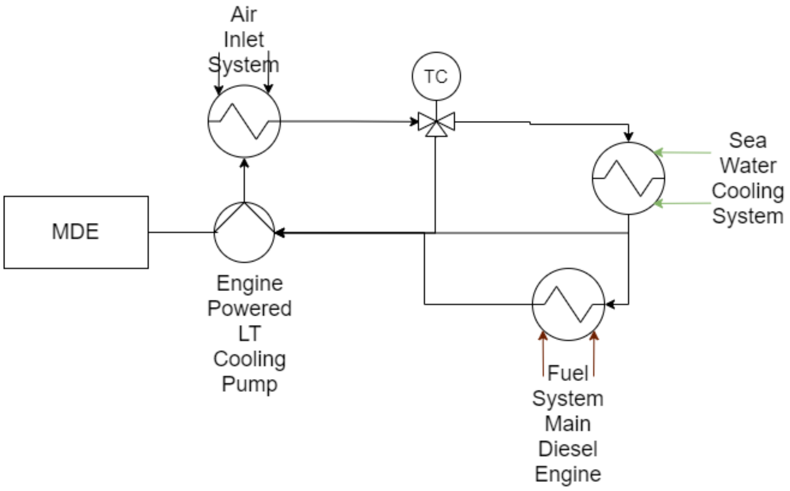

Figure 4.10: MDE LT Cooling system

The seawater cooling system of the main diesel engine provides cooling to the HT and LT cooling system. The pump for this system is also powered by the MDE. The seawater is coming from the Sea Chest outside of the ship and Dumps the water after use over board. The system's Schematic can be seen in figure 4.12.

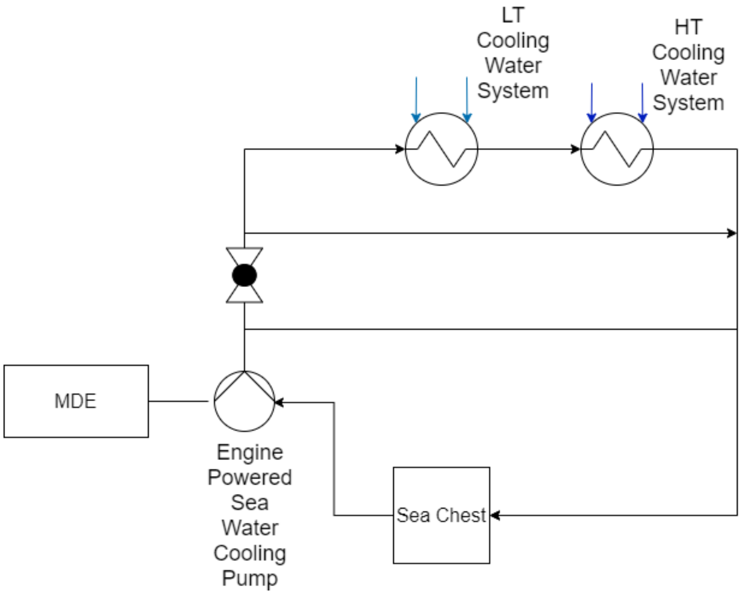

Figure 4.11: MDE seawater Cooling System

Treat Waste Products

Treating waste products is necessary when the products left from the energy conversion cannot be transported directly out of the system due to toxicity or the waste products are still useful. Both occur with the diesel engines. The turbocharger reuses the exhaust gasses coming from the main engine to compress the incoming air. After the gasses went through the turbocharger, they are transported through the exhaust system to provide heating to the heating system and are filtered to extract most of the toxic gasses due to regulations. Exhaust including the turbocharger are schematically visualised in figure 4.5. Both diesel engines have their own in- and outlet system which are connected in case one breaks down. The figure can be mirrored to represent this system for the second main diesel engine.

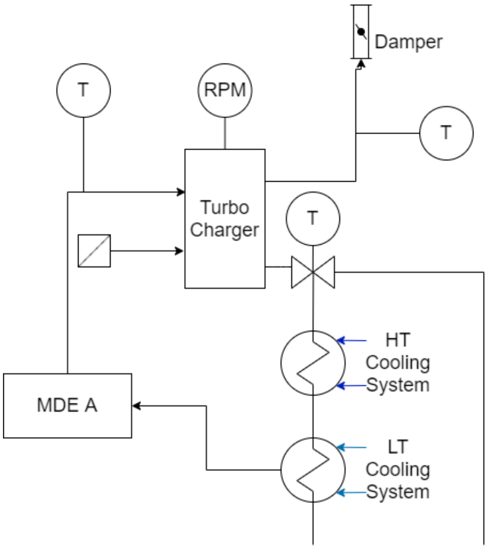

Figure 4.12: Main Diesel Engine Exhaust and Air Inlet System

4.2.3. Electrical Energy to Mechanical Energy

Another way to provide Mechanical Energy to the Propulsion of the ship is through the conversion of electrical energy to mechanical energy. This is done by an electric motor. For the electric motor to function, several other functions have to be performed. The part of the functional decomposition is shown below in figure 4.13.

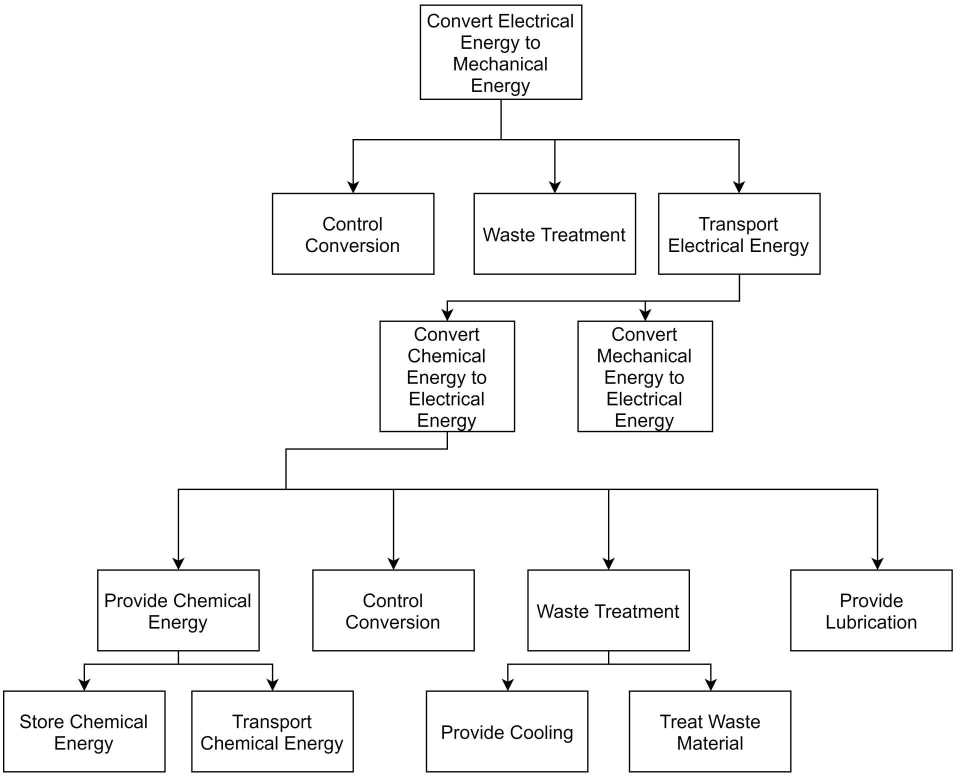

Figure 4.13: Functional decomposition for converting Electrical Energy to Mechanical Energy

Transport of Electrical Energy

Electrical Energy is transported through wiring and a central circuit board which controls the flows of electrical energy. These systems are seen as a black box and will not be studied due to the scope of this project and for the sake of time. They will hereby perform as an ideal electrical transport system and will not have a probability of failure.

Convert Chemical Energy to Electrical Energy

In order to provide electrical energy, a conversion device is needed. On the OPVs this is done by 4 diesel generators. As seen in the functional decomposition, the conversion of chemical to electrical energy is consisting of the same functions as the chemical to mechanical energy conversion that was fulfilled by the MDE. The systems that fulfill these functions are in this case similar and thus will not be discussed further because the main goal of this chapter is to give insight and understanding in the current systems that will be implemented in the reliability study. The actual schematic overviews of the diesel generator and its auxiliary systems can be found in appendix B.

4.2.4. Convert Mechanical Power

The mechanical power provided by the power conversions have their own rpm, they have to be converted to the right ratio so it is usable by the, in this case, propeller of the ship. In order to do that, both converters are connected to a gearbox which changes the torque and speeds of the mechanical powers. This is done by a gearbox, shown in figure 4.14.

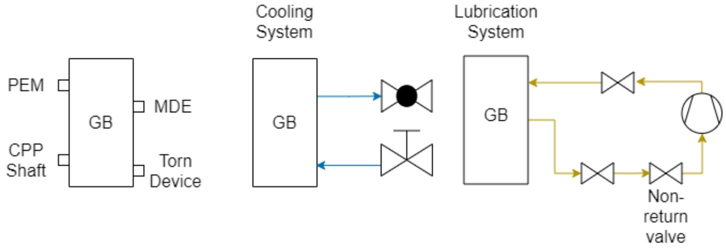

Figure 4.14: Gearbox With representing cooling and lubrication system

With the entire P&P system broken down there is a clear view of what makes up the P&P system and the first research question is answered.

4.3. Maintenance Activities

With an overview of what systems are on board and what functions they fulfill, it is important to know what maintenance activities are necessary to keep these systems operational. Not all activities are and can be done while at sea, but the ones that are make on-board personnel essential for the availability and reliable performance of these systems. These are the tasks that make maintenance free sailing impossible in the current situation and thus is it important to list these activities and see how these can be replaced by solutions that do not require any on board personnel. Planned maintenance done by on-board personnel can be categorized by inspections, preventive maintenance and replacements.

4.3.1. Inspections

Inspections are the most common activity of the maintenance personnel on board of navy vessels. Some inspections are done every day and some less frequent. From the planned maintenance schedule provided by DMO, it is clear these activities are the first that ask for an alternative to make a ship sail without on-board personnel. Inspections monitor the condition of the machinery and thus by inspecting regularly, anomalies in operation can be detected on time and a system failure can be prevented. If maintenance personnel is to be removed from board, these inspections have to be addressed.

4.3.2. Preventive Maintenance

Some systems require regular maintenance to keep them reliable and operational. Lubrication as well as cleaning are tasks that are done on a daily or weekly basis. In order to tell if these tasks can be omitted, the impact of these activities on the reliability of the system has to be known. How the impact of maintenance can be simulated is further discussed in section 6.1.

4.3.3. Replacements

Other, non-maintainable systems required replacement of components. These components are usually subjected to wear.

The list of activities that are done on board for the Main Diesel Engine (MDE) and the Diesel Generator (DG) is presented below in table 4.3.3.
The tasks performed by on-board personnel have a maximum cycle of 1000 operating hours. Tasks with a longer frequency will not be considered necessary to perform on board and thus left out of this list, because they are normally not performed by on-board personnel.
This table provides an overview of the activities that are hindering maintenance free sailing. The next step in the reliability analysis and the feasibility of maintenance free sailing is a failure mode and effect analysis. This will give insight in how a possible failure of the components in the maintenance list will impact the performance of the entire system. To make a complete reliability study of these systems, other important components that can fail coming from the from the physical an functional decomposition will be added to the analysis as well. With this analysis it is possible to point out what components and systems are essential in the performance of the P&P system.

System	Sub system	Component/system	Frequency	Personnel	MTTR	Desciption
MDE	Engine	Engine	24	1	0.20	Inspect Diesel Engine for irregularities
MDE	Fuel System		24	1	0.20	Inspect for leakages
MDE	Fuel System	Service Tank	24	1	0.20	Inspect fuel level
MDE	Fuel System	Fuel Oil Filter	24	1	3.00	Inspect/Clean Fuel Oil Filters
MDE	Lub Oil System		24	1	0.20	Inspect For leakages
MDE	Lub Oil System	Oil	150	1	0.20	Inspect Oil Properties
MDE	Lub Oil System	Oil	500	1	0.20	Inspection Oil by supplier
MDE	Lub Oil System	Oil	24	1	2.00	Inspect/Change Oil
MDE	Lub Oil System	Pre-lube pump	1000			Inspect Pre lub pump
MDE	Lub Oil System	Oil Mist seperator	24			Inspect/Clean Oil Mist Separator
MDE	Lub Oil System	Bypass filter	24	1	3.00	Inspect/Clean Bypass Filter
MDE	Lub Oil System	Lube Oil Pre Heater	24	1	4.00	Inspect/Clean Lube Oil Preheater
MDE	Cooling Water System		24	1	0.20	Inspect for leakages
MDE	Cooling Water System	Expansion Tank	24	1	0.20	Inspect Cooling Water Level
MDE	Cooling Water System	Cooling Water	150	1	0.50	Inspect Cooling water properties
MDE	Cooling Water System	Heat Exchanger	24	1	0.20	Inspect/Clean Heat Exchanger
MDE	Charge Air System		24	1	0.20	Check Pressures and Draining
MDE	Fuel System	Starter Motor	1000	1	1.00	Monthly Maintenance Starter Motor
DG	Control Panel	Control Panel	750	1	0.20	Clean Control Panel
DG	Fuel System	Fuel Injector	250	1	0.20	Inspect Fuel Injector
DG	Fuel System	Fuel Filter	1000	1	0.20	Inspect/Replace Fuel Filter
DG	Lub Oil System	Lube Oil	24	1	0.20	Inspect Oil level
DG	Lub Oil System	Lube Oil	250	1	0.20	Inspect Oil properties
DG	Lub Oil System	Lube Oil	1000	1	2.00	Change Oil
DG	Lub Oil System	Oil Filter	1000	1	1.00	Replace Oil Filter
DG	Cooling Water System	Coolant	24	1	0.20	Check level Coolant
DG	Cooling Water System	Coolant	1000	1	0.20	Inspect Coolant Properties
DG	Starting Air System	Starter Motor	24	1	0.20	Inspect Oil level Starter Motor
DG	Exhaust System	Filter	250	1	1.00	Replace Filter
DG	Engine	Crankcase	1000	1	4.00	Clean Crankcase
DG	Control syst	sensors	1000	1	0.20	Inspect Sensors
DG	Foundation	Piping	24	1	0.20	Inspect for leakages
DG	Foundation	Hoses/clamps	1000	1	0.20	Inspect
DG	Foundation	Engine	1000	1	2.00	Degrease Engine Outside
DG	Flexible Coupling		1000	1	0.20	Inspect
DG	Flexible Coupling		1000	1	1.00	Check alignment

Table 4.1: List of maintenance Activities done on board for the Main Diesel Engine- and Diesel Generator systems

This chapter gave an overview of the functions that have to be fulfilled in order to provide the ship with mobility. This was done by first setting up a functional decomposition and by collecting information from multiple sources, it was possible to set up a physical decomposition to get an understanding of what systems were responsible for fulfilling the functions found in the functional decomposition and what components within this system are relevant for setting of a reliability assessment. Furthermore, this chapter gave insight in the current maintenance activities done by personnel on board. These activities make it impossible in the current situation to sail without maintenance personnel. With this information, it is possible to continue this research and indicate what are the weakest components in the current power and propulsion system, and what activities have to be addressed to make it possible to sail with an unmanned P&P system.

5

Failure Mode and Effect Analysis

With knowledge of the functions that need to be fulfilled for the ship to have mobility and the systems that are responsible, the next step in the reliability analysis is a Failure Mode and Effect Analysis (FMEA). This chapter will try to answer the second research question question:*"What are the weaknesses of the power and propulsion system when not maintained during sailing?"* The FMEA will furthermore provide the input data for the reliability study by complementing the FMEA for every component with a mean time between failure (MTBF) and a maintenance frequency. This analysis is crucial, because it shows how, when, and what fails and what the interaction of components and systems is within the P&P system. By knowing when a component fails and what the impact of failing of that component would be on the functionality of the system can determine whether the power and propulsion system would be reliable enough for unmanned and maintenance free operation. The FMEA is too large to fit on paper, but an example of the most important headings is shown below in table 5.1 to give an idea what has been done.

Because the FMEA is too large to fit on paper, only the data that is relevant for the input of the reliability model is presented in appendix C.
It only consists of data that was made available through DMO and thus several failure modes, effects on systems or other data will be missing. Data can be modified when missing if comparable components or systems do have data. And, most of the effects a failure has on the system has been filled in by own judgement. In some cases, there was no sufficient knowledge available due to busy schedules and other priorities of experts. For instance, a fuel filter is assumed to be replaced every 250 hours. It has to be noted that these assumptions have a significant impact on the conclusions of this thesis but these assumptions were necessary because this thesis is trying to visualize the impact of maintenance on reliability. Without knowledge of what impact maintenance has on the reliability of the P&P system it would not be possible to assess the system reliability for an unmanned systems that doesn't receive maintenance while sailing. Components in the FMEA can be divided into critical and non-critical failures.

Non-critical Failures
Non-critical failures are failure that do not result directly in the system stopping from functioning. For instance, clogged heat exchanger pores do have an effect on the performance of the cooling system, but do not prevent the coolant from flowing through the system and thus is considered to not be a critical failure when this failure occurs. Multiple non-critical failures can result in the failure of the system it is part of, but these interactions are too complicated to judge without expert knowledge and thus will be left out of the scope of this study.

Critical Failures
Critical failures on the other hand do have a direct result of system failure. Examples of critical failures would be the failure modes from table 5.1. All these failure modes have been indicated to result in a failure of the entire MDE-system.

System	Subsystem	Component	Failure Mode	Effect - System level	MTBF (hrs)	Maintenance Freq	Sort
MDE	Engine	Engine Block	High carter level	System Failure	100000	8000	Inspection
MDE	Engine	Cam Shaft	Worn Out	System Failure	100000	16000	Clean/Replace
MDE	Engine	Cam Shaft Bearing	No Bearing	System Failure	100000		
MDE	Engine	Cylinder lining	Unable to Contain Combustion	System Failure	2578.7818	1600	Clean/Replace
MDE	Engine	Cylinder lining	Unable to Contain Combustion	System Failure	2578.7818	1600	Clean/Replace
MDE	Engine	Cylinder lining	Unable to Contain Combustion	System Failure	1289.3909	1600	Clean/Replace
MDE	Engine	Cylinder lining	Unable to Contain Combustion	System Failure	2578.7818	1600	Clean/Replace
MDE	Engine	Cylinder lining	Unable to Contain Combustion	System Failure	2578.7818	1600	Clean/Replace
MDE	Engine	Cylinder Heads	Crack in Cylinder Head	System Failure	80000	4000	Replace Seal
MDE	Engine	Pistons	Piston Cracked	System Failure	70000	8000	Clean
MDE	Engine	Pistons	piston leaking air	System Failure	70000	8000	Clean
MDE	Engine	Piston Rod	Broken Piston rod	System Failure	100000	500	Inspect
MDE	Engine	Radial Bearings	Bearing Damage	System Failure	70000	500	Inspect
MDE	Engine	Radial Bearings	Bearing Damage	System Failure	40000	500	Inspect
MDE	Engine	Seals	Leaking Seals	System Failure	30000	16000	check
MDE	Engine	Crank Shaft	Unable to transfer energy	System Failure	100000	2000	Inspection
MDE	Engine	Thrust bearing	No Bearing	System Failure	50000	8000	Inspection
MDE	Engine	Gears	Worn out Gear	System Failure	100000	4000	Inspection
MDE	Engine	Gears	Broken Tooth	System Failure	70000	4000	Inspection
MDE	Engine	Virbration Damper	Torn Vibration Damper	System Failure	60000	16000	Inspection
MDE	Engine	Cylinder Valves	Worn Out Valves	System Failure	5000	1000	Inspection
MDE	Engine	Cylinder Valves	Broken Valves	System Failure	50000	16000	Replace
MDE	Engine	Cylinder Valves	Broken Valves	System Failure	50000	16000	Replace

Table 5.1: Part of FMEA of the Main Diesel Engines

The failure rate for these components will together with their effect on the system tell what components will be the most critical. However, it is better to judge their critically by means of a reliability analysis. It does give an indication of what possible components may be resulting in a higher reliability when implementing redundancy or more reliable replacements.

The FMEA tells that the most critical components are the components in the MDE itself. Most do have a high MTBF, but when either of those components fail, the MDE and thus a big part of the power is lost. Next to the MDE, the diesel generators contain several critical components for the functioning of their system. To find the most critical components, the first requirement is that a failure of the component has to result in a failure of the entire system.
Secondly, the components are arranged by the mean time between failures. This thus gives a list of components with failure modes that can result in system failure with a relatively low MTBF. A list of the 10 weakest components is presented below in table 5.2.

System	Sub System	Part	Failure Mode	Failure Cause	MTBF (h)	Maint. Freq (h)
DG	Generator	Generator	Fails synchronization		3719.13121	x
MDE	Engine	Cylinder Valves	Worn Out Valves	Wear	5000	1000
MDE	Lub Oil System	Oil Filter	Clogged Filter	Pressure Sensor	5000	168
MDE	Fueling System	Duplex pressure filter	Insufficient Fuel Supply	Inspection	5000	168
MDE	Fuel Oil System	Duplex Fuel Filter	Insufficient Fuel Supply	Inspection	5000	300
MDE	HT Cooling System	Heat Exchanger Seawater (HT Side)	Clogged Cooler	Temperature Sensor	5000	2160
MDE	HT Cooling System	Heat Exchanger Lubrication Oil (HT side)	Clogged Cooler	Temperature Sensor	5000	2160
MDE	LT Cooling System	Heat Exchanger Sea water (LT Side)	Clogged Cooler	Temperature Sensor	5000	2160
MDE	LT Cooling System	Heat Exchanger Fueling System (LT Side)	Clogged Cooler	Temperature Sensor	5000	2160
DG	Lub Oil System	Lubrication Oil Filter	Clogged Filter	Pressure Sensor	5000	300

Table 5.2: 10 weakest components of the P&P system for a manned P&P system

However, it could be components are missing or that the list is not entirely representative to reality, especially for an unmanned system that does not receive maintenance. This data is based on the assumption maintenance can be performed on board, especially for the higher maintenance frequencies. The data does not take this into account and thus this most critical component list is solely based on MTBF and the effect a failure would have on the system it is part of and thus not representative. To actually be able to identify which components are most critical for an unmanned P&P system, the maintenance frequency has to be taken into consideration as well and thus the research question ”What are the weaknesses of the power and propulsion system when not maintained during sailing?” cannot be answered yet. How the maintenance frequency and, most importantly, not doing maintenance according to the maintenance frequency is taken into account when identifying the weakest components is discussed in chapter 6.

6

Reliability Model

To answer what can be done to reduce the risk weak components present in the P&P system, a reliability analysis on the entire system has to be performed by the use of a reliability model. Because during the FMEA it was not clear what impact maintenance had on the reliability, the reliability model will need to show where there are weaknesses in the system when the impact of maintenance and time of usage is included in the reliability study and what components need to be addressed to have an optimal gain in reliability as possible.

This chapter will discuss the reliability model that is used for the reliability analysis and will discuss how the the impact of maintenance and inspections of maintainable components are modelled of the P&P system on board the Holland class ocean going patrol vessels of the Royal Netherlands Navy. It furthermore will discuss how the components are connected and finally, a few situations are sketched to verify the model.

6.1. Basic Events

To understand how the reliability model works, we start at the bottom of the Fault Tree, namely the basic events.

Basic events are the driver behind the reliability assessment. In this model, every failure mode of a repairable component, capable of resulting in system failure, is presented by a basic event. Basic events are calculating failure rates, which are defined as the instant probability of a failure, assumed that it has not yet failed [54]. The basic events are furthermore calculating the reliability with respect to time. When a component is used while the ship is operational, its time of use will normally increase the failure rate, resulting in an increase in probability for the top event of happening, which is failing to provide the ship sufficient mobility. Maintenance on the other hand will normally decrease the failure rate of the event and increase the reliability, meaning the system becomes more reliable. How the increasing and decreasing of the failure rate and reliability is affected by time of use and maintenance is further discussed in 6.1.1 and 6.2. Not all components receive planned maintenance and thus there is a distinction made between components that receive planned maintenance and components that do not. How this distinction is made and how the failure rates are calculated depends firstly on the available data.

Data

All basic events modelled are based on data provided by DMO, where the MTBF is the most important data available. This indicates the mean operating time between two failures of repairable systems, including diagnostic time and repair time as visualised in figure 6.1. The MTBF makes it possible to calculate the reliability and failure rates of the components that make up the P&P system.

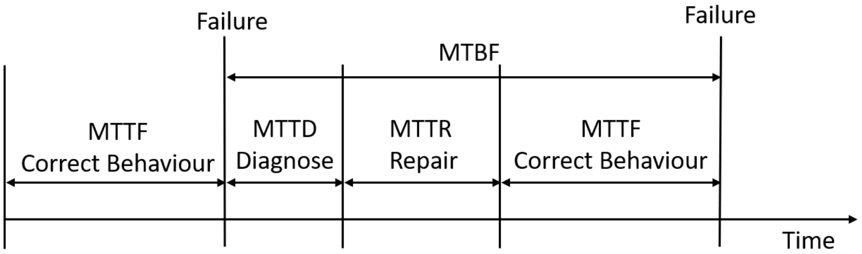

Figure 6.1: Visualization of MTBF

The MTBF is calculated statistically by formula 6.1 from the definition [54].

$$MTBF = \frac{Total\ Operating\ Time}{Number\ of\ Failures} \tag{6.1}$$

With this data, the failure rate λ can be calculated through $\lambda = \frac{1}{MTBF}$ [48]. λ represents an instant probability of failure which is independent of time. Alternatively, the failure rate can be defined as the number of failures per unit time [54]. This means that, with a constant failure rate, the bathtub failure rate curve discussed in 2.2.5 cannot be used and is trimmed down to only the constant part, representing its useful lifetime as suggested in literature [57]. This is visualised in figure 6.2.

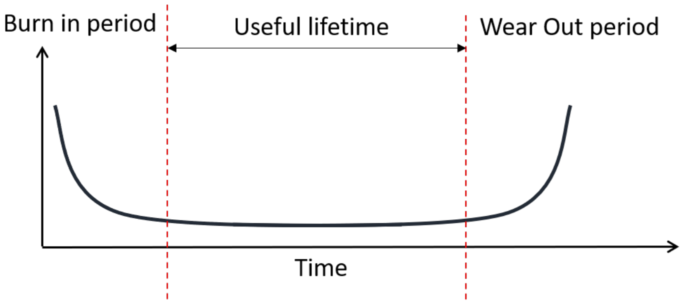

Figure 6.2: Bathtub Failure Rate Curve

With a constant failure rate, the influence of usage and maintenance is not clear and thus to see the impact of these factors an addition to this approach is desirable. It has to be noted that although the impact of maintenance is not directly visible, the MTBF used to calculate the failure rate is a result of preventive maintenance. The absence of maintenance would undoubtedly result in a much lower MTBF and thus a higher failure rate.

To be able to make the impact of maintenance visible, the first thing that needs to be noted is that at least for maintainable components where the bath tub curve exists, the lower part of the curve is in reality not constant. If it was, it would mean that maintenance does not have any impact in lowering the failure rate and would suggest that maintenance is not needed. The bathtub curve exists because of the statistics acquired of failures for similar components and does not say anything regarding the failure rate progression or the direct impact maintenance has on the failure rate. The failure rate function curve for maintainable items has this curve because of maintenance, not despite of it. At this point, the assumption is made that for a component the failure rate is constant over a specific amount of time because of the maintenance frequency. In other words, the failure rate progression is not constant when looking between two maintenance activities and thus must follow a different curve to give maintenance impact on the failure rate. If the failure rate would be plotted against time, the surface under that constant curve must be the same as the "real" failure rate development over usage of time within the time frame of planned maintenance. This theory is visualized in figure 6.3.

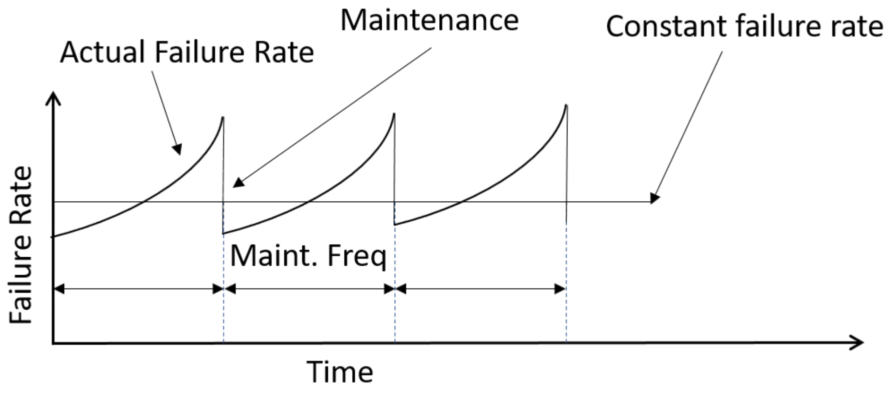

Figure 6.3: Failure Rate Theory

From this figure it can be seen that the surface under the curve which is calculated with the use a the MTBF and the curve which is assumed to be the actual failure rate have are the same within the planned maintenance frequency.
It has to be noted that this theory can only be used on items that receive planned maintenance. Other components that only receive maintenance after inspection has confirmed maintenance is needed do not have a planned maintenance frequency. Information of maintenance on these components is absent or not sufficient and thus the alternative failure rate function cannot be defined. This means that these components have to be modelled differently, which is discussed in section 6.2.2.

In order to use this theory for items that receive planned maintenance and do a reliability assessment, it has to be clear what makes up the failure rate and what curve it follows when it progresses. It furthermore has to be clear what impact maintenance has on this failure rate. This is important when planned maintenance activities can no longer be done on board due to the absence of maintenance personnel and thus is it necessary to know the failure rate progression with respect to usage.

6.1.1. Failure Rate Function h(t)

The failure rate progression can be described by the failure rate function. This function will give the instant probability of failure at any give time t, assuming that the component hasn't failed yet. In order to determine the failure rate function it first has to be clear what part of the total failure rate can be labelled as random (expressed mathematically by a constant) and what part can be indicated as time related (dependent on the time of use and maintenance). Maintenance does have an influence on the failure rate, but it does not lower this to zero, and thus must there be a part which is not sensitive to maintenance. A study done on the reliability of submarines by T.M. Allen [4] concluded that 71% of the failures occurring can be indicated as random. Even though this is concluded from a variety of components, the study shows the same conclusion was drawn by several other studies, namely that random failure predominates. Since no other information was found the assumption is made that for the initial reliability analysis, every component of the P&P system has the same random/time related failure distribution and thus 29% of the failure rate can addressed to be time related for maintainable components. This is visualised in figure 6.4. A sensitivity analysis discusses the impact of this assumption in chapter 7.4.

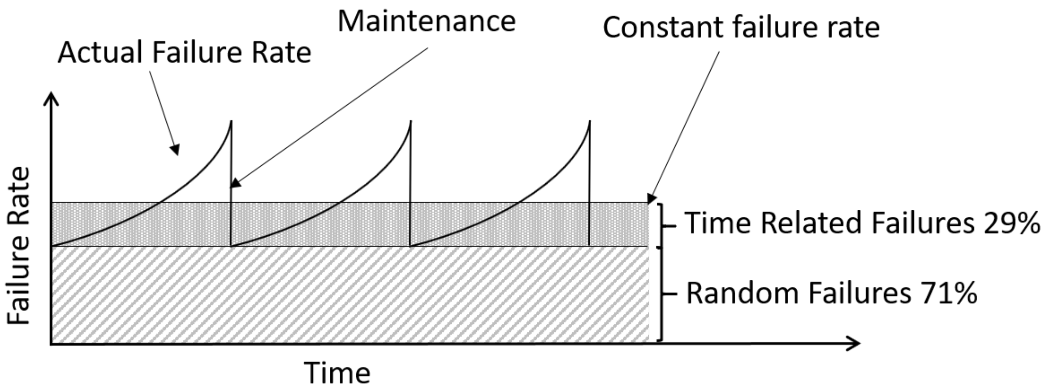

Figure 6.4: Visualization of what time related failure part

Now that the percentage of the failure rate which is constant is known, it is important to find out what particular shape the time-related failure rate follows.

Failure rate progression is in literature known as degradation modeling. It is an approach to perform reliability assessments, remaining useful life predictions and maintenance planning [58]. The degradation of components is normally modelled according to an exponential or Weibull distribution [56]. However, the failure rate function of an exponential distribution is constant and thus is not usable for components that receive planned maintenance as it was assumed the failure rate is dependent on time of use. A constant failure rate would, again, imply there is no significance in doing maintenance as the failure rate is not dependent on time of use. The Weibull distribution on the other hand does have a changing failure rate with respect to time depending on the shape factor [45] and thus will be used for the degradation modelling of the failure rate in this thesis.
The Weibull distribution is a two-parameter distribution and its probability density function is given by [54]:

$$\text{f}(t) = \begin{cases} \frac{\beta}{\eta^\beta} t^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^\beta\right] & (\text{ for } t \geq 0) \\ 0 & (\text{for } t < 0) \end{cases} \tag{6.2}$$

with η being the scale parameter and β the shape parameter.
This distribution function gives the failure rate function as:

$$h(t) = \frac{\beta}{\eta^\beta} t^{\beta-1} \tag{6.3}$$

In order to use this distribution to simulate failure rate progression, the shape parameter β has to be determined first. For $\beta < 1$ the failure rate function would decrease in time [49]. A $\beta = 1$ would give a constant failure rate over time, which would have the same result as an exponential distribution. All failure rate functions for different shape factors are plotted in figure 6.5. A shape factor of $\beta = 3$ is chosen as initial value for the reliability assessment, because it is assumed that failure rate progression is slower when maintenance is just performed and will progress faster over time the longer the component performs without maintenance. This value can of course be criticized as it isn't based on any actual data but merely the assumption a general component's failure rate could behave like this. It therefore will be varied during the sensitivity analysis and the impact it as on the reliability will be studied.

Another point of discussion is that at this point, every component has the same value for β. This is of course not reality. Every component with a different failure mechanism will have a different failure rate function and even among similar components this curve could differ. These factors are not taken into account for this thesis.

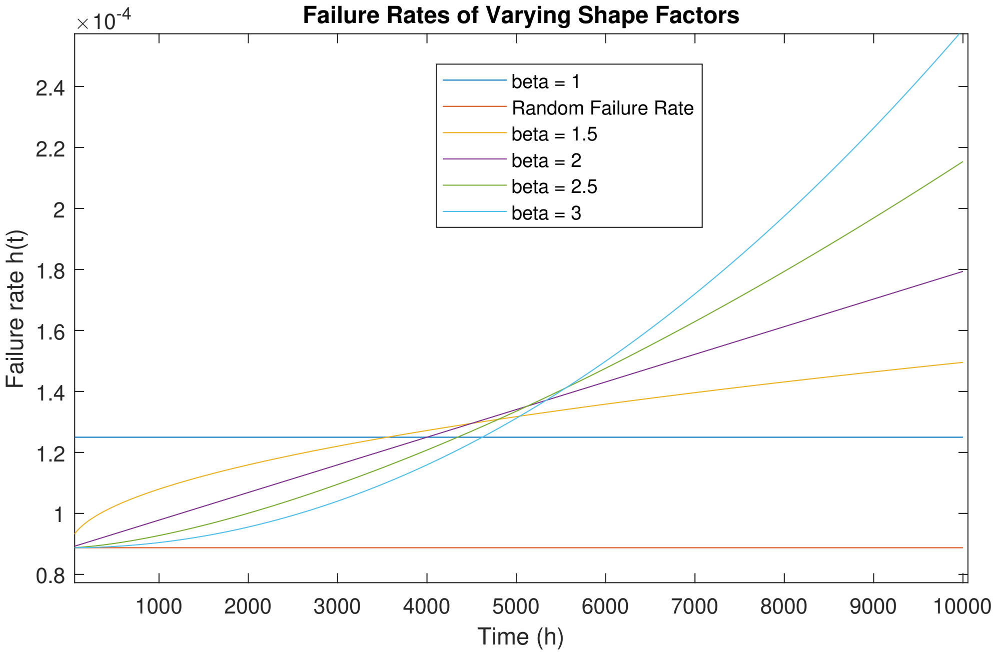

Figure 6.5: Weibull failure rate progression curves of time related failure rate with different shape factors

Impact of Maintenance

Next to how the failure rate develops over time, the impact of maintenance and how it reduces the failure rate is still unknown at this moment. Several failure rate reduction methods have been developed [68]. Chan and Shaw proposed two failure rate reduction methods that are easily applicable [15]. The first method describes a fixed failure rate reduction, independent of time of usage, and a proportional reduction that will reduce the failure rate proportional to the current failure rate of the component. However, both of these methods would imply that in the current situation, where only the useful lifetime with a constant failure rate due to maintenance is being analysed, the failure rate cannot be constant over a longer time period. So another solution has to be proposed. For this thesis, it is assumed that the maintenance performed will bring the failure rate back to the random failure rate, which is independent of time. The failure rate just before maintenance is therefore not of importance. The 3 theories are all visualised in figure 6.6

Failure Rate Threshold

With the failure rate progression and the impact of maintenance now clear, the next step in the modelling phase is to decide at what failure rate components are needed to be maintained, known as the failure rate threshold. Some literature suggests to take a pre-determined value or a probabilistic approach [50], but in this case another approach is used to give a logical explanation to the maintenance frequency.

For components that receive planned maintenance, the failure rate function at the time at which planned maintenance would be performed is defined to be the failure rate threshold. So, for instance, when a component would receive planned maintenance every 100 hours, the failure rate at t = 100h is the failure rate threshold. This means that the model will only indicate the component needs maintenance when the 100 operating hours have passed. This means that for every component, a custom failure rate threshold is calculated that is dependent on the MTBF, the maintenance frequency and the Weibull distribution failure rate function. A sketch of the failure rate with multiple maintenance frequencies is presented in figure 6.7.

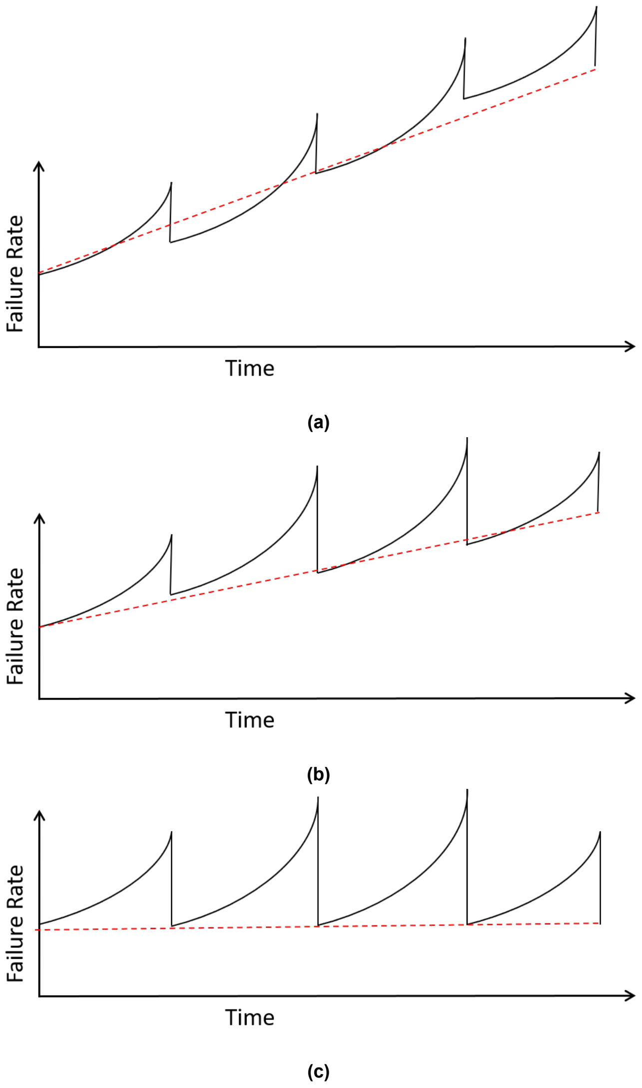

Figure 6.6: (a) Failure rate with a constant reduction in failure rate independent on the failure rate its self. (b) Failure rate with a reduction proportional to its current failure rate. (c) Failure rate with a reduction that reduces the failure rate back to the random failure rate, independent of the current rate.

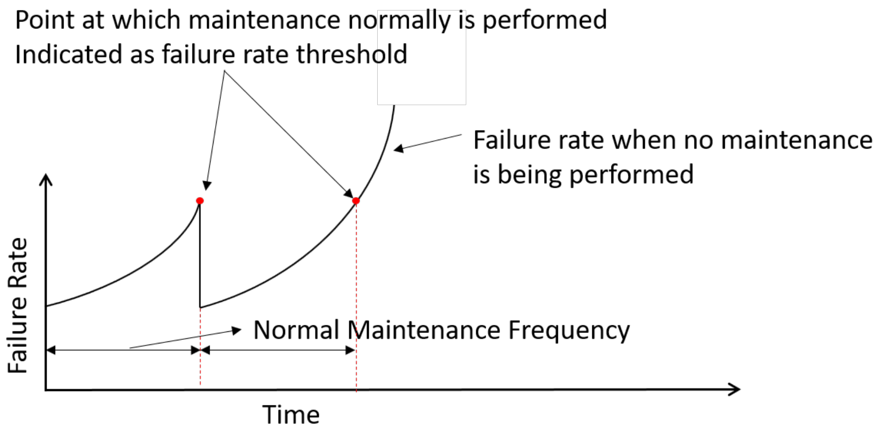

Figure 6.7: Visualization of failure rate threshold, impact of maintenance and failure rate progression when no maintenance is performed

6.2. Calculating Reliability

With the knowledge of the failure rate function, the failure rate threshold and the impact of planned maintenance on the failure rate, the reliability of the P&P system can be calculated. The reliability is defined as the probability a component will perform its function for a defined interval of the probability density function $f(t)$ as presented in the equation below:

$$\mathsf{R}(t) = 1 - \mathsf{F}(t) = \int_t^\infty \mathsf{f}(t)\mathsf{d}t = 1 - \int_{-\infty}^t \mathsf{f}(t)\mathsf{d}t \tag{6.4}$$

With a constant failure rate λ, the reliability can be described with an exponential distribution and is given as:

$$\mathsf{f}(t) = \lambda \,\mathsf{exp}(-\lambda t) \tag{6.5}$$

which gives the reliability of a component with a constant failure rate as:

$$\mathsf{R}(t) = 1 - \int_0^t \mathsf{f}(t)\mathsf{d}t = \mathsf{exp}(-\lambda t) \tag{6.6}$$

However, this still implies that the failure rate can be assumed to be constant which was concluded earlier not to be the case for components that receive planned maintenance. The distinction of calculating the reliability is made between components that receive planned maintenance and components that do not receive planned maintenance, but only after inspection has determined maintenance is deemed necessary.

6.2.1. Planned Maintenance

To calculate the reliability of components that receive planned maintenance, the most logical option would be to use the probability density function of a Weibull distribution shown in equation 6.2. However, within the maintenance frequency, the calculation of reliability according to an exponential distribution, as would be logical with the available data, and the reliability calculated with the Weibull distribution has to be comparable, because it wouldn't be logical if the reliability of the initial situation differs significantly within the maintenance frequency. This is because there is no difference between a manned and unmanned situation within this time scheme. When not comparing to an exponential distribution, there would be no verification of the reliability model. The exponential model is a well accepted method for calculating reliability and thus is assumed to be useful for verification.
This gives the following equation to solve:

$$R(t) = \mathsf{exp}(-\lambda t) = \frac{\beta}{\eta^\beta} t^{\beta-1} \,\mathsf{exp}\left[-\left(\frac{t}{\eta}\right)^\beta\right] \tag{6.7}$$

However, when equating the reliability functions of these distributions, the failure rate of the Weibull distribution has a significant lower value compared to the constant rate, meaning the instant probability of failure at a given time t would be a factor 100 lower compared to the exponential distribution's constant failure rate λ. For instance, at the time a component should receive maintenance e.g. every 250 hours, equation 6.7 calculates an η which would result in the Weibull and exponential reliability function to have the same reliability at t = 250. But, with the calculated eta that makes the reliability functions equal, the failure rate of the Weibull distribution would be a factor 100 lower than the constant failure rate λ of the exponential distribution. Equating the failure rate functions has the same result, meaning that either the failure rate or the reliability cannot be verified. Therefore, a different approach is introduced which will be defined as the hybrid approach. The hybrid approach will combine both methods to make the exponential distribution time dependant, by replacing the constant failure rate λ with the failure rate function as described in 6.1.1. This results in the following reliability function:

$$R(t) = exp(-h(t) \cdot t) = exp(-(\frac{\beta}{\eta^\beta} t^{\beta-1}) \cdot t) \tag{6.8}$$

This is however only the case for the time dependant part of the failure rate. The constant part, which is 71%, does follow the exponential curve. Because both are probabilities and can be seen as independent, the multiplication of these two probabilities will results in the total reliability of the component.

To visualize this, figure 6.8 shows the reliability of an exponential distribution and the reliability of the exponential distribution with a Weibull hazard rate function. As can be seen from the figure, the combination of the random and time dependant reliability combined gives a reliability which lies between the exponential and Weibull curve. The higher the random part, the closer the combined curve will lie to the exponential curve and the higher the time dependent part, the closer it will lie to the Weibull curve.

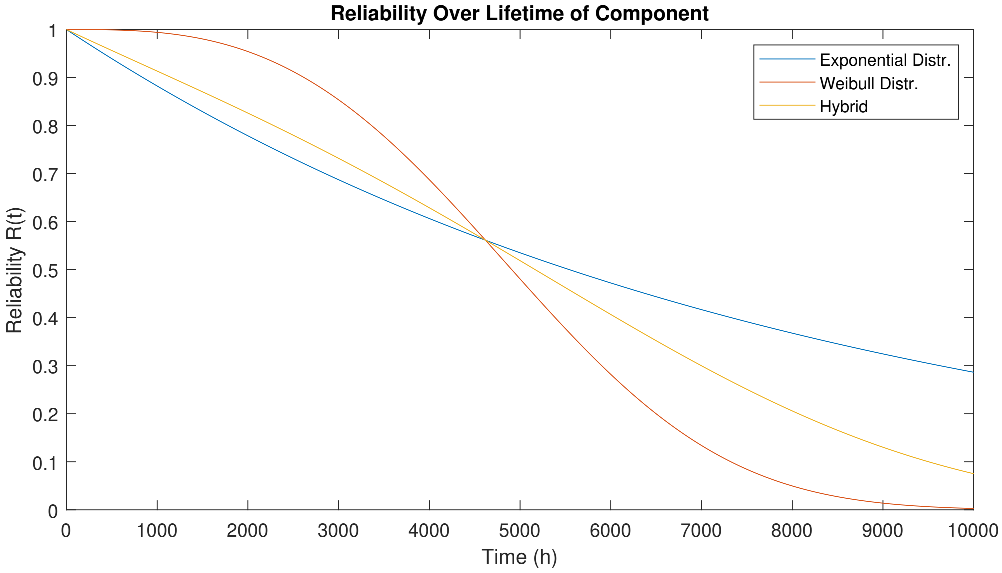

Figure 6.8: Plot of an exponential, hybrid exponential and a Weibull reliability function

Because components that receive planned maintenance have a failure rate function which is dependent of time, the failure rate threshold calculated indicates when the model needs to perform maintenance. When the threshold is reached, the maintenance will be performed when possible and the clock for that component will reset after the maintenance is done. This will bring the failure rate back to the random level. This is visualized in figure 6.9.

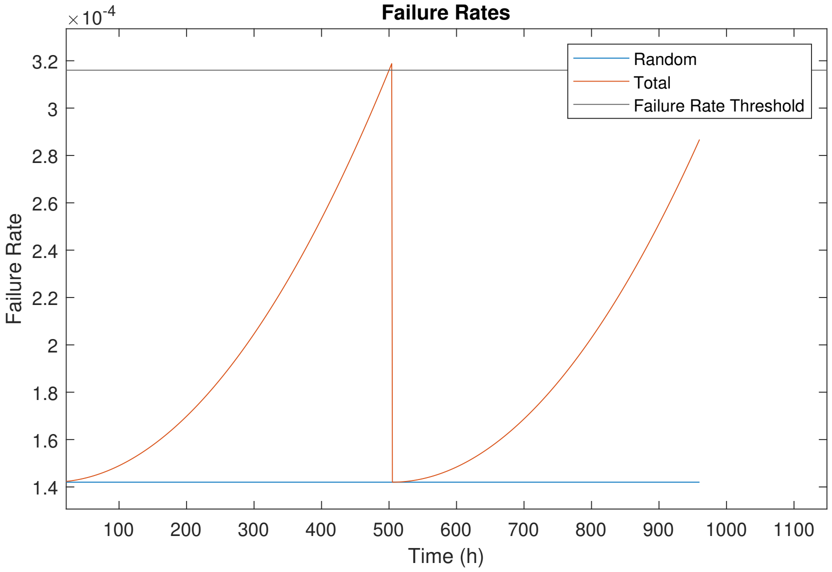

Figure 6.9: Plot of failure rate function of component with planned maintenance

6.2.2. Unplanned maintenance

For components that are repairable but do not receive planned maintenance, inspections make sure the systems work satisfactory and are still reliable enough to perform their function. Inspections can either lead to maintenance or no maintenance depending on the state of the system when inspected. It therefore does not receive planned maintenance and it is at this point not possible to define a failure rate function which is dependant of time for these components. Data of when inspections lead to maintenance is not available and thus the failure rate for these components is kept constant.

However, with a constant failure rate and no failure rate threshold, these components will, when only looking at the failure rate, never receive maintenance and thus the reliability of these components will decline according to equation 6.5 until it has reached zero. Furthermore, these components have such a significant effect on the reliability, that the impact of planned maintenance on the reliability of the P&P system becomes invisible, which would imply that a reliability calculation with only constant failure rates, following an exponential distribution would eventually result in zero reliability for a manned P&P system. From this it can be stated that inspections, and maintenance as a result from inspections, have a significant impact on the reliability and thus have to be taken into account. At this point, the inspections that are taking place within 500 operating hours are considered to have a planned maintenance activity following from the inspections. This is because these frequent inspections will lead to maintenance more often, and maintenance personnel as experts were able to give an estimation regarding the maintenance frequency these components need for the system to stay operational.

It furthermore is assumed these short frequency inspections have a different goal compared to inspections that have a lower frequency. High frequency inspections will inspect the current status of the component and the inspector will judge if it still meets the demands. It solely has the goal to inspect if the component still functions at the time of the inspection.

Components with a lower inspection frequency will ask more knowledge as the inspector has to be sure (with clearly defined specifications or not) if the component will survive until the next inspection. Therefore, inspections done with a frequency starting at every 1000 hours will be assumed to give the inspected component a guarantee ”as good as new”, meaning that the reliability function will be reset and the inspector gives the approval the component will most likely survive until the next inspection. This also means that for these components there is no difference between an inspection that leads to maintenance and an inspection that not leads to maintenance. The result is the same. This theory is visualised in figure 6.15. It can be argued that the reliability after an inspection will never be as good as new when no maintenance is performed, but with no data to work with and the impact on the failure rate unclear, this is one possible option to visualise the impact of maintenance on reliability.

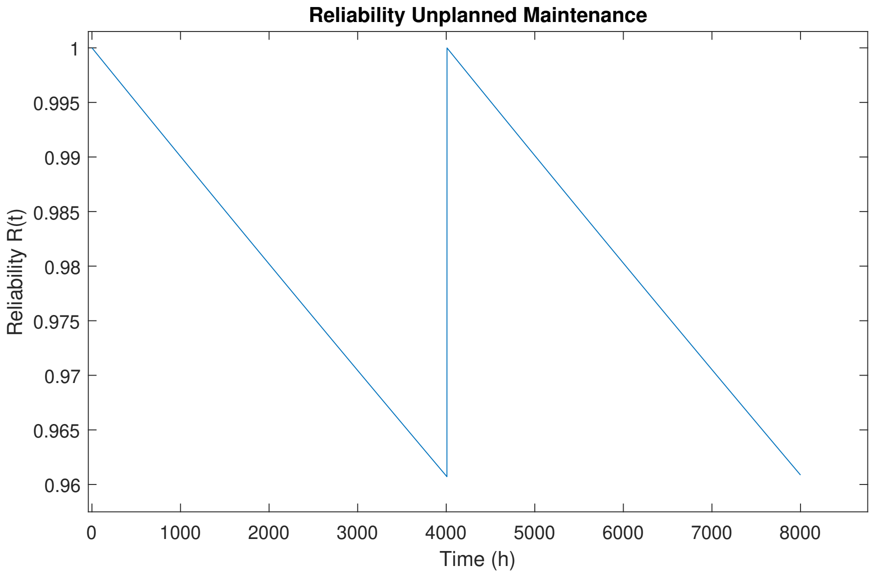

Figure 6.10: Plot of reliability function of component with unplanned maintenance

With the assumptions made, some presented as new and others from literature, it is possible to make an estimation of the reliability of systems on board the the Off Shore Patrol Vessels of the Royal Netherlands Navy. The next section will give an overview of what the FTA of the P&P system looks like and will explain the layout of the FTA.

6.3. FTA of the P&P System

Using the theory described in the preceding sections and the data presented in the FMEA, an FTA that is dependent on time, maintenance and inspections is realized. Figure 6.11 below shows the complete fault tree. As can be seen from the figure, to complete the mission successfully, the P&P system that is considered to be sufficient has to have a minimum of:

- 2 Working MDEs
- One working MDE
- Two Working PEMs and at least two working Diesel Generators

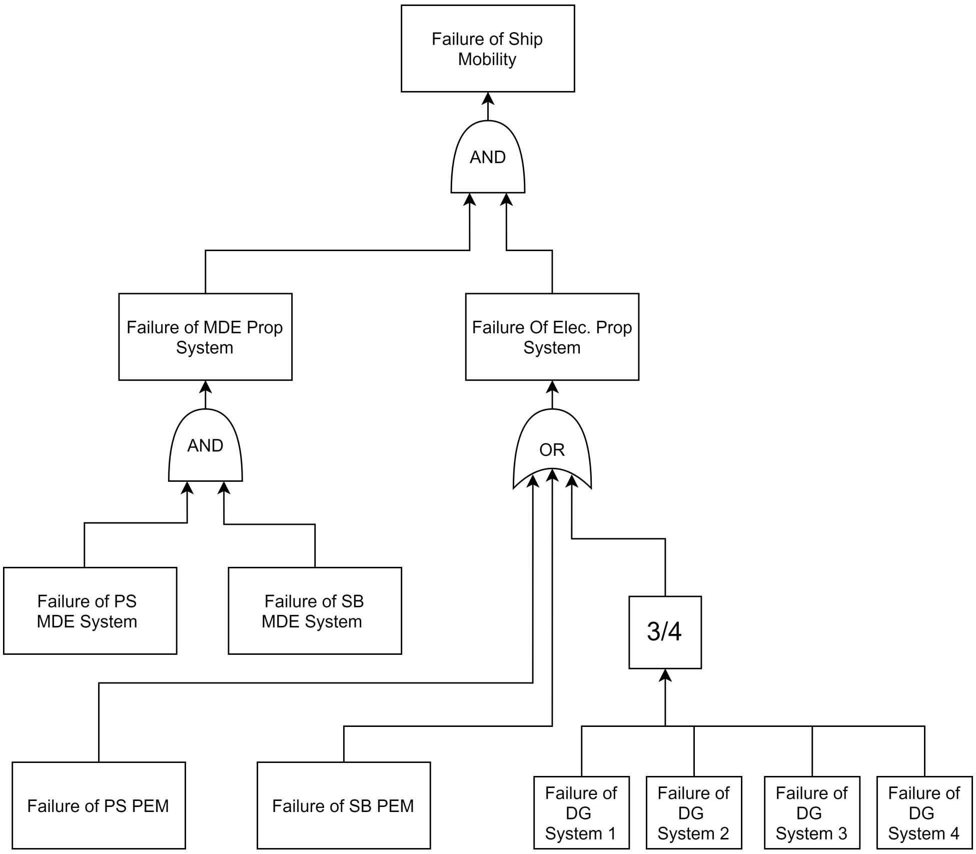

Figure 6.11: Visualization of failure rate threshold, impact of maintenance and failure rate progression when no maintenance is performed

This is necessary to reach a minimum speed of 10 kts [64], which is assumed to be the minimum speed needed to successfully perform a mission. The model thus shows there is some redundancy, but if this is sufficient to sail without maintenance personnel has to be concluded in the next chapter.

6.4. Model Verification

After having programmed the model, the next step is model verification. One way to verify the model is by changing parameters. Changing parameters will change the output and gives to opportunity of checking whether the model behaves as expected. All parameters changed are discussed below and the expected outcome will be compared with the actual outcome. Changes will be made accordingly.

beta = 1

To start off, the Weibull distribution function should behave like an exponential function when $\beta = 1$. The failure rate should be constant, and the reliability should follow an exponential curve. This is simulated as expected as can be seen in figure 6.12. This also shows that, when the components that usually receive maintenance will not reach the failure rate threshold due to constant failure rate. In that case, when $\beta = 1$, these components will be simulated as the components that do not receive planned maintenance as described in 6.2.2.

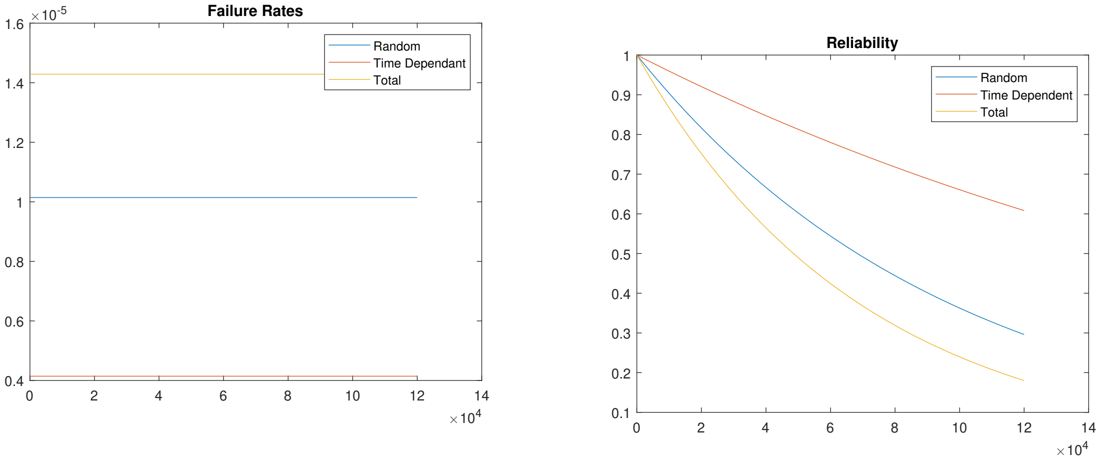

Figure 6.12: Failure rate and reliability of a component when $\beta = 1$

Fraction = 1

The fraction in this model indicates what percentage of the failure rate is random. A fraction of 1 indicates that the failure rate and reliability are 100% time independent and thus should result in a failure rate which is constant and a reliability with respect to time that follows an exponential curve. This gives the same result as $\beta = 1$ and is plotted in figure 6.13.

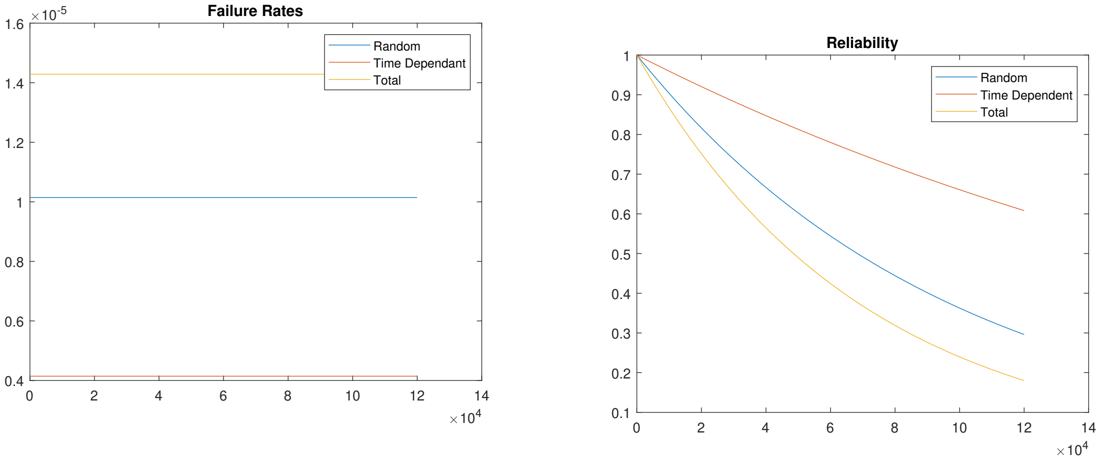

Figure 6.13: Failure rate and reliability of a component when 100% of the failure rate is considered constant

Maintenance Frequency

Next, the model has to simulate inspections and planned maintenance when needed. In other words, the clock of components with planned maintenance has to be reset when the failure rate threshold is reached. Figure 6.14 shows that when the line indicating the failure threshold is reached, maintenance is performed and failure rate clock is reset, lowering the failure rate back to the random value.

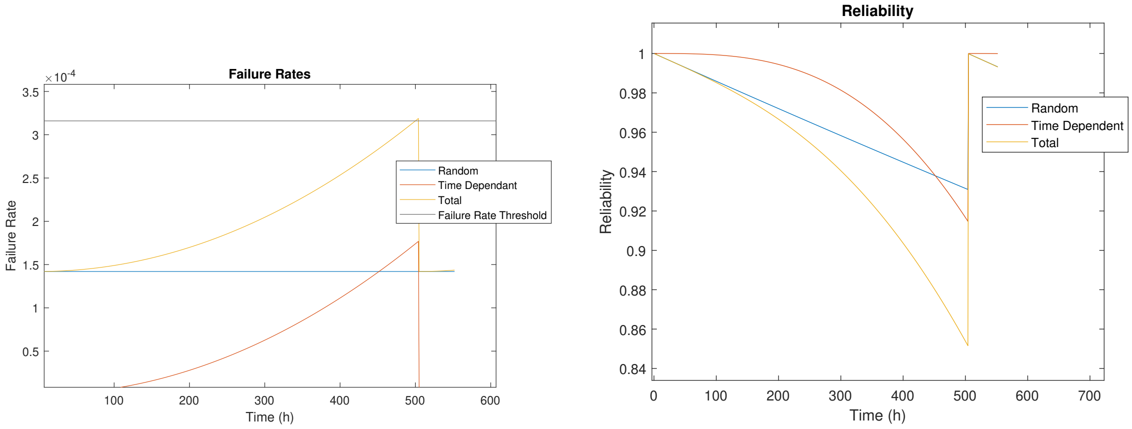

Figure 6.14: Failure rate and reliability of a component that receives planned maintenance

For components that do not receive planned maintenance but inspections, the failure rate should be constant over time, but the clock should be reset when the inspection is carried out. This is visualized in figure 6.15. It shows that in this case, the failure rate stays constant, but the reliability is restored to it's initial value at t = 0 when maintenance is performed after 500 hours, which in this case is the maintenance frequency.

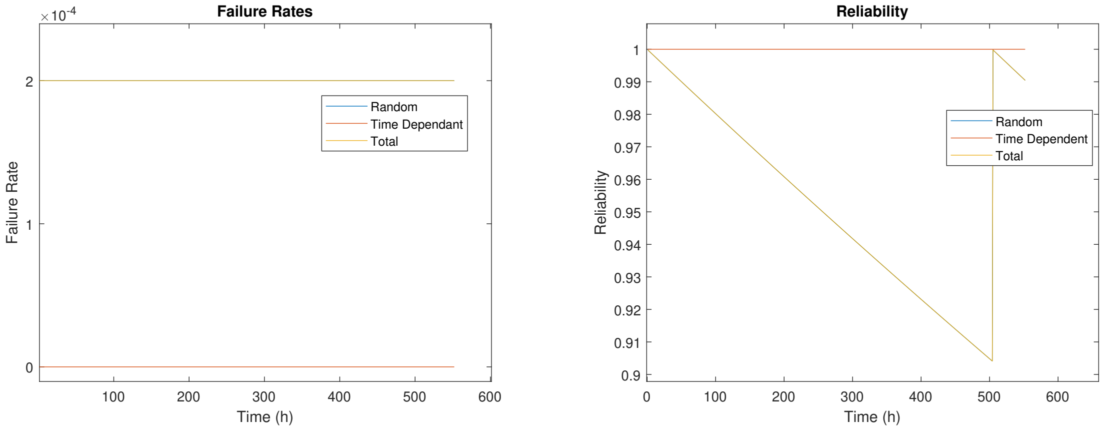

Figure 6.15: Failure rate and reliability of a component that depend on inspections. The "random" and "total" lines are overlapping because there is no time dependant failure rate.

Exceeding the Maintenance Frequency

Thus far, all figures show what happens when the maintenance is done exactly on time. This is because the mission time for verification is set to 24h, i.e. there is a possibility for maintenance every 24h and all maintenance is done within the 24h they are supposed to be done. When the mission time exceeds the maintenance frequency or failure rate threshold, the maintenance is done later because unmanned systems will only receive maintenance and inspections when in port. This is visualised in figure 6.16. It shows that the mission time exceeds the maintenance frequency and thus the failure rate threshold. Both are eventually restored when the mission has ended and there is the possibility to do maintenance. The second figure shows the reliability is declining and not restored after a maintenance frequency of every 500 hours, indicated by the vertical lines. For components that have no planned maintenance but rely on inspections, figure 6.17 shows that the failure still in constant and the clock is reset with the help of the inspection frequency.

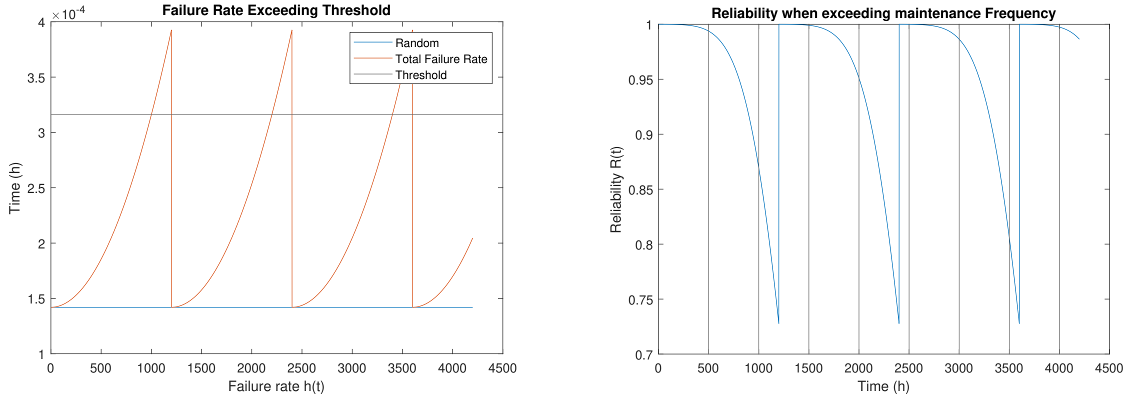

Figure 6.16: Failure rate and reliability of a component when the failure rate threshold is exceeded for components that receive planned maintenance. The vertical lines in the right figure indicate the prescribed maintenance frequency.

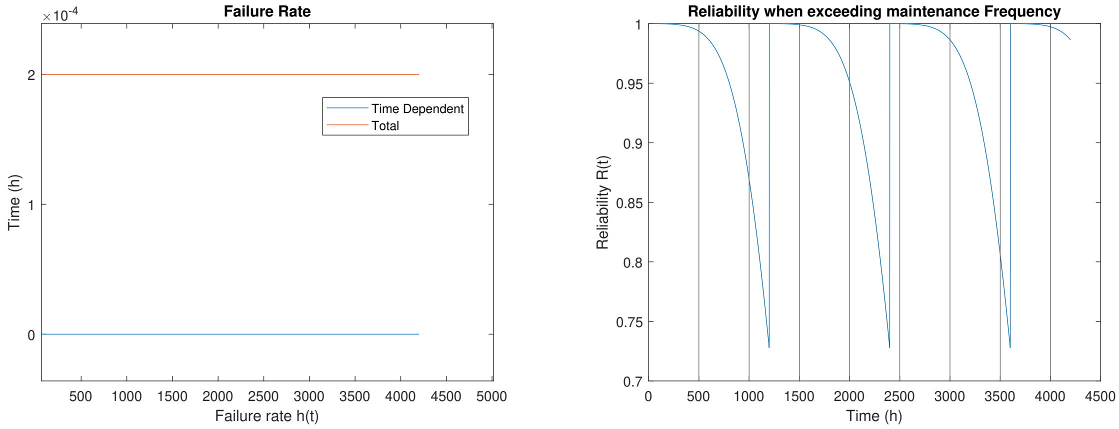

Figure 6.17: Failure rate and reliability of a component when the maintenance frequency is exceeded that do not receive planned maintenance. The vertical lines in the right figure indicate the prescribed maintenance frequency.

16000 hour mark

Within the maintenance schedule, there are a few maintenance moments after a number of running hours namely after 4000, 8000 and 16000 running where the 16000 running hours mark indicates thorough inspections and a major overhaul of the systems. After all inspections and maintenance, the system can be assumed to be new and thus after 16000 hours, the reliability of the entire P&P system should go back to 100% in the model. This has been verified by experts. After the major overhaul after 16000 running hours, the systems can be considered to be ”as good as new”. As can be seen from the figure, the reliability is not going back to 100%, but almost. This is because the maintenance frequency of the turbocharger is higher, namely 32000. This is visualized in figure 6.18.

Total Reliability

Now that it is clear all the components behave according to expectations, the total reliability of the P&P system is calculated. To simulate the current situation, the mission time is one day. This means the crew has the possibility of performing maintenance every day and that when a component should receive maintenance after 500 hours, the maintenance will be done the day after the component has crossed the 500 hour mark. This gives the reliability as visualized in figure 6.19.
Other parameters assumed to simulate the current situation are:

- $\beta = 3$
- 29% of failure rate is time dependent
- Total simulation time 750 days

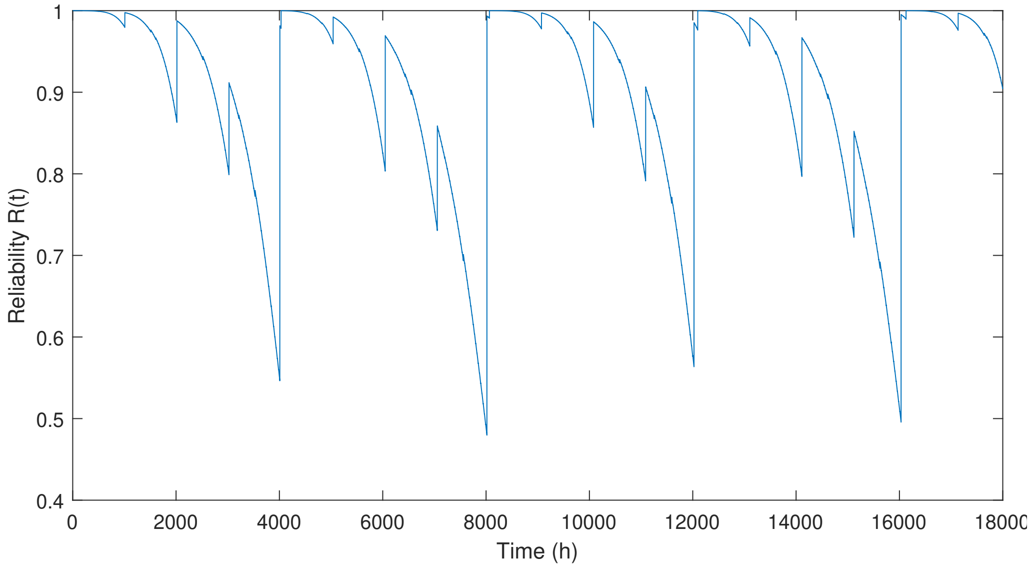

Figure 6.18: Reliability Plot of the P&P system

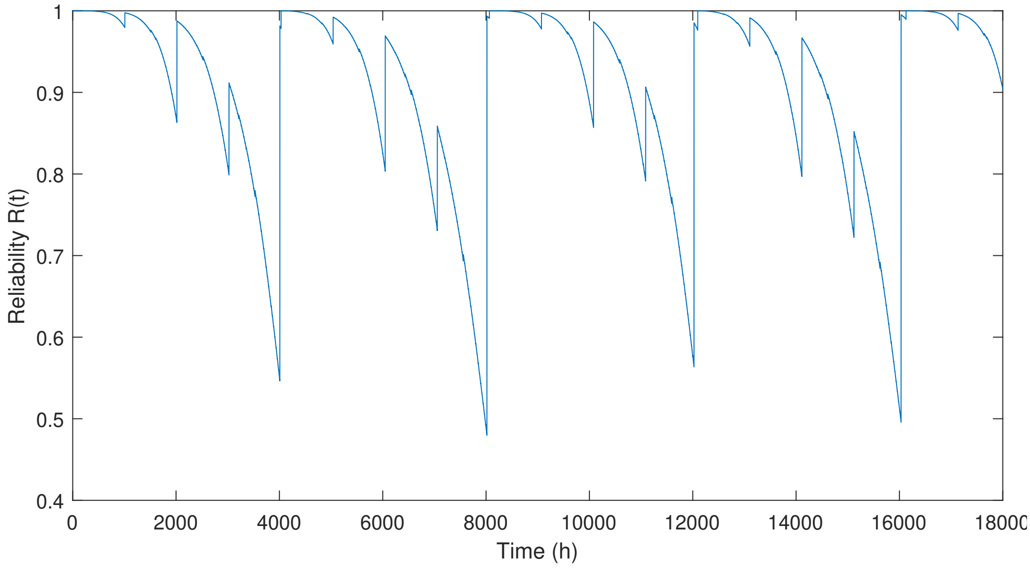

Figure 6.19: Reliability Plot of the P&P system

In this situation the reliability eventually goes almost to zero. Even though this is a conservative approach as the failure of a component will result in a failure of the system or sub-system it is representing, for a situation in which every maintenance task is performed on time this cannot be true. When looking deeper in the model, the components that have the most failure modes defined are the least reliable. For instance, the wiring seems to be the least reliable component of the MDE. This is because this component has 7 failure modes. All connected to an OR-gate, which multiplies the probability of failure. This means that in general the more failure modes a component has, the less reliable the component is. There are undoubtedly failure modes that are missing and thus with one component having more failure modes even though the components is considered to be reliable can give a distorted view of the reliability of the P&P system. Because the MTBF is already a number that has some uncertainty, the decision is made to have only one probability of failure per component. This will of course make the model less precise, but because the goal is to study the impact maintenance has on the reliability of the P&P system and the data and knowledge of the system is already uncertain, this assumption would only benefit the visibility of the impact of maintenance and inspections. The comparison of reliability with multiple failure modes per component and the reliability when a component only has one failure probability is plotted below in figure 6.20.

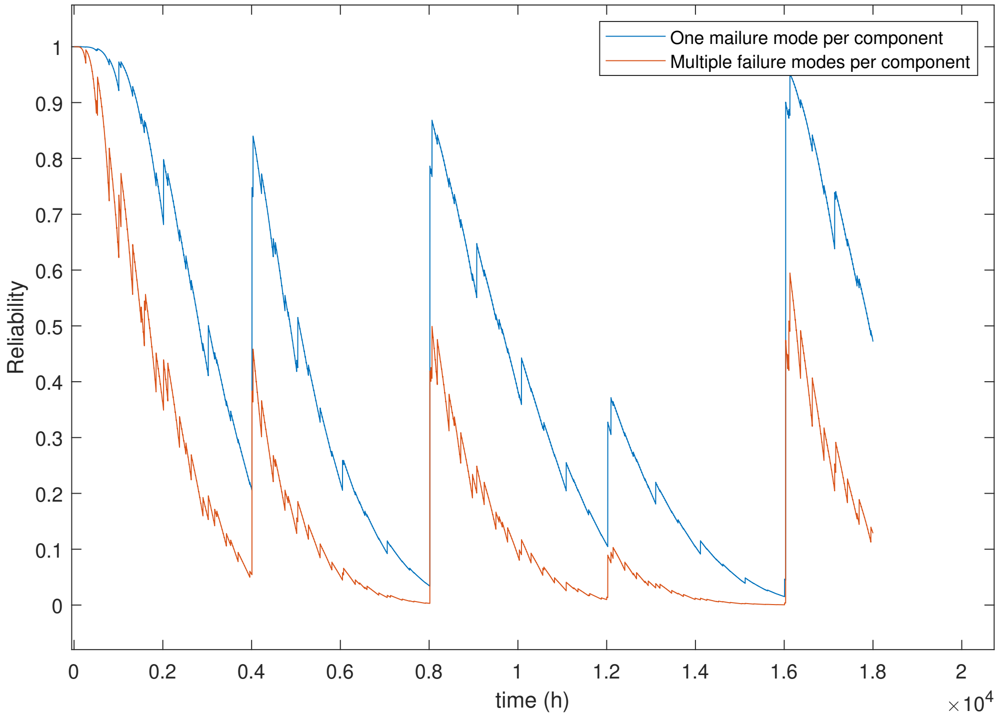

Figure 6.20: Reliability of the P&P system when components have multiple failure modes compared to when components only have one failure probability

Figure 6.20 shows that even with the modifications of having only one failure mode per component the reliability still reaches a level which can be assumed to be unacceptable. Even though there is no data available, a qualitative assessment with a previous reliability model showed that the reliability calculated during this thesis is not so far off. However, this calculation was done for only 720 running hours and thus validation in the long run was not possible. This does not change the fact that, for a situation where all maintenance is performed on time and according to schedule, the reliability is expected to be, and should be, higher. With the model properly verified, the low reliability can be explained through either the conservative approach when looking at reliability, or the data is not in all cases as accurate as it should be.

Conservative Approach

Because of a lot of uncertainties, the reliability of the P&P system has been calculated in a conservative way, meaning that, for instance, in the MDE itself, every failure results in a failure of the MDE system. When looking at all the components taken into account, a component that will not result directly to engine failure is the vibration damper. This is however the only component that is considered to be not as critical. Another explanation could be that there is no distinction between failures. Even though the data provided only has one MTBF and when multiple were found these were combined to one, it could be that by making this simplification, the severity of the failure will vary. This means that one failure may cause the system to perform less, while the other results in a complete shutdown. Further research has to be done in order to define these distinctions and what impact this will have on the reliability of the P&P system.

Inaccurate data

Second was the data that is provided by DMO. While it is assumed the maintenance frequency of every component will somewhat guarantee its performance, calculating the reliability of components at their maintenance frequency shows that not all components are reliable enough when maintained according to schedule.

The fresh water centrifugal pump of the MDE cooling system for instance has, according to calculations, a reliability of 60.3% before it receives maintenance. This means that it could very well be the case some data might not be representative, or that the method used to calculate reliability is not in all cases usable. However, since the qualitative assessment and the method used is a combination of two widely accepted methods to calculate reliability, it is assumed that not all data is as accurate.

To solve this problem, the maintenance frequencies are adjusted when the current assumed maintenance frequency results in a reliability which is lower than 85%. By increasing the maintenance or inspection frequency of these components, figure 6.21 shows the reliability already improves significantly. Even though the actual reliability still seems to not be representative, it can relatively show the impact maintenance has on the reliability of the power and propulsion system. In other words, it still can show what has to be done in order for the unmanned OPV to be as reliable as an OPV with on-board maintenance personnel, with the assumptions made and literature found for this study.

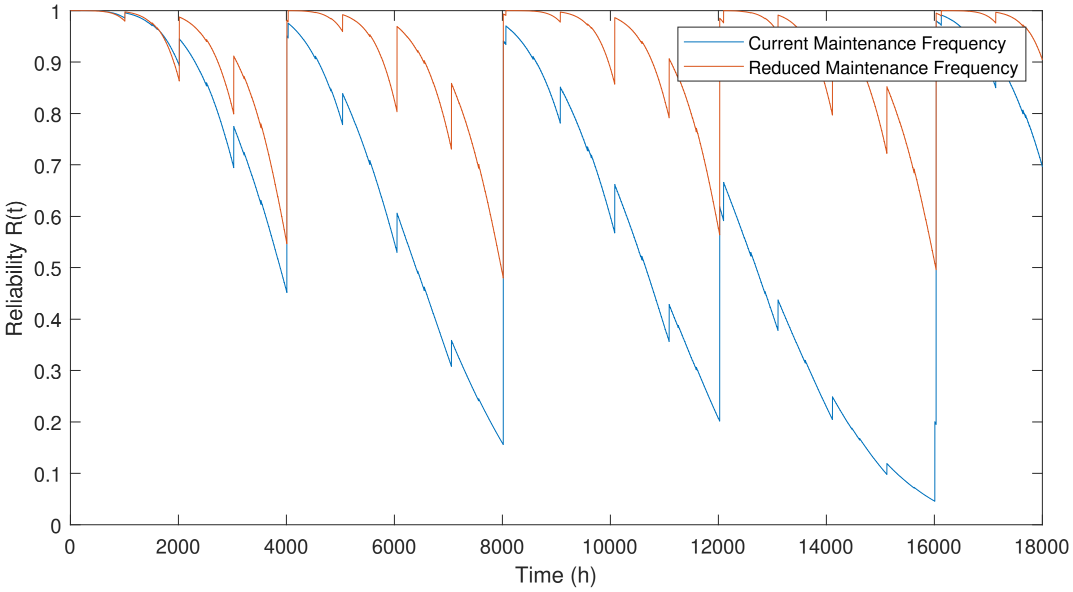

Figure 6.21: Comparison of Reliability of current and reduced maintenance frequencies for several components

7

Reliability Assessment

With the model properly defined and verified, this chapter will firstly present the current situation on board. This includes an overview of all assumptions and parameters relevant for the assessment. Next, the model simulates the reliability for a manned and a 50-day unmanned situation of the OPVs P&P system. The two are compared and will point out the weaknesses of an unmanned P&P system. Weaknesses are components that oppose the biggest risk in the system of not providing sufficient mobility in order to successfully execute a mission. After the weakest components have been identified, possibilities to improve reliability are studied and several solutions for matching the level of reliability of the 50-day unmanned P&P system with that of a manned system are presented. After the system has been improved to be suitable for unmanned operation, a sensitivity analysis is done to study what uncertainty the chosen parameters have.

7.1. Inputs & Assumptions

Before a reliability assessment can be done, the inputs that sketch the situation in which the vessel will be operating is presented below.

The first input is the mission length. For a manned P&P system, the mission length is simulated as 1 day. This results in all maintenance tasks being performed on time and gives the optimal reliability representation of the P&P system. For the length an unmanned version of the OPV would be sailing, Geertsma [27] as cited in Edge et al. [23] suggests a mission length of approximately 90 days. This seams like a big step for ships that are sailing with daily inspections in the current situation and thus a simulation consisting of only 50-day missions is studied for now. This will be compared to the manned system.

Second is the number of missions that is assessed. An analysis consisting of only one mission could very well be possible for a large USV, but an assessment that is consisting several missions could, due to the different maintenance cycles and changing failure rates, result in a different conclusion. The reliability of the power and propulsion system will be assessed for 750 days, because this will show what happens after the planned maintenance of 16000 running hours. Because 16000 hours is a multiple of all maintenance tasks done on board, the cycle should reset and start over again after this number of hours is reached. However, since section 6.4.1 (where the model was verified) changed the maintenance cycle of some components due to their lower reliability, the system should be ”as good as new” after every 8000h, but the simulation is kept as 16000h because further analysis could change these maintenance frequencies again and makes it easier to compare different situations when this occurs.

As discussed in the previous section, the operational modes of the vessel which are assumed to provide sufficient propulsion is an important input as well. For this model, the propulsion is assumed to be sufficient when a speed of 10 kts can be reached. According to Vasilikis [64], the ship needs one of the following configurations to be operational to reach 10 kts:

- 1 functional MDE

- 2 functional MDEs
- Functional Electrical Propulsion System

Further inputs, as discussed in 6.4 are the shape factor of $\beta = 3$ of the time dependant part of the failure rate and a fraction of 71%, which indicates what part of the constant failure rate is actually constant and assumed to be random.

Next to inputs there are several assumptions made to run the model. These are all done to simplify the model in order to make the model less complex and suitable for the time frame of this thesis:

- All Maintenance is done perfectly
- All inspections are done perfectly
- Maintenance brings the component back to its initial reliability and thus resets the simulation clock of the component that receives maintenance
- The machinery is used 100% of the mission time
- All machinery runs in steady state condition
- There are no environmental factors influencing the reliability calculations
- There is no distinction made between what happens after an inspection. Both ”perform maintenance” and ”do nothing” have the same outcome of resetting the simulation clock.
- Every maintenance task of components that have planned maintenance resets the simulation clock of the failure rate
- Partial failures are not taken into consideration

With these inputs and assumptions regarding the assessment, the reliability of the P&P system is simulated in the next section.

7.2. Reliability of the Power and Propulsion system

The reliability of the Power and Propulsion system will be judged based on the lowest reliability the simulation will calculate. Figure 7.1 shows the total reliability of the manned P&P system compared to the unmanned version.

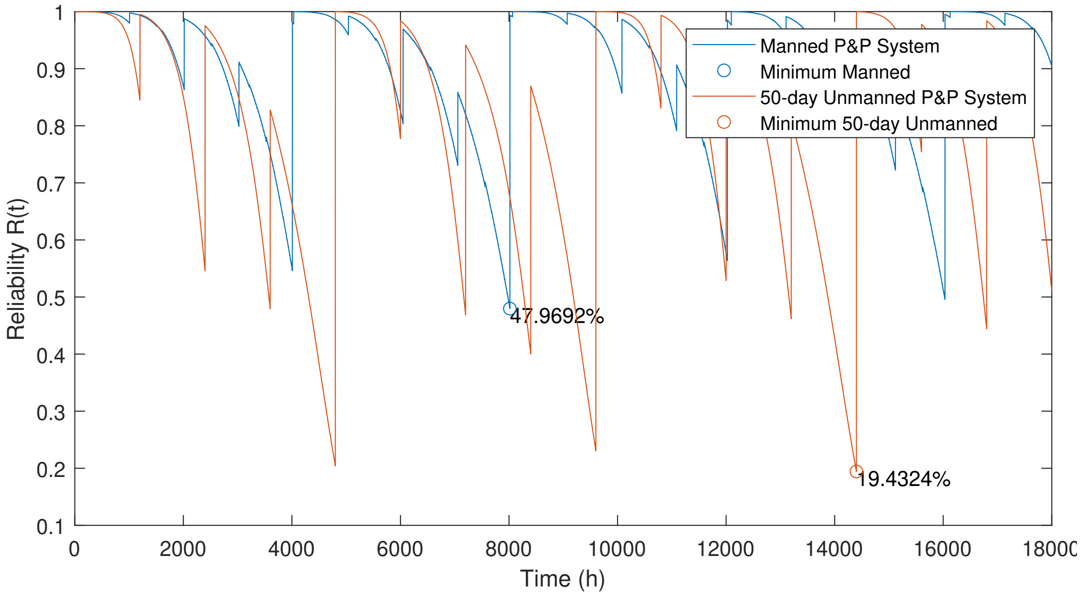

Figure 7.1: Reliability comparison of a manned and unmanned P&P system

From the figure, it can be stated that the manned version of the P&P system outperforms the unmanned system. The lowest reliability calculated for the manned system is 47.97% compared to 19.43% for the

unmanned system. Not maintaining systems that normally ask for inspections and maintenance within 50 days (1200 hours) should make a significant difference in the reliability of the system, especially with the Weibull failure rate which is causing the reliability to drop faster for several components than would be the case with a constant failure rate.
The figure furthermore shows that even with 50 days without maintenance the reliability still reaches the same level as at t = 0 around 5000, 9500 and 14500 operating hours, These should be 4000, 8000 and 12000 as can be seen from the plot of the manned system, but is delayed because not every task can be performed on time. For instance, a maintenance task that should be done every 1000 hours is now done every 1200 hours (after 50 days).

To find out the weaknesses of an unmanned P&P system, figure 7.2 looks deeper into the system. It shows that the MDE and the 4 diesel generators are the least reliable systems and the Permanent Electric Motor (PEM) is the most reliable one. When zooming in further into the MDE and DG systems, which includes the diesel engines and support systems presented in figure 7.3 and 7.4, it shows that next to the engine itself, the lubrication and cooling system are the least reliable systems of the MDE. For the diesel generator, the fueling and lubrication system are least reliable.

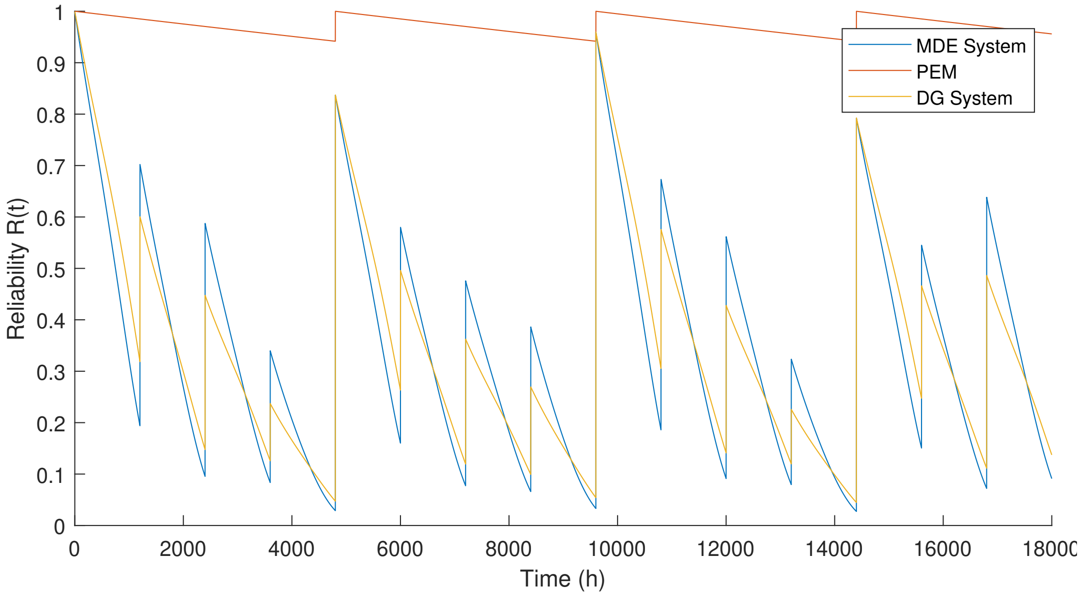

Figure 7.2: Reliability comparison of a MDE system, Permanent Electric Motor and the Diesel Generator System, consisting of 4 Diesel Generators

Zooming in to component level will show what components of every system are least reliable. To keep the report readable, the 20 components with the highest failure rate of both the Diesel Generator- and Main Diesel Engine Systems with respect to their failure rate are presented below in table 7.1. The failure rate of the components is used because it gives a good indication of the reliability of the component and because the model is too extensive to monitor the reliability of every component separately. The failure rates are calculated according to subsection 6.1.1. The failure rate for components that receive planned maintenance are calculated with a combination of a constant part and a time dependant part. The failure rates of components that do not receive planned maintenance but need inspections to decide whether or not maintenance is necessary are considered to be constant:

$$Planned\,Maintenance : h(t) = h_c + h_t = \frac{1}{MTBF} * fraction + \frac{\beta}{\eta^{\beta}} * t^{(\beta-1)}$$

$$Unplanned\,Maintenance : h = \frac{1}{MTBF}$$

In these formulas h(t) is the total failure rate at time t, h_c is the random part of the failure rate and h_t is the time dependant part of the failure rate. η stands for the scale factor and β is the form factor. h = the

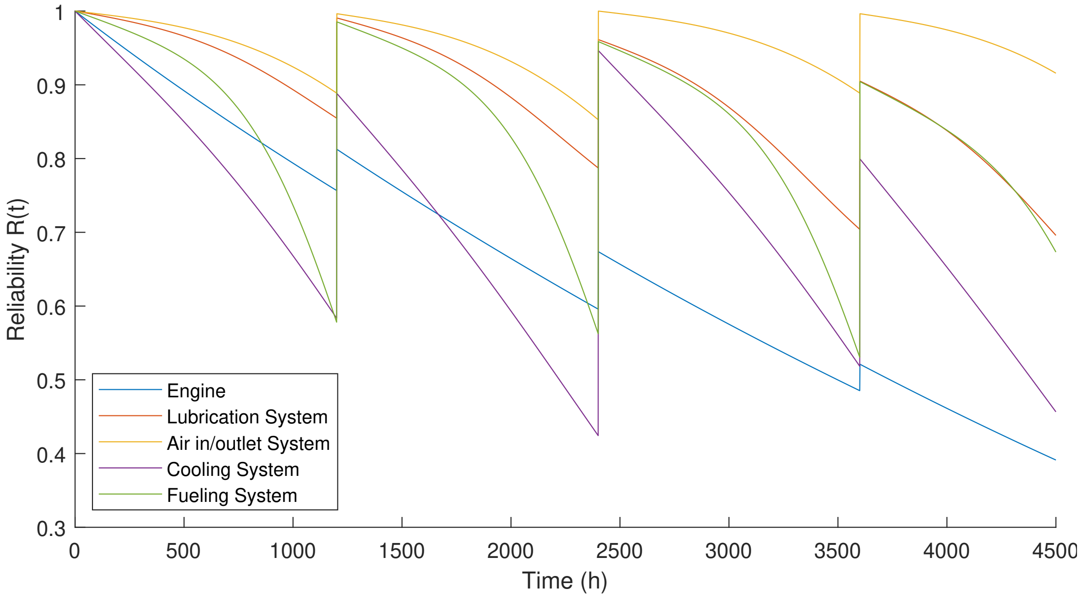

Figure 7.3: Reliability of the MDE and all support systems

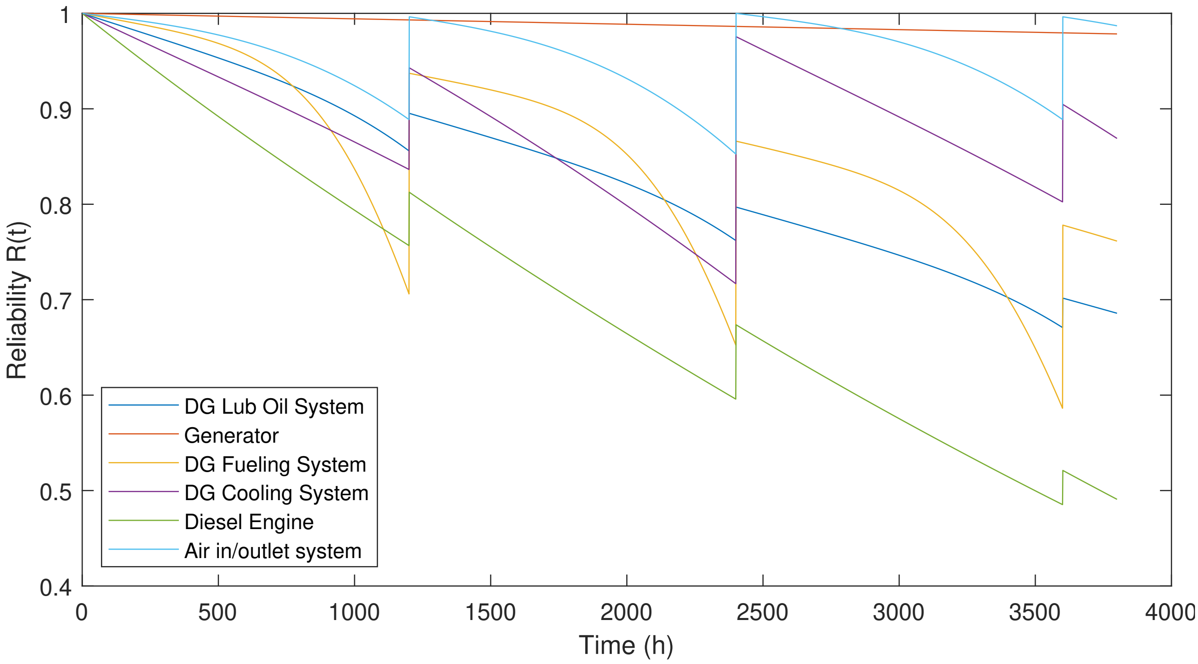

Figure 7.4: Reliability of the Diesel Generator and all support systems

constant failure rate. The maximum failure rate is then determined by taking the maximum failure rate of that component during the entire 750-day simulation. The table with the 20 least reliable components is presented below in table 7.1.

This table gives answer to research question 3:”What are the weaknesses of the power and propulsion system?”. As identified earlier in subsection 2.3.1, the definition of weakness used in this thesis is: Components that have a higher likelihood of failure when no preventative maintenance is being done while at sea. Furthermore, research question 4; ”What are the risks of the weakest components in the power and propulsion system?” is already answered by indicating what component failures are resulting in the failure of that particular system with the FMEA discussed in chapter 5. In the model, there are no gradations in failures of components and thus all failures used for the reliability analysis result in system failure. This is done due to the complexity of the system because it is not for all components

System	Component	Max Failure Rate h(t)	MTBF (h)	Maintenance Frequency (h)	Type
MDE Fueling System	Duplex Fuel Filter	0.0012295	5000	250	Planned
DG Fueling System	Duplex Pressure Filter	0.00114424	5000	250	Planned
MDE Lub Oil System	Oil Filter	0.00039256	5000	500	Unplanned/Inspection
MDE Fuel Oil System	Fuel Oil Cooler	0.00039256	15151	1000	Planned
MDE Cooling System	Engine Powered Sea Water Centrifugal Cooling Pump	0.00012954	17803	1000	Planned
MDE HT Cooling System	Temp Control Valve	0.000100000	10000	24	Unplanned/Inspection
MDE LT Cooling System	Temp Control Valve	0.000100000	10000	24	Unplanned/Inspection
DG Cooling System	Three-way Temp Control Valve	0.000100000	100000	1000	Unplanned/Inspection
Air Inlet System	Turbocharger	9.81400000e-05	20000	1000	Planned
Exhaust System	Filter	9.53072870e-05	20594	1000	Planned
MDE HT Cooling System	Engine Powered Fresh Water Centrifugal Cooling Pump	7.85120000e-05	25000	2000	Planned
MDE LT Cooling System	Engine Powered Fresh Water Centrifugal Cooling pump	7.85120000e-05	25000	2000	Planned
DG Cooling System	Generator Powered Cooling Water Pump	7.85120000e-05	25000	2000	Planned
MDE Lub Oil System	Piping	5.00000000e-05	20000	24	Unplanned/Inspection
MDE Fuel Oil System	Piping	5.00000000e-05	20000	24	Unplanned/Inspection
MDE Lub Oil System	Lub Oil Cooler	4.90700000e-05	40000	4000	Planned
MDE Fuel Oil System	Low Pressure Engine Powered Fuel pump	4.90700000e-05	40000	4000	Planned
DG Fueling System	Engine Powered Fuel Pump	4.90700000e-05	40000	4000	Planned
MDE Lub Oil System	Engine Powered Lubrication Pump	4.79904600e-05	41000	4000	Planned

Table 7.1: 20 least reliable components according to their failure rate

clear what the result of a partial failure or a particular failure mode would be.

7.3. Improvements

According to the model, the unmanned P&P system is not as reliable as a manned system. To answer research question 5:"What can be done to reduce the risk and improve the reliability of weak components of the power and propulsion system?", several options are studied. These include starting with changing the maintenance strategy. This is followed by firstly introducing improvements to the system to make it more reliable and secondly by adding monitoring equipment to remove inspection tasks. By making sufficient improvements, research question 6;"How do improvements/alterations influence the reliability of the power and propulsion system and make the P&P system suitable for unmanned sailing?" can be answered as well.

Predictive Maintenance Strategy

Because this model uses a function to describe reliability, it is possible to look further into the future and see if the reliability would be sufficient at the end of the mission. By changing the maintenance strategy to a predictive maintenance strategy, maintenance tasks are done prior to the mission instead of after and the unmanned system could become more reliable. This is modelled by first checking whether a component will reach its failure rate threshold or inspection moment before starting the simulation instead of after. As can be seen from figure 7.5 the reliability improves significantly from a minimum reliability of 19.32% to 42.73%. But, it does not reach the level of reliability of a system with maintenance personnel on board of 47.97% . This strategy will be taken into consideration while further improving the system. However, to predict the reliability of a component 1200 hours into the future seems not very realistic, especially for every component. The reliability with the condition-based maintenance strategy, which is assumed to be the current maintenance strategy, will therefore be further investigated as well.

System Improvements

System improvements are improvements with the goal to remove maintenance personnel by improving the reliability as such that its reliability would be comparable to the situation of having maintenance personnel on board. This can be done by looking at the layout of the P&P system, or by coming up with solutions for the least reliable components or systems by the use of table 7.1.

When looking at the layout of the system by the use of the FTA, it follows that either one MDE or both PEMs have to function in order to have a sufficient propulsion of 10 kts [64]. The PEMs are the most reliable systems in this layout and thus adding redundancy here by increasing the size of the PEMs

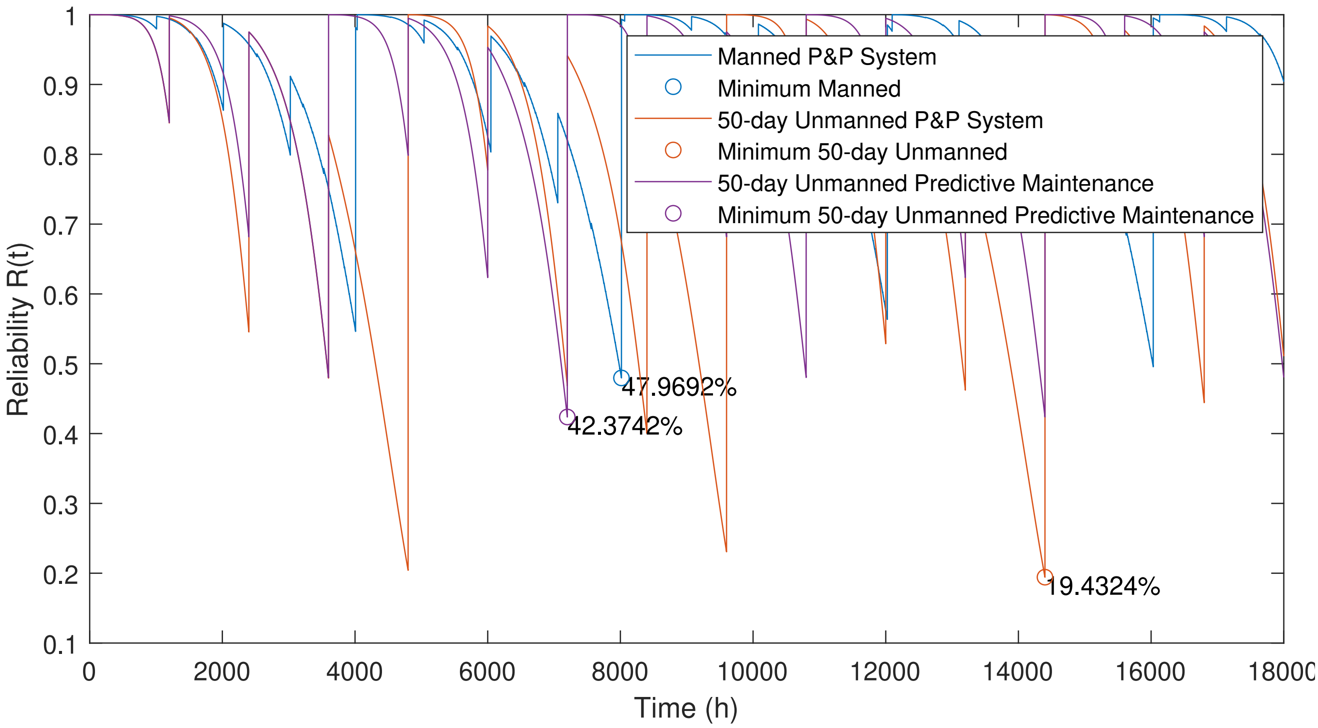

Figure 7.5: Reliability plot of 50-day unmanned mission with different maintenance strategies compared to a manned mission

so the vessel would be able to sail 10 kts on a single PEM has little to no impact on the total reliability of the P&P system. Other solutions would be to add an extra MDE-system or DG-system including its subsystems as lubrication and cooling, but the less drastic approach of adding redundant components is studied first. All improvements are introduced per component, meaning that after every addition the reliability is again calculated to see how this improves the reliability and whether the improvement is sufficient to match the situation with on-board maintenance personnel. The system's reliability is deemed sufficient when the lowest reliability of the improved system during the entire simulation is almost equal to or higher than the situation with on-board maintenance personnel.

When adding redundancy, not all components are used 100% of the time during a mission. For instance a fuel oil duplex filter has two filters that both will ”work” for 600 hours, during a 50-day (1200h) mission. When adding a third filter, and thus making a triplex filter, will result in the filters each having to be operational for $\frac{1200}{3} = 400$ hours. This causes the system to be more reliable and the failure rate to be lower over time when dependent of time.
When all 20 least reliable components are made redundant, the lowest reliability this improved system will reach when going on 50-day unmanned missions is 47.53 %, whereas the lowest reliability a manned version will reach is 47.93%. This is deemed reliable enough and thus all the components from table 7.1 are made redundant in the P&P system.

When considering changing the maintenance strategy to a predictive maintenance strategy, far less components have to be made redundant. By only making the first 5 components from table 7.1 redundant, the system already has a reliability of 56.23% at its lowest. The two solutions are visualized in figure 7.6 together with the manned P&P system for comparison.
However, there are other improvements that can be thought of besides adding redundancy. The current OPVs are producing both electrical and mechanical energy from chemical energy in the form of Marine Diesel Oil, or MDO. Because reliability assessment points out the fueling system and the diesel engine itself are the least reliable systems of the P&P system, other forms of storing energy on board can be considered as an option. Other possibilities like storing energy in batteries could be a good alternative, because it will remove both the current fueling system and the engine. These options haven't been studied due to the fact there is no information regarding their failure behaviour and thus further study

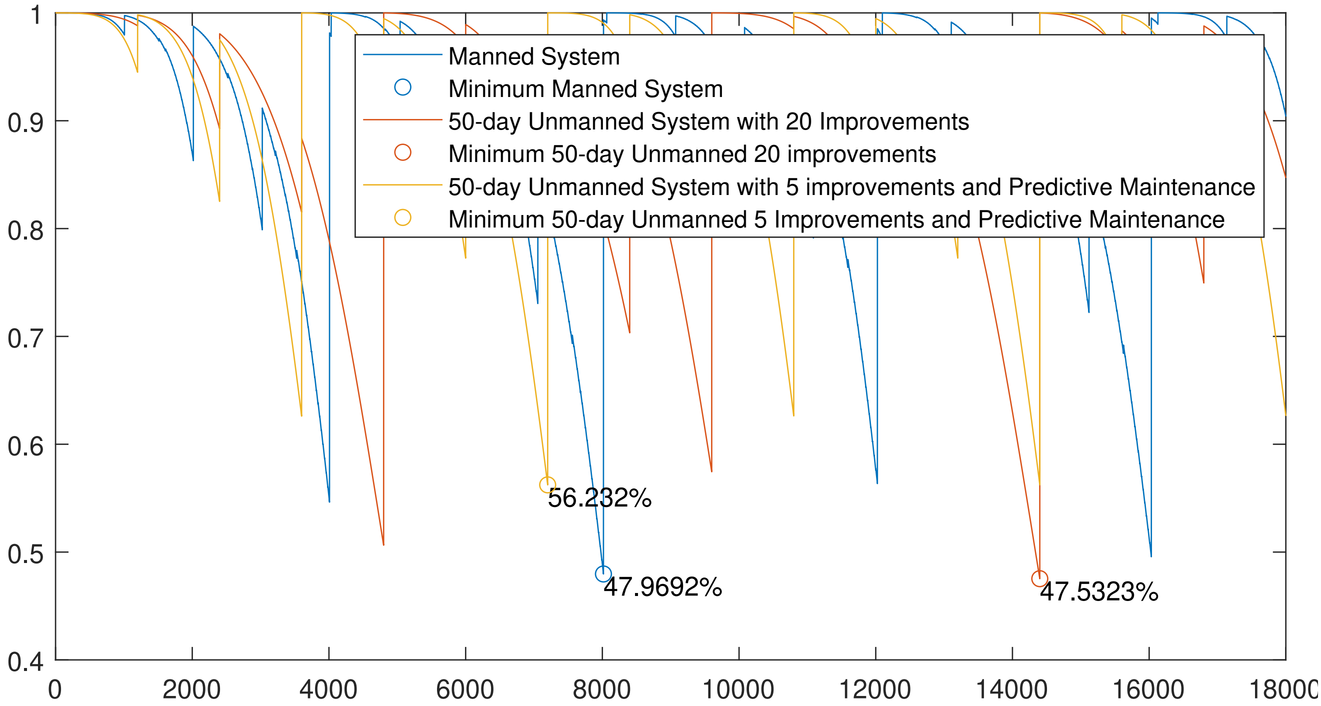

Figure 7.6: Reliability comparison of a manned system and improved unmanned systems for 50-day missions

is advised in researching other possibilities of fulfilling the mobility function for USV's.

Adding Monitoring Equipment

In the reliability model, the assumption is made that the status, or failure rate , of every component is known. In reality this is of course not the case because inspections will give this information, most done every 24 hours. To remove maintenance personnel from board sensors and other equipment that send data to shore to monitor the performance and condition of the on-board systems is introduced. For instance, pressure sensors on either side of the fuel filter measure the state of the filter. When the pressure difference is too high, meaning it has reached its threshold value and the flow of fuel oil through the filters is too low, the on-shore crew will close off the filter and open the valves to a clean one. These improvements remove most of the inspection tasks done by on-board maintenance personnel meaning that less personnel is needed to keep the ship operational. If all inspections can be replaced by sensory equipment, only the cleaning and replacement activities are left for on-board maintenance personnel. For the reliability assessment, inspections are simulated by assessing the reliability of each component every 24 hours, because these are done in this frequency in the current situation. For the unmanned version of 50-day missions, it is assumed there is no sensory equipment, but the inspections are done when the vessel returns to port.

Table 4.3.3 presented in 4.3 is being complemented by an extra column that shortly describes the solutions for removing these inspections by introducing sensors and other measurement equipment.

7.4. Sensitivity Analysis

Due to the number of assumptions made during this study, a sensitivity analysis is desirable. This analysis will show what uncertainty the chosen parameters have on the result of the reliability model.

One of the most important parameters is the shape function, or β. Even for a manned situation, varying β between 1 and 10 gives a significant impact, resulting in the reliability of 0 with the improvements made in the previous section when beta = 10. It is therefor important in further study to figure out the exact shape of this factor for every failure mechanism of the components within the P&P system. When plotting the failure rate function of a time dependant component, increasing β is not only creating

System	Sub system	Component/system	Frequency	Description	Solution
MDE	Engine	Engine	24	Inspect Diesel Engine for irregularities	Camera
MDE	Fuel System	Service Tank	24	Inspect for leakages	Pressure Sensors, Fuel vapor sensor in engine room
MDE	Fuel System	Fuel Oil Filter	24	Inspect fuel level	Level Sensor
MDE	Fuel System	Oil	24	Inspect/Clean Fuel Oil Filters	Pressure sensors in front and back of filters
MDE	Lub Oil System	Oil	24	Inspect For leakages	Pressure Sensor/Level Sensor Expansion Vessel
MDE	Lub Oil System	Oil	150	Inspect Oil Properties	Quality Sensor
MDE	Lub Oil System	Prelube	500	Inspection Oil by supplier	Automated Sensor readings to Oil Supplier
MDE	Lub Oil System	pump	24	Inspect/Change Oil	Quality Sensor
MDE	Lub Oil System	Oil Mist seperator	1000	Inspect Pre lub pump	Flow/pressure sensor + vibration sensor
MDE	Lub Oil System	Bypass filter	24	Inspect/Clean Oil Mist Separator	Quality sensor
MDE	Lub Oil System	Lube Oil Pre Heater	24	Inspect/Clean Bypass Filter	Pressure sensor
MDE	Lub Oil System	Expansion Tank	24	Inspect/Clean Lube Oil Preheater	Temp sensor
MDE	Cooling Water System	Cooling Water	24	Inspect for leakages	Level meter/Pressure Sensor
MDE	Cooling Water System	Heat Exchanger	24	Inspect Cooling Water Level	Level Sensor
MDE	Cooling Water System	Starter Motor	150	Inspect Cooling water properties	Quality Sensor
MDE	Cooling Water System	Control Panel	24	Inspect/Clean Heat Exchanger	Pressure + Temp sensor
MDE	Charge Air System	Fuel Injector	24	Check Pressures and Draining	Pressure Sensor
MDE	Fuel System	Fuel Filter	1000	Monthly Maintenance Starter Motor	Fuel injection pressure sensor
DG	Control Panel	Lube Oil	750	Clean Control Panel	Pressure sensors in front and back of filters
DG	Fuel System	Lube Oil	250	Inspect Fuel Injector	Level Sensor
DG	Fuel System	Lube Oil	1000	Inspect/Replace Fuel Filter	Quality Sensor
DG	Lub Oil System	Oil Filter	24	Inspect Oil level	Duplicate
DG	Lub Oil System	Coolant	250	Inspect Oil properties	Level Sensor
DG	Lub Oil System	Coolant	1000	Change Oil	Quality Sensor
DG	Lub Oil System	Starter Motor	1000	Replace Oil Filter	Level Sensor
DG	Cooling Water System	Filter	24	Check level Coolant	Duplicate
DG	Cooling Water System	Crankcase	1000	Inspect Coolant Properties	Check for Abnormal Readings
DG	Starting Air System	sensors	24	Inspect Oil level Starter Motor	Pressure Sensors
DG	Exhaust System	Piping	250	Replace Filter	Camera
DG	Engine	Hoses/clamps	1000	Clean Crankcase	Camera
DG	Control syst	Engine	1000	inspect Sensors	Vibration sensor
DG	Foundation		24	Inspect for leakages	
DG	Foundation		1000	Inspect	
DG	Foundation		1000	Degrease Engine Outside	
DG	Flexible Coupling		1000	Inspect	
DG	Flexible Coupling		1000	Check alignment	

Table 7.2: List of all inspection tasks done by on-board maintenance personnel, complemented with improvements if possible to remove those tasks from board

a steeper curve for the failure rate, but a higher beta also results in a curve that stays flat for a longer period of time. The reliability and failure rate with changing β are plotted in figure 7.7 and 7.8.

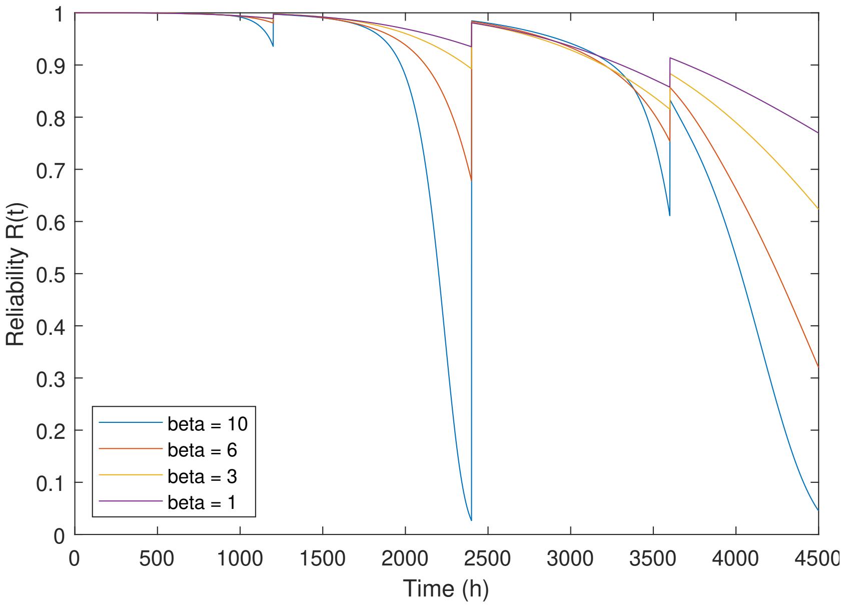

Figure 7.7: Reliability of P&P System with varying β while keeping the fraction 71 %

Another important assumption is that 71% of the failure rate is constant, representing random failures. When varying the so called fraction between 0% and 100%, the impact of this assumption is quite significant as well, visualized in figure 7.9 and 7.10.

Other critical assumptions were the maintenance frequencies, for the fuel and oil filters in particular. Although these have been verified by experts, these assumptions made the filters the components with

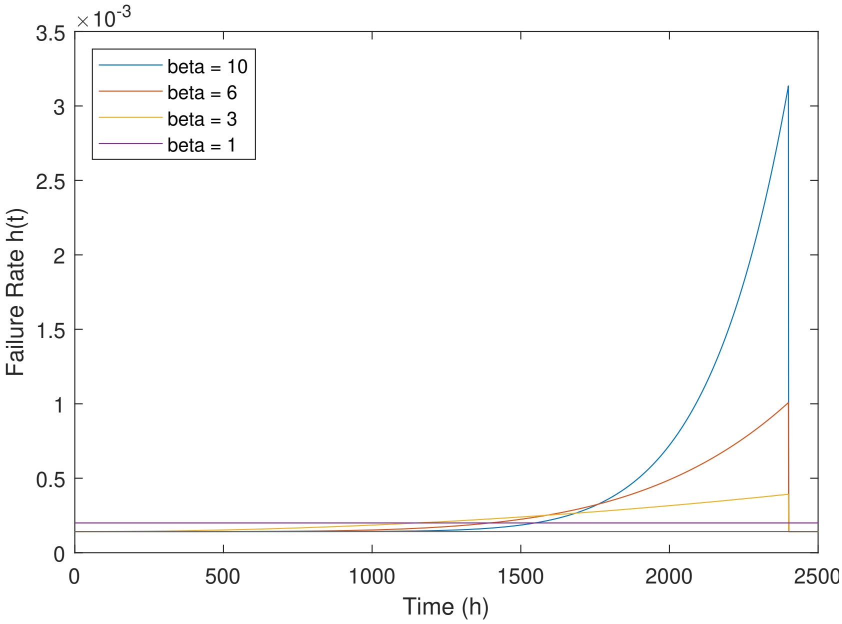

Figure 7.8: Failure Rate of a component with varying β

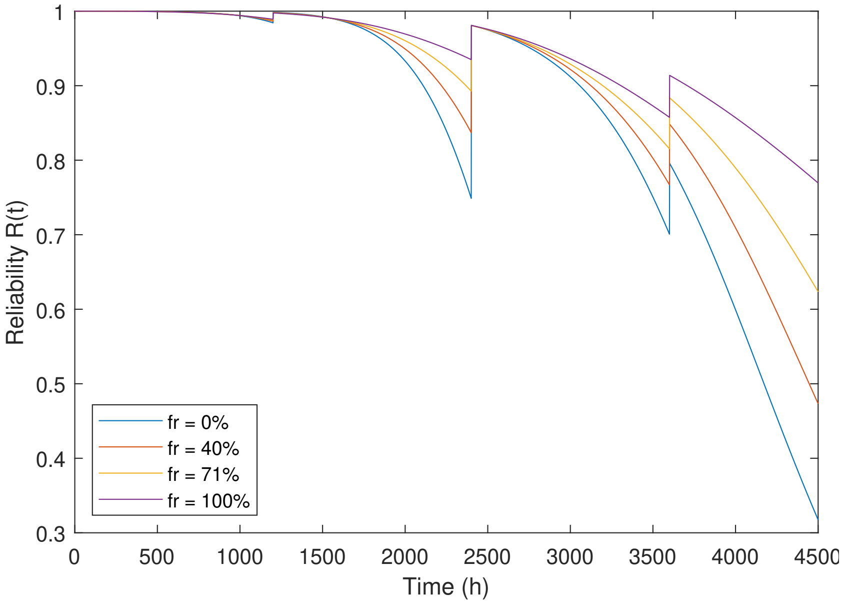

Figure 7.9: Reliability of P&P System with varying fraction

the highest failure rate and thus, when studied separately, the components that were least reliable. It was not clear how many running hours the filters would be operational, only when they needed replacement, meaning they were still operational, but did not meet the requirements anymore.

7.5. Conclusion

This chapter has calculated the reliability of the power and propulsion system on board the Holland Class OPV of the Royal Netherlands Navy for a manned and unmanned situation. By comparing both situations and pointing out the components that oppose the most risk in the reliability of the P&P system, it was possible to answer research questions 3 and 4. By studying various solutions to remove maintenance personnel and dividing this into 4 types of improvements namely changing the maintenance strategy, changing the layout of the system by improving complete systems, improving systems

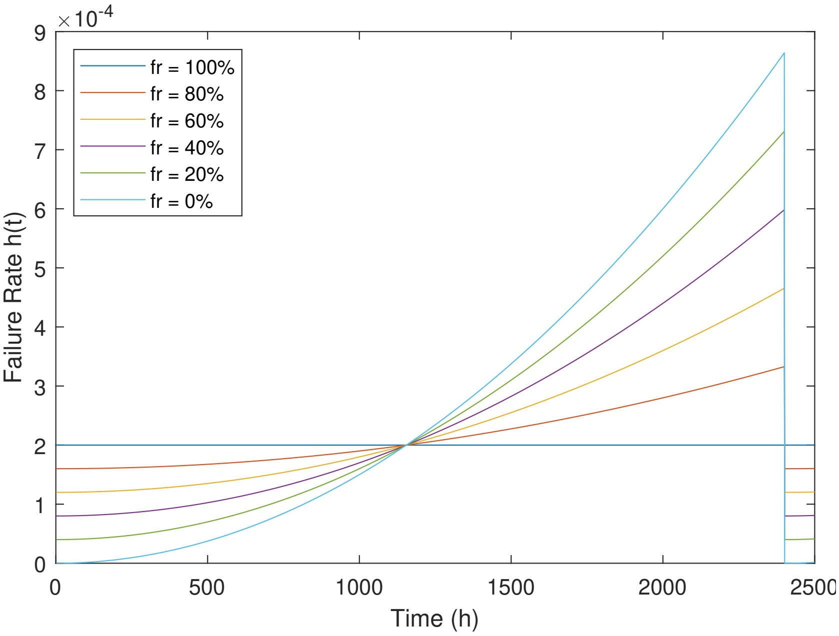

Figure 7.10: Failure Rate of a component with varying fraction

on component level and replace inspection tasks by introducing monitoring equipment, a combination of solutions was found to remove maintenance tasks from board and make the system more reliable. Besides adding maintenance equipment, a combination of changing the maintenance strategy to preventive maintenance and making several improvements on components level by adding redundancy, and keeping the current maintenance strategy and making more improvements were both realistic options. By coming up with these solutions, the 5th and 6th research questions were answered. Finally, a sensitivity analysis shows that the assumptions regarding the portion of the time dependant failure rate and the shape factor β are important assumptions that require further study.

8

Discussion

The goal of this thesis was to give insight in what has to be done in order to make it possible for the Holland Class OPV's P&P system of the Royal Netherlands Navy to sail without any maintenance personnel on board. This is done by creating a model that visualised the direct impact maintenance has on the reliability down to component level and thus the goal of the model was to give insight in how reliable an unmanned P&P system would be without the possibility of performing preventive maintenance while sailing. Even though the model concluded that by changing maintenance strategy and making several components redundant it should be possible to sail with comparable reliability with an unmanned P&P system, there are several aspects in which the model needs to be developed further. This will be done by first discussing the data that has been used. Why did the availability of the data result in the methodology used for this thesis and what could be improved with more data.
Second, the results from the FMEA and the reliability assessment are discussed. Choices and simplifications within the model all have consequences. These are discussed here.

8.1. Data

The data that has been used for this thesis was more comprehensive than that of previous studies done regarding the reliability of unmanned ships ([17] , [11], [3]). This was one of the knowledge gaps that was intended to be filled, by finding more data for studying the reliability of unmanned systems.
However, the failure data was still not sufficient enough to use a statistical approach. A statistical approach could have given a specific failure function for every system and/or components which would result in not having to generalize the shape factor β. It was not possible with the provided data to conclude failure behaviour of components and thus a probabilistic approach was chosen to calculate failure rates and reliability. This required the methodology to first do more research in understanding the systems and failures and then continue in creating a reliability model. The MTBFs together with the maintenance schedules made it possible to use a probabilistic approach to calculate the reliability and a failure rate. Because the MTBF from the data does not show the direct impact maintenance has on the reliability, the Weibull failure rate function h(t) was implemented into the exponential reliability function R(t) to make the failure rate time dependant and make the direct impact of maintenance visible. With this approach, every failure rate functions with various degradation developments can be simulated by changing the shape factor β.

FMEA

The data provided was first used to make an FMEA. The failure mode and effect analysis was then used as the source of data for the reliability assessment. The goal of the FMEA was to get insight in what components are the weakest and pose the highest risk for the functionality of the P&P system.
However, after the FMEA, the conclusion discussed that the impact of not doing maintenance cannot be studied with the data that is available and thus the reliability model was needed to distinguish the weakest components for an unmanned P&P system. In the FMEA, several assumptions were made regarding impact on the system, failure modes and maintenance frequency. The impact on the system

has been rated by own judgement of the writer and thus it is possible that several failures were rated as critical or non-critical due to the missing knowledge within this field. This can change the reliability significantly: Misjudging the criticality of a failure mode can result in over- or underestimating the reliability of the P&P system.
Furthermore, all failure modes and components were added to the analysis only when sufficient data was found, meaning that there could be a possibility failure modes and components are missing that could have a relatively high impact on the reliability of the P&P system.

8.2. Reliability Model & Assessment

To assess the reliability and be able to identify the weaknesses of an unmanned P&P system, the reliability model was created. This showed the direct impact of maintenance with the introduced hybrid approach and with this is was possible to identify the most weakest and critical components and study options for improvement. This showed that most components that are depriving the ship of its reliability are components that have a combination of a low MTBF and a high maintenance frequency. Components such as filters and pumps are components that fall into this category, along with some other components.

Previous research concluded that adding a second drive train could be an option to make the P&P system reliable enough for unmanned sailing [17]. This turns out not to be necessary to make the ship as reliable as a manned system. The results show that by making the 20 least reliable components redundant, a similar reliability can be reached as a manned P&P system. However, it has to be noted that these components receive planned maintenance and thus it is logical that these come out as least reliable. The failure rate of these components rises while the components that do not receive maintenance stays constant, result in their reliability decreasing relatively slower. By changing the components' failure rate function by studying their failure mechanism could potentially sketch a different image of what components are posing the biggest risk for system failure.

The second solution to the reliability problem appeared to be changing the maintenance strategy to a predictive maintenance strategy and making the 5 least reliable components redundant. This shows that redundancy and maintenance strategy are both important factors when studying possibilities for LUSVs. It furthermore showed that the components with the lowest MTBF are not necessarily the weakest components. This can be seen when table 5.2 from the FMEA and table 7.1 from the reliability assessment are compared. This shows the importance taking the need for maintenance into account when studying unmanned systems.
Changing the maintenance strategy in this thesis is done with the assumption that all components are sensitive for predictive maintenance and the failure rate and reliability can be predicted for the entire duration of the mission. This of course is not realistic and thus a suggestion would be to study which components can be maintained with a preventive maintenance strategy.

However, even though including maintenance in the reliability assessment, making components redundant and changing the maintenance strategy all have their impact when assessing reliability, the limiting factor will eventually be the diesel engine itself. The plots show these are the least reliable systems and cannot be made redundant by adding components, but only improving the technology itself appears to be a viable option in making the P&P system suitable for unmanned sailing. Other options would be to change the sort of power source to something will less moving parts, as suggested by Kooij, Colling, and Benson [38] to, for instance, batteries and an electric motor.

As mentioned earlier, the goal of this thesis research was to study the possibilities of adjusting an existing P&P system to make it reliable enough for unmanned sailing. Reliable enough was defined as to have the same reliability of a manned P&P system. Even though the model shows that the reliability can be made comparable with improvements, the model did not include corrective maintenance. Corrective maintenance is done when the system has failed and repairs are needed to make the system operational again. When an unmanned system fails, the severity of the failure should conclude if the system can still be operational. When a manned system fails, there is the possibility the on-board maintenance crew is able to make repairs, making the system operational again. Not all system failure can be repaired with resources and equipment on board, but this factor has to be taken into account before a system can be concluded to have the same reliability. This means that an important factor is left out of the model and thus there are a lot of opportunities in studying this part of the reliability of an unmanned P&P system.

Next to the results from the model, there are some factors that have influence on the results and conclusions that can be drawn. These factors are discussed below in what they are, why these factors were chosen as such and how this impacts the results and conclusions.

8.2.1. Simplifications

The created reliability model is a result of a number of simplifications, assumptions and design choices that all have their impact on the final result. These are discussed below to why they were done and what impact they could have had on the results in chapter 7.

Impact of Maintenance

For this thesis, it is assumed maintenance is done perfectly with the same impact for all components. In reality this is not the case. Every component that receives preventive maintenance is impacted differently and maintenance done is far from perfect. By assuming maintenance is always done perfect, the reliability cycle will repeat itself every x number of hours as was visualised by the reliability assessment. Varying the impact maintenance has on the reliability and failure rate of components will change the overall reliability and the predictability of the P&P system's reliability.

Operating Profile

This study assumed that all systems and thus all components are used 100% of the time the vessel is operational and that they are used in a steady state condition. The usage intensity is left out of scope as well as the actual usage time of every component and system. This means that, for an unmanned mission of 50 days, which is now modeled as 1200 operating hours, some systems are not used 100% of the time. This would result in a different reliability, meaning that systems could be more reliable than actually calculated.

Personnel Logistics

The model does not include personnel logistics. Maintenance tasks that are normally done on board will have to be done in port. This means that either more personnel will be on board during this period, making it possible that some tasks cannot be done separately due to too many people in one place at the same time, or longer periods spent in port due to the same people have to perform more tasks. A logical solution for this was adding redundancy, which lowers the possibility of systems failing completely which will shorten repair times compared to systems that do fail. However, adding extra components also asks for more inspections and preventive maintenance and thus there could be an optimum between adding redundancy, reliability and repairs costs. This is not taken into consideration in the model, because optimizing availability was eventually not one of the goals of this thesis.

Number of Failure Modes

Another discussion point can be made regarding the OR-gates and the number of failure modes per component. Mathematically, the OR-gate was represented by formula 2.4:

$$R(t) = 1 - (1 - R_1(t)) * (1 - R_2(t)) * ..(1 - R_n(t)) \tag{8.1}$$

This shows the reliability of a component or system is becoming less the more failure modes a component has. In general this is logical; the more ways something has to fail the more likely that it will fail. Point of discussion here is that in this thesis, it can be stated with certainty not all failure modes for all components and systems have been found, meaning that the reliability of components and systems will give a somewhat distorted image of reality. The failure modes of components were therefore trimmed down to a single possibility of failure, without making the distinction between different failure modes. Recommendations for further research would be to get more knowledge of the systems and indicating more failure modes to get a more complete image of the reliability of systems within the P&P system.

To summarize this chapter, it is clear that there is still a lot that needs to be done in order to make the reliability calculations better before a detailed assessment can be done regarding unmanned systems. The model does give a good start in showing what redundancy can do to the reliability, the importance of maintenance and the adopted maintenance strategy, but it is far from complete.

9

Conclusions

This research has made an effort to get a better understanding of the possibilities of large unmanned surface vehicles. The main goal of this thesis was to get insight in what has to be done to be able to sail without on-board maintenance personnel. This was done by modelling the reliability of an unmanned vessel without the access to sufficient failure data for a statistical analysis.

The main research question of these thesis was: *”What adjustments to the power and propulsion system of a Navy vessel are necessary to be able to operate for a given period of time, consisting of several missions, without any on-board maintenance personnel?”*

This question will be answered in this chapter by restating some of the sub-questions and conclusions that were drawn throughout the thesis, that finally resulted in being able to answer the main research question.

Chapter 4 answered research question 1 ,*”What system components make up the power and propulsion system of the Holland Class Patrol Vessels of the Royal Netherlands Navy?* and research question 2, *”What maintenance activities hinder maintenance free sailing and how can they be mitigated?”*. This resulted in an understanding of the current hybrid propulsion system and what activities have to be mitigated to remove on-board maintenance personnel. Chapter 4 concluded that there are two sorts of improvements needed to make the P&P system suitable for unmanned operation: Improvements that remove inspections and improvements that remove preventive maintenance tasks.
Chapter 5 tried to answer research question 3, *”What are the weaknesses of the power and propulsion system when not maintained during sailing?”* with the data that was made available by DMO. With the FMEA is was concluded that it was not possible to identify the weaknesses of an unmanned P&P system. This was because the need for maintenance was not implemented into the mean time between failure data and thus the reliability model was needed to make conclusions regarding the weaknesses of unmanned P&P systems. This chapter did however answer the 4th research question:”What are the risks of the weakest components in the power and propulsion system?”. The conclusion regarding the risks of failures was not drawn in chapter 5, but it was concluded in chapter 6 that only failure modes that resulted in system failure would be modeled because of missing failure modes. Partial failures were too difficult to model within the given time frame.

When trying to answer research question 3 with a model in chapter 6, it was concluded the failure data was insufficient to use a statistical method. Even though the data provided by DMO was more comprehensive than the data other previous research has used to study the reliability of unmanned vessels, this thesis was forced to use a probabilistic method to do a reliability assessment. The MTBF and maintenance frequencies of components were sufficient to give insight in what the direct impact of maintenance is.
Furthermore, this chapter concluded that it is possible with the available data to introduce a time dependent failure rate function into the reliability function to simulate the direct impact maintenance has on the reliability of the P&P system. With this information, it was concluded that the weakest components

that prevent the P&P system from unmanned operation are mostly filters and pumps.

To answer sub-question 4;*"What can be done to reduce the risk and improve the reliability of weak components of the power and propulsion system?"* it was concluded redundancy and changing the maintenance strategy are the two improvements worth considering when looking at the existing P&P system.
Limiting factors in the reliability of the current P&P systems are the diesel engines. Because of their numerous amount of moving parts, the diesel engine is the system with the most failure modes and thus makes itself the least reliable system. Other options such as electric motors are advised to be considered when redesigning the P&P system.

From the reliability assessment done with the model, research question 6;"How do improvements/alterations influence the reliability of the power and propulsion system and make the P&P system suitable for unmanned sailing?" could be answered. It can be concluded that is is possible to create a unmanned P&P system that has a reliability that is comparable to a manned P&P system when various improvements are introduced. Improvements could be implementing a predictive maintenance strategy and making the 5 least reliable components redundant, or by keeping the same maintenance strategy and making the 20 least components redundant.
Furthermore, this thesis can conclude that that are still a number of uncertainties that have to be studied further. The severity of a failure, the amount of failure modes and the inter dependency between components when a failure occurs for instance are worth studying to improve the reliability model.

The answers and conclusions that are drawn from the sub-questions help in forming an answer for the main research question. Even though the results of the model suggest that it is possible for the current P&P system to operate unmanned and without on-board maintenance, it can be concluded that further research is needed to fully answer the main research question. At this moment, it is uncertain what the precise adjustments to the P&P system should be to make the system suitable for unmanned sailing. Yes, it is possible to make alterations to the P&P system and changing the maintenance strategy to give the system a comparable reliability when considering planned inspections and preventive maintenance activities. But, an important factor is not taken into consideration during this thesis: corrective maintenance. Corrective maintenance makes sure the systems can be repaired when a failure occurs, making them operational again. Besides that preventive maintenance and inspections are important, corrective maintenance is as or maybe even more important to successfully execute a mission. As long as the possibility of failure during a mission still exists and can be solved by on-board personnel, a ship will most likely be equipped with personnel. This makes it very difficult to replace and put a number on the value of personnel on board. This also means that at this moment, with no clear view of the impact maintenance personnel has on the success rate of a mission, a definitive conclusion regarding if the P&P system of the Holland class OPV of the Royal Netherlands Navy can sail unmanned cannot be made. Even though the model doesn't seem to be helpful with this statement, it still has potential. It does provide an insight in the impact maintenance has on reliability and that even with limited data it should eventually be possible to calculate the reliability of unmanned as well as manned systems. Therefore, this model can provide a base for future research to the possibilities of unmanned P&P systems and bring the world of Large Unmanned vessels a step closer to becoming reality.

10

Recommendations

The goal of this thesis was to study the possibilities of a large unmanned surface vehicle with a reliable enough P&P system. The model showed that it is possible to sail with a comparable reliability as that of a manned P&P system, but several aspects of the model need further development. This chapter will make recommendations for further research to make the model more comprehensive and able to look at more aspects that need to be considered for making the model a usable tool when calculating reliability for unmanned vessels. Therefore, this chapter will make recommendations with the road map to a model that is usable for reliability calculations. It will do this by first make recommendations of how to improve the existing model. These recommendations will have to goal to remove assumptions and simplifications that were made during this thesis research. Second, the other recommendations will expand the model and look at a more complete picture of the considerations that come with making a P&P system unmanned such as finances, personnel and alternative technologies.

10.1. Model Improvements

The first recommendations for further research will improve the model as it is. There are several assumptions and simplifications made that, when researched further, can make the model more realistic.

Operational Profile

In this study it was assumed that the machinery operates in steady state and is used 100% of the time the ship is at sea, while in reality this is not the case. An assumable operational profile of the vessel and a study into the impact of the intensity of usage i.e. the failure rate development of components related to their time and intensity of usage, would be valuable. This will give a more realistic view of the course of the reliability function and would be the first improvement to a better model.

Maintenance from inspections

One of the biggest assumptions made within the model is that inspections reset the clock and does not make a distinction between ”doing nothing” and ”perform maintenance”. This was done because data that indicated what maintenance activities came from inspections was not known and thus made it necessary to make such an assumption. For instance, the activity ”replace fuel oil filter” has a work order in the SAP database of 75 fuel filters. From this information it is not clear after how many running hours a filter is replaced. Because this component is replaced very frequent the engineers were able to give an estimation of the maintenance frequency of this component, but for other components that have a lower inspection frequency this information was not available. This would be the first step in improving the model, by making the failure rate time dependent for all components instead of just a few that receive planned maintenance. A recommendation would be to better monitor when an inspection leads to maintenance. To make better estimations, a bigger database is advisable. Other Navies are sailing with similar operational profiles and engines and could be helping in identifying failure behaviour of the systems on board.

Failure Mechanism, Mode, and Severity
A third step in improving the model would be to study the failure mechanisms of every component that is part of the reliability assessment. By studying the failure mechanism, the failure rate function and its shape function β can be estimated which would improve the model.

Next to failure mechanisms, studying failure modes can indicate how a component can fail. By knowing in what possible ways the component and/or system can fail, the model will be more accurate and closer to reality than just giving the component a probability of ”a” failure. When all the failure modes of the components are found, the severity and inter dependency between failures can be studied as well. This will make the model more dynamic because the consequences of the functionality and failure rate development of other components and systems can be modelled.
Further study into the failure mechanism, mode and severity can be done with more failure data, but before sufficient data is collected, expert knowledge can possibly offer an interim solution.

10.2. Model Additions

Next to recommendations that will improve the model itself, taking away uncertainties that were implemented by simplifications and assumptions, there are several recommendations that can be made to make the model more comprehensive.

Corrective Maintenance
As this thesis concluded, the importance of personnel and the needed reliability of an unmanned system when the possibility of corrective maintenance is taken into consideration is an important factor that for now was out of the scope of this research. How valuable on-board maintenance personnel is should be studied in order for this model to make some realistic calculations. It is therefore recommended to study the failure modes of every component that make up the P&P system and decide whether it would normally be possible to make repairs after such a failure mode would occur.

Implementing Sensory equipment
With the recommendations above, all the information needed to make a model that can be used to calculate the reliability of a P&P system during operation are better defined. The next recommendation of improving the model would be to place sensory equipment. The sensor data can then be used to identify where on the failure rate curve the component or system is and adjust its reliability and failure rate according to the data.

Repair Time and Personnel
Implementing repair time and personnel needed would make it possible to see what the number of personnel, working hours and eventually repair costs are for a manned and unmanned system. It would give a more realistic approach to the time available to do the repairs and could give a more dynamic and interesting result when looking at the reliability of the P&P system. At this point, the systems that need repair just start over when they reached the threshold, but limited time to repair could change the repair strategy and knowing what components will impact the reliability of the system most would be valuable as well.

Alternative Technologies
As a final recommendation, this thesis only looked at the possibilities of adding redundancy to the current P&P system to make it reliable enough for unmanned sailing. There are however numerous other technologies that can be used to fulfill the mobility function and make the P&P system reliable enough for unmanned sailing. Further study is recommended to investigate whether alternative power and propulsion technologies could be reliable enough to make USVs possible.

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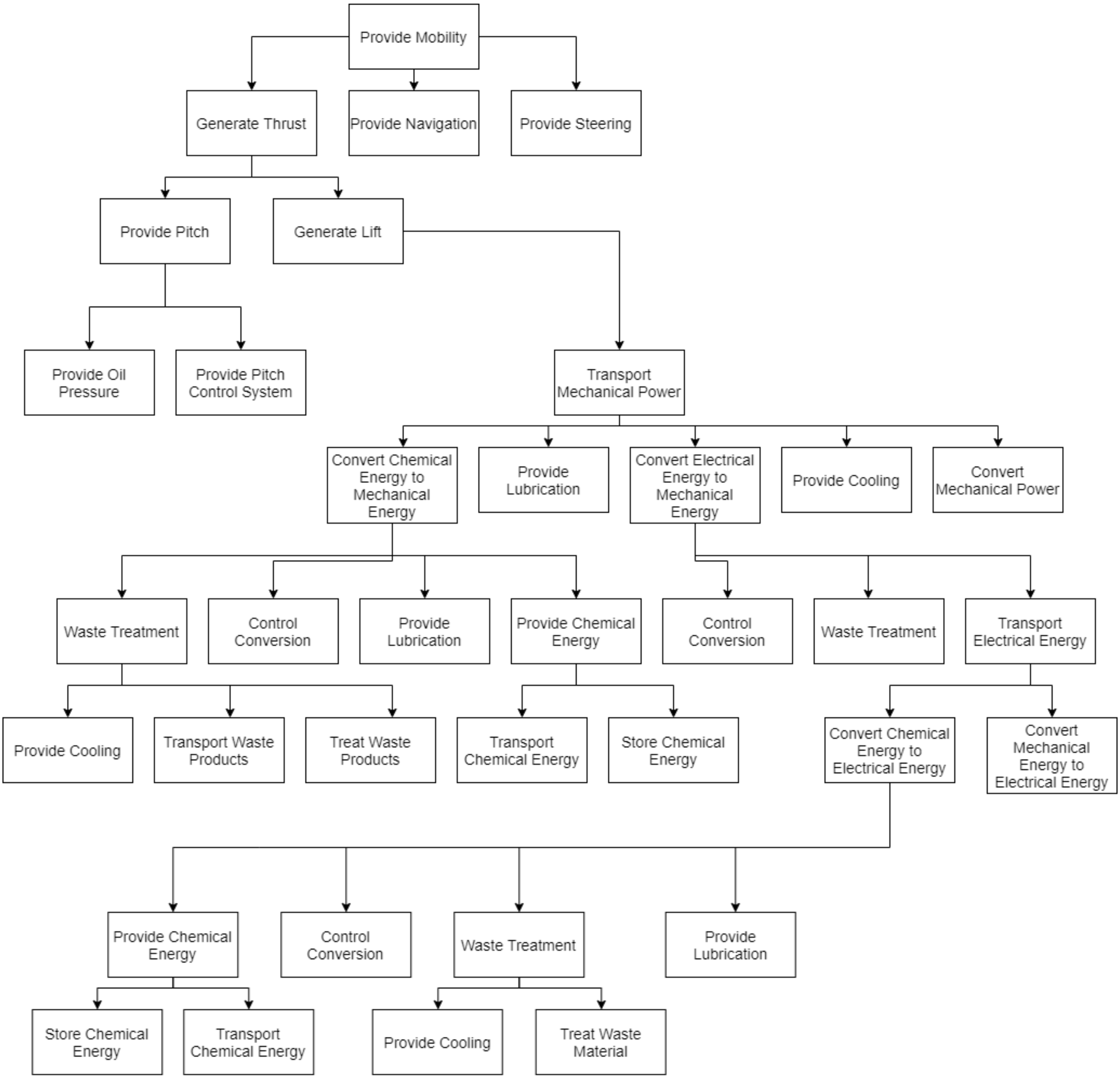
A

Appendix A: Decompositions

A.1. Functional Decomposition



A.2. Physical Decomposition

System	Subsystem	Component
Main Diesel Engine MDE	Engine	Engine Block
		Cam Shaft
		Cam Shaft Bearing
		Cylinder lining
		Cylinder Heads
		Pistons
		Piston Rod
		Radial Bearings
		Seals
		Crank Shaft
		Thrust bearing
		Gears
		Virbration Damper
		Cylinder Valves
	Electric System	Wiring
		Sensors
		Actuator
		ECM
MDE Local Control System	Injection Module	
	Control Module	
	Monitor and control panel	
MDE Lubrication Oil System	Lubrication Oil Cooler	
	Temperature Contol Valve	
	Spring loaded pressure valve	
	Valve	
	Filtering system	Duplex Oil Filter
	Metal Detector	
	Electric powered injection pump	
	Electric powered pre-lubrication pump	
	Electric powered pre-heating pump	
	Engine Powered Lubrication Pump	
	Oil Mist Unit	
		Medium
	piping	
MDE Cooling System	HT Cooling System	Engine powered fresh water centrifugal cooling pump
		Heat Exchanger Inlet Air (HT Side)
		Heat Exchanger Engine (HT Side)
		Heat Exchanger Seawater (HT Side)
		Temp Control Valve
	LT Cooling System	Engine Powered Fresh Water Centrifugal Cooling pump
		Heat Exchanger Inlet Air (LT side)
		Heat Exchanger Sea water (LT Side)
		Temp Control Valve
	Sea Water Cooling System	Engine Powered Sea Water Centrifugal Cooling Pump
		HT Heat Exchanger (Sea Water Side)
		LT Heat Exchanger (Sea Water Side)
	Expansion System	
	piping	
		Medium

MDE Air Inlet System		Turbocharger
		HT Air inlet Cooler
		LT Air Inlet Cooler
		Vibration Dampers
		Temperature Sensors
		Air Filter
		Pressure Sensors
		rpm Sensor Turbo Charger
MDE starting Air System		Start Air Isolation Valve
		Start Valve
		Starter Motor
		Starting Air Tank
		Torn Motor
		Starter Air Amplification Valve
		Air Filters
		Pressure Valve
MDE Air Outlet System		Temperature Sensor
		Exhaust Damper
		Vibration Damper
		Turbocharger (same as inlet syst)
MDE Mountings & Couplings		Clutch
		Vibration Damper
		Engine Foundation Rubbers
MDE Fuel Oil System		Air Controlled Fuel valve
		Fuel Gauge
		Low Pressure Diesel Powered Fuel pump (Transfer Pump)
		Duplex Fuel Filter
		High Pressure Fuel Injection pump
		Fuel Pressure Valve
		Piping
		Fuel Oil Cooler
MDE Propulsion Control System	Platform Management System	
	Engine Room Control	
	Bridge Control System	
	Main Switchboard	
	CPP Control	
	Gearbox Control	
	MPM Control	
	Variable Speed Drive Control	
Electrical Propulsion System	Internal Cooling System	Expansion Tank
		Cooling Pump
		Heat Exchanger
		Pressure gauge
		Pressure Sensor
		Temperature Sensor
		Venting
		Valves
	Inverter	
	PEM	Transformer
		Condensator
	Brake Resistance	Brake
		Inhibitor
	Propulsion Transformer	
	Bow Thruster Motor	
	Back Up Battery	
Gearbox Installation	Thrust Block (Stuwblok)	
	Blocking Device	
	Torn Device	Electric Motor
	Friction Clutch MPM	
	Friction Clutch PEM	
	Lubcrication system	Gearbox hydraulic Oil Pump (2)
		Gearbox Lubrication Oil Pump
		Electric hydr./Lub. Oil Pump
		Duplex Lubrication Oil Filter
		Duplex hydraulic Oil filter
		Lubrication Oil Suction Filter (3)
	Axle Brake	Brake Pads
		Brake Cyclinders
		Mechanical Seals
		Gears

Shaft	Stern Frame (Uithouder)	
	Stern Tube	
	Propeller Shaft	
	Outboard Bearings	
	hydraulic Stop	
	Propeller Shaft Seal	
	propeller Shaft Grounding	
	Torsion/Rotation speed measure system	
	Bulkhead Penetration	
	Inboard Bearings	
Controllable Pitch Propeller		Propeller Blades
		Hub
		Pneumatic Stops
Hydraulic System CPP		Hollow Propeller Shaft
		Feeding Unit
		Hydraulic Oil Pump
	HPU (Hydraulics Power Unit)	Tank
		HP Pump
		LP Pump
	OilTank	Level Sensors(3)
		Tank
		Emergency Pump
		Seals
Diesel Engine Generator	Engine	Engine Block
		Cam Shaft
		Cam Shaft Bearing
		Cylinder lining
		Cylinder Heads
		Pistons
		Piston Rod
		Radial Bearings
		Seals
		Crank Shaft
		Thrust bearing
		Timing chain/V-belt
		Gears
		Virbration Damper
		Cylinder Valves
Generator		Generator
		AVR (Automatic Voltage Control)
DG Lubrication System		Generator Powered Lubrication Oil Pump
		Heat Exchanger Generator Cooling System
		Lubrication Oil Filter
		Three-way temperature controlled valve
		Pressure Valve
DG Cooling System	HT Cooling System	Generator powered cooling water pump
		Heat Exchanger Lubrication Oil
		Blower Cooler
		Expansion Tank
		Three-way temperature controlled valve
	LT Cooling System	Generator powered cooling water pump
		Inlet Air Cooler
		Three-way temperature controlled valve
DG Inlet Air System		Filter
		Turbo Charger Inlet Air Side
DG Exhaust System		Turbo Charger Exhaust Side
		Exhaust Air Cooler
DG Fueling System		Diesel Tank
		Pressure valve
		Fuel Water Separator
		Generator Powered Fuel Pump
		Duplex pressure filter
		High Pressure Fuel pump
		Pressure Valve
		Fuel Cooler

B

Appendix B: Schematic Overview Diesel Generator Systems

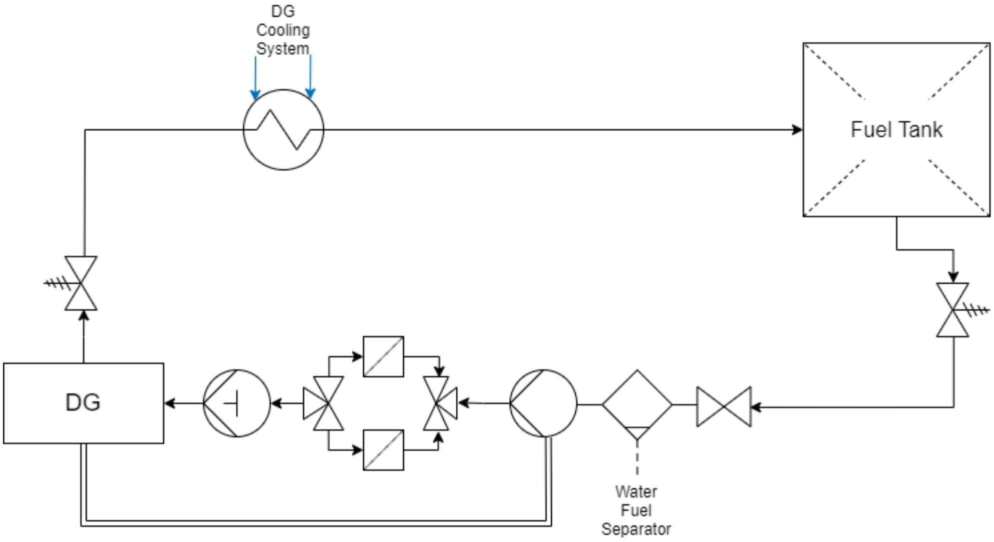


Figure B.1: DG Fueling System

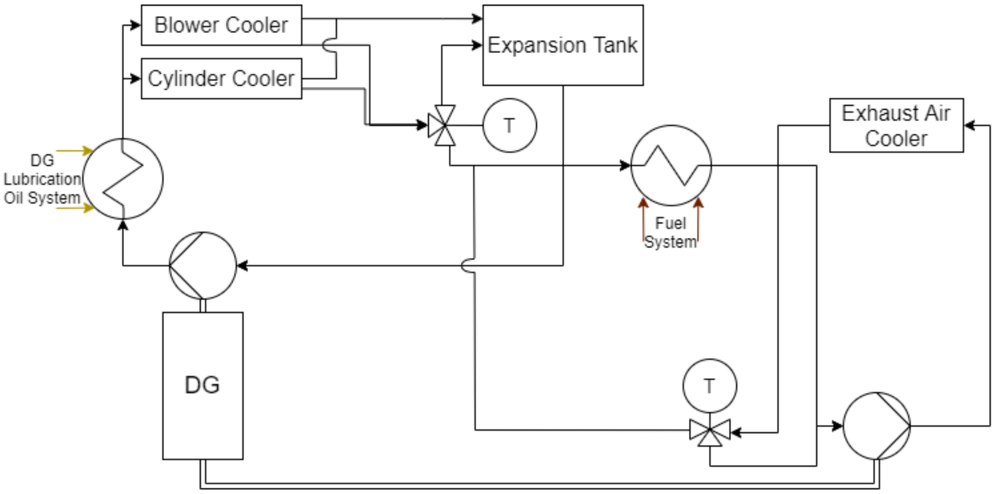


Figure B.2: DG Cooling System

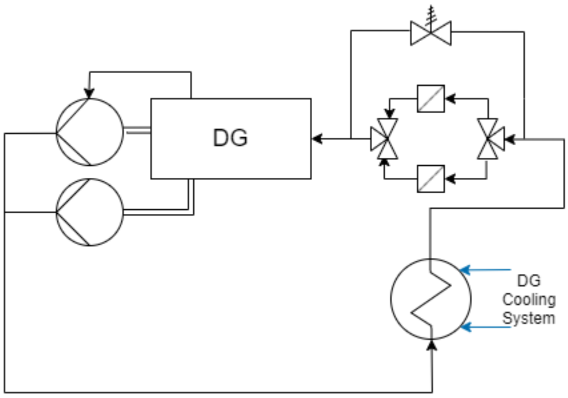


Figure B.3: DG Lubrication Oil System

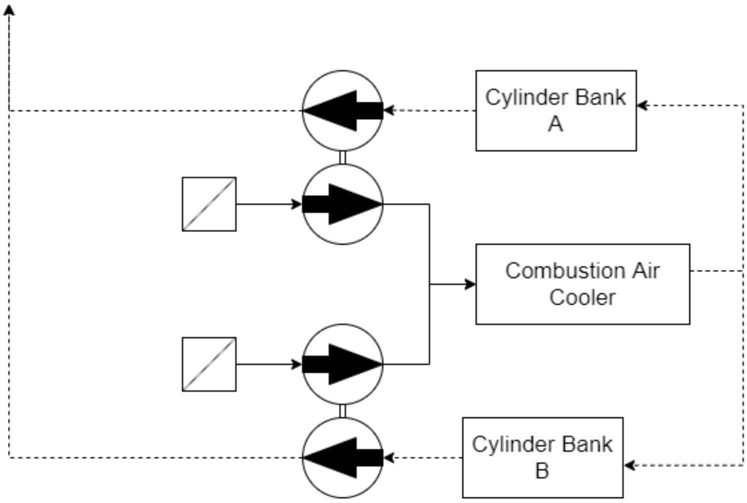


Figure B.4: DG Ait inlet/outlet System

C

Appendix C: FMEA P&P System

System	Part	Failure Mode	Effect	MTBF	MF	Planned
MDE	Engine Block	High carter level	(Sub-)System Failure	100000	8000	No
MDE	Cam Shaft	Worn Out	(Sub-)System Failure	100000	16000	Yes
MDE	Cam Shaft Bearing	No Bearing	(Sub-)System Failure	100000	4000	No
MDE	Cylinder lining	Unable to Contain Combustion	(Sub-)System Failure	232090.4	1600	Yes
MDE	Cylinder Heads	Crack in Cylinder Head	(Sub-)System Failure	80000	4000	Yes
MDE	Pistons	Piston Cracked	(Sub-)System Failure	70000	8000	Yes
MDE	Piston Rod	Broken Piston rod	(Sub-)System Failure	100000	500	No
MDE	Radial Bearings	Bearing Damage	(Sub-)System Failure	55000	500	No
MDE	Seals	Leaking Seals	(Sub-)System Failure	30000	16000	No
MDE	Crank Shaft		(Sub-)System Failure	100000	2000	No
MDE	Thrust bearing		(Sub-)System Failure	50000	4000	No
MDE	Gears	Worn out Gear	(Sub-)System Failure	85000	4000	No
MDE	Virbration Damper	Torn Vibration Damper	(Sub-)System Failure	60000	16000	No
MDE	Cylinder Valves	Worn Out Valves	(Sub-)System Failure	50000	1000	No
MDE	Wiring	Worn out Wiring	(Sub-)System Failure	87600	4000	No
MDE	Sensors	Damaged Sensor	(Sub-)System Failure	87600	24	No
MDE	Actuator	Connection Interference	(Sub-)System Failure	87600	4000	No
MDE	ECM	No Entry Reading	(Sub-)System Failure	219000	4000	No
MDE Lubrication Oil System	Lubrication Oil Cooler	Cooler Clogged	(Sub-)System Failure	40000	4000	Yes
MDE Lubrication Oil System	Temperature Contol Valve	Failed to function	(Sub-)System Failure	48239.27	4000	No
MDE Lubrication Oil System	Valve	Fail to open or close	(Sub-)System Failure	33444.82	4000	No
MDE Lubrication Oil System	Oil Filter	Clogged Filter	(Sub-)System Failure	5000	500	Yes
MDE Lubrication Oil System		Failing Valves	(Sub-)System Failure	30000	1000	No
MDE Lubrication Oil System	Electric powered pre-heating pump	Short Circuited	(Sub-)System Failure	30000	1000	No
MDE Lubrication Oil System	Engine Powered Lubrication Pump	Pump Broke Down	(Sub-)System Failure	40899.8	16000	Yes
MDE Lubrication Oil System	Structural Failure	Leaking	(Sub-)System Failure	20000	24	No
MDE Cooling System	Engine powered centrifugal pump	Broken Blade	(Sub-)System Failure	25000	8000	Yes
MDE Cooling System	Heat Exchanger Inlet Air	Clogged Cooler	(Sub-)System Failure	100000	4000	Yes
MDE Cooling System	Heat Exchanger Heater	Clogged Cooler	(Sub-)System Failure	100000	4000	Yes
MDE Cooling System	Heat Exchanger Seawater	Clogged Cooler	(Sub-)System Failure	50000	4000	Yes
MDE Cooling System	Heat Exchanger Lubrication Oil		(Sub-)System Failure	50000	4000	Yes
MDE Cooling System	Temp Control Valve	Defect Termostat	(Sub-)System Failure	10000	24	No
MDE Cooling System	Engine Powered Centrifugal pump	Broken Blade	(Sub-)System Failure	25000	8000	Yes
MDE Cooling System	Heat Exchanger Inlet Air	Clogged Cooler	(Sub-)System Failure	100000	4000	Yes
MDE Cooling System	Heat Exchanger Sea water	Clogged Cooler	(Sub-)System Failure	50000	4000	Yes
MDE Cooling System	Heat Exchanger Fueling System	Clogged Cooler	(Sub-)System Failure	50000	4000	Yes
MDE Cooling System	Temp Control Valve	Controlling Coolant Temp	(Sub-)System Failure	10000	24	No
MDE Cooling System	Engine Powered Centrifugal Pump	Fails to pump seawater	(Sub-)System Failure	17803.1	8000	Yes
MDE Cooling System	HT Heat Exchanger (Sea Water Side)	Clogged Cooler	(Sub-)System Failure	50150.45	1000	Yes
MDE Cooling System	LT Heat Exchanger (Sea Water Side)	Clogged Cooler	(Sub-)System Failure	50150.45	1000	Yes
MDE Cooling System	Valve	Unable to open/close	(Sub-)System Failure	38417.21	24	No
MDE Cooling System		Leaking Seals	(Sub-)System Failure	30000	24	No
MDE Air Inlet System		Smoking	(Sub-)System Failure	20000	32000	Yes
MDE Exhaust System	Exhaust Damper		(Sub-)System Failure	20594.44	1000	Yes
MDE Fuel Oil System	Transfer Pump	Worn Out pump blades	(Sub-)System Failure	40000	16000	Yes
MDE Fuel Oil System	Duplex Fuel Filter	Insufficient Fuel Supply	(Sub-)System Failure	5000	240	Yes
MDE Fuel Oil System	High Pressure Fuel Injection pump	Clogged Injector	(Sub-)System Failure	70000	8000	Yes
MDE Fuel Oil System	Fuel Pressure Valve	Worn Out Pressure Valve	(Sub-)System Failure	50000	4000	Yes
MDE Fuel Oil System	Piping	Fuel Leakage	(Sub-)System Failure	20000	24	No
MDE Fuel Oil System	Fuel Oil Cooler	Critical Failure	(Sub-)System Failure	15151.52	4000	Yes
Electrical Propulsion System	Transformer		(Sub-)System Failure	80000	4000	No
Generator	AVR (Automatic Voltage Control)		(Sub-)System Failure	174607.1	4000	No
DG Lubrication System	Generator Powered Pump		(Sub-)System Failure	40899.8	4000	No
DG Lubrication System	Heat Exchanger	Clogged Cooler	(Sub-)System Failure	100000	4000	Yes
DG Lubrication System	Lubrication Oil Filter	Clogged Filter	(Sub-)System Failure	5000	500	Yes
DG Lubrication System	Valve	Fail to open or close	(Sub-)System Failure	33444.82	4000	No
DG Cooling System	Generator Powered Pump	Broken Blade	(Sub-)System Failure	25000	8000	Yes
DG Cooling System	Heat Exchanger Lubrication Oil	Clogged Cooler	(Sub-)System Failure	100000	4000	Yes
DG Cooling System	Three-way temperature controlled valve	Defect Termostat	(Sub-)System Failure	10000	4000	No
DG Fueling System	Pressure valve	Worn Out Pressure Valve	(Sub-)System Failure	50000	4000	No
DG Fueling System	Generator Powered Fuel Pump	Worn Out pump blades	(Sub-)System Failure	40000	16000	Yes
DG Fueling System	Duplex pressure filter	Insufficient Fuel Supply	(Sub-)System Failure	5000	250	Yes
DG Fueling System	High Pressure Fuel pump	Clogged Injector	(Sub-)System Failure	70000	4000	No

Table C.1: Failure Mode and Effects analysis of the most critical components of the P&P system

D

Appendix D: MATLAB Script and Simulink Model

D.1. MATLAB Script

Contents

- Calculate variables for failure rate and reliability function
- Set Reliability Monitors
- Run Simulink Model

```
tic
clc;
clear variables;
close all;


T_t = 750;  %Total Mission Time
N = 100000;

DATA = readtable('FMECA_jip.xlsx', 'sheet', 'MATLAB2' );
MTBF = table2array(DATA(:,16)); %MTFB
lambda = 1./MTBF; %Constant Failure rate
m_f = table2array(DATA(:,18)); %Maintenance Frequency
MAINTAINABLE = table2array(DATA(:,21)); %Is the item sinsitive to maintenance? 1 = no, 2 = yes
c = zeros(length(MTBF),1); %Add time constant to reset time simulation clock for rapaired items
beta = zeros(length(MTBF),1);
eta = zeros(length(MTBF),1);
h_c = zeros(length(MTBF),1);
f_th = zeros(length(MTBF),1);
failure_rates = zeros(1,length(MTBF));

for T_m = 1                 %Duration of mission in days
for fr = 0.71           %fraction of hazard rate that is random
for b = 3                 % Shape Parameplot(mobility)ter of Weibull Distribution

    n = T_t/T_m;  %Number of Missions
```

Calculate variables for failure rate and reliability function

```
for i = 1:length(MTBF)

    if MAINTAINABLE(i)== 2
```

```
    %Part which is time dependent
        beta(i) = b;
        eta(i) = m_f(i)*(lambda(i)*(1-fr)*m_f(i))^(-1/beta(i));
    %Part which is random/constant
        h_c(i) = lambda(i)*fr;
        f_th(i) = (beta(i)/(eta(i)^beta(i)))*m_f(i)^(beta(i)-1) + h_c(i);


    elseif MAINTAINABLE(i)== 1 %non-maintainable items
        eta(i) = 1/lambda(i);
        beta(i) = 1; %Failure rate is constant so 100% failure from MTBF
        f_th (i) = 1; %=1 because then it will never be reached for items not sensitive for maintena
    end


end
```

Set Reliability Monitors

```
for q = 1:1

hazard_c = zeros(T_m*24,n);
hazard_t = zeros(T_m*24,n);
reliability_c = zeros(T_m*24,n);
reliability_t = zeros(T_m*24,n);
reliability_total = zeros(T_m*24,n);
HR = zeros(length(MTBF),T_m*24,n);
Lub_upper_branch = zeros(T_m*24,n);
Lub_lower_branch = zeros(T_m*24,n);
Upper_and_lower = zeros(T_m*24,n);


mde = zeros(T_m*24,n);
mde_lub= zeros(T_m*24,n);
mde_fuel= zeros(T_m*24,n);
mde_cool= zeros(T_m*24,n);
mde_air= zeros(T_m*24,n);
mde_syst= zeros(T_m*24,n);
pem= zeros(T_m*24,n);
mobility= zeros(T_m*24,n);
elec_prop= zeros(T_m*24,n);
dg_lub= zeros(T_m*24,n);
dg_cool= zeros(T_m*24,n);
dg_fuel= zeros(T_m*24,n);
dg_gen= zeros(T_m*24,n);
dg_syst= zeros(T_m*24,n);
dg_total = zeros(T_m*24,n);
mde_prop_syst= zeros(T_m*24,n);

engine_block= zeros(T_m*24,n);
cam_shaft= zeros(T_m*24,n);
cam_shaft_bearing= zeros(T_m*24,n);
cylinder_lining= zeros(T_m*24,n);
cylinder_heads= zeros(T_m*24,n);
pistons= zeros(T_m*24,n);
piston_rods= zeros(T_m*24,n);
radial_bearings= zeros(T_m*24,n);
```

```
seals= zeros(T_m*24,n);
crank_shaft= zeros(T_m*24,n);
thrust_bearing= zeros(T_m*24,n);
gears= zeros(T_m*24,n);
vibration_damper= zeros(T_m*24,n);
cylinder_valves= zeros(T_m*24,n);
wiring= zeros(T_m*24,n);
actuators= zeros(T_m*24,n);
ecm= zeros(T_m*24,n);

fuel_pump= zeros(T_m*24,n);
duplex_fuel_filter= zeros(T_m*24,n);
hp_fuel_injection_pump= zeros(T_m*24,n);
fuel_oil_cooler= zeros(T_m*24,n);

ht_cooling= zeros(T_m*24,n);
lt_cooling= zeros(T_m*24,n);
sw_cooling= zeros(T_m*24,n);

ep_cent_pump= zeros(T_m*24,n);
he_lt_cooling = zeros(T_m*24,n);
he_ht_cooling = zeros(T_m*24,n);
valve = zeros(T_m*24,n);
end
```

Run Simulink Model

```
for g = 1:1:n

%Adjust starting and stopping time and run model

    start =   ((g-1)*T_m*24)+1
    stop =  (g*T_m*24)
    set_param('Power_System_v1_10_One_failure_Mode', 'StartTime', num2str(start));
    set_param('Power_System_v1_10_One_failure_Mode', 'StopTime', num2str(stop));
    sim('Power_System_v1_10_One_failure_Mode.mdl');

%Harvest Reliability calculations

for q =1:1

hazard_c(:,g) = simout;
hazard_t(:,g) = simout1;
reliability_c(:,g) = simout3;
reliability_t(:,g) = simout2;
reliability_total(:,g) = simout4;
HR(:,:,g) = hazard_rates';

Lub_upper_branch(:,g) = simout5;
Lub_lower_branch(:,g) = simout6;
Upper_and_lower(:,g) = simout7;

mde(:,g) = MDE;
mde_lub(:,g) = MDE_LUB;
mde_fuel(:,g) = MDE_FUEL;
mde_cool(:,g) = MDE_COOL;
mde_air(:,g) = MDE_AIR;
```

```
mde_syst(:,g) = MDE_SYST;
pem(:,g) = PEM;
mobility(:,g) =  MOBILITY;
elec_prop(:,g) = ELEC_PROP;
dg_lub(:,g) = DG_LUB;
dg_cool(:,g) = DG_COOL;
dg_fuel(:,g) = DG_FUEL;
dg_gen(:,g) = DG_GEN;
dg_syst(:,g) = DG_SYST;
dg_total(:,g) = DG_TOTAL;
mde_prop_syst(:,g) = MDE_PROP;

engine_block(:,g) = ENGINE_BLOCK;
cam_shaft(:,g)=CAM_SHAFT;
cam_shaft_bearing(:,g)=CAM_SHAFT_BEARING;
cylinder_lining(:,g)=CYLINDER_LINING;
cylinder_heads(:,g)=CYLINDER_HEADS;
pistons(:,g)=PISTONS;
piston_rods(:,g)=PISTON_RODS;
radial_bearings(:,g)=RADIAL_BEARINGS;
seals(:,g)=SEALS;
crank_shaft(:,g)=CRANK_SHAFT;
thrust_bearing(:,g) = THRUST_BEARING;
gears(:,g)=GEARS;
vibration_damper(:,g)=VIBRATION_DAMPER;
cylinder_valves(:,g)=CYLINDER_VALVES;
wiring(:,g)=WIRING;
actuators(:,g) = ACTUATORS;
ecm(:,g) = ECM;

fuel_pump(:,g) = FUEL_PUMP;
duplex_fuel_filter(:,g) = DUPLEX_FUEL_FILTER;
hp_fuel_injection_pump(:,g) = HP_FUEL_INJECTION_PUMP;
fuel_oil_cooler(:,g) = FUEL_OIL_COOLER;

ht_cooling(:,g) = HT_COOLING;
lt_cooling(:,g) = LT_COOLING;
sw_cooling(:,g) = SW_COOLING;

ep_cent_pump(:,g )= EP_CENT_PUMP;
he_lt_cooling(:,g) = HE_LT_COOLING;
he_ht_cooling(:,g) = HE_HT_COOLING;
valve(:,g) = VALVE;
end

%Check for threshold
for j = 1:length(failure_rates)
  if b == 1 || fr == 1             %If beta = 1 or if fr = 1 give means there is no time-dependant f

      if stop >= m_f(j)+c(j)
            c(j) = g*T_m*24;

        elseif stop < m_f(i) + c(i)
            c(j) = c(j);
      end
```

```
  else

    if MAINTAINABLE(j)== 2          %If the component has a time dependent failure rate

        if f_th(j) > failure_rates(j)
        c(j) = c(j);

        elseif f_th(j) <= failure_rates(j)

            c(j) = g*T_m*24;

        end

    elseif MAINTAINABLE(j)== 1      %If the component does not have a time dependent failure rate

        if stop >= m_f(j)+c(j)
            c(j) = g*T_m*24;

        elseif stop < m_f(j) + c(j)
            c(j) = c(j);
        end
    end
 end
end
end


for q =1:1
hazard_c = hazard_c(:);
hazard_t = hazard_t(:);
reliability_c = reliability_c(:);
reliability_t = reliability_t(:);
reliability_total = reliability_total(:);
HR = HR(:,:);

Lub_upper_branch = 1-Lub_upper_branch(:);
Lub_lower_branch = 1-Lub_lower_branch(:);
Upper_and_lower = 1-Upper_and_lower(:);

mde = 1- mde(:);
mde_lub = 1- mde_lub(:);
mde_fuel = 1- mde_fuel(:);
mde_cool = 1 - mde_cool(:);
mde_air =1- mde_air(:);
mde_syst= 1- mde_syst(:);
pem= 1- pem(:);
mobility= 1- mobility(:);
elec_prop = 1-elec_prop(:);
dg_lub= 1- dg_lub(:);
dg_cool= 1- dg_cool(:);
dg_fuel= 1- dg_fuel(:);
dg_gen= 1- dg_gen(:);
dg_syst = 1- dg_syst(:);
dg_total = 1- dg_total(:);
mde_prop_syst= 1- mde_prop_syst(:);
```

```
engine_block=1- engine_block(:);
cam_shaft=1- cam_shaft(:);
cam_shaft_bearing=1- cam_shaft_bearing(:);
cylinder_lining=1- cylinder_lining(:);
cylinder_heads=1- cylinder_heads(:);
pistons=1- pistons(:);
piston_rods=1- piston_rods(:);
radial_bearings=1- radial_bearings(:);
seals=1- seals(:);
crank_shaft=1- crank_shaft(:);
thrust_bearing=1- thrust_bearing(:);
gears=1- gears(:);
vibration_damper=1- vibration_damper(:);
cylinder_valves=1- cylinder_valves(:);
wiring=1- wiring(:);
actuators=1- actuators(:);
ecm=1- ecm(:);

fuel_pump=1- fuel_pump(:);
duplex_fuel_filter=1- duplex_fuel_filter(:);
hp_fuel_injection_pump=1- hp_fuel_injection_pump(:);
fuel_oil_cooler=1- fuel_oil_cooler(:);

ht_cooling =1-  ht_cooling(:);
lt_cooling =1-  lt_cooling(:);
sw_cooling =1-  sw_cooling(:);

ep_cent_pump= 1-  ep_cent_pump(:);
he_lt_cooling = 1-  he_lt_cooling(:);
he_ht_cooling = 1-  he_ht_cooling(:);
valve = 1-  valve(:);
end

%plot figures
for q =1:1
figure
plot(hazard_c)
hold on
% plot(hazard_t)
plot(hazard_c+hazard_t)
yline(f_th(find(strcmp('F58',DATA{:,23}))))
title('Failure Rates')
legend('Random','Total','Failure Rate Threshold')
ylabel('Failure Rate')
xlabel('Time (h)')

figure
plot(reliability_c)
hold on
plot(reliability_t)
plot(reliability_total)
title('Reliability')
legend('Random','Time Dependent','Total')
ylabel('Reliability')
xlabel('Time (h)')
```

```
% figure
% plot(Lub_upper_branch);
% hold on
% plot(Lub_lower_branch);
% plot(Upper_and_lower);
% legend('upper','lower','upper+lower')
% title('Lubrication System')
end
save(['One FM Days_' num2str(T_t) '_Tm_' num2str(T_m) '_beta_' num2str(b*10) '_fraction_' num2str(fr

start =

     1


stop =

    24



Error using Reliability_File_v1_11_BASE_FILE (line 122)
Invalid Simulink object name: Power_System_v1_10_One_failure_Mode

Caused by:
    Error using Reliability_File_v1_11_BASE_FILE (line 122)
    The block diagram 'Power_System_v1_10_One_failure_Mode' is not loaded. - Show complete stack tra


end
end
end

toc
```

D.2. SIMULINK MODEL

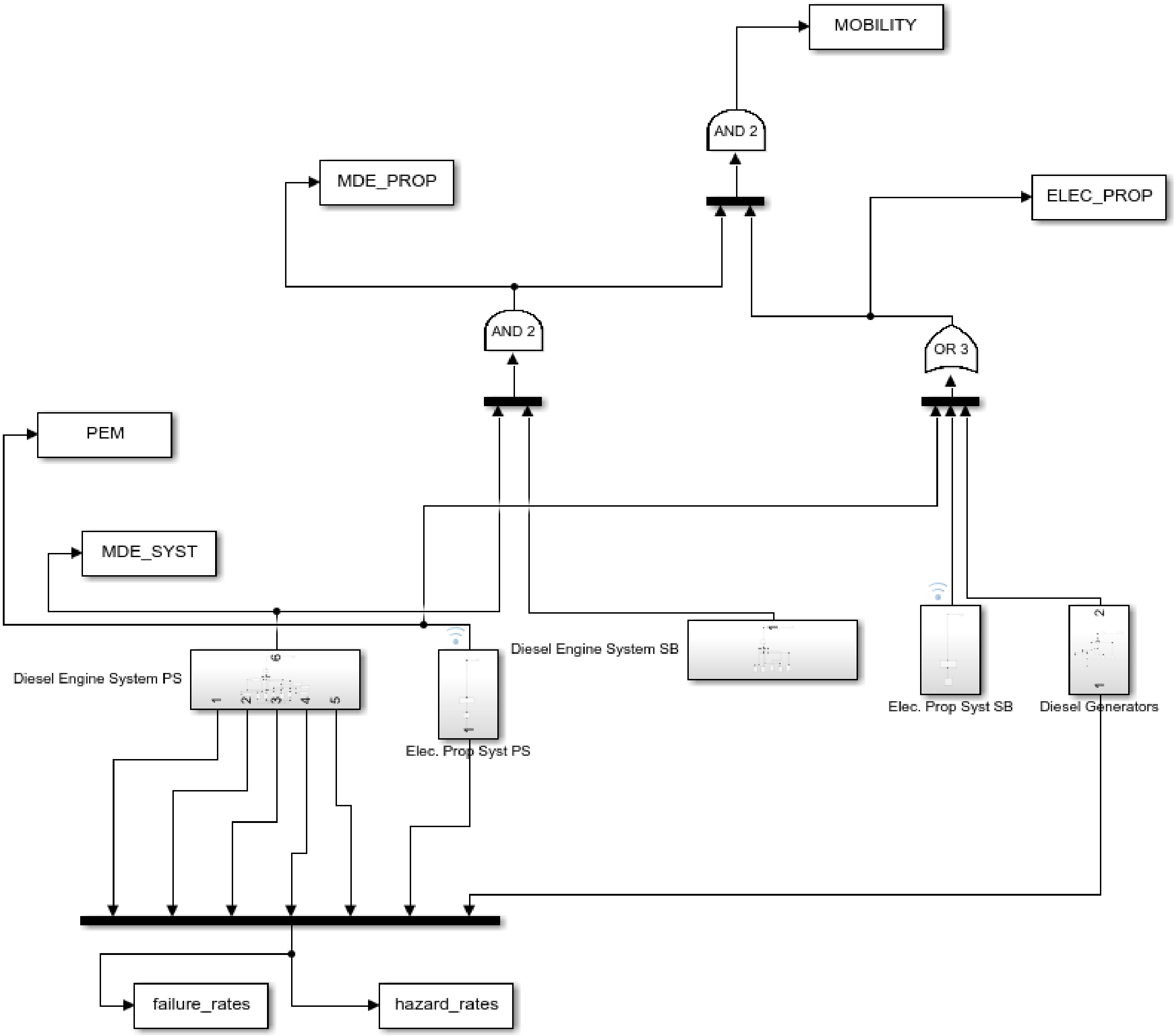


Figure D.1: Simulink Model FTA for a minumum proprulsion of 10 kts

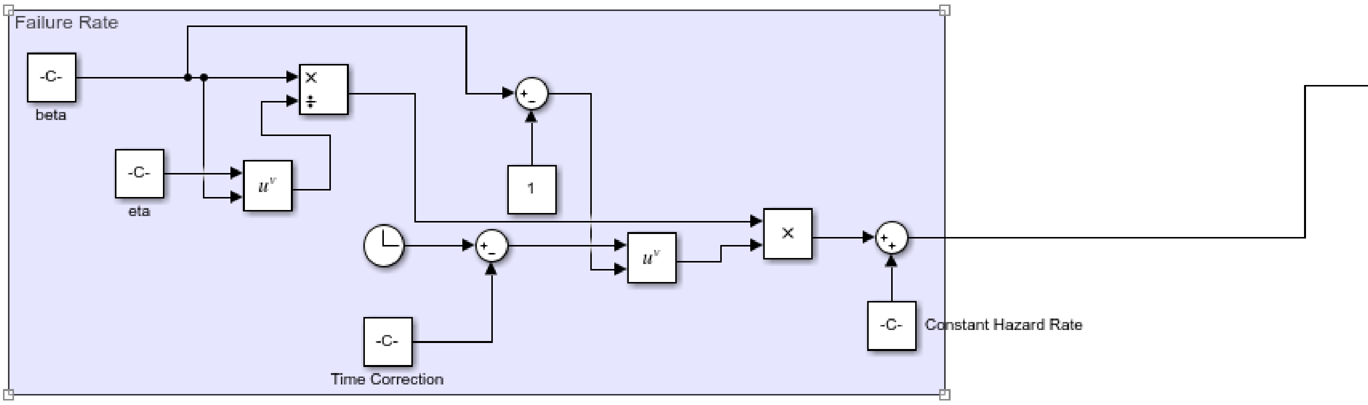


Figure D.2: Calculation of failure rate in Simulink

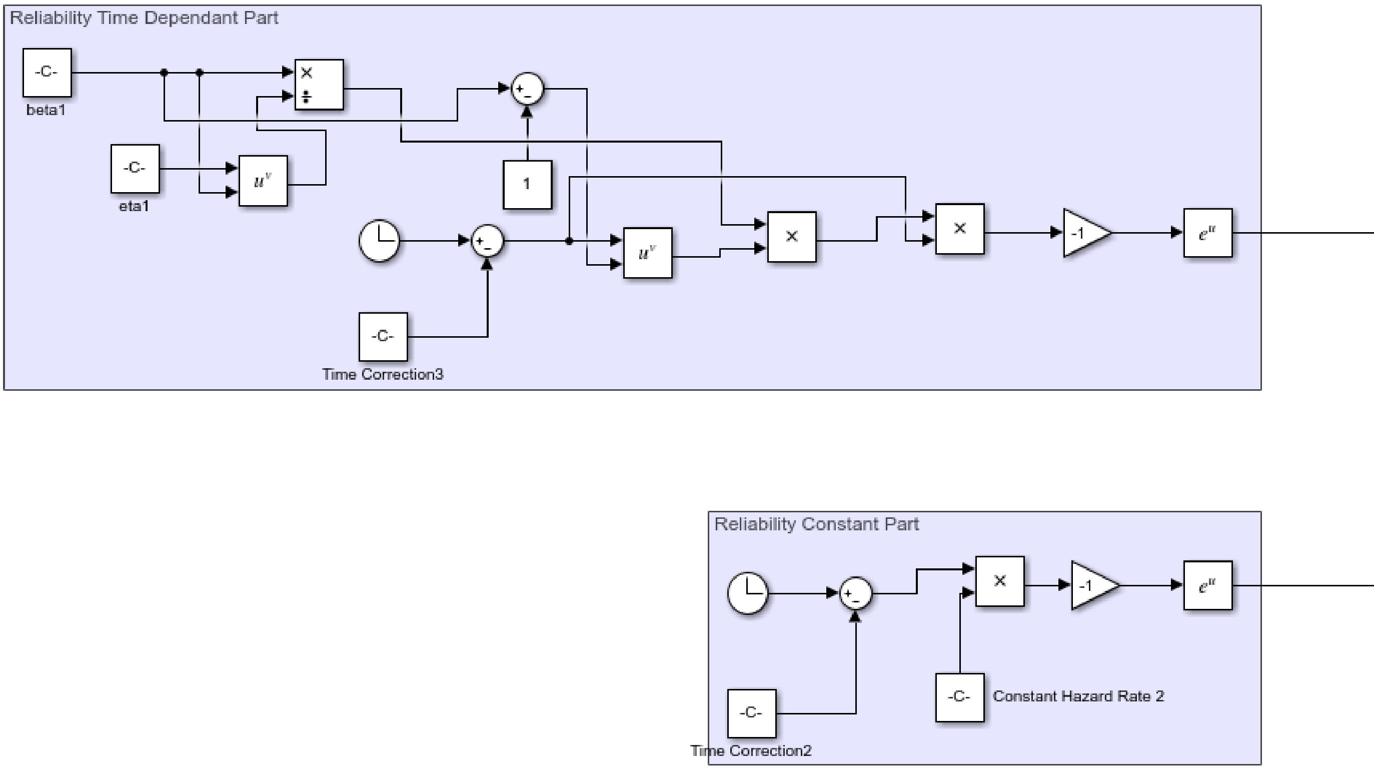


Figure D.3: Calculation of reliability in Simulink