

The Impact of Redundancy on the Availability of Diesel and Diesel-Electric Propulsion Systems: A Quantitative Approach to Assess Reliability

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**DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES
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During the preparation of this work the author(s) used ChatGPT in order to help formulate certain sentences better. After using this tool/service, the author(s) reviewed and edited the content as needed.

Preface

Esta tesis concluye una etapa que me alejó de mi casa, pero me dio un nuevo hogar.

Gracias a mi mamá y a mi papá por apoyarme, aunque hubieran preferido que estuviera cerca. Ahora todo será más fácil papás.

Gracias a mis supervisores por ayudarme a llegar al final de la forma más amable posible y a aprender tanto por el camino.

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This thesis concludes a chapter that took me away from home but gave me a new one.

Thank you to my mom and dad for supporting me, even though they would have preferred me to stay close by. Everything will be easier now, mom and dad.

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Thank you to all my friends, who have listened to me talking about this project countless times. Thank you for all your love and support.

Thank you to all the companies who have shared their time, knowledge and resources for this thesis to be completed.

And finally, thank you to TU Delft for allowing me to meet all these people, and for changing the way I see the world.

All models are wrong,
But some are useful.

George E. P. Box

Abstract

As maritime regulatory bodies tighten restrictions on greenhouse gas (GHG) emissions, the shipping industry is forced to reduce emissions with measures such as fuel consumption optimization, reduction of vessel design speed or reducing the installed power safety buffer. This compromises the historically introduced safety buffer of marine power plants, introducing the need to evaluate the propulsion reliability and availability.

Current regulations, specifically SOLAS II-1 26.2 and 26.3, have strict redundancy guidelines that are evenly applied across different configurations. Applying technological neutrality across conventional and complex configurations can penalize optimized power plant designs. Furthermore, existing literature relies heavily on oversimplified, constant failure rate methodologies that fail to capture realistic mechanical wear-out and maintainability.

To bridge these regulatory and methodological gaps, this thesis implements a quantitative combined deterministic-probabilistic framework. Using ReliaSoft BlockSim, four distinct vessel configurations were modelled as Reliability Block Diagrams (RBD): a baseline single-line diesel configuration (Case A1), a twin-engine diesel drive (Case A2), a diesel-electric system with a closed bus tie (Case B1), and a segregated diesel-electric system with an open bus tie (Case B2). Reliability data was extracted from historical databases, technical literature and academic standards, integrating standard exponential laws and time-dependent Weibull distribution models.

The deterministic analysis demonstrated that all redundant configurations exceeded the Case A1 reference baseline ($R=0.2199$), with Cases A2, B1 and B2 providing reliability gains of 66.2%, 295%, and 280.1% respectively.

Long-term Monte Carlo simulations revealed a critical regulatory inconsistency. The transition from Case B1 to a segregated busbar configuration in Case B2 eliminated a major electrical SPOF, with negligible variation in global availability (98.95% and 98.84%). Importance measures identified propulsion and steering lines and auxiliary systems as the primary bottlenecks, showing an operational importance up to 26.4%.

These findings demonstrate that while physical redundancy is a highly effective method for increasing availability in conventional diesel systems, it forces unconventional diesel-electric vessels into a zone of diminishing returns without delivering meaningful safety improvements. By establishing Case B1 as the ideal equilibrium between financial cost, operational safety, and environmental compliance, this research strongly advocates for a transition toward goal-based availability standards.

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Nomenclature

| Abbreviation | Definition |
|--|---|
| Propulsion Systems and Components | |
| ICE | Internal Combustion Engines |
| ME | Main Engine |
| CPP | Controllable Pitch Propeller |
| VFD | Variable Frequency Drive |
| LP | Low Pressure Pump |
| FO | Fuel Oil |
| LO | Lubrication Oil |
| LT | Low Temperature |
| HT | High Temperature |
| DG | Diesel Generators |
| LNG | Liquified Natural Gas |
| LPG | Liquified Petroleum Gas |
| HVAC | Heating, Ventilation, and Air Conditioning |
| PLC | Programmable Logic Controller |
| Reliability Engineering and Methods | |
| SPOF | Single Point Of Failure |
| RAM | Reliability, Availability and Maintainability |
| RBD | Reliability Blocks Diagram |
| MTTF | Mean Time To Failure |
| MTBF | Mean Time Between Failures |
| MTTR | Mean Time To Repair |
| DES | Discrete Event Simulation |
| FTA | Fault Tree Analysis |
| PDF | Probability Density Function |
| MCM | Monte Carlo Method |
| Organizations and Regulations | |
| IMO | International Maritime Organization |
| SOLAS | Safety Of Life At Seas |
| CII | Carbon Intensity Indicator |
| EEXI | Energy Efficiency Existing Ship Index |
| ETS | Emissions Trading System |
| GHG Emissions | Greenhouse Gas Emissions |
| BV | Bureau Veritas |
| OREDA | Offshore and Onshore Reliability Data |
| IEEE | Institute of Electrical and Electronics Engineers |
| NPDR | Nonelectronic Parts Reliability Data |
| EIREDA | European Industry Reliability Data Bank |
| IAEA | International Atomic Energy Agency |

| Symbols | Definition |
|--|---|
| Reliability and Probability Symbols | |
| R(t) | Reliability Function |
| λ | Failure Rate |
| μ | Repair Rate |
| β | Shape Parameter in Weibull Distribution |
| θ | Scale Parameter in Weibull Distribution |
| A | Availability |
| t | Time |
| System Configuration | |
| E_i | Individual component in a Reliability Blocks Diagram |
| n | Total number of components in a system |
| k | Minimum number of components necessary for System Success in a k-out-of-n logic |

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1

Introduction

1.1 Background

As the maritime regulation bodies push for reducing greenhouse emissions to comply with environmental regulations, industry tries to adapt to it by reducing the ‘safety buffer’ of installed power [1], finding higher density energy sources, optimizing fuel consumption or reducing ship design speed [2]. Specifically, the enforcement of CII, EEXI, and the ETS penalize high installed power and fuel inefficiencies. To comply, modern vessel designs move away from oversized engines to power optimized conventional layouts or flexible configurations. Consequently, this regulatory pressure reduces the historical safety buffer, introducing the need to assess reliability to ensure that safety is not compromised while trying to reach environmental compliance.

According to IMO Regulations, specifically **SOLAS II-1 26.2 and 26.3**, the reliability of single propulsion components must be considered, and to ensure sufficient navigable speed, a separate source of propulsion might be required, especially in the event of unconventional propulsion configurations. For this reason, the reliability and availability— defined as a situation in which an item can perform a necessary function under appropriate conditions of use, assuming maintenance is performed at certain intervals — [3].

According to [4], diesel-electric propulsion systems are increasingly used in marine operations where safety and manoeuvrability are critical. Diesel-electric systems offer high flexibility, as multiple engines can be installed and operated as needed, allowing for enhanced **redundancy**. However, this redundancy does not automatically imply an increased operational availability, because as complexity increases, the number of single failure points may also rise [2].

1.2 Problem Definition

SOLAS is not clear when establishing requirements to calculate availability for unconventional propulsion systems. **SOLAS II-1 26.2** says: The Administration shall give special consideration to the reliability of single essential propulsion components and may require a separate source of propulsion power sufficient to give the ship a navigable speed, especially in the case of unconventional arrangements. Then regulation **26.3** adds: means shall be provided whereby normal operation of propulsion machinery can be sustained or restored even though one of the essential auxiliaries becomes inoperative. However, the Administration, having regard to overall safety considerations, may accept a partial reduction in propulsion capacity from normal operation.

It can be extracted from this that configurations that have **single essential propulsion components** should be especially considered when calculating availability. This can be identified as single points of failure, which unavailability could compromise operations.

Then, to ensure sufficient navigable speed, a **separate source of propulsion** may need to be installed in the case of unconventional arrangements. This directed the idea to analyse redundancy in propulsion components or to consider newer propulsion technologies as diesel-electric arrangements, dual fuel engines, hybrid systems with battery packs or alternative propulsion among others. Diesel propulsion with redundant essential propulsion components can be considered an unconventional arrangement and therefore, its availability could be studied. While complex configurations introduce an increased number of components—potentially leading to an increased failure rate—they also incorporate redundancy. Therefore, understanding the **link between redundancy and availability** is essential to ensure the safety of operations.

The concept of **reparability** is also included, leading us to consider availability instead of reliability. It is mentioned that if essential propulsion components and **essential auxiliaries** operate normally or their operation can be restored, a partial reduction in capability is permitted. What a partial reduction means remains unclear and opens a door for future research to be more precise on minimum required availability and establish criteria for accepting reduction in propulsion capacity.

These regulations allow the problem to be addressed from multiple perspectives. It is possible to analyse to which extent installed power can be tightened while maintaining minimum availability. It is also possible to study the reliability of single essential propulsion components to ensure sufficient navigable speed. Non-conventional configurations can be investigated, ranging from diesel-electric propulsions to cutting-edge technologies, such as fully electric battery-powered vessels.

1.3 Research Questions

Based on the objectives of the thesis, the main research question is formulated:

To what extent do current maritime regulations ensure sufficient availability across different propulsion configurations, and how can ship powering systems be optimized to balance the conflicting demands of regulatory safety compliance, investment and maintenance costs, and energy efficiency?

To answer this question, the following sub research questions need to be answered:

1. What methods have been used to assess availability of marine propulsion systems, and how do they account for redundancy in propulsion components?
2. How do different marine propulsion configurations compare in terms of reliability using SOLAS II-1 26.2 as a compliance benchmark?
3. What inconsistencies exist in current regulations regarding availability requirements for different technologies, and how does this affect system design optimization?
4. How does the reliability of individual systems influence the general propulsion availability and where is the equilibrium point between redundancy and its effect on cost, reliability and safety as defined to comply with environmental regulations?

These questions allow the flow of this project, starting with an evaluation of the State of the art in reliability and availability calculation methodologies for marine propulsion. This review evaluates how current literature studies redundancy in different system configurations in balance with costs and environmental efficiency.

The goal of the second research question is to analyse if an increase in redundancy of the selected propulsion configurations has a direct relation with an improvement of availability, or if the regulations are overdemanding in low-impact areas.

The third question aims to evaluate if the current regulations are being inconsistent while demanding the same level of redundancy assuming technological neutrality.

The last question intends to give insight into design optimization, finding the most critical systems that have the highest effect on system availability and finding a balance in the constraints of design.

1.4 Scope and limitations

The following literature review will be used to further scope the problem. However, there are some limitations that can be established from the beginning:

1. Data Uncertainty

- Generic databases will be used to obtain reliability and availability values. These values may not reflect the exact component analysed and may not consider the operating profile of the vessels.

2. System boundary definitions

- **Exclusion** of auxiliary systems: as the focus of the study is the propulsion system of the vessels, only components that directly affect the sustention of propulsion will be included, ignoring systems as the HVAC, hotel system, starting air or engine room ventilation, even though they could have indirect repercussions.
- **Propulsion configurations:** the study will be limited to two different configurations that will be selected along this project considering their relevance in current fleet.
- **Fixed operational profiles:** a transit profile will be considered, ignoring manoeuvring or different sea states that can affect the engine load and their actual reliability.

2

Literature Review and State of the Art

2.1 Marine Propulsion Systems

In order to comply with IMO greenhouse gas (GHG) emissions regulations, the current trend is to design ships with alternative propulsion as battery/hybrid vessels, LPG, ammonia driven engines, being LNG the leader of this transition. Nevertheless, the current fleet and the order book is more than 90% formed by diesel propulsion vessels [5]. Therefore, there is still a strong necessity to study conventional configurations, accounting as well for the reduction in installed power, that reduces the safety power buffer that was applied in the past.

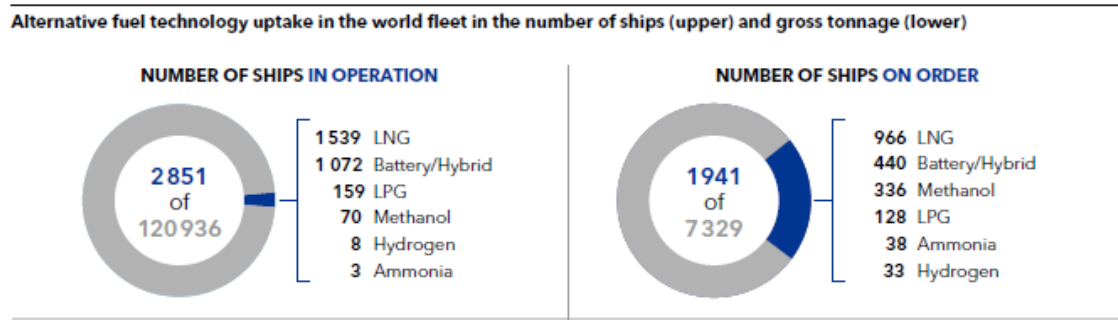


Figure 1. Alternative fuel technology uptake in the world fleet in number of ships [5]

2.2 Reliability Engineering Fundamentals

In order to analyse the quality level of a product or in this case, a system, qualitative and quantitative analysis can be performed. To mathematically measure the quality of these

systems, time dependent factors as reliability, maintainability and availability are introduced.

2.2.1 Reliability parameters

Reliability is in essence the probability of an item to perform its required function in a set time interval, under certain operating conditions [6]. Later on, the necessary boundary conditions will be established such as load profile, area of navigation or vessel mission and the systems and subsystems configurations will be modelled. **Reliability** will tell us how long it takes for the system to fail, considering that reparations are not accounted for. In this case, the system is as strong as its weakest element, assuming that it is a single point of failure. This introduces us to the concept of **Mean Time To Failure (MTTF)** that is defined as the expected time between two successive failures when the system cannot be repaired. It considers that components can have different types of degradation which will reduce the reliability value.

$$MTTF = \int_0^{+\infty} R(t) dt$$

Equation 1. MTTF obtained from integration of Reliability function

From this we can deduce that the MTTF represents the area under the reliability function, commonly expressed in hours [6].

The **failure rate** is a measure of failures that occur in a given interval of time conditioned by the fact that the system has survived until then. A failure rate of 0.01 at 100 hours means that a system that survives to 100 hours has a probability of 1% of failing in the next hour. Depending on the system, that gives us an indication on how reliable the system will be in the next period of time and allows to develop a predictive maintenance plan [7].

Maintainability indicates the ability of an item to continue in acceptable conditions of use, or be able to return to that point. This concept is linked to **Mean Time To Repair (MTTR)** bringing the idea that the system is repairable. Therefore, reliability is not the appropriate concept anymore. In this case **availability** is a concept that includes the downtime of items and their ability to be repaired. It will tell us which percentage of the time the system is functioning, against the time that is being repaired or waiting for reparations.

$$A = \frac{MTBF}{MTBF + MTTR}$$

Equation 2. Availability equation

2.2.2 Failure distribution models

Failure rates follow different distribution models, being the most widely known the bathtub curve.

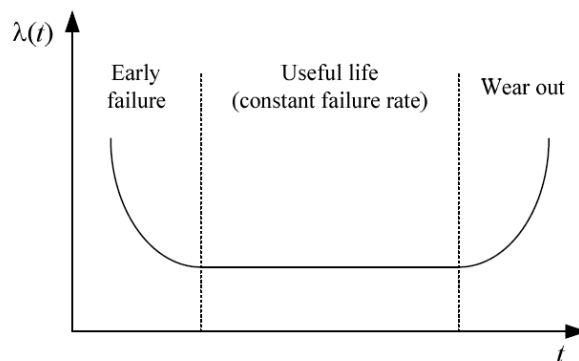


Figure 1. Bathtub curve

This representation is characterized by three phases:

- After the start of the items life cycle, a **high failure rate** decreases rapidly over time. This is related to early life failures that are fixed, increasing the time between failures.
- At the end of this region, the failure rate will **stabilize**. Failures are not predictable anymore and will follow random patterns.
- The final region is the **wear-out phase** where failures are attributed to age and wear of components. To reduce the rapid increase of failure rate in this area, periodic predictive maintenance can be carried out or replacement of elements can be considered, increasing the availability of the system [6].

There are other distribution models and in order to properly characterize the system, each individual component needs to be assigned a failure distribution. Among others, the ones that will mainly be used to model the propulsion system of a vessel will be:

- **Exponential law**: it follows the behaviour of the constant-region of the bathtub curve where failures are random and assumes that a component has the same probability of failing in the next hour as it had in the previous one.

$$R(t) = e^{-\lambda t}$$

Equation 3. Exponential Reliability Equation

$$MTTF = \frac{1}{\lambda}$$

Equation 4. MTTF Equation [7]

This distribution is characterized by one positive scale parameter, the failure rate λ . It also shows how the MTTF increases as the failure rate increases its frequency.

- **Weibull distribution:** to overcome the restrictive assumption of the exponential law about the constant failure rate the Weibull model is applied. It better describes the infant mortality phase of components or systems in function of three parameters: θ parameter of scale known as characteristic life and β being a form parameter. When $\beta > 1$ it indicates the system's failure rate is increasing, when $\beta < 1$ it is decreasing.

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^\beta}$$

Equation 5. Reliability of a Weibull Distribution

Failures can be classified according to the cause of their occurrence: [6]

- **Early life failures:** generally attributable to weaknesses during construction and that can usually be identified during manufacturing.
- **Wear out failures:** degradation generally occurring with the passage of time.
- **Random failures:** due to uncontrollable or unknown factors, their probability is independent of time.
- **Misuse failures:** caused by stresses applied when the element capabilities were exceeded.

Finally, we can differentiate between primary and induced failures. Being the first ones caused by the element itself, and the second ones attributable to the failure of another component.

2.3 Prior Research Analysis

This chapter aims to answer the first research question:

What methods have been used to assess availability of marine propulsion systems, and how do they account for redundancy in propulsion components?

In order to perform this state of the art, a systematic search has been carried out and divided into four categories: regulations, propulsion configurations, availability models and optimization. For this purpose, relevant keywords have been defined for each category:

- **Regulations**
 - SOLAS II-1 26.2 and 26.3
 - IMO Regulations
 - Redundancy requirements
- **Propulsion configurations**
 - Marine propulsion configurations
 - Diesel-electric propulsion systems
 - Ship powering systems
 - Propulsion redundancy
- **Availability models**
 - Propulsion system availability
 - Marine system reliability assessment
 - Probabilistic availability analysis
- **Optimization**
 - System design optimization
 - Redundancy optimization
 - Safety-cost equilibrium

These keywords have then been introduced to databases as Google Scholar, TU Delft Repository, Science Direct, ResearchGate, or the Bureau Veritas regulatory database VeriSTAR Regulations, among others.

The search was focused on scientific papers, technical standards and specialized books, which were then classified into one of the four categories previously mentioned. The initial search collected around 50 documents. After an initial filtering by document type (books, international rules, technical papers), publication year (2000-2025), and direct relevance to marine propulsion availability, the number was reduced to 10. These papers provide information about RAM analysis, different propulsion systems, impact of redundancy on availability and probabilistic methods. **Annex C** presents a summary of the **main research articles** considered in this thesis mentioning the publisher, the methodology used and the key findings and their relevance for this project.

The traditional approach of using deterministic models to calculate system's availability provides useful insights to understand the robustness of the configuration. Nevertheless, the intricate relations between components and subsystems in the propulsion architecture of vessels requires a model that accounts for maintainability and redundancy of elements.

[6] provides **fundamental reliability and availability concepts** as well as deterministic calculation models that will allow to choose the more appropriate one in the case of study.

Furthermore, it includes information on the physics of failure. Information regarding parametric reliability models will be useful when intended to refine the availability analysis, for example the application of Weibull distributions that represent more realistically the behaviour of elements such as pumps, engines or mechanical systems in general.

[8] carried out a **RAM analysis** (Reliability, Availability, Maintainability) on the propulsion system of a fleet with ten years of failure data. This project is particularly relevant to the present thesis, as it employs the same deterministic foundation that will be used to obtain typical reliability values. Furthermore, it sets a base for connecting availability analysis with system safety considerations, which this thesis aims to further develop considering a probabilistic framework.

[9] made a cost, emissions and risk comparison between diesel, diesel-electric and hybrid propulsion. It gives insight into relevant **marine propulsion configurations** considering the relevance, flexibility and sustainability factor.

[10] studies redundancy designs in order to find the highest level of reliability of a vessel power plant, providing insights into maintainability and reparations as strategies to reduce costs.

In the work of [11] **Monte Carlo Method (MCM)** is used to prove that it is not sufficient to perform an analytical evaluation of the propulsion system analysed and that a stochastic approach captures better the probabilistic characteristics of components. This supports the idea that a probabilistic model is necessary to evaluate different redundancy levels to calculate system's availability.

[12] studied the reliability of an electrical power grid considering probability distributions of component failure and repair data applying **exact and probabilistic** calculations methods. An importance measure analysis is performed to highlight which event's improvement would reflect into the highest system improvement.

A "**Probabilistic Availability Analysis** for Marine Energy Transfer Subsystem Using Bayesian Network" has been developed in [13]. This paper captures the probabilistic nature of failures and considers environmental and operational variables. It provides valuable insight into dynamic modelling and reflects the advantages that BN have in reflecting the relations between components. On the other hand, it can be highly complex if the system has numerous elements. A sensitivity analysis is also carried out in order to relate maintainability with the highest availability value.

[14] uses a **Discrete Event Simulation method** to assess the reliability and availability of manned and unmanned vessels. This method offers a more realistic operation scenario, reducing the number of assumptions used as it considers operational conditions, repairable components and maintenance actions. Common cause failures are presented as a drawback originated as system complexity increases.

[15] study the impact of dependent and independent failures in manned and unmanned vessels, stating that reliability can be increased by increasing **redundancy**. The data source of their calculations has been OREDA, an Offshore Reliability Database which is the most comprehensive resource of reliability data in the maritime sector. Even though offshore structures and ships are different, the equipment used in their machinery system is similar or even identical, making it reasonable to extrapolate information.

[16] studied the reliability of marine propulsion systems with varied **levels of redundancy** investigating the probability of failures over time under different architectures.

Literature shows that different methods have been applied to assess availability and reliability of propulsion systems. [6] and [8] introduce reliability concepts and RAM analysis, providing a valuable baseline. It also identifies critical components but does not get in depth into the effects that stand-by components have in system reliability.

Probabilistic methods such as Monte Carlo simulations and Bayesian Networks have been used in [11] and [13] to capture the variability of external factors such as weather conditions or speed, although they focus their study on subsystems or experimental setups rather than on full propulsion configurations.

[9] and [10] present relevant marine propulsion systems and redundant structures, accounting for the fact that parallel configurations increase global availability as the system only fails if both elements fail.

[14], [15] and [16] study the effects of redundancy into system availability however, they assume constant failure rates where other distributions would fit the reality more accurately.

In conclusion, as it has been seen in these projects, reliability has been widely studied using deterministic methods that can show the robustness of a system. These methods though do not account for the reparability of the components of the propulsion system therefore, probabilistic models take place. Monte Carlo Models, Bayesian Networks or Discreet Event Simulations are methods to assess reliability that allow to model more complex structures that include redundant components. They use exponential distributions for the different elements while this cannot always be the most accurate distribution. This is what this thesis intends to, **analyse complex models being accurate on the characterization of the components assigning the proper probability distribution**, and accounting for the redundancy of components that translates to parallel or k-out-of-n structures. These will ideally increase the global reliability as more paths to

success exist. This statement will be validated as some studies presented the idea that redundancy adds complexity and unexpected failures may occur.

2.4 Gap in Knowledge

The literature review presents a robust foundation for the reliability and availability analysis in the maritime sector. Nevertheless, several gaps have been identified relative to non-conventional propulsion systems and the integration of realistic distribution failure rates. The following gaps justify the necessity of this research:

- **Over Simplification of Failure Distributions**
Previous studies [14], [15] and [16] use a mathematical simplification repeatedly using exponential distributions to characterize the system's components. This approach is convenient to perform a RAM analysis but fails to capture the complexity of elements such as pumps or engines, that are subject to aging and wear and tear. This introduces a clear need to evaluate availability assigning more accurate failure models.
- **Lack of System Level Probabilistic Analysis**
Current research focuses on analysing the reliability of specific subsystems or applies deterministic models that neglect maintainability and repairability. MCM and Bayesian networks have been explored but they have not been used to perform a comparative between different propulsion configurations. There is also a lack of understanding on how different levels of redundancy (series, parallel, k-out-of-n) affect global availability.
- **Influence of Individual Component Reliability on Global Design**
While considering the whole propulsion system of a vessel, there's still some lack of knowledge regarding the sensitivity of individual propulsion components' availability. An accurate study could be made on single points of failure and the reliability importance that all elements have in the whole system's availability.

This thesis will address this study opportunities focusing on evaluating availability assigning accurate distribution models and considering different levels and types of redundancy. Furthermore, it will finally, identifying and evaluating critical elements and their importance in the final availability.

3

Methodology

To address the gaps identified in the previous section, this research proposes the following methodology that has been condensed in a flow diagram. This systematic workflow ensures that the study is replicable and provides a solid foundation to evaluate reliability and availability in propulsion systems, addressing the regulatory and methodological gap that has been found in the previous section.

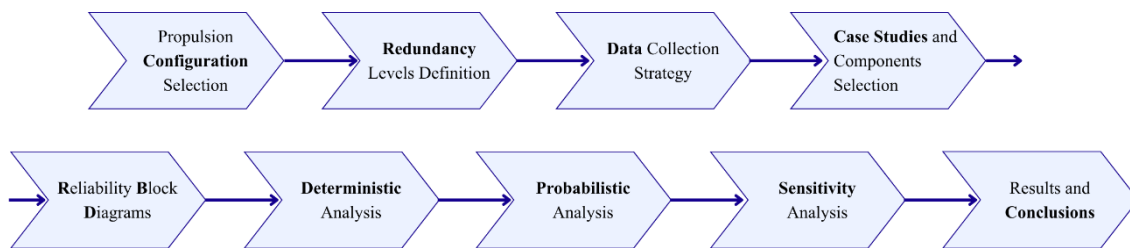


Figure 2. Methodology process

The following sections will include a study of the available quantitative methods that can be used to assess reliability. The analytical and the probabilistic methods will be applied using an implementation tool selected at the end of this chapter.

3.1 Quantitative methods selection

3.1.1 Analytical methodologies

Literature [6], [15] and [13] suggests that deterministic methods are a first step to assess reliability. However, these methods are often insufficient and to obtain more conclusive results, an integration with probabilistic methods to capture failure and repair randomness is necessary.

Deterministic models typically consider the aforementioned concept of MTTF to calculate reliability through the analytical application of Reliability Block Diagrams

(RBD) and Fault Tree Analysis (FTA). These calculations assume mean and constant failure $\lambda(t) = \lambda$ and repair times $\mu(t) = \mu$ [3], following an exponential distribution.

[6] and [17] recommend the combination of closed-form formulas with RBD for the speed of implementation and an intuitive visual representation.

As previously discussed, analytical methods provide a fast and clear analysis of reliability in propulsion systems. Their disadvantage lies in their limitations and the rapid increase in complexity as systems include fewer simple configurations as parallel, k-out-of-n, or dependencies. At this point, analytical calculations become very complex, requiring a more powerful computational approach. This allows for results capable of handling larger amounts of data and configurations.

3.1.2 Probabilistic methodologies

As mentioned previously, deterministic methods provide a baseline to assess availability but fail in capturing the variability of failures [18] and get too complex to solve when redundancies and parallel or other configurations are introduced. To overcome these limitations, probabilistic methods such as Monte Carlo simulations, Markov Chains, Bayesian Networks or Discrete Event Simulations have been applied in literature [19], [20], [13] and [21].

Monte Carlo Simulations are a scientific tool to solve complex problems that are analytically intractable as they are too time-consuming, costly or impractical. In general terms, they require to model the system as probability density functions that will be repeatedly sampled in order to obtain results. Some of the disadvantages are that they are computationally intensive, they do not provide exact answers and that the results are only as good as the model and inputs used [18].

A second method are **Markov Chains** that represent systems as a set of discrete events. They are suitable for failure and repair rates that follow exponential distributions but have a limited applicability as their complexity grows rapidly when the number of components increases [20].

Bayesian Networks are probabilistic models useful for systems where dependencies between components are a key element. They could be an ideal model for systems with continuous operation as DP vessels, providing useful outputs when historical data is limited. Nevertheless, they require some expertise in modelling, obtaining uncertain results when dependencies are not properly introduced [13].

Discrete Event Simulation (DES) is another approach that represents chronologically failures, repairs and maintenance activities. It is a very detailed model that moves across change of states, representing highly realistic scenarios as can be seen on [21], where

availability is assessed between manned and unmanned vessels. As can be seen in this paper, DES captures dynamic interactions providing valuable insights into long-term availability, although being highly time-consuming and detailed.

The **selection criteria** for the most suitable probabilistic method are going to consider timeframe and scope of this thesis, data available and complexity of the system to model. Therefore, Discrete Event Simulation and Bayesian Networks will be discarded as they do not fit within the timeframe requiring an expertise in modelling not yet acquired by the author.

Monte Carlo Simulation seems the best candidate as it allows to model different architectures with different redundancy levels by simulating random failure and repair events over a mission timeframe. It also complies with one of the objectives of this thesis, model components with the most appropriate probabilistic distribution, which may differ from exponential. Some of the **outputs** that can be obtained will be mean availability vs redundancy level for each architecture, to understand how redundancy increases or reduces availability.

In general terms, Monte Carlo simulations follow three basic steps: [19]

- **Model the system** as a probability density function (PDF).
- Repeatedly **sample** from the PDFs to simulate multiple vessel life-cycle iterations to account for the randomness of mechanical failures and repair durations.
- Compute the **statistics of interest** such as average availability, downtime distribution or confidence intervals.

There are several tools available for the implementation of the Monte Carlo Simulation Method (MCM). Some options will be compared considering availability of software, learning curve, replicability for transparency, and flexibility to be able to include various configurations.

Table 1. MCM Implementation Options

| Tool/Software | Availability of software | Learning curve | Replicability | Flexibility | Output |
|-----------------------|---|--------------------|----------------------------------|----------------------------------|--------|
| Excel | + | - | + | - | - |
| Python | + | + | + | + | +/- |
| MATLAB | + | + | + | + | +/- |
| AnyLogic | - | - | +/- | + | + |
| ReliaSoft BlockSim | - | - | +/- | + | + |
| | +: open source, available -: commercial, expensive | -: low +: steep | +: high +/-: medium -: low | +: high +/-: medium -: low | |

Due to the limited time available for this thesis, the **learning curve** is a crucial criterion to consider. As none of the evaluated tools has been extensively used before, **AnyLogic** and **ReliaSoft BlockSim** have the advantage to offer a very visual interface, where systems and elements can be modelled as interconnected blocks.

Furthermore, this type of software provides automatic graphical representations as FRED (Failure Reporting, Evaluation, and Display) Reports, and combined reliability and availability curves diagrams, among others. These advanced **outputs** can be obtained with no coding effort as Python or MATLAB would require.

In contrast, while **Python, Excel and MATLAB** offer high **replicability** as the developed scripts can be easily shared and reviewed, they require a more intensive coding effort to achieve the same level or architectural detail.

MATLAB is widely available in academia although it remains a commercial tool, as it happens with **AnyLogic** and **ReliaSoft**. This perk is palliated by the availability of trial versions to validate results.

Ultimately, considering all previous criteria and the aim to provide valuable results as well as visual and clear representations of those, **ReliaSoft BlockSim** has been selected. Access to the software has been facilitated by the owner company **HBK Hottinger Brüel & Kjær**, allowing to model complex and redundant structures within the same

environment. It also provides a single platform to model the Reliability Block Diagrams as well as to obtain the analytical and probabilistic results intended.

Preliminary testing of the software demonstrated that ReliaSoft BlockSim is a powerful tool to provide advanced outside beyond basic metrics. One example is the importance analysis which provides the weight each component and system has in the final reliability result. Another example is the allocation analysis which recommends system modifications to achieve a goal reliability value [7].

4

Model Architectures

This section aims to bridge the regulatory gap identified in SOLAS II-1 26.2 and 26.3 by analysing the availability of single essential propulsion components and essential auxiliary systems, specifically considering unconventional designs and configurations.

The starting chapter includes the study and selection of representative propulsion arrangements, followed by the definition of the redundancy levels that will characterize each vessel's architectures. An introduction to the selection and use of the reliability modelling framework will be included as well as the data collection strategy. The final step of this chapter will be a study of the available analytical and probabilistic models to select the most suitable for this project, followed by an introduction to how to model the propulsion systems with the selected deterministic and stochastic methods.

Chapter 5 will select the **case studies** and will do an analysis of the relevant systems and subsystems that are within the scope of this project.

Chapter 6 aims to perform the **analytical calculations** to obtain insight into the robustness of the systems and compare them.

Chapter 7 will start with a theoretical framework of the **probabilistic model** used, followed by the execution of the simulations and concluding with the validation of the results.

A comparison of the **results and a sensitivity analysis** will be included in chapter 7 to obtain insights into element relevancy, aiming to compare configurations and highlight the most critical components, among additional discussions.

The **conclusions and recommendations** for the industry and future work will finalize this master thesis.

4.1 Propulsion configurations selection

4.1.1 Existing Propulsion Configurations

Marine propulsion systems refer to the technology that propels water-borne vessels through the water. These systems apply force on the surrounding water to create a reaction force that pushes it in the required direction [22].

In order to calculate availability on propulsion systems, the primary propulsion configurations are introduced [23], [2], [9], [24] and [25].

- Internal Combustion Engines (ICE)
 - a. **Conventional Diesel Engines:** the industry standard configuration.
 - b. **Dual Fuel Engines:** systems capable of burning traditional fuels as well as alternatives such as LNG, hydrogen, methanol or ammonia.
- Turbines
 - a. **Steam Turbines:** historically relevant, its use has reduced significantly in the past decades. Still used in specific applications as LNG carriers or ice breakers.
 - b. **Gas Turbines:** reliable system with a low weight to power ratio.
- Electric and Hybrid systems
 - a. **Diesel-Electric Propulsion:** flexible system demanded on vessels with variable power demands.
 - b. **Hybrid with Batteries:** combination of conventional engines with energy storage that accounts for peak shaving conditions and emission reduction.
 - c. **Battery Electric:** zero-emission systems that rely entirely on battery packs for the vessel's propulsion.
- **Fuel Cells:** zero-emission alternative that converts hydrogen or methanol into electricity with a high efficiency.
- **Nuclear Propulsion:** based on onboard reactors that generate heat, creating steam to drive turbines for propulsion.
- Alternative Propulsion
 - a. **Wind Assisted Propulsion:** technologies that convert wind into thrust to ease the load on the main engines.
 - b. **Solar Photovoltaic System:** uses solar panels to convert light into direct current.

The diversity of propulsion systems above described shows the complexity of modern maritime transport industry. ICE and turbines have been widely used and follow known reliability standards. Nevertheless, newer arrangements as electric or wind assisted propulsion, have introduced new failure modes and uncertainty in their pursue of reducing greenhouse emissions.

From an availability perspective, hybrid and alternative propulsion systems have introduced more complex configurations as the system is not purely mechanical but

electrical and chemical power sources have to be integrated. Consequently, as seen on [26], there is a lack in standardization for sufficient propulsion reliability, especially in the case of unconventional arrangements. This justifies the necessity to evaluate availability of both traditional and unconventional propulsion systems.

4.1.2 Assessment criteria

The configurations selected will need to represent widespread technologies as well as systems with future relevance and enough technological maturity. They will also have to represent different architectures for comparison reasons and have enough failure data in order to perform availability calculations. Another factor to consider is the environmental aspect where emission reduction technologies play an important role [27]. Finally, as mentioned in SOLAS II-1 26.2, unconventional configurations need to be considered.

Table 2. Criteria for propulsion configuration selection

| Assessment criteria | |
|---|-----------------------------------|
| Failure data available | Redundancy applicability |
| Technological maturity | Complexity of system architecture |
| Representativeness in the current fleet | Future potential |
| Environmental consideration | |

Taking into account the criteria required and considering the availability of failure data as the most important factor, diesel conventional propulsion will be used as a benchmark. The main drawback this architecture presents is the applicability of redundancy, as for configurations that require several numbers of propulsion lines this has space and distribution limitations [28]. Nevertheless, redundancy can have different forms and [10] gives us a clear example in their case study on functional redundancy.

Diesel-electric propulsion has a higher flexibility, which allows to assess how availability varies along an increased redundancy [29].

Considering the previous criteria, some configurations can be discarded as the alternative propulsion (wind assisted and solar photovoltaic) since it is currently used as an auxiliary source of energy and not as the main one. Nuclear power is also discarded as there is a lack of reliability data available and it presents limited future potential due to safety, ethics and social acceptability [2].

Steam turbines have lost relevance in favour of diesel engines due to their reduced efficiency, and gas turbines are currently used in specific applications such as warships and very-high power generation cases therefore, failing in representativeness in the current fleet. The same happens with full battery propelled vessels, where only a few

examples can be found [30]. Therefore, technological maturity and representation in the fleet are very limited, not complying with the criteria for selection in this project. Hybrid propulsion with batteries presents similar challenges but as it contains diesel-electric propulsion and it has a higher representation in built vessels, failure data is easier available [31]. There is extensive literature written on fuel cells, but commercial application is very limited on maritime power supply [32], compromising the failure data available.

Finally, only one configuration is left: dual fuel engines using LNG, ammonia, methanol or hydrogen among other as fuel. The main drawback of this configuration is that the focus of study should be the engine itself instead of the whole propulsion, as intended in this project.

The next chapter performs a criteria assessment to choose the two most suitable configurations according to the selection metrics.

4.1.3 Final selection

The configurations that remain after the initial screening are the conventional diesel engines, diesel-electric propulsion and hybrid diesel-electric with batteries arrangements. The following table intends to assess these configurations according to the selection criteria to select only two.

Table 3. System assessment according to criteria

| Criteria | Propulsion configurations | | |
|---|---------------------------|-----------------|-----------------------|
| | Conventional Diesel | Diesel-electric | Hybrid with batteries |
| Failure data available | +++ | ++ | + |
| Technological maturity | +++ | ++ | + |
| Representativeness in the current fleet | +++ | ++ | + |
| Environmental consideration | + | ++ | +++ |
| Redundancy applicability | ++ | +++ | +++ |
| Complexity of system architecture | + | ++ | +++ |
| Future potential | ++ | +++ | +++ |

+ / ++ / +++: Low/Moderate/High Compliance

The final choice has been a propulsion system with a **conventional diesel engine** and a **diesel-electric configuration**. A traditional diesel configuration allows to identify basic components and provides a threshold for comparison reasons. Diesel-electric systems will be used for its flexibility in varying load demand and for environmental considerations as they have a reduced installed power compared to conventional propulsion. This reduces greenhouse emissions, which aligns with the current emission reduction goals of IMO [33].

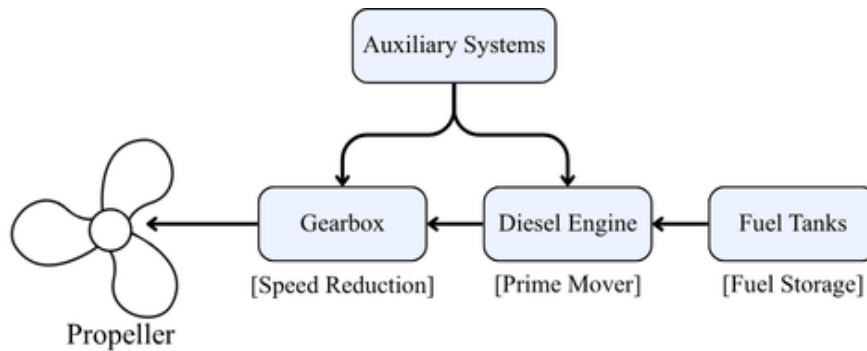


Figure 3. Conventional Propulsion Configuration

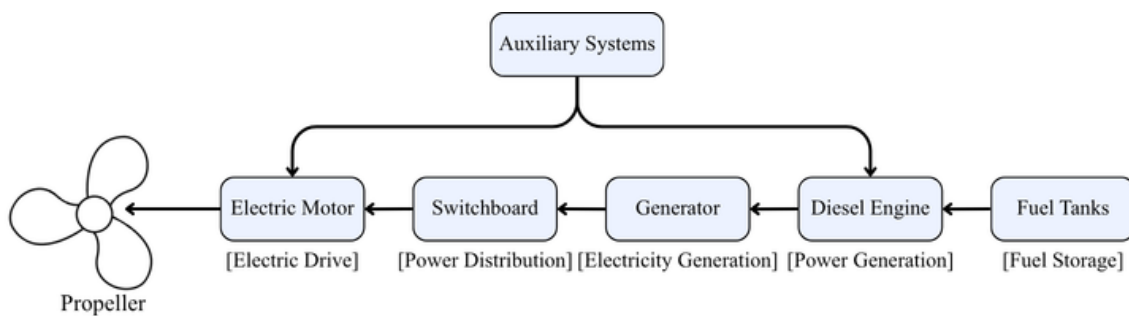


Figure 4. Diesel-Electric Propulsion Configuration

Figure 3 and Figure 4 represent the propulsion configurations selected with the main propulsion components as an initial definition of the boundaries that will be considered. When redundancy levels are defined, a complete representation of the diagrams will be depicted. The top picture represents the conventional propulsion and the second imagen corresponds to a diesel-electric arrangement.

4.2 Redundancy Levels Definition

This thesis aims to fill the gap that was left in **SOLAS II-1 26.2 and 26.3**. This regulation encourages the analysis of reliability for single essential propulsion components in order

to sustain propulsion even when essential auxiliaries become inoperative. In practice, essential auxiliaries tend to have redundant components to improve operability.

When analysing traditional propulsion, we will be studying vessels with only one main engine, therefore the redundancy will rely in the number of essential auxiliaries. The regulation provides a list of auxiliaries that require special consideration, mainly because they are in charge of sustain or restore propulsion.

The study of diesel-electric systems will focus on the functional redundancy of the electric distribution system. The details will be shown in the case studies.

Based on the aforementioned regulations, Arjen Alblas, one of the supervisors of this thesis, developed a framework that correlates different goal standard levels with categories that describe the propulsion system, such as the essentiality of the system and the redundancy of static components.

Table 4. Goal standard characteristics

| Goal standard | I | II | III | IV | V |
|---|-------------------------|------------------|-----------------|--|-----------------------------------|
| Service (under review) | Non-essential | ----- | | Essential | ----- |
| Failure occurrence probability | | Recurrent | Remote | | Extremely remote |
| Machinery equipment | No propulsion | Single equipment | Means | Redundancy in all propulsion equipment | IV and physical separation |
| Static components | -----No redundancy----- | | | Duplicate | Duplicate and physical separation |
| Minimum redundancy required regulations | | | SOLAS II-1 26.3 | SOLAS II-1 26.2 | IMO MSC/Circ. 1580 |

Level I represents an element that is not self-propelled and therefore, the type of propulsion and redundancy level rely on the element that generates the thrust. **Level II** reflects scenarios with single essential propulsion components and no redundancy in static components. **Level III** has been defined according to SOLAS II-1 26.3, that indicates that single essential propulsion components are not sufficient for the normal vessel operations and means for partial redundancy shall be provided. Static components

are not duplicated. **Level IV** includes redundancy in the machinery equipment as well as in the static components. **Level V** indicates the same level of redundancy as in level IV and includes the need for physical separation of static and active components.

The intended levels to study in this thesis are going to be **Level II and III**. They have been selected as they represent very common vessels in the industry as general cargo vessels or bulk carriers. When they are operating long-distances, the choice of propulsion tends to be diesel main engines. For shorter distances, diesel-electric propulsions are commonly installed for their flexibility and to comply with environmental regulations [33].

By focusing on these levels, the study ensures wide representation of the current fleet and ensures an availability comparison inside the same propulsion technology. This will be done horizontally and vertically. Assessing the differences in increasing redundancy for the same propulsion type will allow to evaluate the robustness of the system, while comparing availability between propulsion types allows to give insights into the most reliable between the two options. The application the propulsion system is intended for will determine the final selection, but this will allow to make more informed decisions.

Our initial hypothesis states that availability increases as redundancy becomes higher. This statement combined with the propulsion selection translates to the following table.

Table 5. Hypothetical availability behaviour across propulsion systems (+: low availability, ++: medium availability, +++: high availability)

| Goal standard level | Conventional Diesel Propulsion | Diesel-Electric Propulsion |
|----------------------------|---------------------------------------|-----------------------------------|
| II | + | ++ |
| III | ++ | +++ |

Table 5 introduces the four case studies that will be modelled in following chapters. These scenarios are designed to evaluate the impact of redundancy. In the case of conventional diesel propulsion, availability will be determined by the redundancy of auxiliary system components, such as electric motors, pumps or filters, among others... In contrast, diesel-electric propulsion introduces the concept of functional redundancy through the electrical distribution network and multiple generator sets [10].

4.3 Reliability Modelling Framework

As mentioned on [6], “the first step in evaluating a system’s reliability is to construct a reliability block diagram, which is a graphical representation of the components of the system and how they are connected” (p. 96).

The main benefits of using RBD are the ease to model large systems, considering reparation rates and the different failure and repair distribution models. Furthermore, it accounts for dependencies between components and allows to incorporate any system additions [34].

In the previous chapter, the **redundancy levels** have been chosen based on a regulatory gap and have provided guidance on the case studies that will be selected. The next step will include a **component selection**, either at sub-system or component level. It will be this project’s task to define when a subsystem availability configuration is sufficient to calculate global availability or when a more detailed analysis to a component level is needed. **Available data** is important in order to characterize the system in the most accurate way and the process of data collection will be explained in the next subsection. When this information is gathered, the process of modelling the RBD can start. The IEEE Gold Book standard network recommended the use of RBD to determine reliability and availability values from power systems, as will be considered in the vessel’s propulsion analysis [34].

There are basic parameters that need to be accounted when developing an RBD. Failure rate, MTTF and MTBF among other concepts have been explained in Chapter 2.2. The elements of the system are connected in three possible ways:

- **Series configuration:** represents the simplest and most common reliability structure in fields such as electronics and can be applied to the propulsion system of a vessel as some components present serial dependency. In a system formed by n elements E_i , with $i=1, \dots, n$, the system is operative if all the elements are functioning correctly [17]. One of the hypotheses of this thesis is that all elements are independent thus the failure of one does not increase the failure probability of another. Consequently, the total system reliability (and availability) is the product of the reliability of each single block. However, marine propulsion architectures exhibit different levels of redundancies, so purely series-configuration are insufficient to model the system.

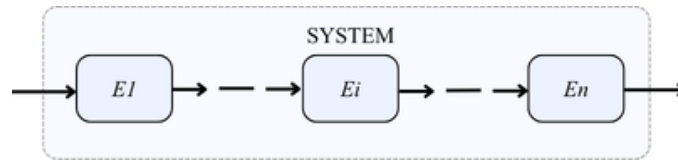


Figure 5. RBD for series system configuration [17]

- Parallel configuration:** also called redundant configuration or active redundancy, is the key to increase system's reliability when individual components redundancy is insufficient [6]. It allows the system to be operative when at least one of the components in parallel is functioning. As represented before for the series configuration, Figure 6 represents a RBD for the parallel configuration.

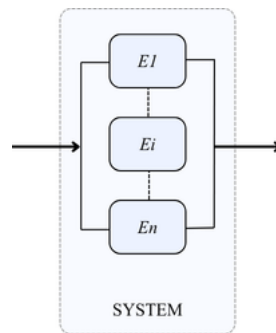


Figure 6. RBD for parallel system configuration [17]

The general idea with this type of redundancy is that the increased number of components increases the system's availability. However, this hypothesis needs to be evaluated for different scenarios as the spread of the failure of one component to another or single points of failure (SPOF) can modify the outcome. Another point to consider is the **repairability factor** which is different for mechanical and for electronic components. Traditionally, mechanical failures were fixed onboard when occurring, reducing the downtime as crew was trained to solve the problem and spare parts were available. Electronic or control failures are dependent on the owner of the software or the technical assistance of the manufacturer [15]. These systems have higher reliability values although the maintainability is lower. This issue can be seen in elements as the variable frequency drive (VFD) which are elements that control the speed and torque of electric motors. When this element fails, electric motors cannot perform their function and there is dependency on the manufacturer or a replacement, which can take hours or days. Therefore, availability must be analysed to evaluate whether the increased reliability of electronic components compensates for the increased MTTR. This will be done according to SOLAS II-1 26.2 where one requirement is to evaluate the function of redundancy in **restoring propulsion**.

The previously mentioned redundancy corresponds to what is called **active redundancy**. In this case, the redundant elements experiment the same load at all times. This is common for elements as the steering gear or Ethernet lines, where the load is 100% for both elements. Not all components work the same way; **warm redundancy** is another example of behaviour where all redundant elements are operating under a reduced load. This is common for centrifugal pumps, where if two are installed, they would be working at 50% of the load. If one would fail, the other one would assume the extra load to sustain the system. **Stand-by redundancy** or cold redundancy can be found in systems where one of the elements is under no load until the other one/s fails. Typical examples include starting air compressors and emergency generators [10].

- **k-out-of-n logic**: this configuration is applied in the diesel-electric propulsion configuration. While maximum speed is achieved when all generators are operational, SOLAS focuses on navigable speed, which reduces the number of active components required to k . Therefore, to have an operative system, at least a k number of elements out of a total of n have to be functioning normally. For a system like the one presented, k elements provide the required power, while the remaining units act as a safety margin in stand-by. Initially, this functional structure increases the system's availability, as multiple failures can occur before the vessel loses propulsion, but the spread of failures and common SPOF may cause a different outcome.

Finally, a model assumption is that the propulsion system will be modelled using **binary states**. Components are considered to be either fully operational or failed. Although degradation exists in real-world scenarios, it is excluded from this research as the primary objective is to evaluate system-level availability in the frame of SOLAS II-1 26.2, which focuses on sustaining propulsion rather than in analysing the effects of continuous wear or partial performance loss.

4.4 Data Collection Strategy

Failure rate data can be collected through testing or reporting from operations. Despite the long history of the shipping industry, there is no comprehensive and unified database of reliability for marine machinery systems. Even though there are differences between the machinery equipment used in offshore installations and in vessels, many of the equipment used in both industries is identical or similar. That is the reason why reliability data will be mainly obtained from **OREDA**, the Offshore and Onshore Reliability Database used in the offshore industry. This approach has been used in other studies

relating to ships as in [15], [35] and [36]. To be able to obtain this information, a partnership has been agreed between the author and OREDA. Specific reliability data from OREDA will not be revealed but statistical analyses and conclusions derived from it can be published.

To account for the difference in operational conditions, all information will be processed as OREDA does not provide a single reliability value but bounds. This uncertainty is solved by considering the uncertainty intervals provided. **Lower, mean and upper bounds** will allow to obtain the best, mean and worse case scenarios as will be shown in the sensitivity analysis [37].

For electrical components, the primary source used will be the **IEEE Gold Book**, that among other information it provides the reliability data needed [34]. This book though, considers failure and repair rates as exponentially distributed which is not always the most accurate description for all elements. As mentioned before, this thesis will apply as much as possible the failure distribution that fits better each individual element. Some electrical components that would benefit from a Weibull distribution would be generators or electric motors, which failure rate increases with wear-out.

Reliability values will be extracted from the previously mentioned databases although it will be critical to establish the **component boundaries** from where the data was obtained. Some datasets include elements as sensors and auxiliary or control systems. Others would exclude them and, in that case, it would be necessary to account for them separately. This consideration is relevant to avoid **double counting**, a failure in modelling that can reduce global availability.

The integration of this data into the model is the quantitative approach that will allow to achieve the primary objective of this thesis: provide an availability assessment that bridges the current regulatory gap in SOLAS II-1. To model the complex architecture of the propulsion system of a vessel and perform analytical and probabilistic calculations.

The quantitative method applied will be selected in the next section followed by a brief quick start guide on the most useful functionalities.

5

Case Studies

In this chapter several topics will be discussed. Starting by defining the **main functions** that want to be studied in the reliability analysis.

After that, the **systems and subsystems** that will be considered will be explained. This will be the structure of the diagrams without including specific elements yet but ensuring that the systems included are essential to comply with the main functions.

The third point will select the **study cases** based on the requirements previously mentioned of redundancy and propulsion type and some additional information as vessel type and excluded elements will be added.

The fourth subsection will clarify some **assumptions** that need to be accounted in the development of the RBD.

The next step includes the **components selection** for each case of study, giving insights into elements that have not been accounted and why, or the grouping of components in order to simplify the diagrams and avoid the previously mentioned double-counting of components. This will also allow to elaborate an element table to have an overview of the information that will be needed from reliability databases. As mentioned before, the reliability data obtained from OREDA is confidential and will not be revealed, but results and insights obtained from it will be presented.

Finally, the development of the **RBD** for each case can be made, using ReliaSoft BlockSim, and including all the elements and their relations. Detailed graphical representations of all systems and subsystems will be included in Annex A Detailed Reliability Block Diagrams

5.1 Main function definition

The principal function that is needed to evaluate is defined according to SOLAS II-1 26.2 and 26.3 [26]. It indicates that the **reliability of single essential propulsion components**

needs to be studied to maintain a **navigable speed**. This first part is what led to define level II of redundancy, considering conventional and unconventional arrangements as the diesel-electric propulsion.

The second part intends to assess the ability to **sustain normal operation of propulsion machinery** even when an **essential auxiliary** component becomes inoperative. This being analysed by incorporating **means**, that for this study are modelled as a second propulsion source, as will be represented in level III.

Some necessary assumptions are:

- **Partial redundancy:** full power is not required, only navigable speed, which indicates that partial reduction in propulsion capability is accepted.
- **Success criteria:** navigable speed is going to be considered as at least one propelling line functioning when two are installed, or full propulsion when one line is installed.
- **Exclusions:** the restoration of propulsion falls outside of the scope and therefore, the starting air system is not included in the study. The second exclusion is the exhaust system as it is a robust system with a low failure rate and its failure behaviour is predictable. It would be interesting to analyse if the system itself or the environmental regulations were the main focus.

These functional requirements establish the framework for the reliability models, considering different redundancy levels and two propulsion configurations. This will allow to assess how different propulsion arrangements cope with safety and operational standards. The following section will describe the systems and subsystems that will be considered and their role in the ship's propulsion.

5.2 Systems and Subsystems Definition

To reduce the complexity and provide clarity to the diagrams, the propulsion system is divided into five main functions:

- **Critical Auxiliary Systems:** formed by the essential auxiliary subsystems that maintain normal propulsion operations. These are: Fuel Oil Subsystem, Lubrication Oil Subsystem, Low Temperature Cooling Subsystem and High Temperature Cooling Subsystem.
 - **Fuel Oil Subsystem:** its main functions are storing, filtering, distributing, and supplying fuel oil at the required pressure to the prime movers using a configuration of redundant tanks, duplex filters and pumps.

- **Lubrication Oil Subsystem:** this subsystem provides cooled lubrication oil to components with friction as the main engine or the gearbox through a parallel configuration of mechanical and electrically driven pumps.
- **Low Temperature Cooling Subsystem:** this subsystem circulates fresh water through boxcoolers using pumps to dissipate thermal loads from machinery components and auxiliary heat exchangers.
- **High Temperature Cooling Subsystem:** system in charge of regulating the temperature of the engine using mechanical and electrical pumps.
- **Electrical Power Generation:** includes the elements necessary to generate propulsion as diesel generators and main switchboards in the diesel-electrical propulsion case. For the conventional propulsion scenario auxiliary generators will be considered as they are the source of power for electrical motors, electrically driven pumps and sensors and other essential elements.
- **Propulsion and Steering System:** consisting of the elements connected in the propulsion line and some essential subsystems that ensure the normal operation as the CPP Control Subsystem, the Stern Tube Lubrication Subsystem and the Steering Gear Subsystem.
 - **CPP Control Subsystem:** this subsystem manages the hydraulic oil pressure required to actuate and adjust the pitch angle of the propeller blades by means of startboxes and hydraulic power units.
 - **Stern Tube Lubrication Subsystem:** series configuration of oil tanks and seals that cools and lubricates the shaft bearing. Furthermore, it prevents the leakage of oil into the environment and the ingress of sea water into the system.
 - **Steering Gear Subsystem:** the main objective of this subsystem is to control the direction of the flap rudder by means of a dual-RAM hydraulic steering mechanism.
- **Control and Safety Devices:** this block will represent a combined failure rate of several elements as pressure and temperature transmitters for pumps or coolers, electrically driven control valves, quick closing valves, moisture sensors, mixing valves and PLCs among others.
- **Static Components:** includes elements as flexible hoses, rigid piping and non-essential tanks.

These five blocks shape the standardized basis for the reliability analysis, which will be applied in the next chapter to four propulsion scenarios. Although the connection between these systems and subsystems may vary across each case study, it will allow a consistent reliability assessment through the modelling with Reliability Block Diagrams.

5.3 Study Cases

Due to non-disclosure agreements, the specific identities of the vessels cannot be revealed. However, they have been selected according to the assessment criteria presented in section 4 and the redundancy levels defined in section 4.2 according to SOLAS II-1.

The nomenclature used to identify the study cases will be as follows:

Table 6. Study Cases Nomenclature

| | Diesel | Diesel-Electric |
|-----------|---------------|------------------------|
| Level II | Vessel A1 | Vessel B1 |
| Level III | Vessel A2 | Vessel B2 |

Each vessel represents the different configurations that are aimed to study as presented below.

- **Vessel A1**
General cargo vessel
 Conventional diesel propulsion
Main engine connected to a gearbox, shaft and CPP propeller
Short-sea operations
- **Vessel A2**
Tanker vessel
 Conventional diesel propulsion
2 main engines connected to their gearbox, shaft and CPP propeller
Short-sea operations
- **Vessel B1**
Multipurpose dry cargo vessel
 4 diesel generators
2 electric motors for propulsion connected to a gearbox, shaft and CPP propeller
 1 main switchboard with **closed bus tie**
Short-sea operations
- **Vessel B2**
Multipurpose dry cargo vessel
 4 diesel generators
1 main switchboard with **open bus tie modelled as two independent busbars**
 2 electric motors for propulsion connected to a gearbox, shaft and CPP propeller
Short-sea operations

The first category, **vessel A1 and A2**, focus on the **direct mechanical drive systems** where the prime mover is coupled to a CPP propeller via a gearbox and shafting.

The single screw configuration serves as a baseline to evaluate the studied SOLAS regulation. In this model, the main components of the propulsion line act as single points of failure. The failure of any of them results in a loss of propulsion.

Vessel A2 counts with two independent conventional diesel propulsion lines, each one with independent auxiliary systems. In this case, the success of the mission is defined as the success of any of the two propulsion lines, independently of the increased difficulty to navigate, which could be considered in future studies.

Case studies B present a different approach, with a main power plant formed by 4 **diesel generators**, that provide energy to a main switchboard. This element is in charge of distributing the energy through the entire propulsion system, and it is analysed in two ways.

First, case study B1 presents a normally closed (NC) bus tie, an element that connects the two busbars. It has been modelled as a single busbar, as it functionally acts as one. This means that failures can be propagated from one bar to the other. The success logic follows a 2-out-of-4 redundancy for power generation.

Study case B2 differs in considering an open bus tie, which results in two independent bus bars (A and B). Each bus bar is fed by two generators and powers one propulsion motor and one sub distribution board that moves the energy across the auxiliary consumers. The success of the mission requires only one bus bar and the essential propulsion elements connected to functions. This configuration increases the segregation and reduces common-cause failures as a failure on the main switchboard would be in this case.

5.3.1 Case Study A1

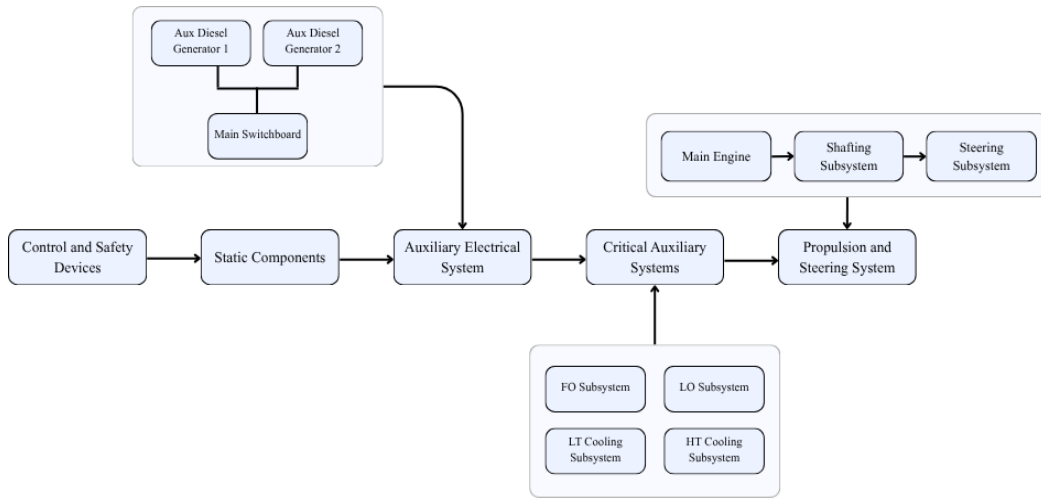


Figure 7. Main elements, systems and subsystems. Case Study A1

5.3.2 Case Study A2

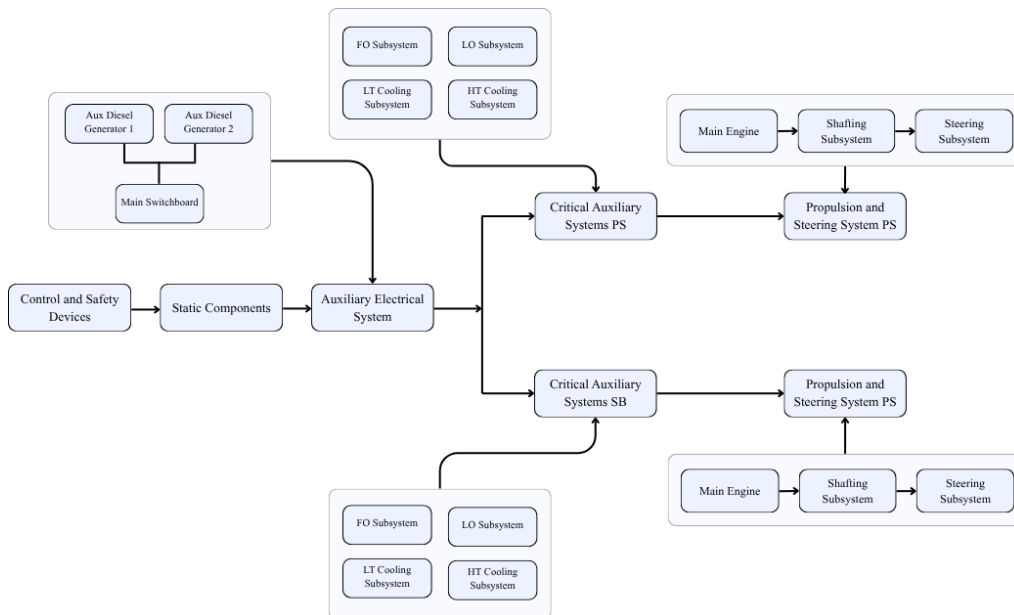


Figure 8. Main elements, systems and subsystems. Case Study A2

5.3.3 Case Study B1

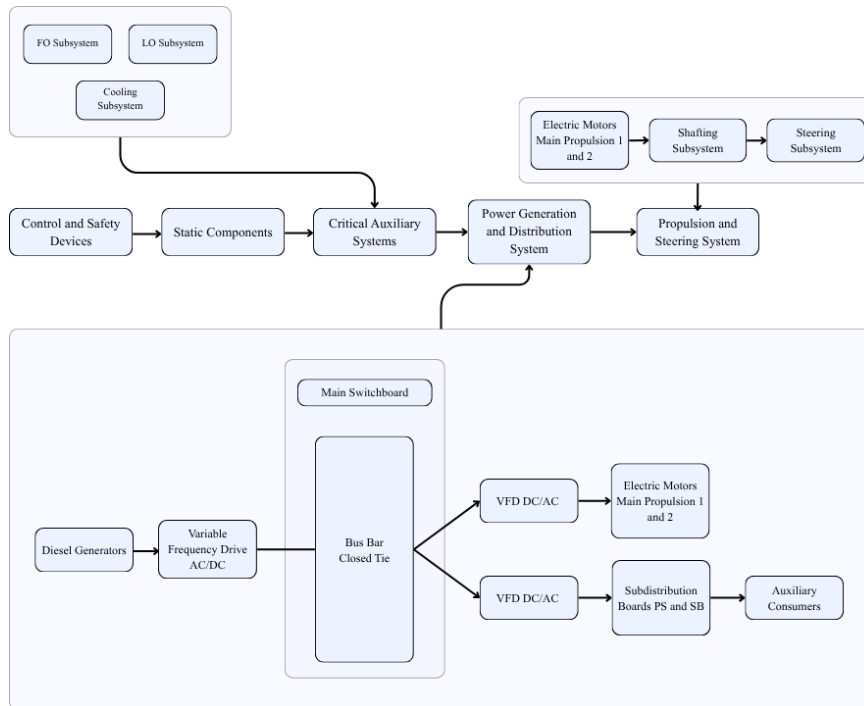


Figure 9. Main elements, systems and subsystems. Case Study B1

5.3.4 Case Study B2

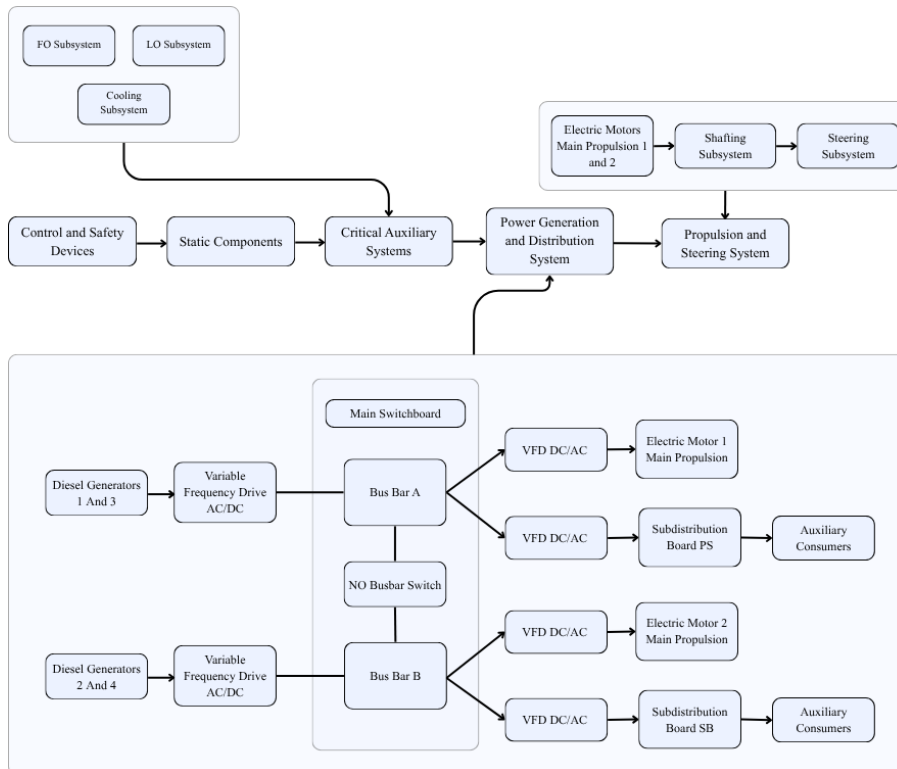


Figure 10. Main elements, systems and subsystems. Case Study B2

This is a graphical representation to simplify the complex relations in the propulsion systems of these vessels. The four case studies are categorized by propulsion technology (diesel and diesel-electric), architectural redundancy (Cases A1 vs A2 and B1 vs B2), and electrical segregation (open vs closed bus tie). Category A focuses on conventional mechanical propulsion, where Case A1 serves as a non-redundant baseline and Case A2 introduces full physical redundancy with twin independent propulsion lines and auxiliary systems. Category B analyses diesel-electric configurations: vessel B1 evaluates a system with a closed bus tie where four generators share a single main switchboard, while vessel B2 eliminates this single point of failure by incorporating a segregated bus tie.

This section includes a discussion of the Reliability Blocks Diagrams of the first Case Study. The developed RBD for all four case studies will be presented in Annex A Detailed Reliability Block Diagrams.

Configuration A1 represents a **single line Conventional Diesel Propulsion**. The reliability model identifies the main functions as a series configuration formed by the control and safety devices, the static components that correspond to the piping, flexible hoses and non-essential tanks, the auxiliary electrical system, the auxiliary systems and the propulsion and steering system.

The elements located in series represent single point of failures as the main switchboard, the main engine or the gearbox. The parallel configurations as the auxiliary gensets, filters or pumps increase system’s reliability by increasing the probability that at least one there is one possible path to the following block.

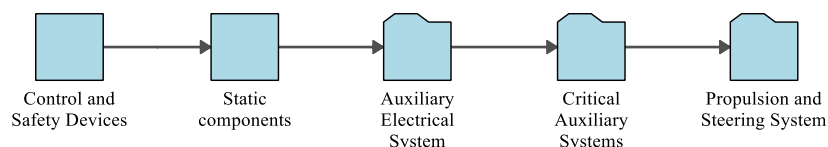


Figure 11. A1 - Main Functions

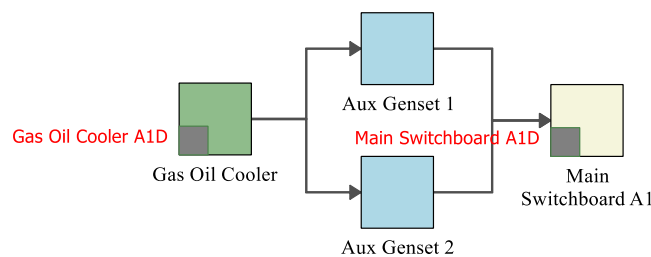


Figure 12. A1 – Auxiliary Electrical System

The auxiliary systems consist of a series configuration of fuel oil, lubrication oil, and low and high temperature cooling subsystems. The series configuration represents the need of all the blocks to succeed to obtain the final goal which is sufficient propulsion. Sufficiency has been previously defined as at least one propulsion line in operation, which in Case A1 is the only one found.

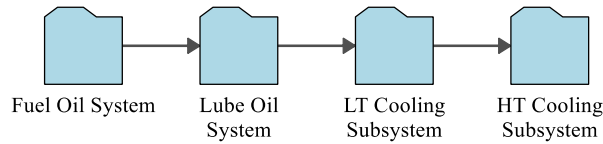


Figure 13. A1 - Auxiliary Systems

The redundant pumps that can be found in the fuel oil subsystem are mechanical and they have been modelled with a duty cycle of 0.5 each. This setup reflects standard maritime engineering practices, where pumps are periodically alternated by the crew to ensure uniform wear-out and prevent early mechanical degradation.

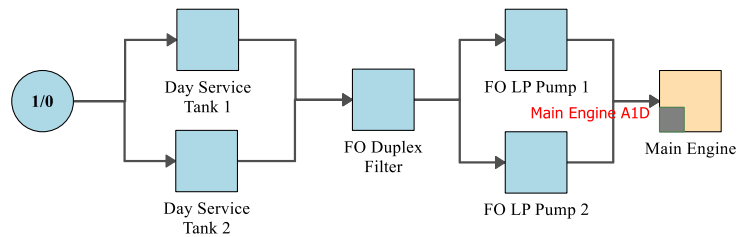


Figure 14. A1 - Fuel Oil Subsystem

In the lubrication oil subsystem, a different pump configuration is found. To model the operational behaviour of this parallel configuration, asymmetric duty cycle values have been assigned to the pumps. The mechanical pump is gearbox-driven and is assigned a duty cycle of 1, as it operates continuously. The electrical pump is in stand-by mode, and a duty cycle of 0 has been applied. This constraint ensures that the backup element remains inactive while the primary pump is functioning, accumulating zero hours of stress and mechanical degradation. Once the mechanical pump experiences a failure, the electrical pump engages and starts accumulating operational wear-out.

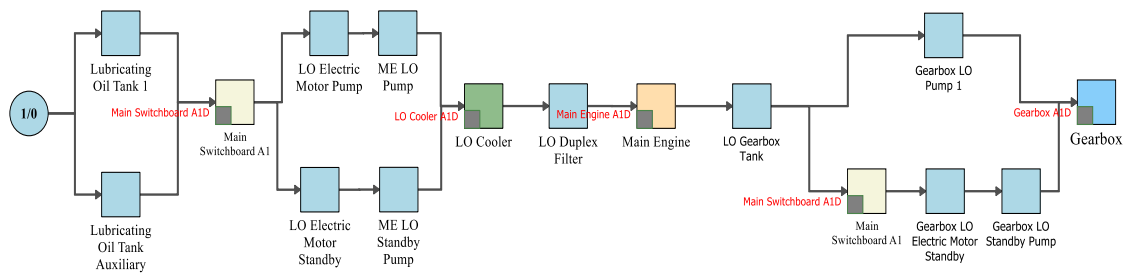


Figure 15. A1 - Lub Oil Subsystem

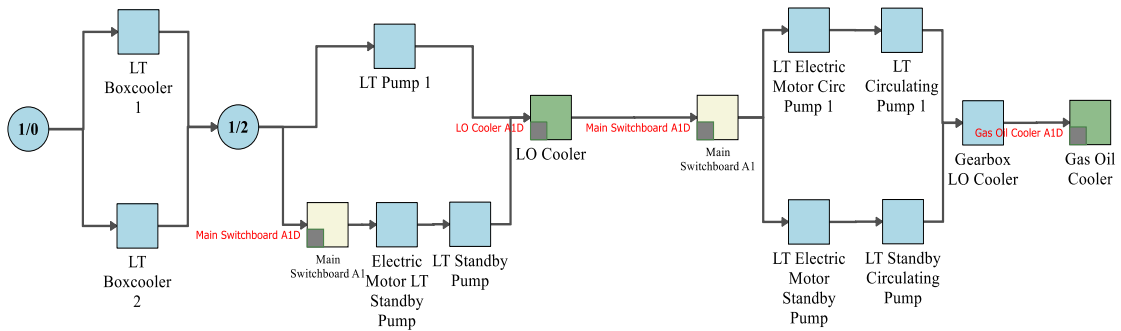


Figure 16. A1 - LT Cooling Subsystem

Other elements worth mentioning are the nodes, which are circular blocks that represent the minimum number of successful paths required for the system to operate. As can be seen in Figure 17, the HT Boxcoolers modelled in parallel lead into a node indicating 1/2. This implies that for this section of the HT Cooling Subsystem to function, at least one of the boxcoolers must remain operational. Conversely, there are other parallel configurations, as the Starterboxes in Figure 21, that do not feature this explicit node. In these situations, the node was excluded to avoid unnecessary graphical repetition, as the software automatically interprets a standard parallel configuration without a node as a 1-out-of-2 success logic.

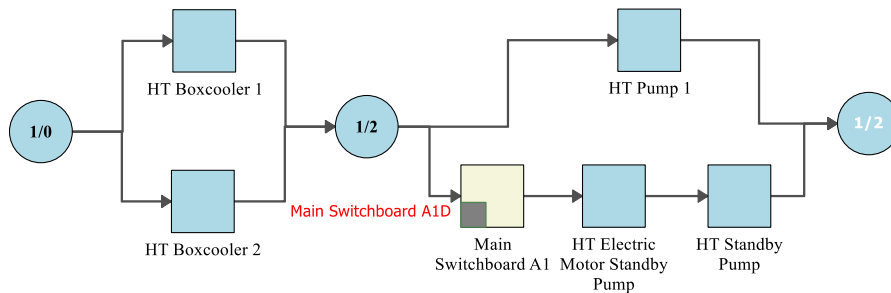


Figure 17. A1 - HT Cooling Subsystem

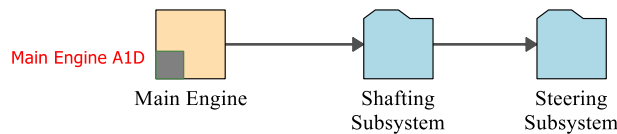


Figure 18. A1 - Propulsion and Steering System

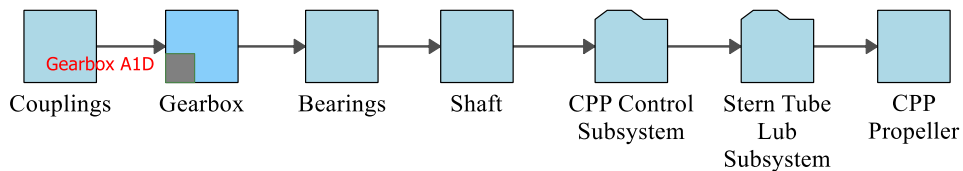


Figure 19. A1 - Shafting Subsystem

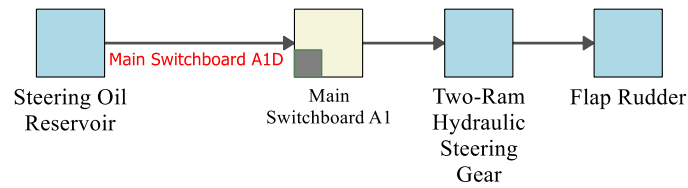


Figure 20. A1 - Steering Subsystem

To avoid the double counting error, the physical and functional boundaries of the system components have defined. Auxiliary elements such as sensors, cabling, and indicators have been included in the failure rate of the Control and Safety Devices block. Passive structural elements, including piping networks and flexible hoses, are accounted under the Static Components block.

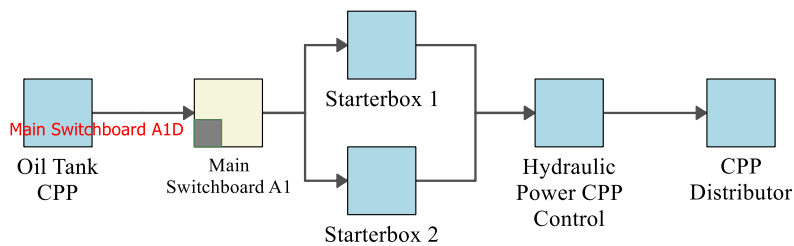


Figure 21. A1 - CPP Control Subsystem

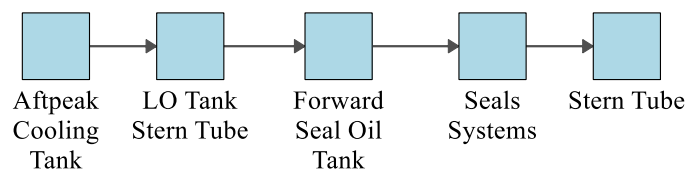


Figure 22. A1 - Stern Tube Lub Subsystem

5.4 Assumptions

To maintain the focus on the impact of architectural redundancy some assumptions will be made:

- **Model assumptions**
 - **Safety and control systems:** a global reliability value will be assumed for these systems to reduce uncertainty in the analysis. These reduces the precision of the final result but makes the model more manageable, as the number of elements is reduced but still accounted for.
 - **Failure independence:** failures will not be spread from one component to another, unless explicitly stated.

- **Binary states:** components are considered to be either fully operational or failed as explained on 4.3.
- **Starting air subsystem:** it is assumed that the analysis is done when the ship is sailing, therefore no starting procedure is considered assuming the reliability of it 100%.
- **HVAC and hotel load:** these systems present an equivalent configuration and reliability in the four cases of study. Their inclusion would reduce the sensibility of the probabilistic model, therefore only components that directly affect propulsion are considered.
- **Operating profiles**
 - **Coastal operating profile:** has direct impact on the availability analysis, specifically in the MTTR (Mean Time To Repair), which is significantly reduced compared to deep-sea operations.

5.5 Introduction to ReliaSoft BlockSim

ReliaSoft BlockSim provides a platform for system reliability, availability and maintainability analysis (RAM). It allows to model complex systems using reliability block diagrams (RBD), fault trees and Markov diagrams. This thesis makes use of RBDs to model the propulsion system of the cases of study. This software has two calculation engines to perform RAM calculations, analytically using exact computations or probabilistically applying discrete event simulations (DES) and Monte Carlo Simulations Model (MCM). As the intention of this thesis is to use both methods, this software is a powerful tool that allows to compare results in the same interface.

Furthermore, it has additional capabilities:

- **RAM analysis** using different configurations to represent the model: series and parallel, load sharing, standby redundancy or duty cycles, that represent the percentage of the time each component is working.
- Build **complex models** identifying areas of poor reliability for system enhancement. For this purpose, the tool FRED Reports (Failure Reporting, Evaluation and Display) provides visual representation of the system's weaknesses.
- Identify **bottlenecks** to optimize resource allocation, improving overall availability.
- Obtain **overlay plots** to compare multiple results in the same graphic, useful for comparing different configurations or showing the effects of a design modification.

In this thesis, BlockSim is used as the main computational engine to evaluate the reliability and maintainability of the propulsion system, applying the previously mentioned methodology: first, an analytical approach to determine theoretical reliability, allowing to identify bottlenecks and provide insights into system improvement. Secondly,

simulations consider maintainability tasks and probability distributions selected to each component, ensuring a robust assessment of the propulsion system's availability.

5.5.1 Modelling Assumptions and Functional Dependencies

To ensure a realistic simulation within BlockSim, several modelling assumptions were adopted and tools provided by the software have been used.

- **Thermal load modelling**

All four-case studies present auxiliary cooling systems which include boxcoolers, a type of heat exchangers. Although these elements usually work in a load-sharing configuration, a standard parallel redundancy has been adopted, assuming that at least one boxcooler is enough to dissipate the excessive heat. This approach has been supported by the lack of data of boxcoolers operating at different loads.

- **Standby redundancy and automatic start**

The logic applied on pumps used in the cooling system or in the oil and fuel system is that one engine driven pump acts as the main component. When a failure has been detected, the electrical pump gets into action, assuming the load. This way of modelling is not consistent in the analytical calculation methods, therefore a parallel load approach has been applied. This process is more straightforward to cases where both pumps were mechanical and alternatively used.

To account for this alternation, duty cycles have been applied as will be explained next.

- **Duty cycle applications**

This mode has been applied to redundant pumps assigning them a duty cycle of 0,5. This accounts for the reduced mechanical wear in those units along time. This doubles the component's MTTF in the probabilistic simulation, as the component only ages during 50% of the mission time. For redundancies where one pump is mechanical and the second one electrical, a duty cycle of 1 is assigned to the first, and 0 to the second. The software identifies that the mechanical pump accumulates the total of the wear-time, and only when it fails the electrical pump will get activated "as new".

- **System dependencies: Mirror Blocks**

Functional dependencies have been modelled using Mirror Blocks. This applies to electrical components which rely on the correct functioning of the electrical system or engine driven components which depend on the motor's movement.

- **Components grouping**

To maintain modelling clarity in ReliaSoft BlockSim and prevent double-counting errors, auxiliary and passive components have been integrated into two macro-reliability blocks

withing the Main Functions RBD, as seen in Figure 11: Control and Safety Devices and Static Components.

The **Control and Safety Devices** block groups the failure rates of monitoring networks, safety instrumentation, and automation hardware. Rather than evaluating thousands of individual blocks, these components are combined into a single functional block. An example can be seen in Figure 14, where the operational success of the Duplex Filter and the FO Pump is directly linked to pressure indicators, temperature sensors and remotely activated valves. Under this methodology, the failure rates of these specific elements are not omitted but accounted into the centralized Control and Safety Devices block.

The **Static Components** block accounts for passive structural elements with characteristically low failure rates, such as piping networks, flanges, and flexible hoses connected to machinery subjected to heavy vibrations. These hoses maintain their low failure rate when periodic inspections are carried out. A clear application of this boundaries approach ca be seen in the Main Engine in Figure 18, which is isolated from the rigid piping by means of flexible hoses to absorb operational vibrations and prevent fatigue ruptures. Figure 19

6

Analytical Simulations

This chapter aims to answer the second research question:

How do different marine propulsion configurations compare in terms of reliability using SOLAS II-1 26.2 as a compliance benchmark?

The objective of this chapter is to evaluate the reliability of four propulsion architectures named Case A1, A2, B1 and B2 over a standard operational mission. The first study case will be used as a benchmark as it represents the requirements of **SOLAS II-1 26.2** which states that the reliability of single essential propulsion components should receive special attention. It adds that to ensure a navigable speed, especially in the case of unconventional arrangements, a separate source of propulsion can be required.

In this study, **Case A1** is modelled as a single propulsion line which lacks physical redundancy making it the most vulnerable configuration. **Case A2** presents the scenario where a separate source of propulsion has been included. **Case B1** and **B2** represent the unconventional arrangements and achieve redundancy with the integration of several diesel-electric generators. **Case B2** goes one step further by considering two segregated bus bars, which eliminate the SPOF that the Main Switchboard with an individual bus bar is.

This chapter will analyse if the redundancy requirements are necessary for diesel vessels and for unconventional configurations as the diesel-electric, or if regulations are over-demanding in low-impact areas-

6.1 Analytical Calculations in BlockSim

The analytical assessment was performed using exact reliability computations using the software ReliaSoft BlockSim. This has been done for a given mission time (t) of 8000 hours which represents approximately one year of vessel operations. Mission success has been defined as the probability that at least one propulsion line of the vessel can be maintained. The propulsion analysis scope has been defined in Section 5.3, which includes control and safety devices, static components, auxiliary systems, auxiliary electrical systems, power generation and distribution systems and propulsion and steering systems.

6.2 Deterministic Analysis Results

The reliability over time for all four configurations has been plotted for a mission duration of $t=8000$ h (approximately one year of operations). This time corresponds to the period where all configurations' reliability tends to zero. This section analyses reliability, therefore, maintainability is not considered. In real-life operations, failures can be resolved as it will be studied in Section 7. Probabilistic Simulations

Case study A1 has been selected in order to comply with SOLAS regulations. This mechanical configuration presents several single points of failure. If the main engine, the gearbox, or the shafting fails, the whole system's reliability will drop to zero. Case A1 compliance is critical to individual component's failure and means that the ship is safe as long as every component functions.

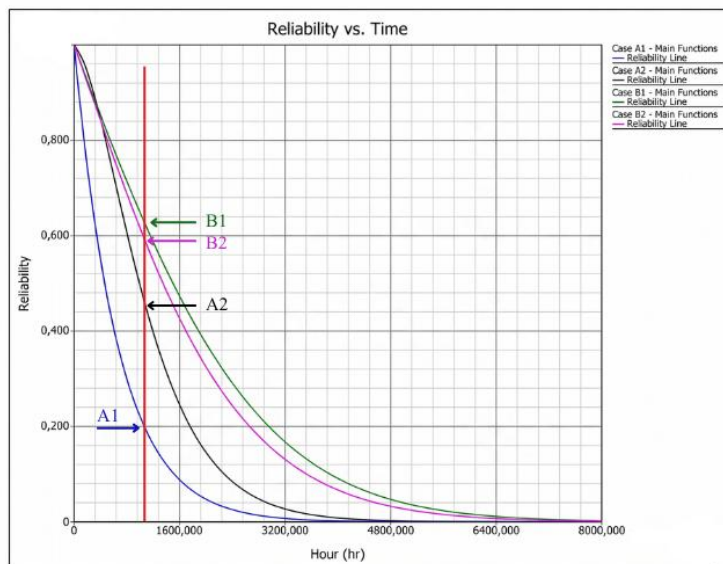


Figure 23. Deterministic Analysis of System Reliability Over Time

The transition from a single-line propulsion system that served as a benchmark to redundant configurations (A2, B1, B2) shows that the reliability curve has shifted to the right, increasing system's reliability.

To analyse if the vessels are able to complete a period of missions without undergoing major dry-dock maintenance, their reliability is analysed at a time $t=1000$ hours. This timeframe provides a sufficient window to observe how reliability drops between major shipyard maintenance periods.

If all configurations are analysed at $t=1000$ hours, the reliability values are as follows:

Table 7. Comparative Reliability with SOLAS Benchmark

| | Reliability at t=1000 h | Comparison Benchmark (A1) | to SOLAS II-1 26.2 Compliance |
|---------|-------------------------|---------------------------|-------------------------------|
| Case A1 | 0.2199 | 100% | Minimum compliance |
| Case A2 | 0.3654 | 166.2% | Exceeds compliance |
| Case B1 | 0.6487 | 295% | Exceeds compliance |
| Case B2 | 0.6159 | 280.1% | Exceeds compliance |

Table 7 illustrates that all redundant cases (A2, B1, B2) confidently overcome the benchmark reliability established by Case A1.

The probability of success of Case A2 has been increased by approximately 66.2% compared to the benchmark. This is as for a given failure in the auxiliary systems and the propulsion and steering systems, there is a second independent path that allows mission success.

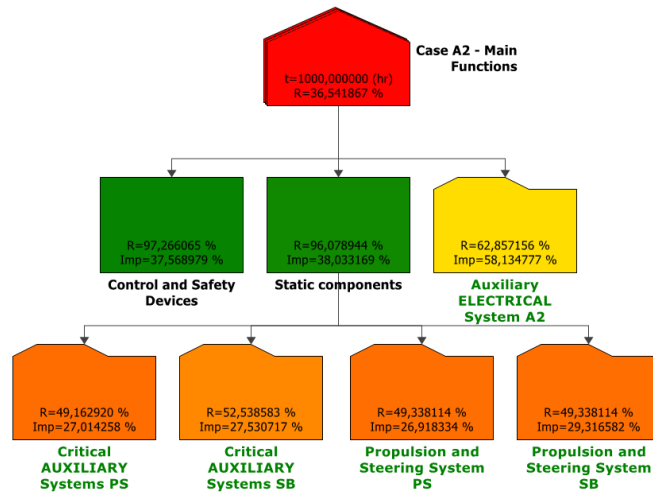


Figure 24. FRED (Failure Reporting, Evaluation, and Display) Report for Case A2

As evidenced in Figure 24, the orange blocks represent the critical systems. In this case the ones that need to be specially considered are the auxiliary and the propulsion and steering system. They present the lowest reliability but as they are segregated into two possible ways of success, the effect of failures in the elements of the system is taken care by the redundant system. On the other hand, the green blocks are systems with a high reliability value but a single success path. The failure in their components is more critical but this is addressed by the high reliability of individual components.

Cases B1 and B2 represent the unconventional configurations and at the same time, the safety peak of the analysed configurations at 1000 hours of operation. In these cases, the reliability has almost tripled as the success of the mission is no longer tied to a single source of power. The vessels can lose half of its propulsion by losing 2-out-of-4

generators, which allows more failures than a single or two sources, as seen in cases A1 and A2.

6.2.1 SPOF Ratio

Another factor that adds value to respond to the research question is which is the ratio of SPOF to component's number.

Table 8. SPOF Ratio

| | Blocks Number | SPOF Blocks | SPOF Ratio |
|---------|----------------------|--------------------|-------------------|
| Case A1 | 57 | 26 | 0.456 |
| Case A2 | 100 | 4 | 0.040 |
| Case B1 | 67 | 20 | 0.299 |
| Case B2 | 68 | 19 | 0.279 |

As can be seen on Table 8, **Case A1** represents the most vulnerable case with nearly half of the components being critical. This translates to a low failure tolerance, resulting in a low reliability as seen in Table 7.

Case A2 exhibits a complex configuration, where the number of blocks has nearly doubled compared to Case A1, but with only 4 blocks being SPOF. This suggests that twin-screw propulsions are an effective way to reduce SPOF, increasing reliability if component's reliability values are maintained.

While Study **Cases B1 and B2** exhibit a considerably higher SPOF ratio than the second case, they still present an improvement over the baseline (A1). The increase in reliability of these scenarios is achieved through the integration of **highly reliable components**, a characteristic typical of modern electrical elements.

Figure 25 shows the correlation between SPOF Ratio and system Reliability. It can be seen that while **Case A2** increases its reliability as SPOF are drastically reduced, Cases B do not follow that pattern. Reliability is tripled despite maintaining a SPOF of failure of approximately 30%, highlighting the impact of high-fidelity components.

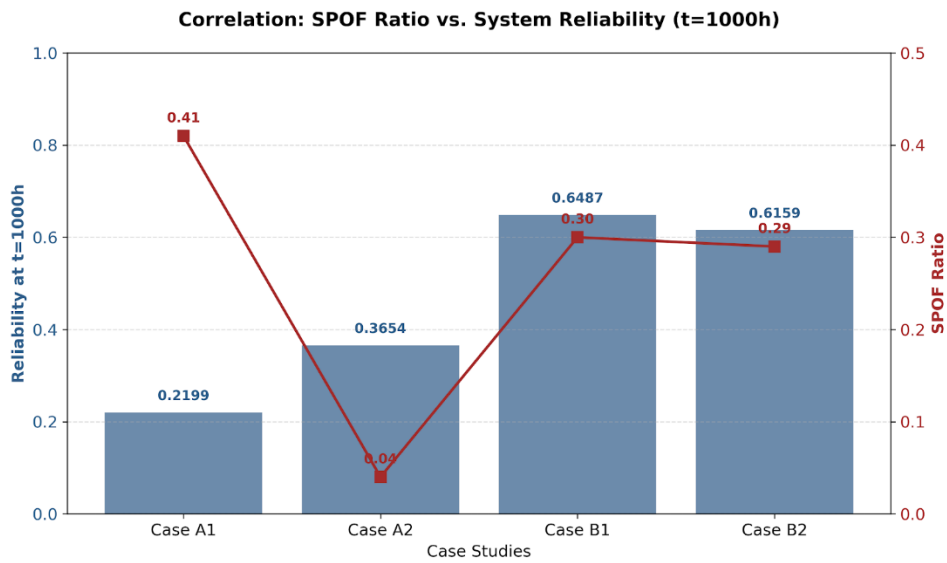


Figure 25. SPOF Ratio vs System Reliability

6.3 Conclusion

This research demonstrates that while the single propulsion line (**Case A1**) fulfils the minimum requirements established by SOLAS II-1 26.2, it remains the most vulnerable architecture due to its high density of Single Points Of Failure (SPOF).

The analysis reveals that implementing physical redundancy in the propulsion configurations increases the global reliability. Two types of redundancy have been studied: first, Case Study A2 shows duplicity in all the propulsion line. Secondly, B Cases show two factors that influence reliability: first, the high-fidelity of components and second, redundant k-out-of-n configurations as seen on diesel-generators, or independent bus bars as showed in Case B2. Redundancy presented a safety margin that varies between 66% and 195% (Table 7).

Ultimately, these results suggest that current regulations provide a necessary benchmark, but it may be overdemanding for redundant and unconventional configurations, that already achieve a more than sufficient reliability value.

7

Probabilistic Simulations

This chapter will investigate the availability of four propulsion configurations through probabilistic simulations. This numerical approach will provide sufficient evidence of the need of physical redundancy as required by SOLAS II-1 26.2 and 26.3.

This section therefore aims to answer the third research question:

What inconsistencies exist in current regulations regarding availability requirements for different technologies, and how does this affect system design optimization?

This section will introduce the probabilistic method used, the component's failure distributions, the simulation parameters applied to obtain the numerical results followed by a comparative analysis of the outputs to assess the efficacy of redundant and unconventional arrangements in the maritime industry.

7.1 Introduction to Monte Carlo Simulations

Monte Carlo Method simulation (MCM) uses random sampling and statistical modelling to solve complex deterministic problems. This is a scientific tool used for problems that are analytically intractable or too time-consuming, costly or impractical.

MCM generally follow three steps: first, the system's elements are assigned a probability density function that matches their behaviour as explained in Section 2.2.2. The next step consists of repeatedly sample from the PDFs, randomly sampling several times to analyse different failure and success scenarios. The last step is to obtain the statistics of interest as mean availability could be [18].

This method has some disadvantages: it can require extensive computing resources, does not give exact solutions and provide results that are only as good as the model and the data introduced. Therefore, before committing to this type of analysis, other alternatives as analytical or experimental methods should be considered. This thesis took this into account and performed deterministic calculations as a way to validate results (Section 6).

This method will be applied to the four case studies using the setup defined in chapter 7.3.

7.2 Component failure data

The type of probability density distribution assigned to each component in the system depends on the nature of the element and the use and load it is subjected to [38]. It has been found that elements that are characterized by **Weibull distributions** — models that describe infant mortality — need two parameters to obtain the reliability curve: β (a form parameter) and θ (a scale parameter).

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^\beta}$$

Equation 6. Weibull Distribution Parameters

When $\beta > 1$ ($\beta < 1$), the Weibull distribution describes a system with an increasing (decreasing) failure rate. The cases where $\beta=1$, the Weibull distribution coincides with the **exponential law**. In those circumstances, the failure rate is constant and $\theta = \text{MTTF}$ or $1/\lambda$, being λ the mean failure rate. [17]

Mechanical components tend to follow Weibull distributions due to wear-out and fatigue. β can be assigned according to the typical nature of the component's failure behaviour:

- $\beta = 1,5$ to $2,0$: common for mechanical parts subject to light loading
- $\beta = 3,0$ to $4,0$: applied to heavy mechanical components as bearings or gears.

Other components will be assigned an exponential distribution, a type of PDF that describes the constant region of the bathtub curve and assumes that a component has the same probability of failing in the following time-step than it had in the previous one.

$$R(t) = e^{-\lambda t}$$

Equation 7. Exponential Distribution Parameters

Annex B presents the list of components modelled in the four Case Studies with the assigned distribution that models the failure behaviour. Table 9 presents the selected distributions for the elements of the first case study systemically grouped with a justification of the reasons why this distribution has been assigned.

Table 9. Components' distribution selection

| Component Group | Elements | Distribution type | Mathematical Justification |
|---------------------------------------|--|-------------------|--|
| Automation and Electrical Control | Control Systems, Main Switchboard, Starterbox | Exponential | Electronic elements characterized by constant failure rates. |
| Passive Piping Network | Static Elements | Weibull | Models continuous wear from vibration, fluid erosion and corrosion. |
| Heavy Prime Movers and Transmission | Main Engine, Gearbox, Shaft, Bearings, Couplings, Propeller | Weibull | This distribution models mechanical fatigue, gear-teeth wear, and torsional stress degradation over long periods of time. |
| Rotary Machinery | Mechanical Pumps | Weibull | Models continuous mechanical wear-out, degradations and erosion. |
| Structural Blocks and Static Elements | Boxcoolers, Coolers, Stern Tube, Tanks, Filters | Exponential | Passive steel structures with high characteristic lives. Filters modelled with an exponential distribution as failures are random due to clogging or unpredicted ruptures. |
| Hydraulic and Mechanical Actuators | Two-Ram Hydraulic Steering Gear, Flap Rudder, Hydraulic Power CPP Control, CPP Distributor | Weibull | Models structural wear-out, alignment loss, and hydraulic cylinder seal degradation under dynamic forces. |
| Electrical Drives | Electric Motor, Aux Gensets | Weibull | The selected distribution models thermal stress and the aging of the stator. |
| | Seals Systems | Weibull | Models continuous friction wear and aging of rubber. |

7.3 Probabilistic Simulation Execution

The strategy followed to perform the probabilistic analysis has been to define the time of simulation to the vessel life, which is on average 20-25 years, to capture the failure rate of components with high MTTF values. A comparison between the four case studies using Case A1 as a benchmark will allow to understand if an increase in complexity represents a higher availability, or if different approaches should be considered.

Mission success is defined as the probability that at least one propulsion line is operational. This is a strict requirement for the shafting in Cases A1, B1 and B2 as they only have one propulsion line. In Case A2, where two independent propulsion lines are installed, at least one needs to be functioning.

The third setup condition to define is the number of iterations that will be run, which will be studied in Chapter 7.4.

7.4 Convergence Analysis and Validation

To ensure the statistical significance of the probabilistic results a convergence analysis has been performed for the first case study. The goal is to obtain stability in the results as MCM relies on random variables (MTTF, MTTR). Standard deviation results have been obtained for 100, 1000 and 10000 iterations.

Table 10. Convergence Analysis for Case A1

| Iterations | 100 | 1000 | 10000 |
|------------------------|----------|----------|-----------|
| Mean Availability | 0.745441 | 0.722029 | 0.720567 |
| Standard Deviation | 0.333284 | 0.315685 | 0.310709 |
| Relative Variation (%) | 3.452 | 0.203 | Reference |

Even though convergence has been achieved at 1000 iterations, to capture the failures of components with high MTTF values, the simulation has been extended to 10000 iterations. This number will capture low probability events, obtaining a more accurate reliability. Moreover, this value offers an acceptable equilibrium between results precision and software processing time.

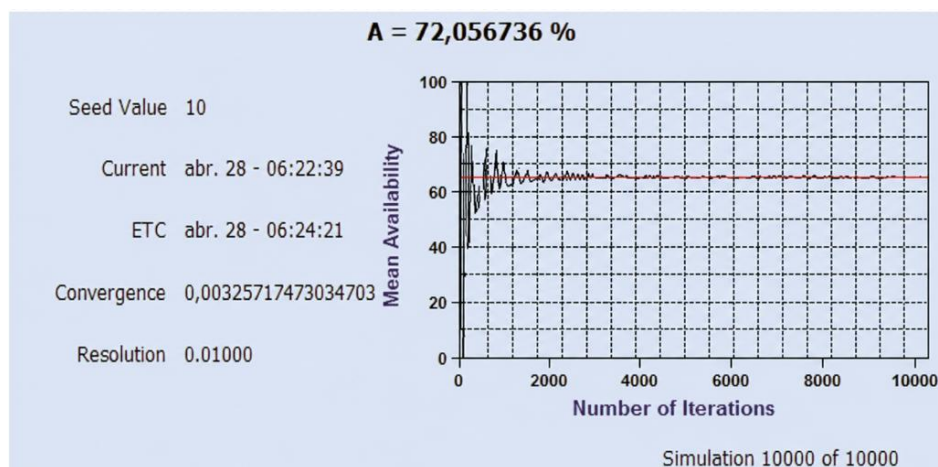


Figure 26. Convergence Analysis of Mean Availability for Case A1

Figure 26 clearly shows the convergence effect over 10000 simulations and the unstable behaviour at early-stages of the process, being this the reason why 1000 iterations could not be chosen to obtain precise results.

7.5 Comparative Results of Case Studies

The probabilistic simulations were run to obtain the Mean Availability of the four Case Studies for a period of 20 years. Before presenting these results an overview of the differences between the analytical analysis performed in Section 6 and the results obtained in the current section will be presented.

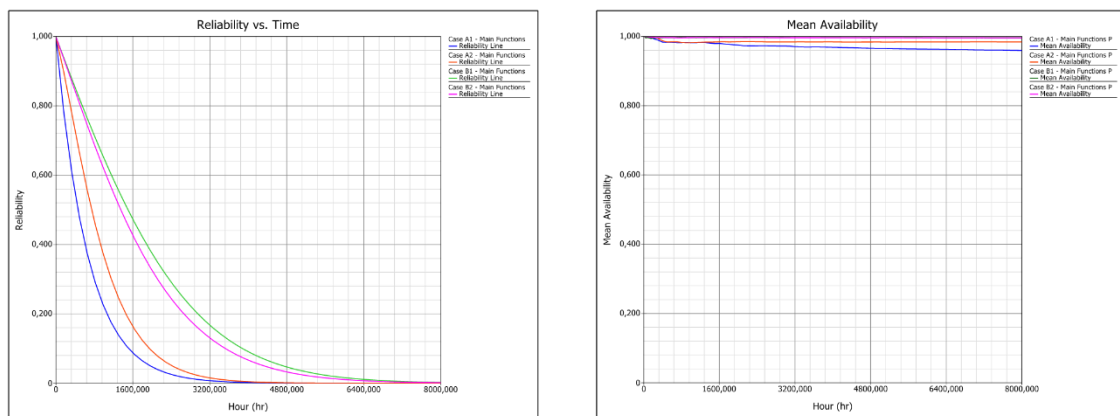


Figure 27. Comparison of Deterministic and Probabilistic Results at $t=8000\text{ h}$

The main difference between the obtained results relies in the fact that availability considers **maintainability**. In this system, elements that fail can be repaired according to the defined MTTF and the duration of the reparation procedure. These are inputs that have been defined according to the obtained data. For this reason, availability values are considerably higher.

Following simulations have shown that availability at the vessel's life cycle is maintained above 0,7. This will indicate the limits of the Y-axis as to have an increased detail of the results. Another figure has been added to obtain the detail of Case B1 as the line is overlapping with Case B2.

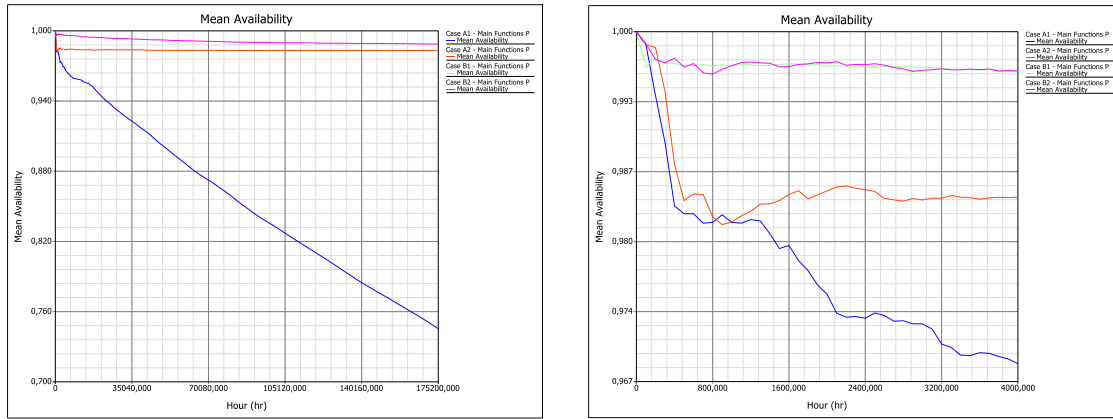


Figure 28. [Left: Probabilistic Analysis of Main Availability Over Time] [Right: Detailed Main Availability of Case B1]

Figure 28 shows a clear performance gap between the benchmark scenario (Case A1) and the redundant configurations (A2, B1 and B2).

Case A1 exhibits the steepest decline in availability over time, resulting in the weakest configuration of all the studied ones. There is a notable difference between Cases A1 and A2 and since the auxiliary and propulsion components are similar, this difference can be attributed to the lack of redundancy in the first scenario.

The inclusion of a separate source of propulsion in **Case A2**, as suggested by SOLAS II-1 26.2, shifted the availability curve significantly upwards. This twin-propulsion with separate auxiliary systems allows the system to remain operational despite component failures. It represents a great improvement over the base case although some aspects have to be considered, like the installation and maintenance cost of nearly double the amount of elements as depicted in Table 8.

Cases B1 and B2 present the highest availability results (Table 11). Both cases present unconventional configurations, adding a level up of redundancy on Case B2 by modelling two separate busbars. Both curves present a stable behaviour and their superior performance can be attributed to two main reasons: first, the high reliability of electrical components. Second, the power plant design that offers a high flexibility with 4 diesel generators.

Table 11. Mean Availability per Study Case

| | Case A1 | Case A2 | Case B1 | Case B2 |
|------------------------------|-----------|-----------|-----------|-----------|
| Mean Availability (%) | 72.056736 | 98.334155 | 98.955683 | 98.849872 |

These values are conditioned on the fact that mission success is defined as at least one propulsion line operating. This definition accounts for SOLAS when mentioning that only navigable speed is required, allowing for a partial reduction in propulsion capability.

Section 8.1 will present more insights into the component and system importance and how it affects global reliability. This will provide arguments to analyse if SOLAS is being overdemanding in requiring redundancy in auxiliary components and in propulsion components that present single points of failure (SPOF).

Table 12. Mean Availability Comparison

| | Case A1 | Case A2 | Case B1 | Case B2 |
|-------------------------------------|----------------|----------------|----------------|----------------|
| Mean Availability (%) | 72.056736 | 98.334155 | 98.955683 | 98.849872 |
| Mean Components Availability | 99.229075 | 99.663828 | 99.922109 | 99.498405 |

Table 12 is a comparison of the Mean Availability value of the whole system as obtained from the probabilistic software. Additionally, the Mean Availability value of the individual components has been calculated, not considering the different configurations (series, parallel or k-out-of-n). This provides validation into the effect of redundancy in system's availability.

Case A1 presents the most notable difference between the Mean Component Availability and the Mean Availability of around 22.17%. This is due to a scenario with a non-redundant configuration where components are modelled in series. Any single failure in a critical component represents a disruption that does not have any other possible success path. All other scenarios (**Cases A2, B1 and B2**) have a negligible gap between both availability results, demonstrating that redundant configurations are less susceptible to individual failures and more to individual reliability values.

This data provides evidence that SOLAS II-1 26.2 and 26.3 is inconsistent while applying similar redundancy criteria to different technologies. It can be seen that redundancy is an effective way to increase redundancy in conventional configurations (Case A1 and A2) but lacks relevance in diesel-electric propulsion systems. Case B1 presents a single point of failure in a propulsion component. To account for it, Case B2 modelled the main switchboard as two separate bus bars. Despite the increase in redundancy, the difference between configurations was minimal.

7.6 Conclusions

This chapter has carried on a probabilistic analysis to provide evidence to answer the research question regarding inconsistencies in the regulations and their impact on system design optimization. The findings lead to the following conclusions:

- **Effectiveness of SOLAS in Conventional Systems**

The integration of two separate propulsion lines with segregated auxiliary systems allowed the availability of Case A2 to increase nearly 26% compared to Case A1.

This increase has been caused by a parallel configuration that created new success paths, reducing the impact of failures in individual components.

- **Regulatory Inconsistency in Technological Neutrality**

A nearly neglectable difference in availability has been found between Cases B1 and B2. It proves that redundancy in essential propulsion components is not the path to increase availability in diesel-electric systems. The key in unconventional configuration as the studied one, relies in inherent high-fidelity of electrical elements and the functional flexibility of a k-out-of-n power plant.

- **Impact on System Design Optimization**

Current regulations establish a common standard to different technologies, not considering the effect of redundancy in system's availability. It has been proved its effectivity varies among conventional and non-conventional configurations. Establishing a common framework economically penalizes technologies with inherently high availability (Cases B1 and B2), without significantly increasing availability. Adding redundancy to account for SPOF to comply with regulations leads to increased capital and maintenance costs.

In summary, while current regulations have been proved necessary in ensuring safety in conventional designs, they lack the technological neutrality to optimize unconventional architectures. In order to ensure safety, SOLAS should transition towards goal-based availability standards, leaving space for designers to optimize efficiency and costs while maintaining safety.

8

Sensitivity Analysis

This section aims to answer the following research question:

How does the reliability of individual systems influence the general propulsion availability and where is the equilibrium point between redundancy and its effect on cost, reliability and safety as defined to comply with environmental regulations?

To answer this question the chapter will be organized into three sections: first, the propulsion systems' importance will be analysed to understand which points and critical and could be optimized to increase availability. The second section will investigate where is the limit between increasing redundancy and obtaining diminishing returns. Finally, some insights will be given of the effects of environmental regulations into safety and system design optimization.

8.1 Component Importance Measure

SOLAS requires the same level of redundancy across different propulsion configurations. This section will investigate the importance of the auxiliary and the propulsion systems in all case studies to provide insights into the necessity of redundancy in these systems.

Table 13. Subsystem's Importance Comparison

| Systems' Importance (%) | Case A1 | Case A2 | Case B1 | Case B2 |
|--------------------------------|----------------|----------------|----------------|----------------|
| Control and Safety Devices | 13.3 | 15.4 | 18.6 | 18.5 |
| Static Components | 13.4 | 15.5 | 18.9 | 18.7 |
| Auxiliary Systems | 26.4 | 22.3 | 19.1 | 19.5 |
| Electrical System | 20.6 | 23.8 | - | - |
| Power Generation and Distr. | - | - | 18.7 | 18.9 |
| Propulsion and Steering System | 26.3 | 23.0 | 24.7 | 24.4 |

Table 13 provides the system's importance of the different case studies at a time of $t = 1000$ hours. It indicates the probability that the whole system fails if the specific system fails, calculated as a percentage. The following insights can be extracted from it:

- Importance values are relatively low in Cases A as the system presents several SPOF. This dilutes the importance of each failure as numerous other components can stop navigation.
- On the other hand, Cases B present a more evenly distribution of importance for all systems which indicates that the general availability is highly dependent on the availability of individual components.
- Regulation SOLAS II-1 26.2 requires giving special consideration of the reliability of essential propulsion components. Rule 26.3 focuses on the elements of the auxiliary systems. As can be seen in Table 13 this is not consistent with the actual behaviour of the vessels.

Case A1 availability would benefit from improving redundancy or including high-fidelity elements in the **Auxiliary** and in the **Propulsion and Steering Systems**. Similar to Case A1, Case A2 would additionally improve its availability by improving the **Electrical System**. Case Study B1, which corresponds to a diesel-electric power plant with a Main Switchboard, will be seen its availability increased if the **Propulsion and Steering system** is optimized. The same follows to Case B2, with a slightly lower importance value, caused by the separation of the Main Switchboard into two bus bars.

In conclusion, this analysis showed that individual system reliability influences general success depending on the **type of architecture**. Non-redundant configurations would benefit from improvements in Auxiliary and Propulsion Systems, as suggested by SOLAS II-1 26.2. In unconventional configurations, the sensitivity relies in the reliability of individual components, specifically in the Propulsion and Steering line, that presented an importance as high as 24.7%. Global availability can be optimized by addressing the identified **bottlenecks** of each configuration rather than applying the same methodology suggested by SOLAS II-1 26.3 to all of them.

8.2 Reliability-Cost-Safety Analysis

Equilibrium

SOLAS makes use of redundancy as a primary mechanism to meet safety standards. This chapter evaluates the trade-off between an increase in complexity and the gain in operational availability, considering the increase in design cost to comply with safety regulations.

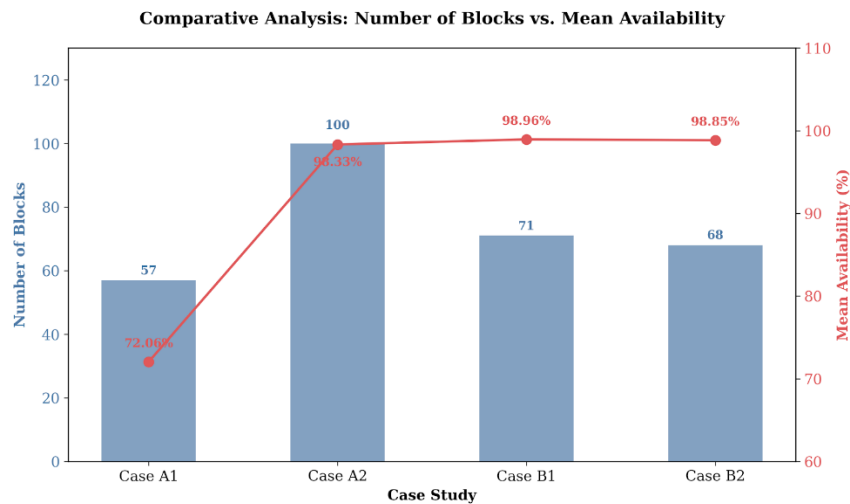


Figure 29. Comparative Analysis of Number of Blocks against Mean Availability

The previous graph shows the comparison of the mean availability of all the case studies against the number of blocks in each scenario. Some insights can be extracted:

- **Mechanical Redundancy In Cases A1 and A2**

Moving from the first case to the second is the most straightforward approach to comply with SOLAS II-1 26.3. Additional auxiliary systems have been included to improve availability, which has achieved above 98%. This has been obtained by **increasing 75% the components number**, which obviously comes with a cost of installation and maintenance.

- **High-Fidelity Effect Comparison Between Cases A2 and B**

The comparison of these three study cases is straightforward as all of them have nearly the same mean availability value. The difference here relies on the number of installed components. While Case A2 needed 100 elements to achieve 98% availability, diesel-electric configurations reached that same level with around **30% less components**. The exact effect of this reduction could be further studied analysing the cost of each individual component as to understand if the reduction in the number of components is not diminished by an increased cost of high-fidelity components.

- **Equilibrium Point of Diminishing Returns**

The switch from case B1 to B2 shows that although logical redundancy has been introduced, mean availability does not increase and in fact, is slightly reduced. This represents the point where costs increase while availability does not.

Case A2 strictly complied with SOLAS safety regulations at the expense of a high cost, while Case B1 has been presented as the optimum scenario where the highest availability has been reached at a moderate number of blocks. In summary, this analysis proves that the equilibrium is found not in the quantity of components but in the selection of the technology with the best intrinsic reliability.

8.3 Compliance with Environmental Regulations

IMO is causing shipowners to find ways to reduce its greenhouse emissions to comply with environmental regulations. One mechanism among others is reducing the ‘safety buffer’ of installed power [1] It has been studied that this reduction is safe only if redundancy or high-fidelity technologies are incorporated.

Diesel-electric technologies have proved efficient in reducing GHG emissions while maintaining a high mean availability value (Table 11). This large safety buffer provides high flexibility, allowing the ship to optimize its power plant to reduce the installed power.

Case A2 on the other side, complies with SOLAS redundancy requirements but the installation of additional components increases the required installed power, increasing at the same time emissions (Figure 29).

In conclusion, if the requirements to select a propulsion configuration are based on an equilibrium between reliability, cost and safety, diesel-electric configurations have proved the best candidate as they maintain a high availability value without the necessity of incorporating additional elements. Furthermore, it gives the possibility to reduce environmentally harmful emissions by reducing the installed power.

9

Discussion

9.1 Interpretation of Results

The combined deterministic and probabilistic methodology applied in this thesis has produced consistent results on how redundancy affects propulsion availability across different system architectures. The most relevant finding is not the confirmation that redundancy improves availability but rather the technology dependent nature of this relationship.

The deterministic analysis confirmed that all redundant configurations (Cases A2, B1 and B2) surpassed the benchmark established by Case A1 by 66.2%, 295% and 280.1% respectively. These results are consistent with the hypothesis that parallel configurations reduce system failure rate by providing alternative success paths.

However, the SPOF ratio analysis added a nuance into how this improvement has been achieved. Case A2 achieved its improvement primarily through the drastic reduction of single points of failure (SPOF ratio dropping from 0.456 to 0.040). Cases B1 and B2 maintained a ratio of approximately 0.30 and still achieved a significantly higher reliability. This demonstrated that high-fidelity electrical components can compensate for a system with a higher SPOF density. This finding has direct implications for how current regulations understand the concept of redundancy.

The probabilistic Monte Carlo Simulations showed a mean availability gap between Case A1 (72.06%) and the redundant configurations with values exceeding 98%, adding justifications to the benefit of redundancy to increase availability. Furthermore, there is a negligible difference between Case B1 (98.96%) and B2 (98.85%) despite the second case introducing segregation of the main switchboard. The added complexity did not translate into any benefit, and availability marginally declined, suggesting that the system reached a zone of diminishing returns.

The analysis of the Components Importance Measure showed the Auxiliary and the Propulsion and Steering Systems as the primary bottlenecks in the conventional diesel configurations, with importance values up to 26.4%. In diesel-electric configurations the Propulsion and Steering System retained a high importance while the contribution of individual systems was more evenly distributed. This showed the broader redundancy architecture of the power plant and resulted in a practical implication: optimization efforts

are better directed through the mechanical propulsion line as it is the system with the highest importance.

9.2 Comparison with Previous Work

The findings in this thesis align with prior research as mentioned in Section 2.3. The RAM analysis introduced by Bayraktar and Nuran [8] served as a reference, and the deterministic results identified the Auxiliary and the Propulsion systems as bottlenecks with the highest failure rate.

A significant contribution from this thesis is the integration of time-dependent Weibull distributions. This is a methodological gap found in Eriksen and Lützen [15] and in Ware and Collette [16], where their work relied on exponential distributions for all components. The use of Weibull models for elements subjected to wear-out, fatigue or vibrations as pumps, bearings or engines produces more accurate reliability curves that reflect the real behaviour of these components over time.

In accordance with Tarelko [10], this thesis shows that redundancy reaches the point of diminishing returns in diesel-electric configurations. Both studies confirm that functional redundancy through a flexible power plant configuration can effectively substitute physical component duplication, optimizing system reliability without adding unnecessary structural complexity.

9.3 Limitations

This research has several limitations that need to be acknowledged when interpreting the results.

First, the reliability data set used has been primarily OREDA, a **database** developed for offshore applications rather than for the shipping industry. Although some of the machinery equipment is comparable, the environment in which it is used differs highly. The uncertainty in the data used can be addressed by using data from a relevant sample of vessels.

Secondly, the models assume **binary states**, fully operational or failed, not considering the reality of degraded operating modes. In practice, propulsion systems can operate at a reduced capacity, and it is allowed as mentioned in SOLAS II-1 26.3.

The third assumption has been to consider that failures do not **propagate** and maintain independence between components. This is a conservative simplification as common-cause failures exist in complex systems. This is a trait usually seen in diesel-electric systems that share an electrical network, as can be observed in Cases B1 and B2. An

example would be the trip of circuit breakers caused by severe current surge, due to localized electrical short-circuits.

The fourth limitation is to assume the vessels operate in coastal routes. This is particular for the analysed cases and has a high-impact on the **Mean Time To Repair**. Results for deep-sea operations where repair times can drastically increase could see a shift in availability between configurations.

Finally, the **reliability-cost-safety equilibrium** analysis has been done qualitatively, not integrating capital and operational costs to perform a quantitative study.

9.4 Implications

These findings have particular implications for regulatory bodies and for naval architects. For the IMO and Classification Societies, the results provide quantitative evidence that the application of uniform redundancy requirements across different propulsion architectures constitutes a form of **technological neutrality** that penalizes designs with inherent high availability without delivering significant safety gains. An example of this has been seen in Cases B1 and B2, where the addition of segregated bus bars did not increase mean availability.

This thesis presents an innovative solution: a transition towards **goal-based availability standards**, where designers have to demonstrate that a propulsion system meets a minimum availability threshold rather than comply with uniform architectural requirements.

The optimal Case identified has been Case B1, where the highest availability has been achieved with fewer components than the twin-screw propulsion configuration, and the power plant optimization reduces GHG emissions. This provides the optimal balance among all studied cases from a reliability, cost and environmental perspective.

9.5 Future Work

Five possible research directions have been identified to extend the work presented in this thesis. First, real vessel's operational **failure data** could be gathered and incorporated in the model to validate the models. The second possibility is the integration of **cost data** to obtain a quantitative analysis that could help find a balance between availability, cost and environmental requirements. This would provide justification into investment selection for alternative technologies.

Following SOLAS II-1 26.3 prescriptions, future work could analyse **degraded operational states** rather than binary failure modes. This would introduce a benchmark into propulsion reduction scenarios. To further analyse and model the propulsion systems, the **common-cause** failure modelling could be introduced, being more accurate in the exact behaviour of components, mainly electrical ones.

Finally, the analysis performed in this thesis could be extended to **alternative technologies** as hybrid battery diesel systems or hydrogen fuel cells among others (see Section 4.1.1). As these configurations approach commercial maturity the need for more specific regulatory guidance becomes an increasing need.

10

Conclusions

This thesis investigated the impact of redundancy on the availability of diesel and diesel-electric propulsion systems through a deterministic and probabilistic combined methodology. Four Study Cases (A1, A2, B1 and B2) were modelled and analysed using Reliability Block Diagrams and Monte Carlo Simulations in ReliaSoft BlockSim. This section will summarise the findings of the Research Questions presented in section 1.3.

What methods have been used to assess availability of marine propulsion systems, and how do they account for redundancy in propulsion components?

The Literature Review revealed that deterministic methods have been the traditional baseline to evaluate reliability. However, this methodology assumes constant failure rate and does not consider the reparability of components or the stochastic nature of mechanical failures. To overcome these limitations, probabilistic methods as the Monte Carlo Methods, Bayesian Networks and Discreet Event Simulations have been applied. This thesis combined deterministic calculations and MCM, applying more precise failure distributions, including Weibull models for mechanical components. This resulted in a more realistic availability evaluation that considered the different study cases.

How do different marine propulsion configurations compare in terms of reliability using SOLAS II-1 26.2 as a compliance benchmark?

The deterministic analysis proved that all redundant configurations overcame the reference benchmark established by Case A1. This case fulfilled the minimum requirements established by SOLAS, remaining the most vulnerable configuration due to the high ratio of SPOF and the lack of additional paths to success. At 1000 hours of analysis, Cases A2, B1 and B2 gained availability improvements of 66.2%, 195% and 180% respectively, with respect to a single line propulsion scenario. These results proved that while SOLAS is necessary to ensure safety in single line propulsion systems, it may be overdemanding for redundant and unconventional configurations that achieve these values without including the previously mentioned regulations.

What inconsistencies exist in current regulations regarding availability requirements for different technologies, and how does this affect system design optimization?

The study made in Section 7. Probabilistic Simulations revealed a regulatory inconsistency in the application of the SOLAS II-1 26.2 and 26.3 Convention. Equivalent redundancy criteria were applied to fundamentally different technologies. Evidence was found in the difference in Mean Availability of Cases B1 and B2. While redundancy was introduced in a SPOF, availability was diminished. This proves that redundancy is not the most effective method to increase mean availability in systems that benefit from the high-fidelity of electrical components and the flexibility of a k-out-of-n power generation plant.

How does the reliability of individual systems influence the general propulsion availability and where is the equilibrium point between redundancy and its effect on cost, reliability and safety as defined to comply with environmental regulations?

The sensitivity and importance analysis identified the Auxiliary and the Propulsion and Steering Systems as the most influential subsystems in conventional propulsion configurations. This supports the improvements that SOLAS requires to ensure navigation. On the other side, diesel-electric configurations presented the Propulsion and Steering System as the most relevant subsystem. The intrinsic individual components availability has been found to be the key driver of global availability, rather than the number of installed redundant elements.

The equilibrium point of diminishing returns has been identified at the transition from Case B1 to B2, where complexity and cost increases without obtaining an availability improvement. To assess the environmental compliance, the number of elements and installed power has been considered. At the highest level of availability, it has been observed that the systems with less complexity are the diesel-electric, which have the flexibility to tighten the installed power, reducing the safety buffer of power and reducing emissions.

Therefore, Case B1 has been found the ideal scenario of balance between cost, availability and environmental compliance.

In summary, these findings support a transition in maritime regulations towards goal-based availability standards, enabling designers to optimize propulsion systems according to their technologies, maintaining safety industry standards.

11

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Annex A

Detailed Reliability Block Diagrams

In this section the Reliability Block Diagrams modelled for each case of study are going to be presented. The program used to build the configurations has been ReliaSoft BlockSim. The first graphs to be shown will be the ones that correspond to the conventional propulsion configuration in the two levels of redundancy. The second half will include the diesel-electric diagrams in the two redundancy levels.

| | Diesel | Diesel-Electric |
|-----------|-----------|-----------------|
| Level II | Vessel A1 | Vessel B1 |
| Level III | Vessel A2 | Vessel B2 |

A1 Case Study A1

This configuration represents a **single line Conventional Diesel Propulsion**. The reliability model locates the main propulsion line in series configuration, where the Main Engine and the shafting and steering systems are in series. The redundant elements can be found in the essential auxiliary components as pumps, filters or tanks, which are modelled in parallel improving system's reliability.

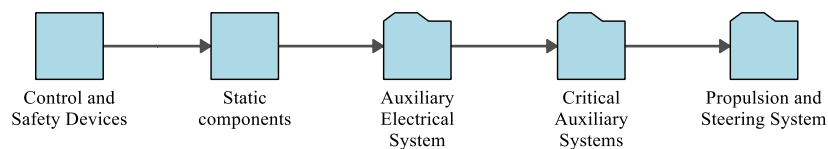


Figure 30. A1 - Main Functions

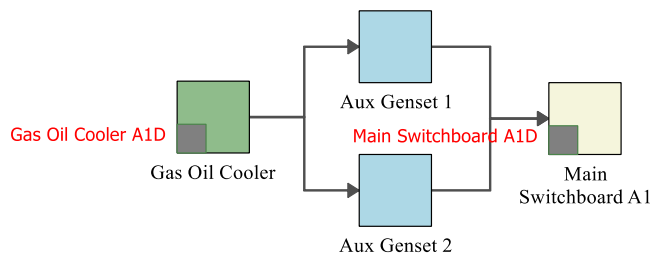


Figure 31. A1 – Auxiliary Electrical System

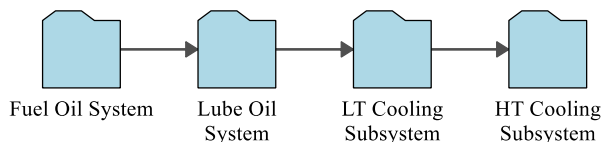


Figure 32. A1 - Auxiliary Systems

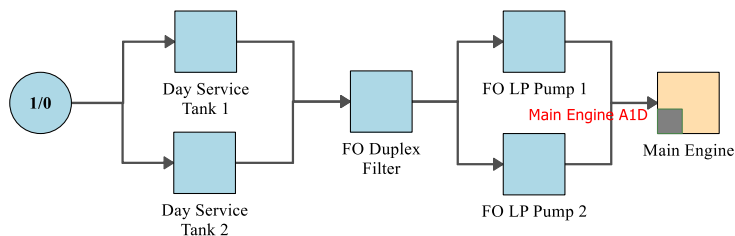


Figure 33. A1 - Fuel Oil Subsystem

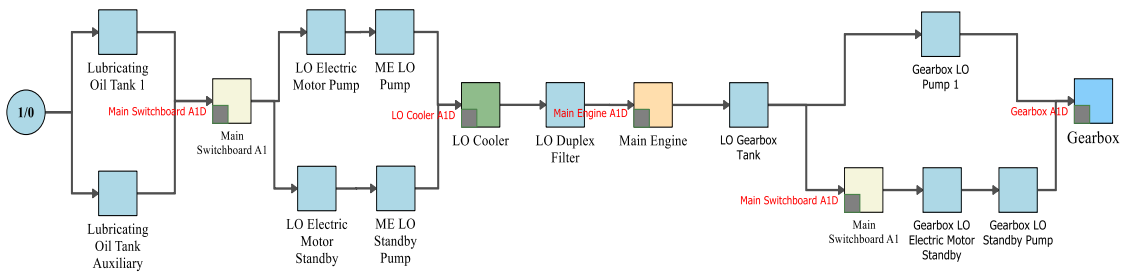


Figure 34. A1 - Lub Oil Subsystem

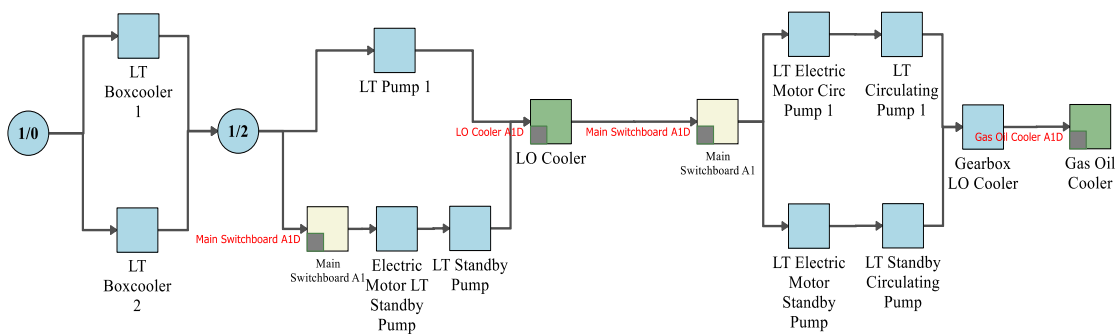


Figure 35. A1 - LT Cooling Subsystem

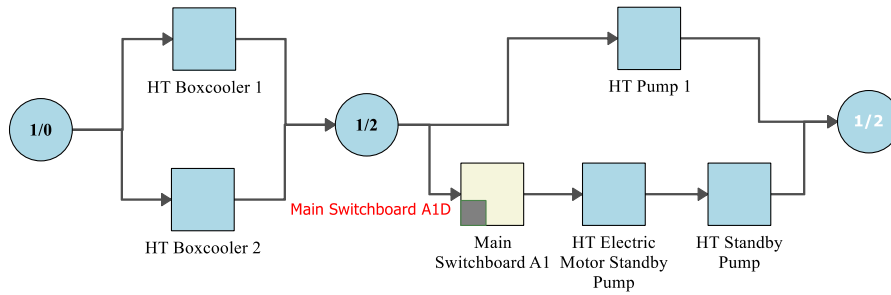


Figure 36. A1 - HT Cooling Subsystem

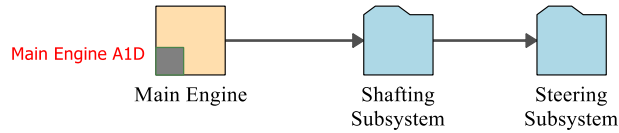


Figure 37. A1 - Propulsion and Steering System

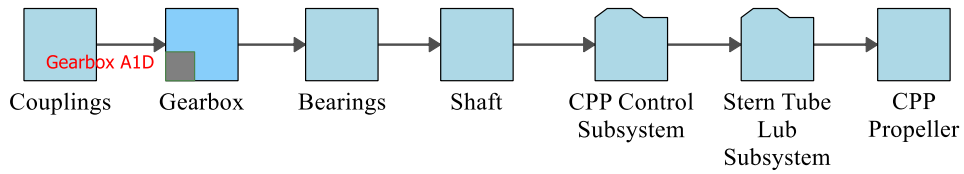


Figure 38. A1 - Shafting Subsystem

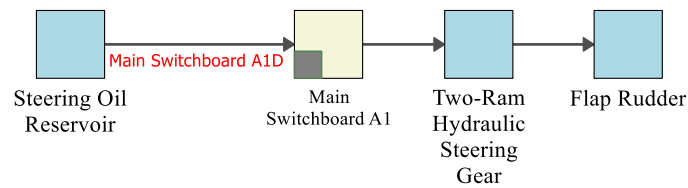


Figure 39. A1 - Steering Subsystem

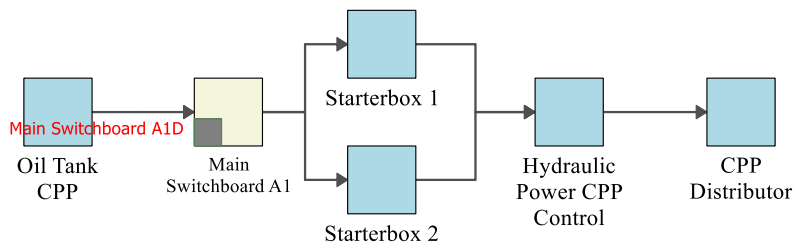


Figure 40. A1 - CPP Control Subsystem

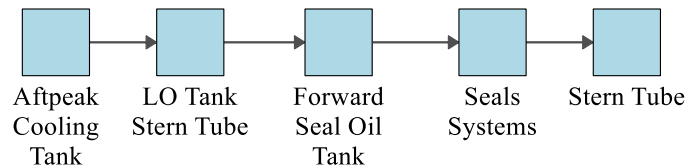


Figure 41. A1 - Stern Tube Lub Subsystem

B1 Case Study A2

The following systems and subsystems represent the configuration of a **Conventional Diesel Propulsion** with **twin propulsion line**, port and starboard side. The Auxiliary Systems and the Propulsion and Steering Systems have a symmetrical configuration, modelled in parallel to improve reliability. Therefore, only the port side has been represented to ensure clarity and avoid repetition. Additional redundancy can be found within the Auxiliary Systems, in elements as pumps, filters and tanks, modelled in parallel.

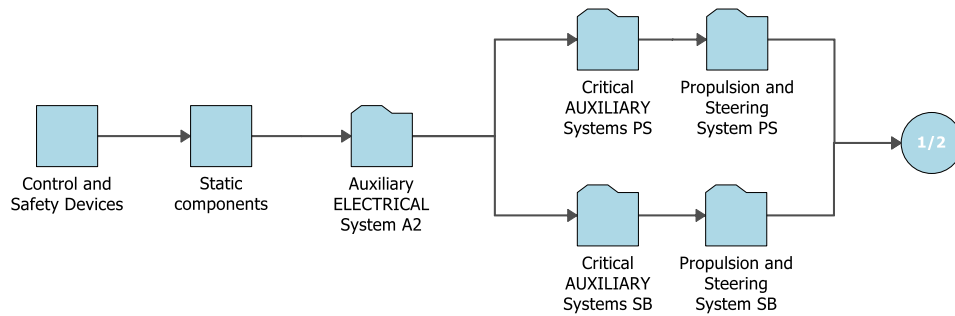


Figure 42. A2 - Main Functions

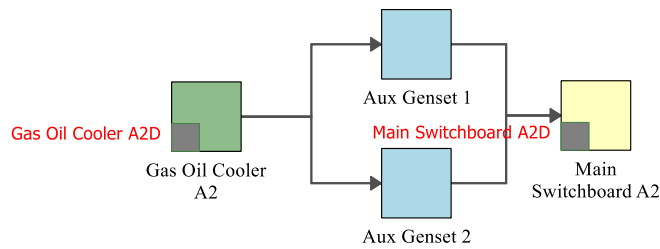


Figure 43. A2 – Auxiliary Electrical System

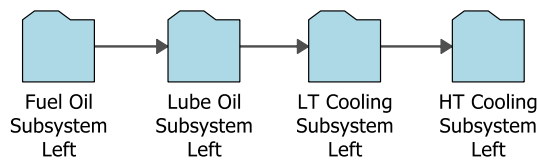


Figure 44. A2 – Auxiliary Systems

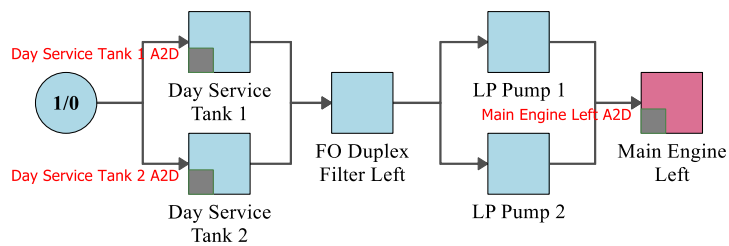


Figure 45. A2 - Fuel Oil Subsystem

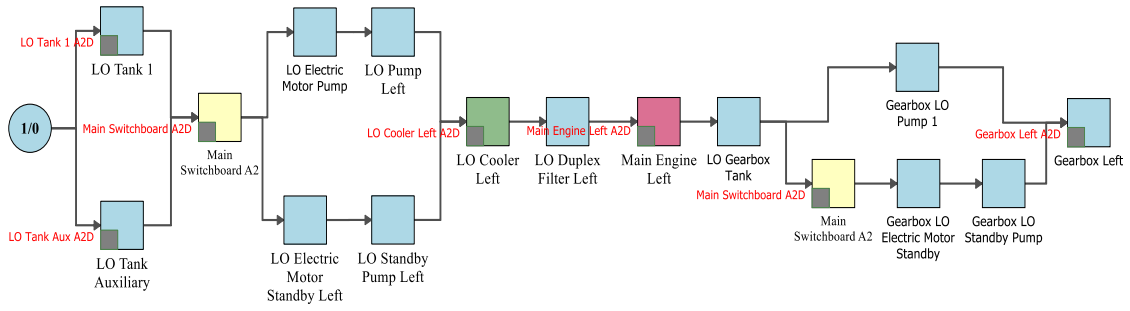


Figure 46. A2 - Lub Oil Subsystem

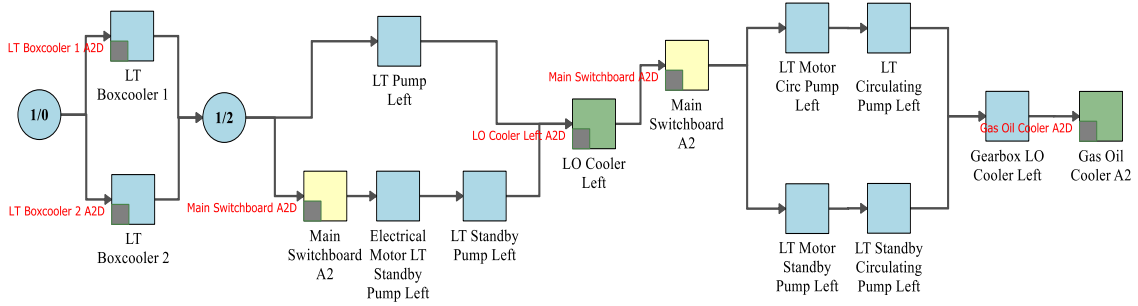


Figure 47. A2 - LT Cooling Subsystem

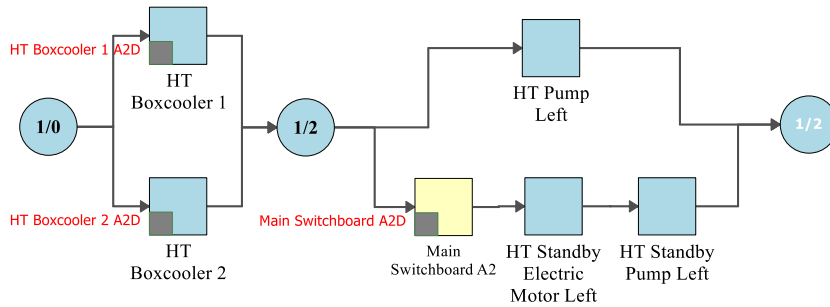


Figure 48. A2 - HT Cooling Subsystem

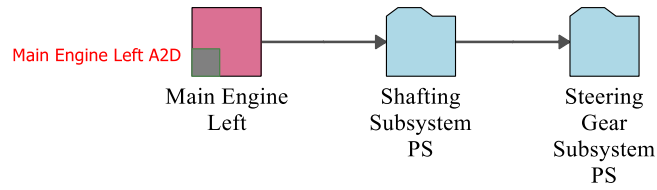


Figure 49. A2 - Propulsion and Steering System

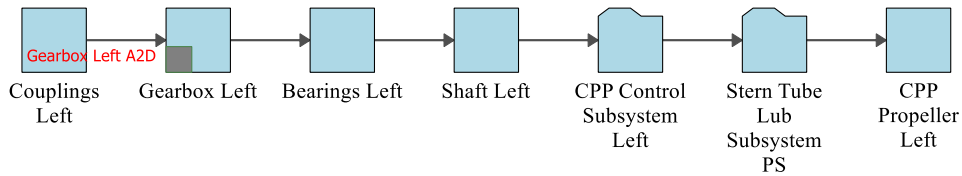


Figure 50. A2 - Shafting Subsystem

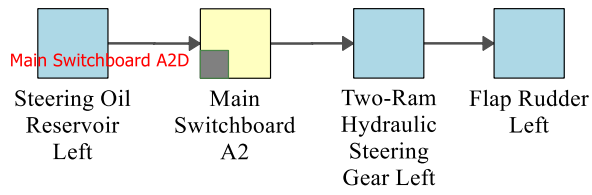


Figure 51. A2 - Steering Subsystem

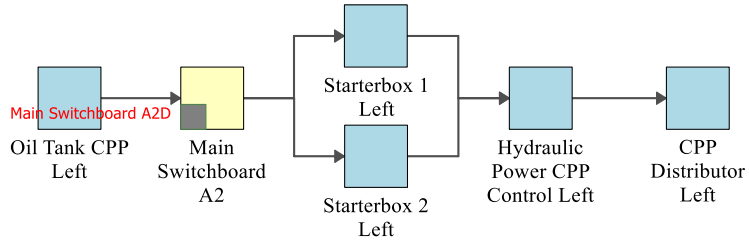


Figure 52. A2 - CPP Control Subsystem

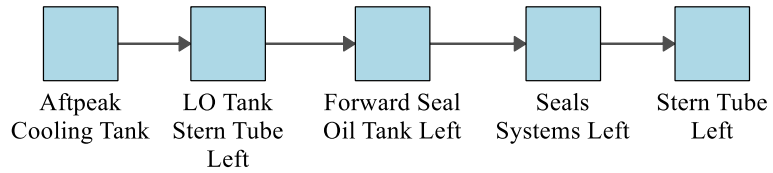


Figure 53. A2 - Stern Tube Lub Subsystem

C1 Case Study B1

The following figures represent a Diesel-Electric Configuration with a functional redundancy approach. The power plant is modelled as a k-out-of-n logic, where at least 2 out of the 4 generators need to be functional to maintain navigable speed. In this case, the Main Switchboard is modelled a single bus bar (closed bus tie), representing a SPOF for power distribution.

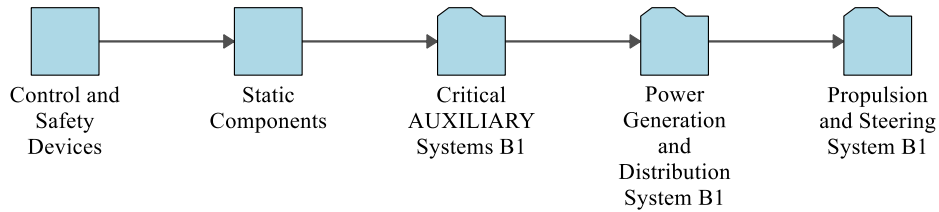


Figure 54. B1 - Main Functions

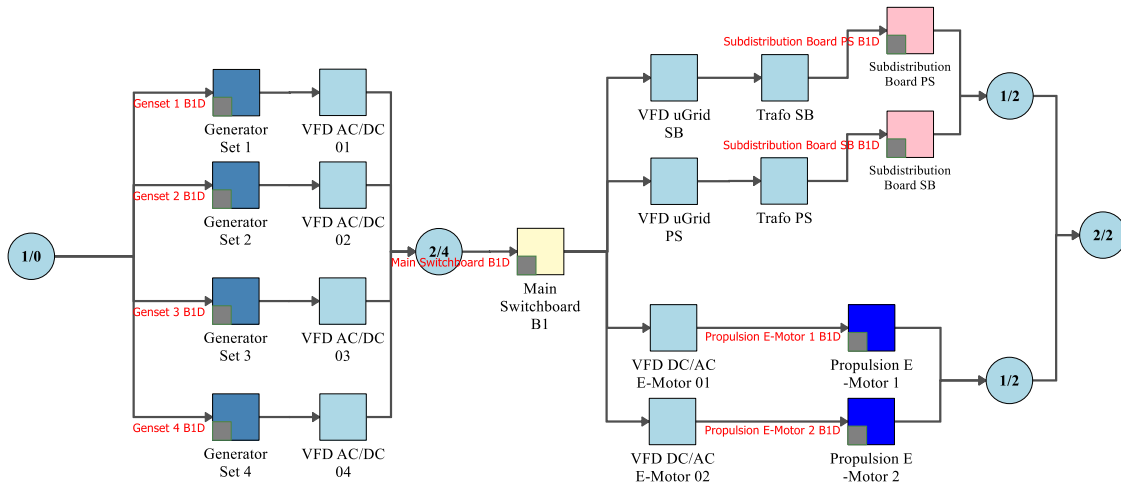


Figure 55. B1 - Power Generation and Distribution System

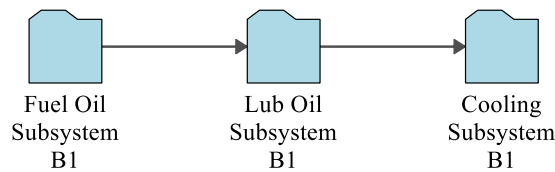


Figure 56. B1 - Auxiliary Systems

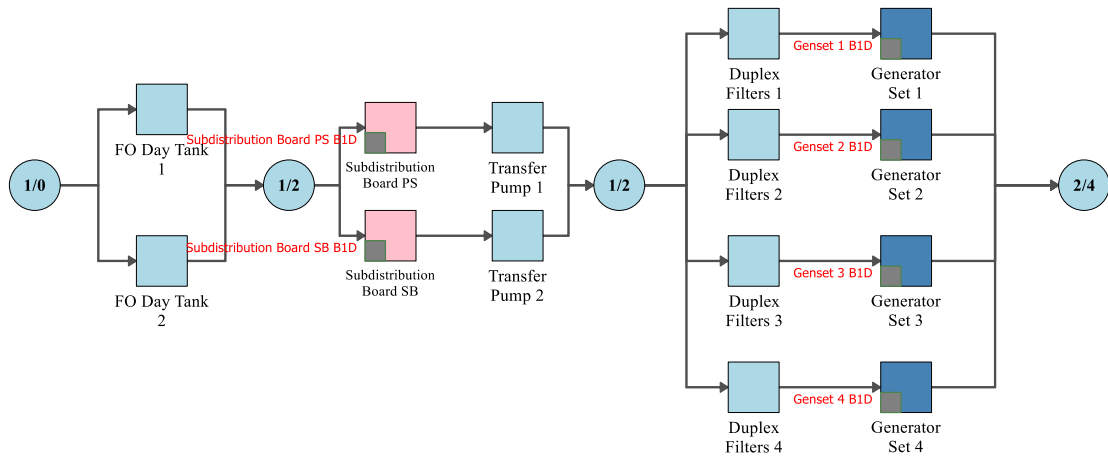


Figure 57. B1 - Fuel Oil Subsystems

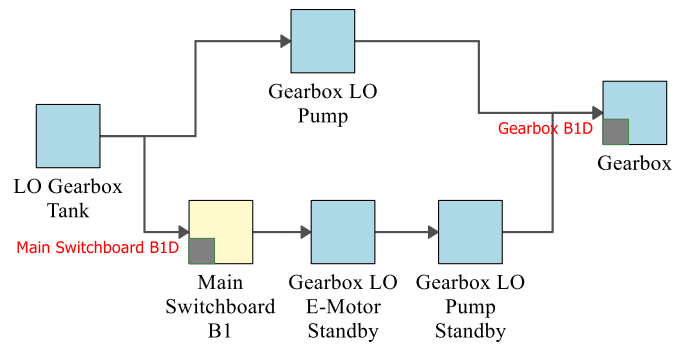


Figure 58. B1 - Lub Oil Subsystem

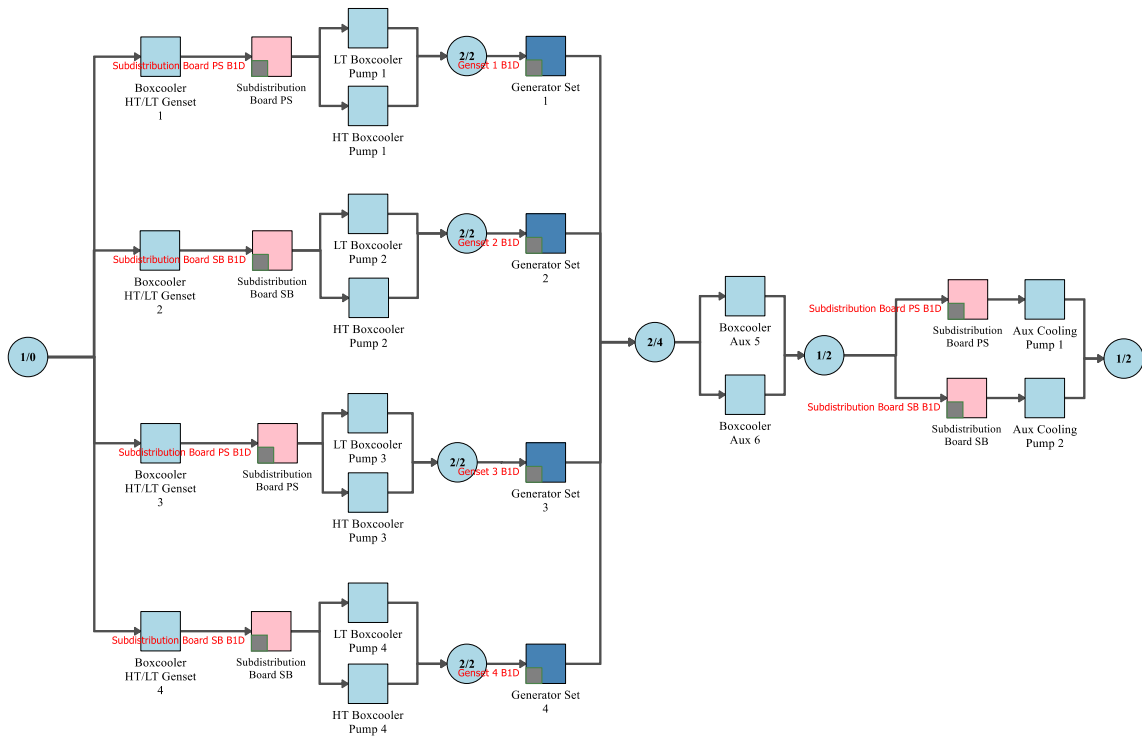


Figure 59. B1 - Cooling Subsystem

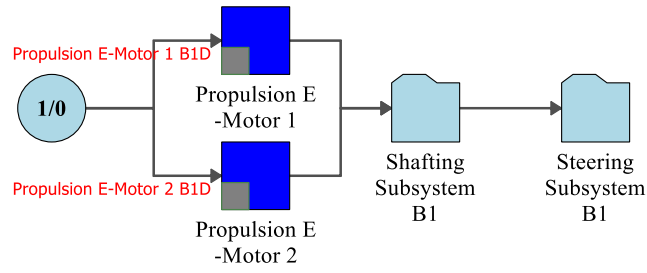


Figure 60. B1 - Propulsion and Steering System

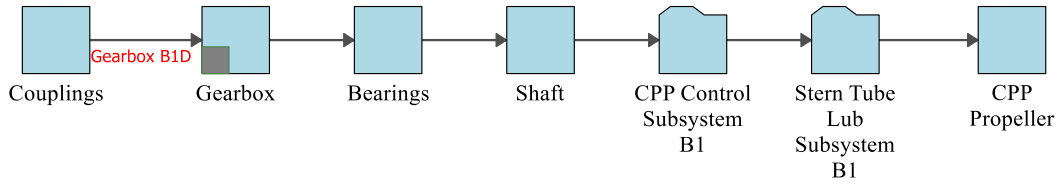


Figure 61. B1 - Shafing Subsystem

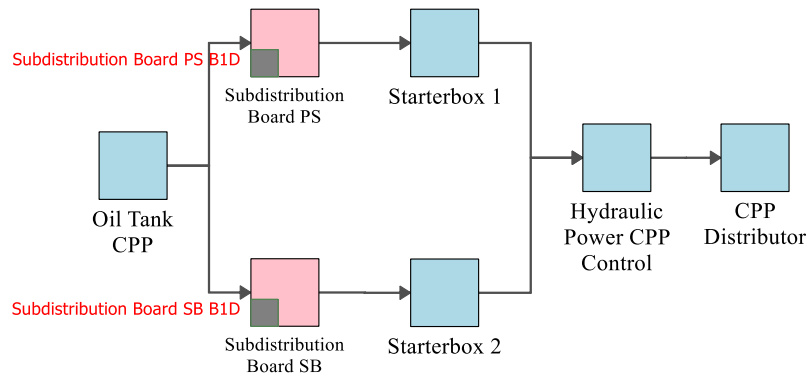


Figure 62. B1 - CPP Control Subsystem

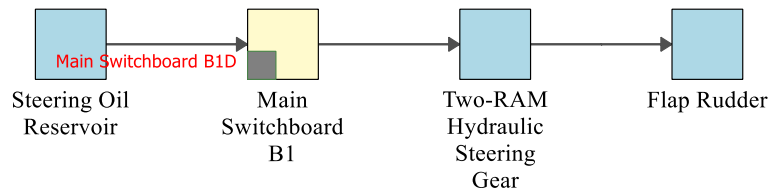


Figure 63. B1 - Steering Subsystem

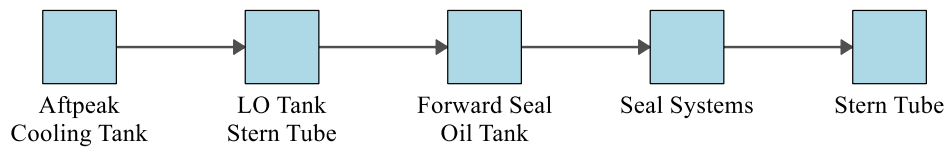


Figure 64. B1 - Stern Tube Lub Subsystem

D1 Case Study B2

Case Study B2 improves the redundancy modelled in the previous case by considering the Main Switchboard as two independent bus bars (open bus tie). This configuration eliminates the Main Switchboard as a SPOF but includes propulsion line segregation. This reduces the transmission of common-cause failures from one bus bar to another.

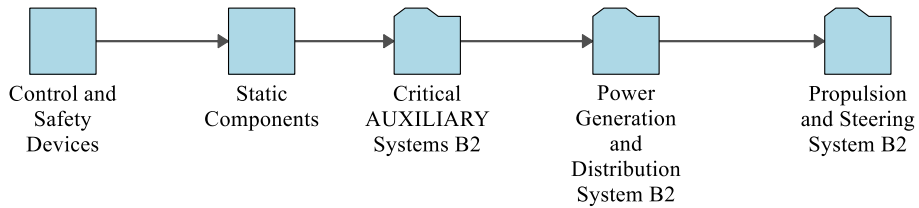


Figure 65. B2 - Main Functions

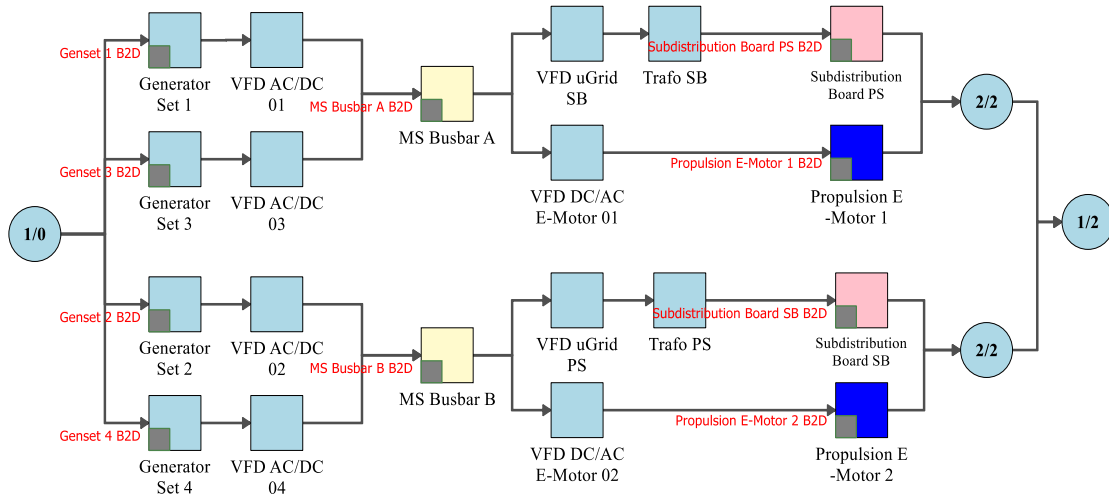


Figure 66. B2 - Power Generation and Distribution System

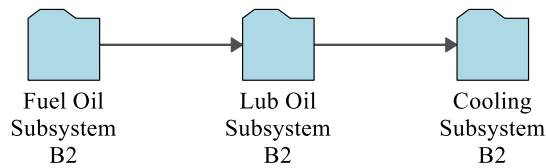


Figure 67. B2 - Auxiliary Systems

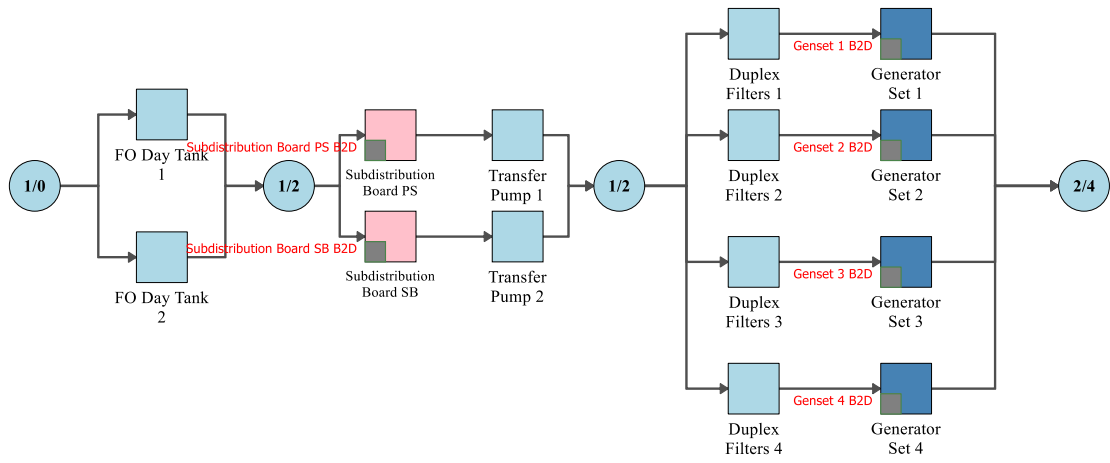


Figure 68. B2 - Fuel Oil Subsystem

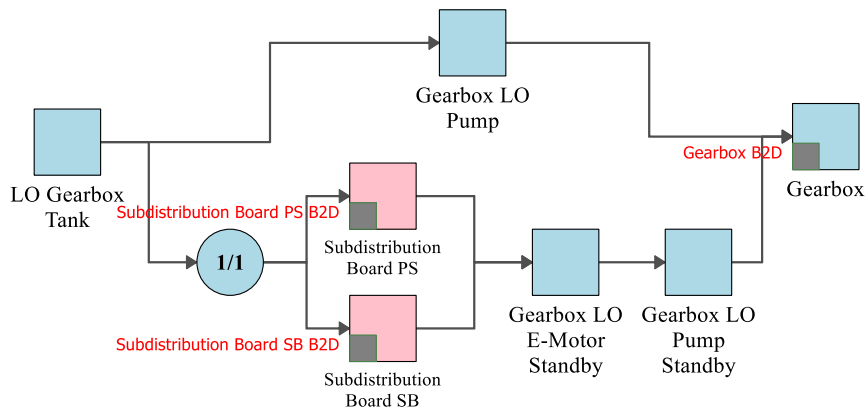


Figure 69. B2 - Lub Oil Subsystem

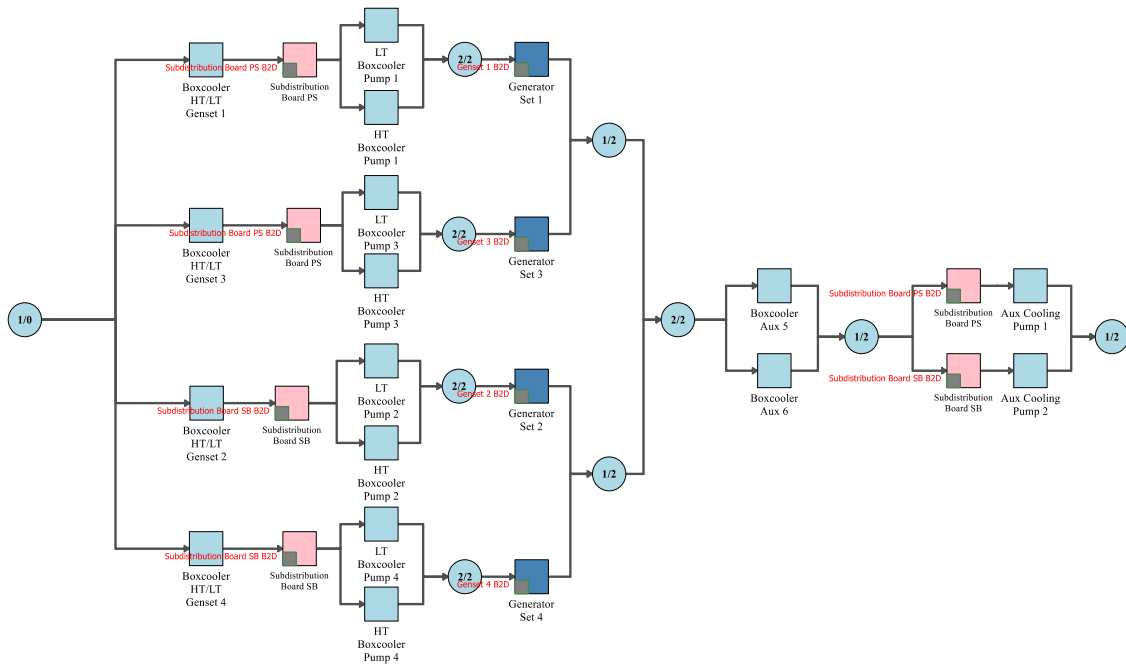


Figure 70. B2 - Cooling Subsystem

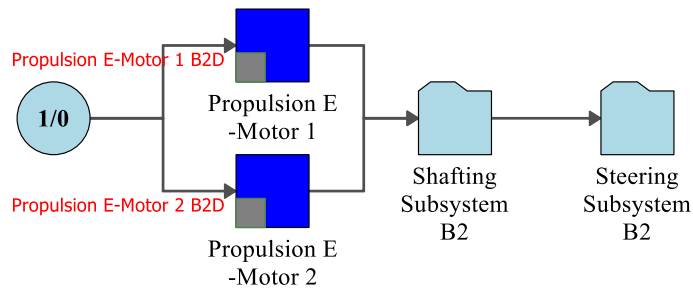


Figure 71. B2 - Propulsion and Steering System

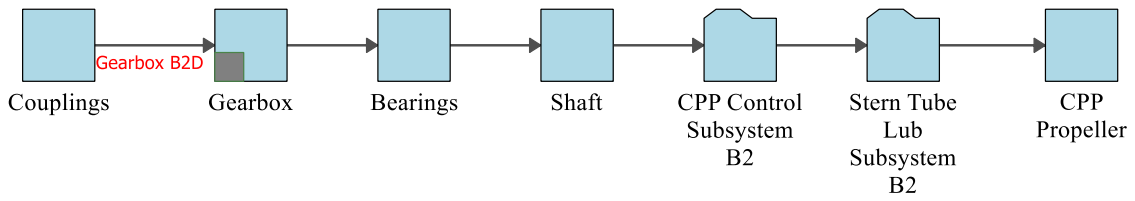


Figure 72. B2 - Shafting Subsystem

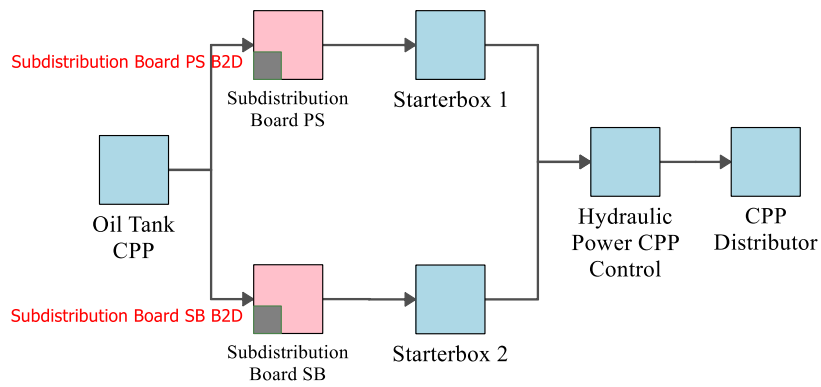


Figure 73. B2 - CPP Control Subsystem

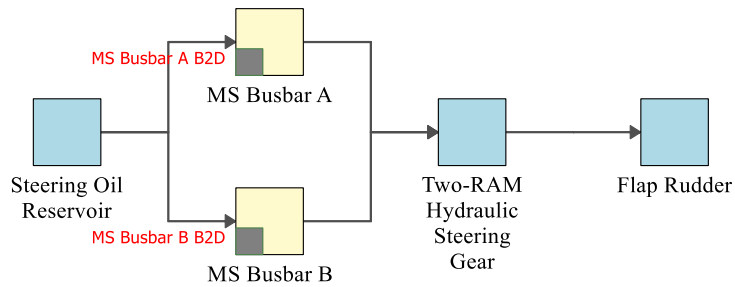


Figure 74. B2 - Steering Subsystem

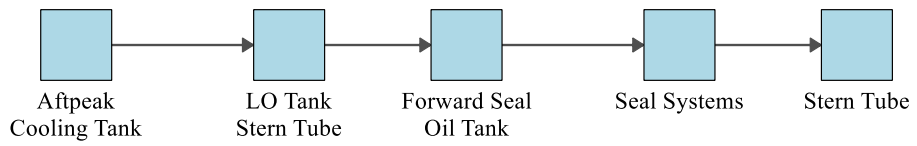


Figure 75. B2 - Stern Tube Lub Subsystem

Annex B

Components Reliability Distributions

This section includes the list of components present in the four Case Studies, the system and subsystem they are part of, and the reliability distributions that have been assigned to each of them with the sources that provided this information. Due to a non-disclosure agreement with OREDA, specific reliability and maintainability values and parameters cannot be shared. However, they have been fully integrated into the simulation models to obtain system results.

Component List Cases A1 and A2

| ID Component | System | Subsystem | Distribution type | Source |
|--------------------------------|----------------|-------------------|-------------------|--------|
| Control System | Main Functions | | Exponential | [8] |
| Static Elements | Main Functions | | Weibull | BV |
| Day service tanks | FO | FO Supply | Exponential | EIREDA |
| FO Duplex filter | FO | FO Supply | Exponential | IAEA |
| FO LP Pump 1 | FO | FO Supply | Weibull | IAEA |
| FO LP Pump 2 | FO | FO Supply | Weibull | IAEA |
| Lubricating Oil Tank 1 | LO | Lub Oil ME Supply | Exponential | EIREDA |
| Lubricating Oil Tank Auxiliary | LO | Lub Oil ME Supply | Exponential | EIREDA |
| LO Electric Motor Pump | LO | Lub Oil ME Supply | Weibull | OREDA |
| LO Pump | LO | Lub Oil ME Supply | Weibull | OREDA |
| LO Electric Motor Standby | LO | Lub Oil ME Supply | Weibull | OREDA |
| LO Standby Pump | LO | Lub Oil ME Supply | Weibull | OREDA |
| LO Cooler | LO | Lub Oil ME Supply | Exponential | OREDA |
| LO Duplex Filter | LO | Lub Oil ME Supply | Exponential | IAEA |

| | | | | |
|---------------------------------|--------------------------------|-------------|-------------|--------|
| LT Boxcooler 1 | Cooling | LT Cooling | Exponential | [61] |
| LT Boxcooler 2 | Cooling | LT Cooling | Exponential | [61] |
| LT Pump 1 | Cooling | LT Cooling | Weibull | OREDA |
| Electric Motor LT Standby Pump | Cooling | LT Cooling | Weibull | OREDA |
| LT Standby Pump | Cooling | LT Cooling | Weibull | OREDA |
| LT Electric Motor Circ Pump 1 | Cooling | LT Cooling | Weibull | OREDA |
| LT Circulating Pump 1 | Cooling | LT Cooling | Weibull | OREDA |
| LT Electric Motor Standby Pump | Cooling | LT Cooling | Weibull | OREDA |
| Standby Circulating Pump | Cooling | LT Cooling | Weibull | OREDA |
| LO Gearbox Cooler | Cooling | LT Cooling | Exponential | OREDA |
| GasOil Cooler | Cooling | LT Cooling | Exponential | OREDA |
| HT Boxcooler 1 | Cooling | HT Cooling | Exponential | [61] |
| HT Boxcooler 2 | Cooling | HT Cooling | Exponential | [61] |
| HT Pump 1 | Cooling | HT Cooling | Weibull | OREDA |
| HT Electric Motor Standby Pump | Cooling | HT Cooling | Weibull | OREDA |
| HT Standby Pump | Cooling | HT Cooling | Weibull | OREDA |
| Main engine ABC 8EL23 | Propulsion and Steering System | | Weibull | OREDA |
| Coupling | Propulsion | Shafting | Weibull | NPDR |
| Gearbox | Propulsion | Shafting | Weibull | OREDA |
| Bearings | Propulsion | Shafting | Weibull | OREDA |
| Shaft | Propulsion | Shafting | Weibull | NPDR |
| CPP Propeller | Propulsion | Shafting | Weibull | NPDR |
| Steering Oil Reservoir | Propulsion | Steering | Exponential | OREDA |
| Two-Ram Hydraulic Steering Gear | Propulsion | Steering | Weibull | NPDR |
| Flap Rudder | Propulsion | Steering | Weibull | BV |
| Oil Tank CPP | Propulsion | CPP Control | Exponential | EIREDA |
| Starterbox 1 | Propulsion | CPP Control | Exponential | NPDR |
| Starterbox 2 | Propulsion | CPP Control | Exponential | NPDR |
| Hydraulic Power CPP Control | Propulsion | CPP Control | Weibull | NPDR |
| CPP Distributor | Propulsion | CPP Control | Weibull | NPDR |

| | | | | |
|------------------------------|------------|----------------|-------------|--------|
| Aftpeak Cooling Tank | Propulsion | Stern Tube Lub | Exponential | EIREDA |
| LO Tank Stern Tube | Propulsion | Stern Tube Lub | Exponential | EIREDA |
| Forward Seal Oil Tank | Propulsion | Stern Tube Lub | Exponential | EIREDA |
| Seals Systems | Propulsion | Stern Tube Lub | Weibull | NPDR |
| Stern Tube | Propulsion | Stern Tube Lub | Weibull | NPDR |
| Aux Genset 1 | Electrical | Auxiliary Gen | Weibull | OREDA |
| Aux Genset 2 | Electrical | Auxiliary Gen | Weibull | OREDA |
| Main Switchboard | Electrical | Auxiliary Gen | Exponential | IEEE |

Component List Cases B1 and B2

| ID Component | System | Subsystem | Distribution type | Source |
|------------------------------------|-----------------------------------|-----------|-------------------|--------|
| Control and Safety Devices | Main Function | | Exponential | [8] |
| Static Components | Main Function | | Weibull | BV |
| Generator Set 1234 | Power Generation and Distribution | | Weibull | OREDA |
| Circuit Breaker | Power Generation and Distribution | | Exponential | IEEE |
| VFD AC/DC | Power Generation and Distribution | | Weibull | IEEE |
| Main Switchboard Closed Tie | Power Generation and Distribution | | Exponential | IEEE |
| VFD DC/AC uGrid and E-Motor | Power Generation and Distribution | | Weibull | IEEE |
| Trafo | Power Generation and Distribution | | Weibull | IEEE |
| Subdistribution Board | Power Generation and Distribution | | Exponential | IEEE |
| FO Day Tank | FO | | Exponential | EIREDA |
| Transfer Pump | FO | | Weibull | IAEA |
| Duplex Filters | FO | | Exponential | IAEA |
| LO Gearbox Tank | LO | | Exponential | EIREDA |
| Gearbox LO Pump | LO | | Weibull | OREDA |
| Gearbox LO E-Motor Standby | LO | | Weibull | OREDA |
| Gearbox LO Pump Standby | LO | | Weibull | OREDA |
| Gearbox | LO | | Weibull | OREDA |
| Boxcooler HT/LT Genset | Cooling | | Exponential | [61] |
| LT Boxcooler Pump | Cooling | | Weibull | OREDA |
| HT Boxcooler Pump | Cooling | | Weibull | OREDA |
| Boxcooler Aux | Cooling | | Exponential | [61] |
| Aux Cooling Pump | Cooling | | Weibull | OREDA |

| | | | | |
|--|--------------------------------|-----------------------|-------------|-----------------|
| Propulsion E-Motor | Propulsion and Steering System | | Weibull | OREDA |
| Couplings | Propulsion | Shafting | Weibull | NPDR |
| Bearings | Propulsion | Shafting | Weibull | OREDA |
| Shaft | Propulsion | Shafting | Weibull | NPDR |
| CPP Propeller | Propulsion | Shafting | Weibull | NPDR |
| Oil Tank CPP | Propulsion | CPP Control Subsystem | Exponential | EIREDA |
| Starterbox | Propulsion | CPP Control Subsystem | Exponential | NPDR |
| Hydraulic Power CPP Control | Propulsion | CPP Control Subsystem | Weibull | NPDR |
| CPP Distributor | Propulsion | CPP Control Subsystem | Weibull | NPDR |
| Steering Oil Reservoir | Propulsion | Steering | Exponential | EIREDA |
| Two-RAM Hydraulic Steering Gear | Propulsion | Steering | Weibull | NPDR |
| Flap Rudder | Propulsion | Steering | Weibull | BV |
| Aftpeak Cooling Tank | Propulsion | Stem Tube Lub | Exponential | EIREDA |
| LO Tank Stern Tube | Propulsion | Stem Tube Lub | Exponential | EIREDA |
| Forward Seal Oil Tank | Propulsion | Stem Tube Lub | Exponential | EIREDA |
| Seal Systems | Propulsion | Stem Tube Lub | Weibull | Lagersmit |
| Stern Tube | Propulsion | Stem Tube Lub | Weibull | Berg Propulsion |

Annex C

Summary of Research Articles

| Year | Publisher | Methodology | Key Findings |
|-------------|-------------------------|---------------------------------|---|
| 2021 | Elsayed [6] | Deterministic | Provides fundamental reliability and availability concepts. Deterministic calculation models. |
| 2022 | Bayraktar and Nuran [8] | Deterministic | RAM analysis with several sources of failure data. |
| 2018 | Jeong et al. [9] | Comparative | Gives insight into decision-making criteria for different propulsion configurations, considering costs, risks and emissions. |
| 2008 | Insel [11] | Probabilistic | Uses MCM to evaluate system's reliability considering that this approach captures better the probabilistic distributions of mechanical components. |
| 2026 | Akula [12] | Deterministic and probabilistic | Reliability study of a power grid system that applies RBD to do the deterministic analysis and considers reparability in the availability calculations. |
| 2020 | Yang and Sørensen [13] | Probabilistic | Novel approach to estimate availability in different states for an offshore structure. Applies Monte Carlo Simulations to obtain failure times of the systems components and considers reparations. |
| 2025 | Zhu [21] | Probabilistic | Study that applies Monte Carlo Simulations to compare the reliability of manned and unmanned vessels. |

| | | | |
|------|-------------------------|---------------|--|
| 2022 | Eriksen and Lützen [15] | Probabilistic | Probabilistic study that analyses the effects of redundancy and dependant failures and how it affects reliability. |
| 2024 | Ware and Collette [16] | Probabilistic | Introduced OREDA as a valuable database, Probabilistic analysis applying the RBD logic to compare the reliability of propulsion subsystems with different types of redundancy. |
| 2018 | Tarelko [10] | Comparative | Studies the effects of redundancy in availability considering types of redundancies and SOLAS II-1 26.2 |

MGO Separator

Gen. cooling

Gen. cooling

ER VENT

ENGINE ROOM

ER VENT

Gen. cooling

Gen. cooling

10

15

20

UP

DN

ALARM SYSTEM

CONVERTER ROOM

ble pipe duct

Main

controls

G4

G3

G2

G1

WATER