Siri Trige
Frida Volden Tiller

Life Cycle and Risk Assessment of Implementation of Rotor Sails on Chemical Tanker

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
June 2023

Master's thesis

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MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2023

For stud. techn.

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Background

Ways to decrease emissions in the shipping industry are a hot topic, awaiting new emission restriction legislation from both the EU and IMO in the future. Most of the attention is on zero-emission fuels, newbuilds, and how they can be completely green. In the meantime, thousands of ships will operate for another 5-30 years, where significant retrofits to switch propulsion systems are not an option. Adding energy-saving or energy-harvesting devices that do not require complete retrofits may be an excellent option to cut emissions on already existing ships. Rotor sails are one such device that is relatively simple to install. Theoretically, ships can save up to 30% in power savings. However, the technology has yet to be extensively tested in practical situations on actual ships. Lack of experience and high investment costs are why ship owners opt for other solutions when looking into energy-saving devices for their ships.

Objective

This thesis aims to decide whether the implementation of rotor sails on an existing chemical tanker vessel will be beneficial concerning power savings, emission reduction, costs, including change in risk level. The results will regard a specific ship but could be helpful to decision-makers in other cases as well.

Tasks
The candidate is recommended to cover the following parts in the project thesis:

a. Review state of art within the topic. That means to document what others have done and published previously.
b. Document the system in which the problem is located.
c. Document the problem in a generic way.
d. Document relevant approaches and methods for addressing and solving the problem and choosing an approach/method for one's own work.
e. Conduct an LCA consisting of:
    a. Goal and scope definition

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   - b. Inventory analysis
   - c. Impact assessment
   - d. Interpretation of results
   - e. Cost analysis (LCC)

f. Conduct a risk assessment consisting of:
   - a. Change analysis for the system
   - b. Assessment of identified important risk factors.

g. Discuss strengths and improvement potential in one's approach and work – with respect to conclusions.

h. Suggestions for further work.

General
In the thesis the candidates shall present their personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Supervision:
Main supervisor: Prof. Bjørn Egil Asbjørnslett
Company contact at Odfjell Management: Jan Arne Opedal

Deadline: 11.06.2023

Trondheim, January 2023

Preface

This master thesis is the final work of our Master of Science degree in Marine Technology at the Norwegian University of Science & Technology (NTNU). The thesis corresponds to 30 credits and is written during the spring semester of 2023.

We both started this degree in the fall of 2018. In our third year, Frida chose to specialize in marine systems design and Siri in safety and asset management. In our fourth year, we spent a semester at Universidad Politécnica de Cartagena (UPCT) in Spain, but the rest of the degree has been completed in Trondheim at NTNU.

When deciding on what we wanted our thesis to focus on, we were especially interested in improving fuel efficiency on existing ships or making them greener. After discussions with our supervisor and opening contact with Odfjell, the most mutually interesting choice was the implementation of rotor sails. With our different specializations, it was natural to consider this from a life cycle and risk perspective.

While we both have more substantial knowledge than the other within some topics, we have had many of the same courses and have, in essence, collaborated on all parts of the thesis. As a result, all the parts of the thesis have interested us both, and the cooperation has been effortless.

Frida Volden Tiller and Siri Trige

Trondheim, June 2023

Frida V. Tiller

Siri Trige

Acknowledgments

We would like to express our appreciation to our supervisor Professor Bjørn Egil Asbjørnslett, for invaluable discussions and excellent guidance. Also, this endeavor would not have been possible without our collaboration with Odfjell. We would especially like to thank Jan Arne Opedal and colleagues, who provided us with guidance and data for this project.

We want to give our sincerest thanks to postdoc researcher Dražen Polić, who assisted us with rotor sail power generation calculations from outside of our expertise. His guidance and sharing of knowledge has been priceless.

We are also very grateful for the continuous support and discussions with classmates and friends. Discussions with our fellow student Martin Sande Rygg, who used some of the same methods and software, have been especially fruitful.

In the end, we would like to thank each other for support, inspiration, and friendship throughout the years and master thesis work.

Summary

This master thesis examines the implementation of rotor sails as an aid in propulsion for ships using life cycle and risk assessment. The primary focus is implementation on existing vessels rather than those that are built with the use of energy-harvesting devices in mind. The reason for this is to decrease the emissions of the already existing fleet that will continue to sail for another 10 to 30 years.

Implementing energy-saving and energy-harvesting technologies onboard ships is a highly relevant topic; however, many technologies remain untested. The goal is that the assessments will make it easier to evaluate rotor sails as a possible energy-harvesting solution for existing ships. Throughout the thesis, we describe the theory and methods relevant to the problem. This includes theory and research about rotor sails, regulations and policies, and descriptions of the methods used within life cycle analysis and risk assessment.

The life cycle assessment results show that ship operation with rotor sails will have lower emissions and fuel consumption than regular operation. Expected power savings for the main machinery are 10.5% and total expected power savings are 9.2%. The total expected power savings are lower because of the power consumed by the rotor sails during operation. Power savings are also calculated for calm sea and heavy sea, where the expected power savings for the main machinery are 12.3% and 8.7%, respectively. The expected power savings for different operational speeds are also calculated to better understand the ship's operation with rotor sails. The impact assessment of the life cycle assessment results in an 11.5% expected reduction of global warming impact and an improvement for human health equal to 80 years of full health.

The subsequent cost analysis shows that whether implementing rotor sails on the ship is economically profitable is highly dependent on the fuel price. Predicting fuel price was not part of the scope of this thesis, but the results have been presented for three fuel price cases: high (1200 USD/t), medium (500 USD/t), and low (200 USD/t). The results show that the payback period is between 5 years and longer than the remaining lifetime of the ship (20 years), depending on the fuel price. Additionally, the cost results show that costs linked to the auxiliary machinery will increase with rotor sails. This is because the rotor sails use the auxiliary engines as their power supply, thereby increasing their overall load.

Through the risk assessment, it was discovered that the most crucial change to the established system was a change in explosion risk. An explosion risk assessment showed that the general explosion risk increased by 47.2% when rotor sails without ATEX-compliancy were implemented. When the rotor sail was ATEX compliant, the increase was 23.2%, about half of before. The worst case leads to a new general explosion risk of 0.002583, which is still acceptable.

It was concluded that implementing rotor sails on the chemical tanker would be environmentally beneficial and safe but economically dependent on the fuel price. The operational costs vary with the fuel costs. For fuel prices lower than around 500 USD/t, which is today's price, the installation and operation of rotor sails will not be beneficial from an economic perspective.

Sammendrag

Denne masteroppgaven undersøker implementering av rotorseil som fremdriftshjelpemiddel på skip ved hjelp av livssyklus- og risikovurderinger. Hovedfokuset er implementering på eksisterende skip, og ikke på skip som er bygget med tanke på bruk av energihøstende teknologi. Grunnen til dette er at man ønsker å redusere utslippene fra den eksisterende flåten som vil fortsette å seile i 10 eller 30 år til.

Implementering av energibesparende og energihøstende teknologier om bord på skip er et høyst relevant tema, men mange løsninger er fortsatt uprøvde. Målet er at vurderingene skal gjøre det lettere å evaluere rotorseil som en mulig løsning for energihøsting på eksisterende skip.

I oppgaven beskriver vi teori og metoder som er relevante for problemstillingen. Dette inkluderer teori og forskning om rotorseil, regelverk og retningslinjer, og beskrivelser av metodene som brukes innen livssyklusanalyse og risikovurdering.

Resultatene fra livssyklusanalysen viser at drift av skipet med rotorseil vil ha lavere utslipp og drivstofforbruk enn vanlig drift. Forventet reduksjon av hovedmaskineriets energiforbruk er 10,5% og total forventet energireduksjon er 9,2%. Den totale forventede besparelsen er lavere på grunn av energibehovet til rotorseilene under drift. Det er også beregnet besparelser for rolig og kraftig sjø, der de forventede besparelsene for hovedmaskineriet er henholdsvis 12,3% og 8,7%. De forventede energibesparelsene for ulike skipshastigheter er også beregnet for å få en bedre forståelse av skipets drift med rotorseil. Konsekvensanalysen av livssyklusvurderingen viser en forventet reduksjon av bidrag til global oppvarming 11,5% og en forbedring av menneskers helse tilsvarende 80 år med full helse.

Den påfølgende kostnadsanalysen viser at hvorvidt det er økonomisk lønnsomt å implementere rotorseil på skipet, avhenger i stor grad av drivstoffprisen. Å forutsi drivstoffprisen var ikke en del av denne oppgaven, men resultatene er presentert for tre mulige tilfeller for drivstoffpris: høy (1200 USD/t), middels (500 USD/t) og lav (200 USD/t). Resultatene viser at tilbakebetalingstiden er mellom 5 år og lengre enn skipets gjenværende levetid (20 år), avhengig av drivstoffprisen. I tillegg viser resultatene at kostnadene knyttet til hjelpemaskineriet vil øke ved å implementere rotorseil. Dette skyldes at rotorseilene bruker hjelpemotorene som strømforsyning og dermed øker den totale belastningen.

Gjennom risikovurderingen ble det oppdaget at den mest avgjørende endringen i det etablerte systemet var eksplosjonsrisikoen. Eksplosjonsrisikovurderingen viste at den generelle eksplosjonsrisikoen økte med 47,2% da rotorseil uten ATEX-kompatibilitet ble implementert. Når rotorseilene er ATEX-kompatible, er økningen på 23,2%, omtrent halvparten av tidligere. Det verste tilfellet førte til en ny generell eksplosjonsrisiko på 0,002583 som fortsatt er akseptabelt.

Det ble konkludert med at implementering av rotorseil på kjemikalietankeren vil være sikkert og miljømessig gunstig, men økonomisk avhengig av drivstoffprisen. Driftskostnadene varierer med drivstoffkostnadene. Med drivstoffpriser lavere enn rundt 500 USD/t, som er dagens pris, vil installasjon og drift av rotorseil ikke være økonomisk gunstig.

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Nomenclature

Abbreviations

AoPs	Areas of Protection
CII	Carbon Intensity Indicator
CMEMS	Copernicus Marine Environment Monitoring Service
DALY	Disibility-Adjusted Life Years
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency eXisting ship Index
ETA	Event Tree Analysis
EU ETS	European Union Emission Trading System
FMECA	Failure Modes, Effects, and Criticality Analysis
FTA	Fault Tree Analysis
GHG	Greenhouse Gasses
GWP	Global Warming Potential
HAZOP	Hazard and Operability
HEP	Human Error Probability
HRA	Human Reliability Analysis
IHA	Ignition Hazard Assessment
IMO	International Maritime Organization
ISO	International Organization for Standardization
JSA	Job Safety Analysis
LCA	Life Cycle Assessment
LCB	Longitudinal Center of Buoyancy
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEL	Lower Explosive Limit
MLD	Master Logic Diagram
NCR	Nominal Continuous Rating
NPV	Net Present Value
PHA	Preliminary Hazard Analysis
PV	Pressure Vacuum (masts)
RPM	Revolutions Per Minute
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SMCR	Specified Maximum Continuous Rating
STPA	Systems-Theoretic Process Analysis
SWIFT	Structured What-If Technique

TWA	True Wind Angle
TWS	True Wind Speed
UEL	Upper Explosive Limit
WACC	Weighted Average Cost of Capital
WASP	Wind Assisted Ship Propulsion

Symbols

A	Requirements matrix
C	Characterization matrix
c_L	Lift coefficient
d	Total impacts vector
D_{str}	Total impacts matrix per stressor
D_{pro}	Total impact matrix per process
e	Total stressor vector
E	Total stressor matrix for each process
I	Identity matrix
L	Leontief Inverse
L_{OA}	Length Overall
P_{noWASP}	Required power for ship without WASP
P_{req}	Required power
P_s	Power saved
r	Normalized yaw angular speed
S	Stressor matrix
T_{prop}	Required trust for the propeller
u	Surge velocity
x	Output vector
y	External demand vector
Y	Hydrodynamic derivative
Z	Flow matrix
β	Drift angle of vessel
η_e	Efficiency from mechanical energy to electrical energy
η_p	Efficiency of propeller

Chapter 1

Introduction

A huge focus point for the shipping industry is greenhouse gas (GHG) emission reduction. The coming EU regulations with goals of 55% emission reduction from 1990-2030 and climate neutrality within 2050 are only one of the drivers of this development. Additionally, access to investors, capital, and customer expectations are applying pressure for lower emission operations [1]. Much of the focus is on how to make new-built ships as low-emitting as possible; however, many ships in operation will be in operation for another 10-30 years, and these ships must be considered as well. Major retrofits on existing ships are expensive and may be technically complex, especially compared to the possible savings. Smaller energy-saving or energy-harvesting devices are likely better for ships where complicated retrofits with, for example, new engines are not an option.

The implementation of alternative fuels has sparked debates within the maritime sector regarding the reduction of GHG emissions. Many of these zero-carbon fuels, such as E-Ammonia and E-Hydrogen, are made using electricity from renewable sources. However, if the entire maritime sector were to transition to these E-fuels, energy consumption would increase significantly, potentially doubling or tripling the current levels when considering the entire life cycle [2]. This renewable energy could be more useful in other sectors where GHG emissions are a more significant problem and do not have renewable energy sources as readily available. Ships, for instance, have the potential to utilize wind energy for propulsion to a higher degree than other transport segments.

Currently, there are many options for energy-saving and energy-harvesting devices for use on ships. These include different kinds of hull appendages, flow-improving propeller attachments, solar panels, wind sails, and more. They all exist to varying degrees of intervention on the ship and varying costs. One of these solutions is rotor sails, made to harvest wind power for ship propulsion.

Rotor sails, or Flettner rotors, are a relatively simple retrofit for most ships. There are several providers today, but the technology has yet to be extensively tested. Furthermore, only a few ships have installed the rotor sails, so in our thesis, we would like to explore the implications of installing rotor sails on existing ships. If the industry is going to embrace this technology, it is essential to determine how emissions, risks, and costs will be affected. Our thesis will focus on life cycle assessment (LCA), risk assessment, and cost-benefit analysis to uncover the implications.

In order to determine whether the solution is cost-efficient and environmentally acceptable, combining different methods to evaluate the different options is helpful. First, the processes can be analyzed with an LCA to predict the emissions before and after implementing rotor sails. In addition, the power savings and costs will be analyzed to have a better basis for the decision of implementing rotor sails or not. A risk assessment will assess whether implementing rotor sails on the ship will impact the risk picture on board. Even if savings and costs look beneficial for the ship owner, safety must also be considered. Placing new moving machinery on deck can impact the risk levels for the crew, visibility, fire/explosion, supplying machinery, and stability. All these must be considered to evaluate whether the rotor sails are a justifiable investment.

The objectives of this master thesis are to investigate whether implementing rotor sails on an existing chemical tanker vessel is beneficial regarding power savings, emission reduction, costs, and increased risk. To find out whether the installation is a viable option for existing ships, we have a collaboration with Odfjell - a chemical tanker shipping company based in Bergen. We will consider a series of sister vessels that sail mostly deep sea.

Chapter 2

Problem Description

2.1 Information about the Ships

The series of ships we are looking at are deep-sea chemical tanker vessels. They generally transport chemicals throughout most of the world, and the ships have capacity to carry many different cargoes in their 32 separate tanks with a summer DWT of 49 100 Mt. The overall length is 183 m, moulded breadth is 32 m, and moulded depth is 20 m. The ships are relatively new with build years of 2019 and 2020, which means the majority of their planned lifetime is still ahead of them.

2.2 Presentation of Problem

Wind-assisted ship propulsion (WASP) is a method of reducing emissions on ships, being explored as a means for a more sustainable shipping industry. However, if the industry shall embrace such a solution, it must be shown to be financially sustainable, that it attains actual results, and that it is safe.

Much effort is being put into exploring the best options for new ships and how these can be constructed for zero- or low-emission operation. However, in the meantime, thousands of ships are still planned to operate for another 10-30 years. Therefore, if the shipping industry is going to succeed in lowering its emissions altogether, lowering emissions from these existing ships must also be considered.

For this reason, it is interesting to explore quantitatively the life cycle effects and risks for an existing ship when implementing an energy-saving device. Namely, the energy-saving device considered in this thesis is rotor sails. A technology established on the market, with several providers, but has yet to be implemented on many ships. This is likely due to the high cost without the promise of significant savings.

The uncertainty around savings, despite sound theoretical studies, is linked to the fact that savings from any WASP will be highly individual to each ship. It will depend on route and wind profiles, operational profile, and placement. Additionally, monetary savings will be highly dependent on the development of fuel prices in the future.

Ships are generally not constructed with the possibility of adding more equipment later in mind. Adding devices that influence both the propulsion and structural integrity requires complex evaluations. Machinery, propellers, stability, and visibility can, among others, be negatively affected.

The study's results should be helpful to decision-makers considering rotor sails on similar ships. The study will include an analysis of changes in emissions, costs, and risk factors. Ultimately, we should clearly see the differences between the ship in continued regular operation and the ship with rotor sails implemented.

Optimizing and changing sailing routes for wind optimization will not be considered in this thesis. Historical route data will be used to decide on wind expectations.

2.2.1 Rotor Sail Implementation

Rotor sails exist in several heights and diameters, and one can choose to have many or just one. For the purpose of this thesis, we will consider four rotor sails placed at the front part of the ship, where they are outside the way of other vital operations. The sails we will consider are 24.5 m in height, and their specifications will be further specified in Table 9.2 in chapter 9.

The reason for the number of rotor sails and their placement comes from the wishes of our collaborators at Odfjell. The goal of implementing the rotor sails must be to harvest as much wind energy as possible, and obviously, the rotor sails will produce more propulsive power the more there are. However, on a tanker vessel, the deck is dominated by pipes and other vital equipment so open deck space is limited. Additionally a symmetrical setup for the sails was desirable because it will cancel some of the stability effects.

2.2.2 Ship Operation Description

As mentioned, the ships operate mostly deep-sea and carry liquid chemicals. Except for planned dry-dockings or unexpected issues that prevent regular operation, the ship will be in constant operation. As an estimate based on operational data, the ship has about 50/50 sailing time and port time.

Maintenance of the ship is performed either during operation or when dry-docking. Dry-docking happens every fifth year for the first 15 years and more frequently after that. Continuous low-scale maintenance and switching of parts may be done while the ship is in operation, but overhauls and extensive planned maintenance processes are performed during docking.

The implementation of the rotor sails would happen during planned dry-docking maintenance operations. This prevents an additional off-hire time for the ship and allows for an installation process when the ship is without possibly dangerous cargo.

Part I

Literature Study and Method Descriptions

Chapter 3

Rotor Sails

Rotor sails or Flettner rotors are big upright cylinders attached to the ship's deck. Their purpose is to harvest wind power to maximize fuel efficiency. This works because when the wind conditions are favorable, the main engine may be throttled back, and thus less energy is used. Overall, providers claim fuel savings of 5-30% [3] [4].

The basic concept is known as the Flettner rotor and is based on the Magnus effect, which is explained in section 3.1. The concept is named after Anton Flettner, a German aviation engineer who demonstrated the concept in 1926. However, Finnish engineer Sigurd Savonius was the one who initially invented it [3]. Throughout this thesis, we will use the term rotor sail rather than Flettner rotor.

3.1 The Magnus Effect

The theory at play that ensures the functioning of the rotor sails is called the Magnus effect, which is illustrated in Figure 3.1. This theory is well known in sports as a "curveball," where a spinning ball gets an altered trajectory because it spins in the air [5]. The Magnus effect will, for a ship in a crosswind, produce thrust many times that of a conventional sail of equivalent area [5].

The theory says that the circulation around the rotating cylinder is a consequence of the unsymmetrical flow pattern produced by the upper and lower boundary layers separating at different positions [5]. This causes the flow on one side to be longer and faster, while on the other side, it will be shorter and slower, thereby creating a difference in pressure between the sides. The pressure difference creates the thrust, which is the Magnus force. The most critical factors for the magnitude of the force for a rotor sail are the spinning rate, the velocity through air, and the body's geometry [5].

The Magnus effect utilized on a rotor sail is slightly different than on a ball. The sail is not flying through the air but instead mounted on a ship. Therefore, the wind speed is what creates the necessary velocity through air. Figure 3.2 illustrates what happens with a spinning rotor sail when the wind approaches more or less perpendicularly. The added wind resistance has a slight drag force, but the lift force is much larger. Yet, the drag will cause the resultant propelling force to have a slightly skewed angle compared to the lift force.

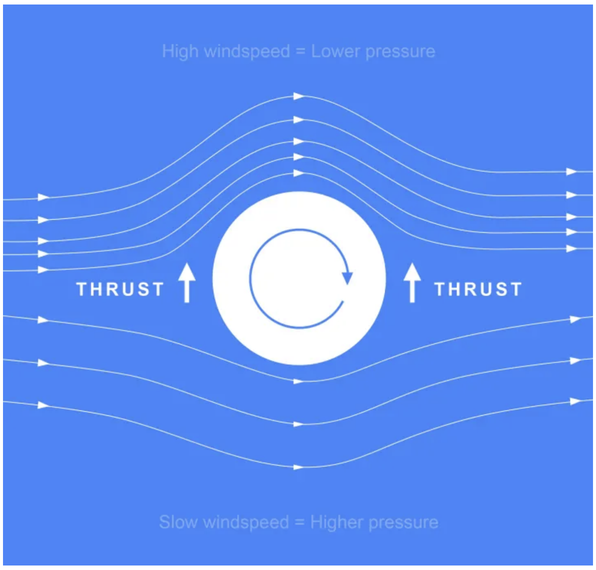


Figure 3.1: Magnus effect on spinning body[3]

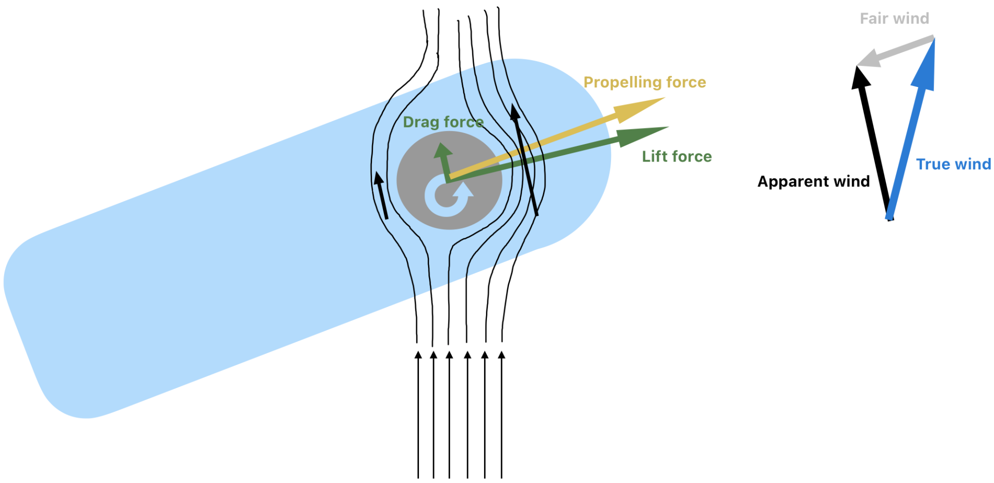


Figure 3.2: Magnus effect illustrated on rotor sail

As the ship is moving while using the rotor sails, the wind will be experienced differently compared to when standing still. This is shown with the arrows on the right in Figure 3.2. True wind refers to the speed and angle of the wind unaffected by any obstacles. On the other hand, apparent wind refers to the wind speed and angle experienced by the moving ship. As the ship advances, it generates its own wind due to its motion, known as the relative wind. This relative wind combines with the true wind, resulting in the apparent wind. When the true wind and the ship's relative wind align, the resulting apparent wind is called the fair wind.

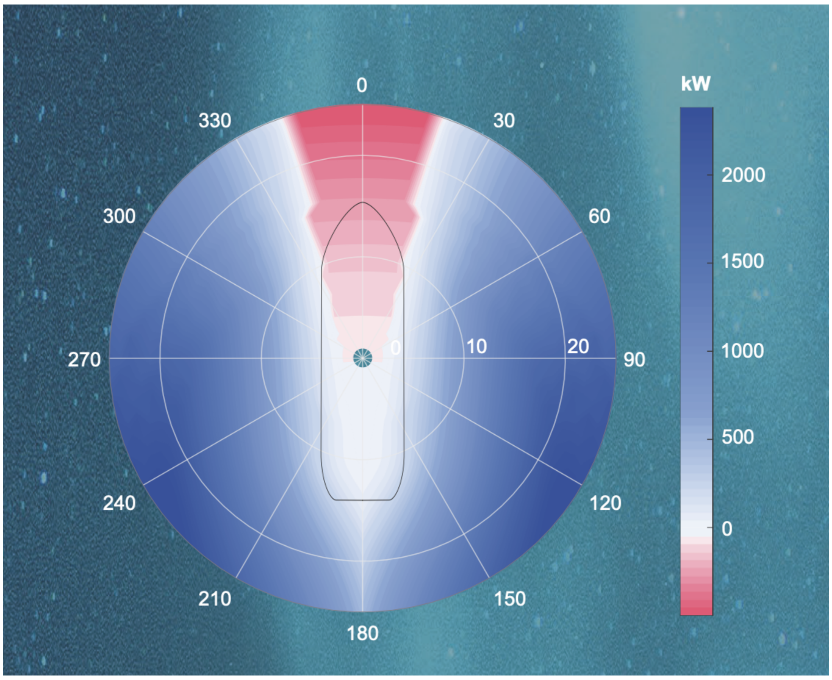


Figure 3.3: Polar diagram for propelling force of 1 24x4 rotor sail mounted on a ship[6]

Another fact that can be observed from Figure 3.2 is that the wind direction will have an effect on the the propelling force. Norsepower has illustrated this, showing the expected propelling force produced by a 24x4 rotor sail with different wind directions. This polar diagram is shown in Figure 3.3. Here it must be noted that a rotor sail can typically rotate in both directions, adapting to current wind conditions.

The diagram clearly shows that wind directions between 30 and 330 degrees, except right around 180, should give power of around 500-2000 kW for one rotor sail. So only wind coming from before the ship or directly behind will have adverse effects [6]. Nevertheless, winds close to a perpendicular direction will be most beneficial.

3.2 Technical Solution

The rotor sail is usually built up with a steel structure, the tower, which is inside a composite material that makes up the actual sail (the outside cylinder). Additionally, there are lower and upper bearings and an electric drive. The drive rotates the rotor at the necessary speed and in the correct direction. In order to not impact the ship's structural integrity and cargo capacity, the rotor sails are usually made as lightweight as possible and often amount to less than 0.1% of the vessel deadweight [7].

The outside of the rotor is made of lightweight material and looks like a big cylinder with a plate on top (see Figure 3.4). The height can range from about 18 to 35 meters [6]. The endplate on top is vital for the sail's efficiency; in fact, the implementation of endplates doubles the lift force produced compared to no endplates [5].

Figure 3.4: Berge Mulhacen and Berge Neblina with Anemoi rotor sails [7]

The tower is the inside steel structure, keeping the rotor sail upright. It includes bearings at the top and bottom.

The electric drive varies in power output depending on the height of the sail. For example, Norsepower says that the nominal power of their rotor sails is 60-143 kW [6]. However, the drive's power source should be able to carry a higher load because there may be situations where more power to the sail is necessary. The drive of the rotor sail is electric because of the ease of changing the rotational direction - which is necessary for adapting to the current wind direction [5]. Moreover, it is simple to hook up to the low voltage grid of the ship. Nevertheless, in cases where the ship's low voltage supply is insufficient, or if the supply to the rotor sails makes the low voltage network unstable, installing a battery or similar power supplies might be necessary. In addition, some ships may need to run an extra auxiliary engine that generally would not run during sailing to supply the rotor sail.

Necessary equipment

Some equipment, except for the actual rotor sail, must also be installed when refitting a ship for installation. Generally, this amounts to ship wind sensors (on the bow and above the bridge), bridge control system, power and control hardware, power and control cabling, foundations, hydraulic tilting mechanism (optional), and rail system (optional) [6] [4].

The bridge control system is how the ship's crew can control the system. It is normal to have systems that require little crew intervention. The system automatically controls the rotor sails' rotational speed and direction using the wind sensors' data [4]. Furthermore, it provides status and performance data, equipment monitoring, and automatic safety shutdowns.

Power and control hardware, and cabling are necessary because each rotor sail requires an electric power supply. If the low voltage network on the ship has sufficient supply, the easiest solution is to use it for the rotor sail power supply. This way, it is possible to avoid installing batteries or other additional power sources.

Foundations are necessary to mount the rotor sails, and each foundation must be tailored to the vessel in question. When placing the foundations, it is vital to consider the stability and structural integrity of the ship. Depending on the rotor sail size, the foundation may weigh up to 25 tons. Additionally, if the rotor sails are installed with tilting mechanisms or rail systems, this will also influence the foundations, how they are constructed, and the complexity of their installation.

The main advantage of adding tilting mechanisms is that ships that need to cross under bridges will still benefit from the technology without worrying about air draft restrictions. Furthermore, keeping the rotor sails out of the way while loading/unloading cargo may be helpful, especially for bulk ships.

If air draft restrictions are not an issue, but moving the rotor sails for port operations is necessary, a rail system may be a good solution. This allows for moving the rotor sails out of the way and easy access to vital spaces on deck. Rails may be an optimal solution for ships carrying bulk that requires space for crane operations.

3.3 Power Management System

Rotor sails will give a lift that increases the speed of the ship. However, increasing the ship's speed to a higher speed than during regular operation is not necessarily beneficial. In general, an increase in speed also exponentially increases the resistance of the ship (see Figure 3.5), and the produced power will not be utilized at its full potential [8][9]. An increased speed because of the rotor sails might lead to the same fuel consumption as regular operation, hence the same fuel costs and emissions. A benefit of increasing the speed with the rotor sails could be to deliver the cargo faster and make more deliveries in a shorter time.

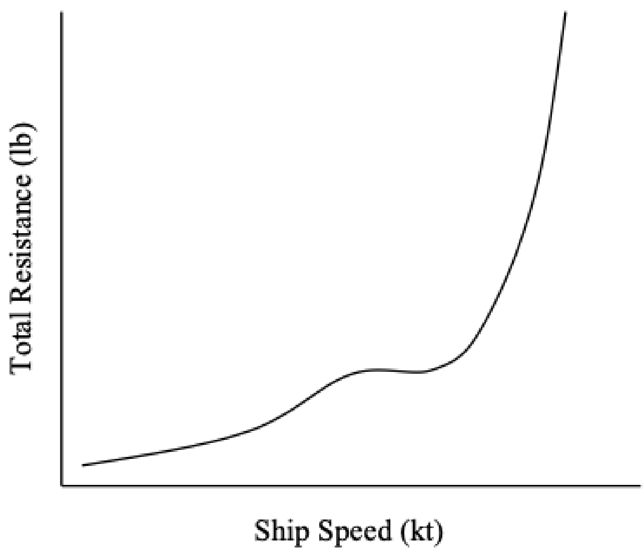


Figure 3.5: Graph showing exponentially increasing resistance with speed [9]

A graph from model tests for the ships considered in this thesis also shows that the ship power increases exponentially with the ship's speed (Figure 3.6).

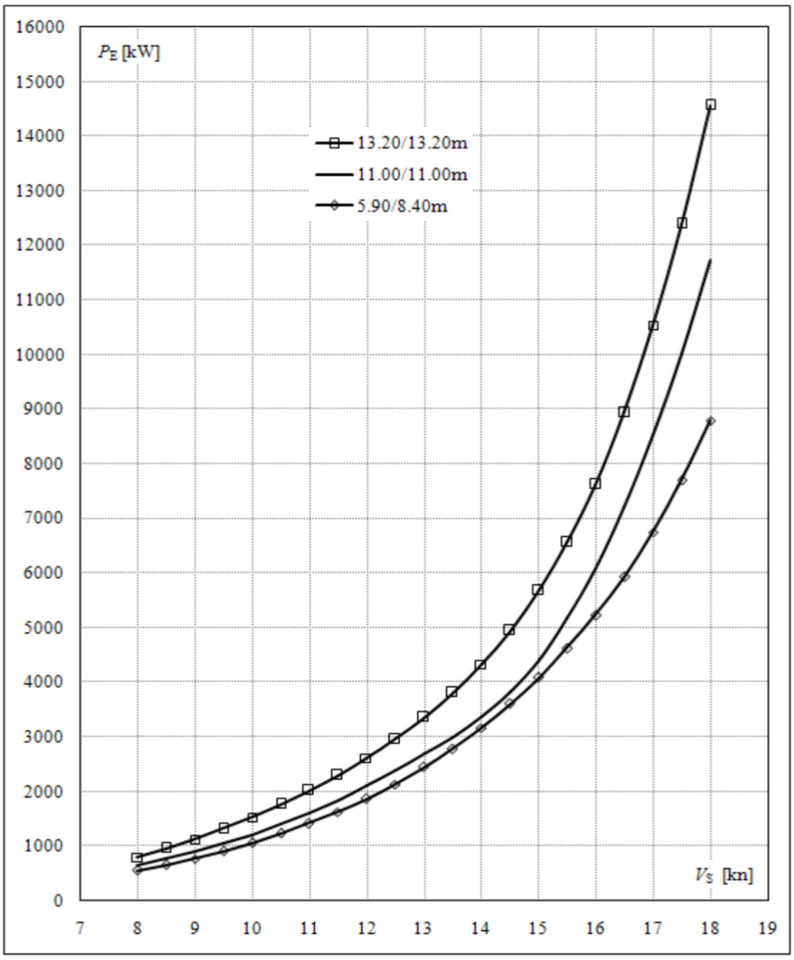


Figure 3.6: Effective power from model tests for different drafts

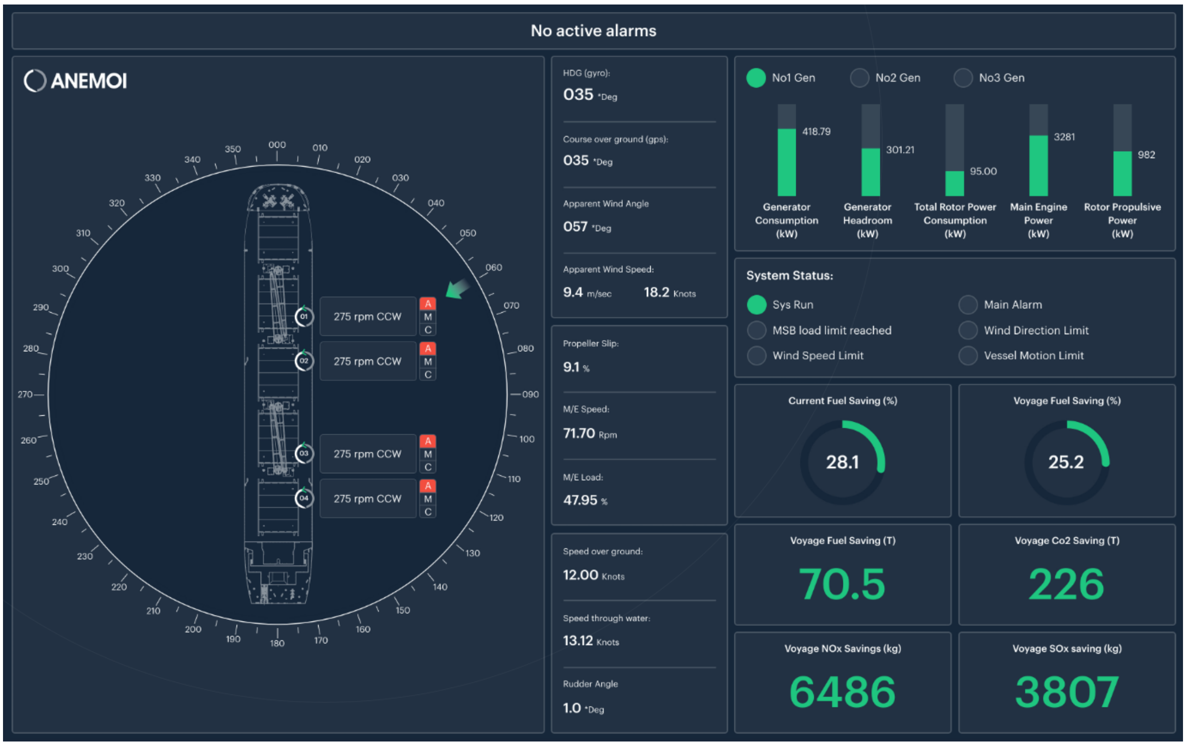


Figure 3.7: Control system display from Anemoi Marine [7]

Simply put, there are two options for rotor sail operation; maintain speed with less power consumption or increase speed. There are many ways to control the main engine, such as constant consumption, speed, and arrival time. Unfortunately, the technology from rotor sail providers does not offer a control system where the rotor sails' power output directly communicates with the ship's main machinery. Therefore, the ship's main machinery must be regulated separately.

As mentioned, the control system of the rotor sail will optimize the net power output from the sail by changing the rotational direction and speed of the rotor. An example of a control system display from Anemoi Marine is shown in Figure 3.7.

3.4 Low Loads on the Main Machinery

Considering fuel consumption, it is more beneficial to maintain the same speed as in regular operation and decrease the power from the main machinery. However, throttling down the main engine to a certain level and letting it run on a low load compared to the specified maximum continuous rating (SMCR) can lead to more maintenance and complications on the main machinery.

There will usually be an optimizing point for each engine, named normal continuous rating (NCR). It is the most efficient point and where we would generally like to run the engine. A problem in the industry is that engines are often over-dimensioned [10]. This usually occurs because of class requirements and demands from ship owners.

The engine should be run optimally for the best specific fuel oil consumption (SFOC) and efficiency. However, when using energy-saving or -harvesting equipment, the goal is to use less of the main engine power. When this is added to the fact that many engines are already over-dimensioned, the result is even lower loads for the engine. Ships operating engines on low loads may experience unfortunate symptoms other than increased SFOC and reduced efficiency. As mentioned in a master thesis investigating the matter, the most common side effects were wet stacking and soot deposits in the cylinders and turbocharger [10].

Wet stacking is when unburned fuel or carbon remains in the exhaust system. When the temperature increases again at higher loads, the unburned fuel can ignite and cause local combustion, harming the engine parts. It can cause minor engine damage, which may become more significant problems over time [10].

The soot formation results from low cylinder pressure and temperature, which causes incomplete combustion. Over time, the formations may form carbon deposits in the cylinder liner, piston, and injection nozzles. However, the carbon deposits will burn away if the engine is regularly brought up to a higher load [10].

What may also happen with incomplete combustion is that there is more return fuel, which adds to the demands on the fuel cooling system because more hot fuel is returned [10]. Furthermore, another possible issue from low loads is the lower pressure in the cylinder, causing poorer sealing efficiency. This, again, may allow combustion gasses and unburned fuel to leak into the oil pan, diluting the lubrication oil. Again this issue will be solved by running the engine at a higher load for some time because the unburned fuel will evaporate [10].

In order to experience severe consequences from low load operations, the loads must either be extremely low (less than 40% SMCR) or happen over a long period without being run at optimum level sometimes. The issue for a ship with varying loads will be smaller than a ship with continuously low loads.

Chapter 4

Regulations and Policies

Within the shipping industry, two vital aspects that require careful consideration are emissions, environment, and safety. Regulatory mandates, investor expectations, and growing consumer demand for sustainable practices drive the urgency to reduce GHG emissions in maritime operations. Many developments within ship emission regulations influence the ways ships can operate. Changing ship operations can only be considered while looking into relevant safety regulations. These are not in a phase of change; however, they constantly get more stringent to ensure safety in all aspects.

4.1 Emissions and Environment

The pressure on ship owners to reduce the GHG footprint comes from three primary drivers: regulations and policies, access to investors and capital, and cargo owner and consumer expectations [11]. Several conventions, regulations, and laws prevent specific emissions or amounts of emissions from ships. These may vary with regions, while others are applicable everywhere. The goal is to control the rate of climate change on the planet.

The latest addition to ship emission regulations came into effect on January 1st, 2023, which are CII (Carbon Intensity Indicator), EEXI (Energy Efficiency eXisting ship Index), and SEEMP (Ship Energy Efficiency Management Plan) Part III [11].

CII rating gives each ship a rating from A to E based on fuel consumption data [12]. Ships with poor ratings must implement a corrective action plan, and incentives may be given to ships with good ratings. Administrations, port authorities, and other stakeholders are encouraged to provide incentives to ships rated as A or B [12]. This, again, may cause financial liabilities to ship owners greater than the cost of making energy efficiency measures.

A ship's EEXI determines its energy efficiency compared to a baseline. For each kind of ship, there is a required EEXI to be below to ensure that the ship meets minimum energy efficiency standards. EEDI is essentially the same as EEXI, however, for new-builds. The index rewards ships that are more energy efficient compared to a baseline.

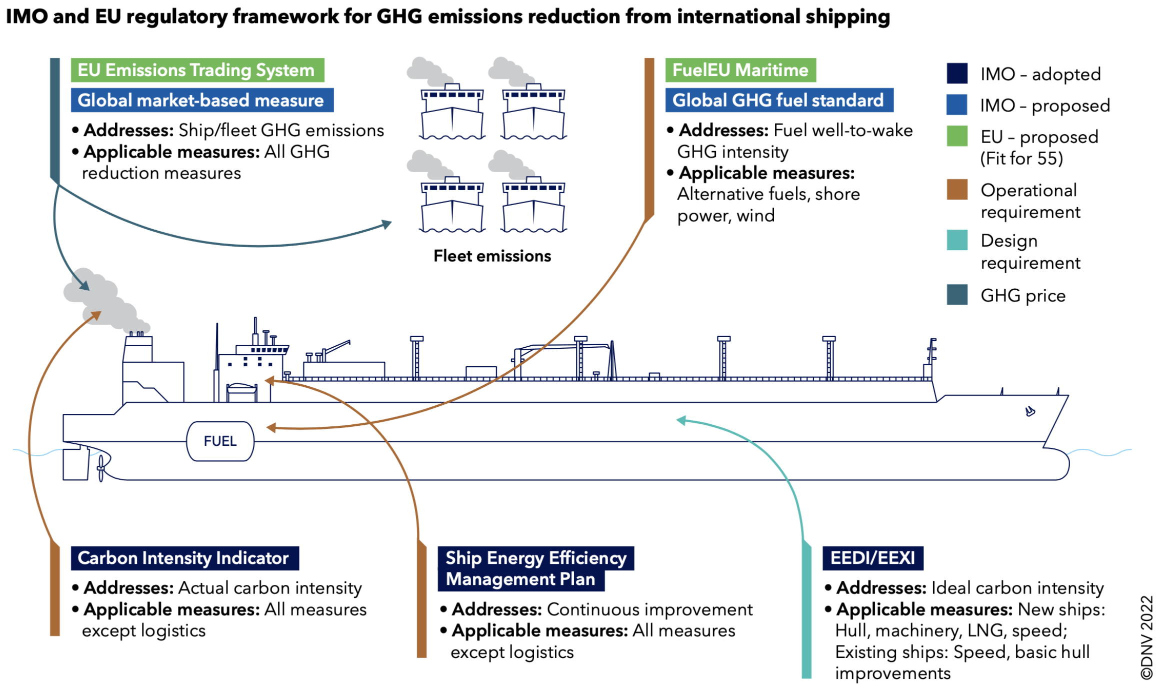


Figure 4.1: Regulatory framework for GHG emisson reduction as presented by DNV [11]

SEEMP Part III is a section of the Ship Energy Efficiency Management Plan (SEEMP) that guides on how to use energy efficiency measures to reduce greenhouse gas emissions from ships. It outlines actions that can be taken to improve the energy efficiency of a ship and reduce its environmental impact. The measures can include using low-sulfur fuel, optimizing voyage planning, reducing speed, and implementing energy-saving technologies. The goal of SEEMP Part III is to help shipping companies reduce their carbon footprint and meet international regulations for emission reduction.

Further, the EU has proposed to include shipping in its Emissions Trading System (ETS) and FuelEU Maritime regulation to increase the use of carbon-neutral fuels. These proposals have been approved this year (2023) and will take effect in 2024, and 2025 [11]. The EU ETS will be a system of emission allowances that can be bought and traded. The prices are not fixed because they will be market-dependent. After implementation, the allowances are planned to be reduced by 4.2% per year [11]. Like in any market, the decreased availability will drive up the price - incentivizing ship owners to reduce their emissions. Between 2023 and 2030, the expected allowance prices are between 14 and 150 USD/tCO_2; after 2030, the price may be up to 250 USD/tCO_2 [11].

While the EU ETS will only affect ships traveling to, from, and within Europe, IMO has a similar regulation proposal in the pipeline. In 2023, the IMO Strategy will be updated, potentially making its emission-reduction goals more ambitious [11]. New regulations will then be created, which could include market-based measures that place a price on CO_2 and require tracking of fuel emissions.

They have four different proposals for the measures; one considers the ship's entire lifetime (well-to-wake), and another only considers tank-to-wake. Then the two others use the CII-score or implement a trading system similar to the EU ETS [11]. Either way, IMO will likely implement new emission-reducing measures in the next few years [11]. So ships sailing outside of Europe will also be affected by the increased effort toward sustainability in the shipping industry.

All this is summarized in Figure 4.1, from DNV's Energy Transition Outlook 2022.

Regulations are a significant driver of decarbonization in shipping. The apparent reason is that shipowners, like in any business, usually choose the most cost-effective option rather than the most environmentally friendly one. However, regulations allow for both abolishing bad practices and facilitating economic bonuses for those that put money and effort into a more energy-efficient fleet.

4.2 Safety

The SOLAS (Safety of Life at Sea) convention is an international treaty that concerns the safety of merchant ships [13]. The convention specifies safety standards for ships' construction, equipment, and operation. Therefore, when considering implementing new structures on deck, it is essential to pay attention to the regulations so that the ship as a whole is still in accordance.

In addition to this general convention for all ships, the EU has specific directives to regulate explosive environments. These directives are not ship-specific but apply to relevant land businesses as well.

ATEX means EXplosive ATmosphere and is two EU directives focused on the safety and health of employees (ATEX Workplace directive 1999/92) and equipment used in explosive atmospheres (ATEX equipment directive 2014/34) [14]. Safety in explosive atmospheres is a complicated subject and requires strict rules regarding behavior and equipment. The equipment that can be used in the different zones has to adhere to stringent regulations. The zone classifications demonstrate the probability of an explosive atmosphere being present without considering the risk regarding ignition sources being present [14]. More about zone classifications and their specifications is written in chapter 6.

Chapter 5

Life Cycle Assessment as a Method

Life cycle assessment (LCA) is a commonly used method in decision support. Two of the most common ways to use the results from an LCA are to compare products and processes to find which of them has the lowest impact on the environment or to improve a product or process by finding where in the process the environmental impacts are highest [15] [16].

There are many ways of conducting an LCA and *LCA-like analysis*, and the International Organization for Standardization (ISO) has described an international standard. The principles and framework are described in ISO 14040:2006 [17], while the requirements and guidelines are described in ISO 14044:2006 [18].

In some cases, there is a need for studies to fulfill only some of the criteria for the international standard of LCA. Examples include gate-to-gate and cradle-to-gate studies, where the whole life cycle from cradle-to-grave is not considered [17]. The choice of method and scope depends on the intended use and the subject of the study. They can be very similar, and most of the steps and requirements from LCA apply to these methods, but they are still not considered an LCA according to the international standard.

5.1 Phases of the LCA Methodology

The international standard describes four steps or phases of an LCA study; "the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase" [17]. These are shown as an iterative process in Figure 5.1.

5.1.1 Goal and Scope Definition Phase

The first phase of the study is about determining and describing the goal and scope of the study. The scope of the study includes the functional unit, system boundary, LCIA methodology, data specification and quality requirements, comparisons, and considerations of critical review [18]. During the study, unforeseen constraints or limitations might make it necessary for the scope and goal of the study to be revised.

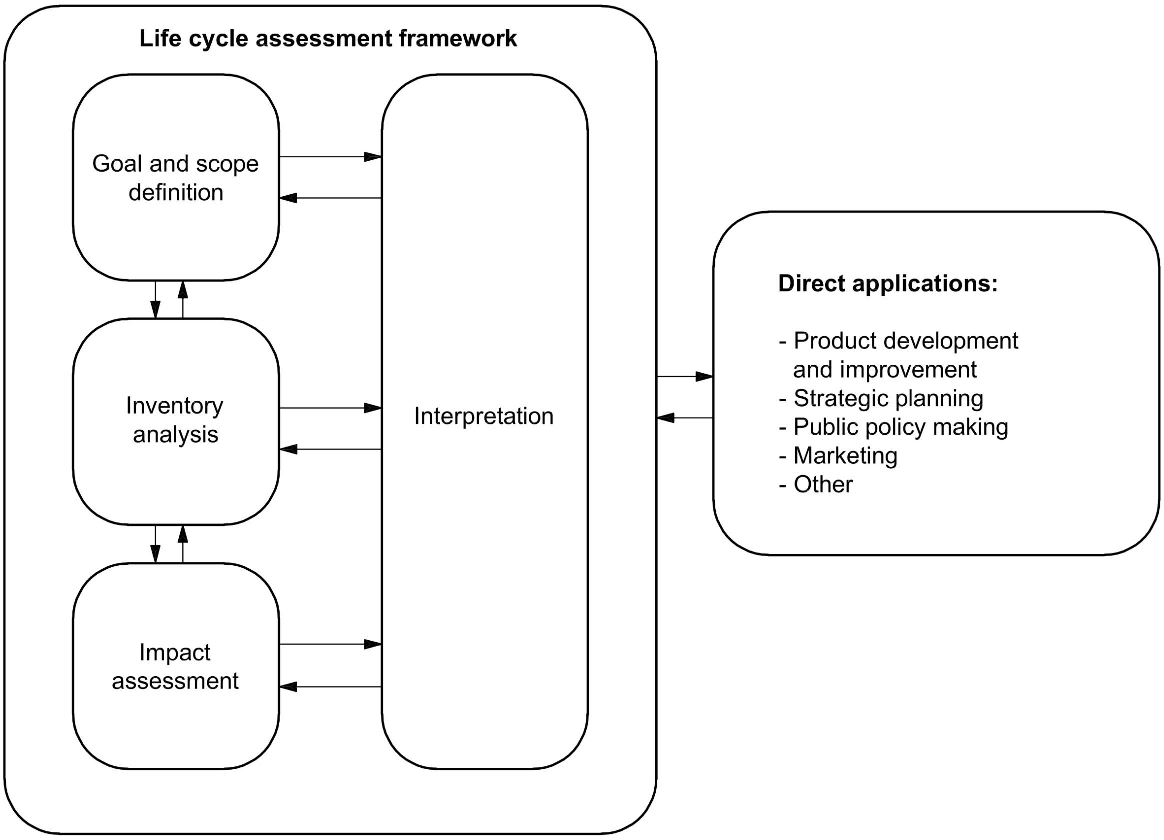


Figure 5.1: Phases of an LCA [17]

5.1.2 LCI Phase

The inventory analysis collects and calculates relevant data for the different processes from the system boundary. Conducting the inventory analysis is an iterative process because the more data collected about the system, the more is learned about the system [17].

Collecting the data must be done in a way so the goal of the analysis is accomplished. For comparative LCAs, collecting data to make the two cases comparable is vital.

Mathematical approach

This thesis will utilize the model formulation and notation developed by Wassily Leontief as presented by Anders Hammer Strømman in the compendium for the course TEP4223 - Life Cycle Assessment at NTNU [19].

Figure 5.2 is an illustration of a simple production system with three production nodes. The coefficient of requirements is denoted by a_{ij}, and external demand by y_j. a_{ij} is the amount required by process i per unit output of process j and is shown in equation (5.1)

$$a_{ij} = \frac{\text{amount of i required}}{\text{output of j}} = \frac{x_{ij}}{x_j} \tag{5.1}$$

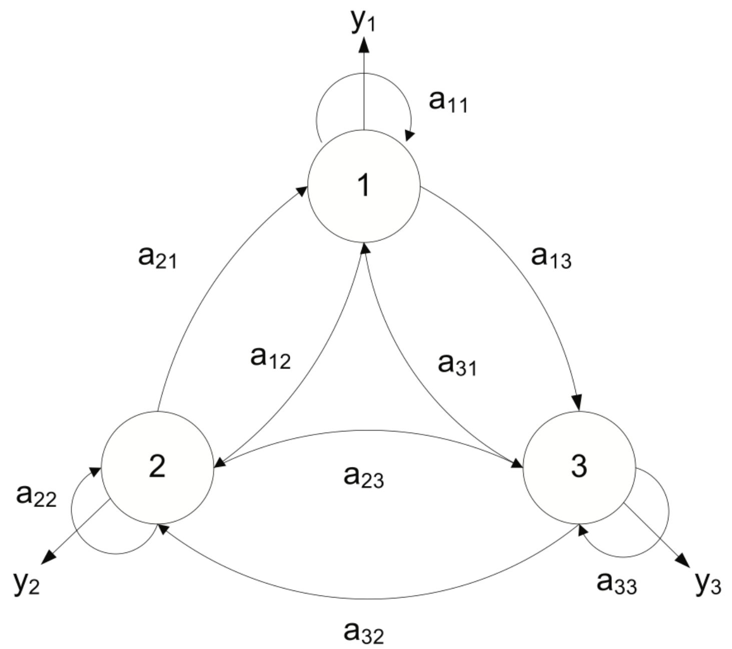


Figure 5.2: Production nodes and inter-connectivity with requirements [19]

In the next equation (5.2), the requirement vector is shown. This is an organization of all the inputs per unit output for each process. In the vector we can see the inputs from processes 1-3 stated.

$$a_{ij} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \end{bmatrix} \tag{5.2}$$

The requirements matrix, A, appears when combining the requirement vectors. This shows the requirements for all the processes per unit output. The full matrix is shown in equation (5.3), and Figure 5.2 shows the connections illustratively.

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{5.3}$$

Next we can introduce the production balance equation ((5.4)), where x is the output vector, $A \cdot x$ is the internal demand and y is the external demand. The same equation is shown with vectors and matrices in (5.5).

$$x = Ax + y \tag{5.4}$$

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \tag{5.5}$$

Often, the external demand y is known from the functional unit, and the requirements matrix A from an LCA database, so the output (x-vector) is what must be found. This is typically done with the Leontief inverse. The derivation of the equation is as follows (in (5.6) and (5.7)).

$$x = Ax + y \Leftrightarrow (I - A)x = y \Leftrightarrow x = (I - A)^{-1}y \tag{5.6}$$

$$L = (I - A)^{-1} \Rightarrow x = Ly \tag{5.7}$$

Next, when the output vector, x, is known, it is possible to find the flow matrix, Z. The equation is shown in equation (5.8). Z describes the flow of energy, materials and products between the different processes. It is simply calculated by multiplication of the requirements matrix and the output matrix.

$$Z = A\hat{x} \Leftrightarrow \begin{bmatrix} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x_1 & 0 & 0 \\ 0 & x_2 & 0 \\ 0 & 0 & x_3 \end{bmatrix} \tag{5.8}$$

The total stressor vector based on final external demand, e, can be calculated from equation (5.9). This equation also includes S, which is the stressor matrix containing the stressors for the output of each process corresponding to the amount in the requirements matrix.

$$\begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = S(I - A)^{-1} \cdot y = S \cdot L \cdot y = S \cdot x \tag{5.9}$$

Further, we can calculate E, the matrix of stressors generated from each process for a given external demand. This allows us to understand what processes contribute to each stressor. The calculation is shown in (5.10).

$$E = \begin{bmatrix} e_{1,1} & \cdots & e_{1,pro} \\ \vdots & \ddots & \vdots \\ e_{str,1} & \cdots & a_{str,pro} \end{bmatrix} = S\hat{x} = S\widehat{Ly} = S\widehat{(I - A)^{-1}y} \tag{5.10}$$

5.1.3 LCIA Phase

A life cycle impact assessment (LCIA) interprets the resulting data from the LCI by using the emissions calculated from the LCI to translate them into different impact categories [15].

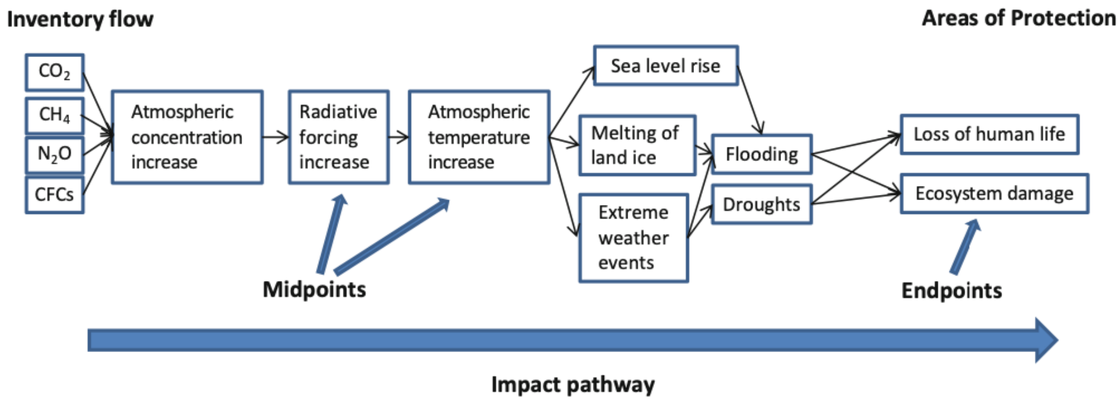


Figure 5.3: Example of an impact pathway for global warming [15]

This is done by implementing characterization factors that convert the resulting stressors from the LCA to impact categories. ISO 14044 describes that the chosen impact indicator for the LCIA can be anywhere on the impact pathway [18]. It must represent an impact caused by the inventory flow that, in the end, will lead to damage to the areas of protection (AoPs). In Figure 5.3, there is an example of an impact pathway where the impact indicators for global warming can be found anywhere between atmospheric concentration increase and loss of human life or ecosystem damage.

There are two common ways of categorizing the impact categories; midpoint and endpoint indicators. The midpoint indicators describe single environmental problems such as global warming potential, ozone depletion, and similar. The endpoint indicators often describe the environmental impacts on a high aggregation level [20] [16].

The midpoint impact indicators are often certain and close to the physical intervention as they are well-established terms calculated from the emissions of a process. On the other hand, they often do not show the effect or damage of the stressors. An example is shown in Figure 5.4, where human toxicity is a midpoint impact indicator. It is to a certain level known how the different gasses and stressors will affect a human body and therefore stated which stressors will lead to human toxicity. According to the research, this makes the result somewhat certain, but it does not directly represent how the quality of human life is affected.

The endpoint impact indicators are easier to communicate as they give a more specific representation of the damage because of the stressors. This can also make them more uncertain as the calculations can include factors from research or empirical data.

Human health is an endpoint impact indicator in the example in Figure 5.4. It is an indicator that is generally easy to grasp. At the same time, there is a higher level of uncertainty compared to the midpoint indicators as it is not always certain how human health is affected by the different midpoint indicators [15]. The effect on human health can vary for different geographical locations, genes, ages, and genders [21] [22].

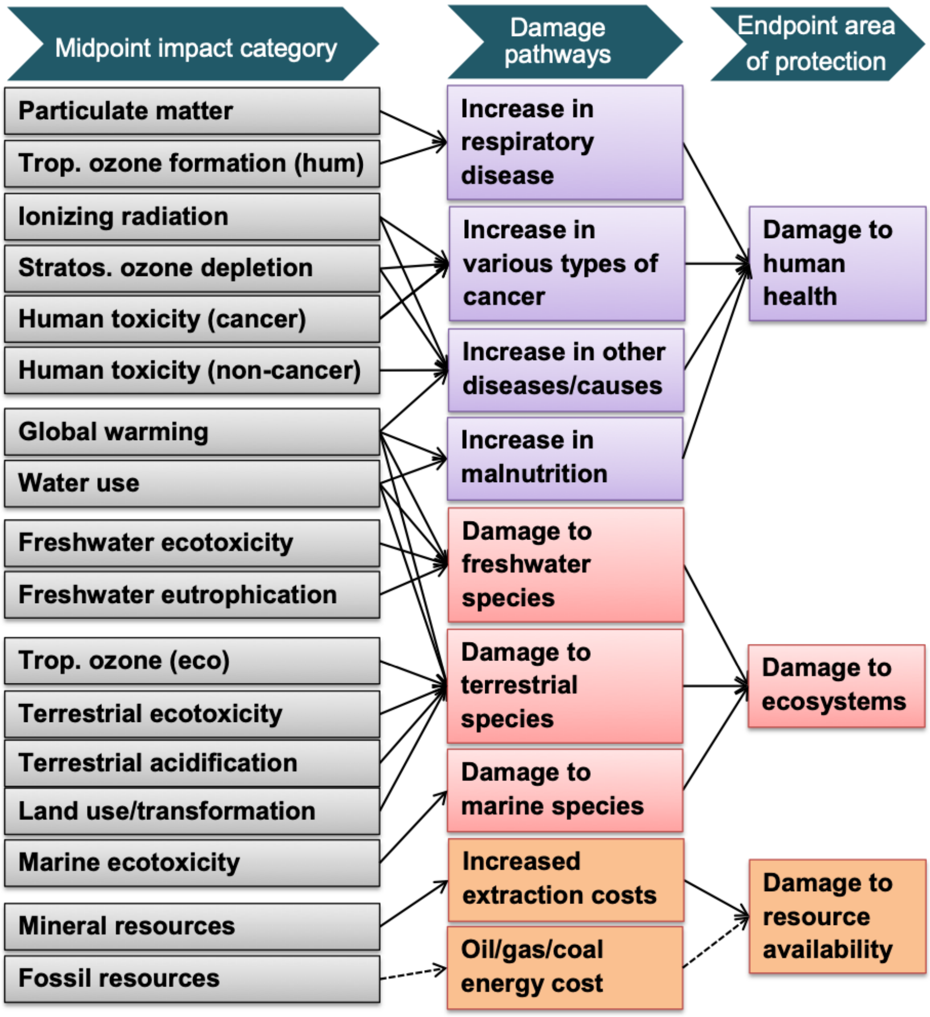


Figure 5.4: Flow between midpoint and endpoint indicators [20].

ReCiPe

As the international standard is general and relatively unspecific in the impact assessment method, many different impact assessment methods have been created. In addition, the methods might have various characterization factors and apply to different LCI analyses [23].

One common impact assessment method is the ReCiPe method. The method was updated in 2016 from the previous method of 2008 to find the global or local impacts instead of only the European impacts [16]. The method consists of 18 midpoint indicators and three endpoint indicators, most of which are shown in Figure 5.4 with their respective pathways. They are also explained more below.

- **Global Warming Potential (GWP) / climate change** – Expresses the amount of impact integrated over time caused by the emission of 1 kg GHG relative to the impact over the same amount of time by the release of 1 kg of CO_2. [16]
- **Ozone Depletion Potentials (ODP)** – An increase in ODP comes from an increase in ozone-depleting substances, which leads to a decrease in the atmospheric ozone

concentration. This, in turn, will let a larger portion of UVB radiation enter through the atmosphere, which again negatively affects human health by increasing skin cancer and cataracts. ODP is expressed in kg CFC-11-eq to air. [16]

- **Ionizing Radiation Potential (IRP)** – Ionizing radiation is naturally found in light from the sun, microwaves, and x-rays. The impact on humans is an increased risk of cancer. It is measured relative to the emission of 1 kg reference substance Cobalt-60-eq to air. Cobalt-60 is a radioactive isotope. [16]

- **Particulate matter formation potentials (PMFP)** – PMFP describes the emissions of small particles, named particulate matter (PM). Humans can inhale PM, causing damage to the lungs and enter the bloodstream. PMFP is given in kg PM2.5 to air. [16]

- **Photochemical oxidant formation: ecosystem quality and human health / Ecosystem Ozone Formation Potential (EOFP) and Human Health Ozone Formation Potentials (HOFP)** – EOFP and HOFP are air pollutants that cause primary and secondary aerosols in the atmosphere. This is not ozone emitted directly into the atmosphere but ozone formed due to photochemical reactions. It is a health hazard to humans and can harm vegetation. Measured in kg NO_x-eq to air. [16]

- **Terrestrial Acidification Potential (TAP)** – Deviations from optimum acidity levels in the soil harm species because changes in acidity levels will cause shifts in a species' occurrence and can, over time, cause the extinction of certain species. It is measured in kg SO_2-eq to air. [16]

- **Freshwater Eutrophication Potential (FEP) and Marine Eutrophication Potential (MEP)** – Freshwater or marine water eutrophication occurs due to the discharge of nutrients into the soil, freshwater bodies, or marine water. Increasing the nutrient emissions will increase the nutrient uptake by autotrophic organisms and heterotrophic species, leading to relative species loss. Measured in kg phosphorus-eq (P) to freshwater (FEP) or kg nitrogen-eq (N) to marine water (MEP). [16]

- **Human Toxicity Potential: cancer (HTPc)** – Toxic substances emitted that are carcinogenic to humans. Measured in kg 1,4-DCB-eq to urban air. [16]

- **Human Toxicity Potential: non-cancer (HTPnc)** – Toxic substances emitted that are not carcinogenic to humans. Measured in kg 1,4-DCB-eq to urban air. [16]

- **Terrestial Ecotoxicity Potential (TETP), Freshwater Ecotoxicity Potential (FETP), and Marine Ecotoxicity Potential (METP)** – Toxic substances emitted to industrial soil, freshwater, and marine water. Measured in kg 1,4-DCB-eq to industrial soil, freshwater, or marine water. [16]

- **Agricultural Land Occupation Potential (LOP)** – This includes two cases: land cover change and use of new land. The land cover change affects the area's original habitat and species composition. Using new land for agricultural and urban activities can disqualify land as a habitat for some previously lived species. Measured in $m^2 \cdot yr$ annual cropland. [16]

- **Water Consumption Potential (WCP)** – Water consumption is the use of water so that the water is evaporated, incorporated into products, transferred to other watersheds, or disposed of into the sea. As a result, water consumed is no longer available for humans or the ecosystem. Measured in m^3 water consumed. [16]

- **Surplus Ore Potential (SOP)** – Extraction of mineral resources leads to an overall decrease in ore grade - meaning a decrease in the concentration of that resource in ores worldwide. This increases the ore produced per kilogram of mineral resource extracted. Surplus ore potential leads to surplus cost potential because mining sites with higher grades or lower costs are the first to be explored. Measured in kg Copper-eq. [16]
- **Fossil Fuel Potential (FFP)** – The ratio between a fossil resource's energy and crude oil's energy content. Fossil fuels with the lowest extraction costs are extracted first. Measured in kg oil-eq. [16]

Mathematical approach

The impact assessment also has a mathematical approach to be followed which will be explained here. This part is also based on the compendium of Strømman [19].

The characterization matrix, C, is shown in equation (5.11), and it contains conversion factors for each stressor. The factors allow for converting emissions from different substances with the same environmental impact into equivalents. The most common is to convert other emissions into CO_2-equivalents or SO_2-equivalents.

$$C = \begin{bmatrix} c_{1,1} & \cdots & z_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & z_{imp,str} \end{bmatrix} \tag{5.11}$$

After establishing the characterization factors we can find the vector of total impacts, d, for a given external demand.

$$d = \begin{bmatrix} d_1 \\ \vdots \\ d_{imp} \end{bmatrix} = \begin{bmatrix} c_{1,1} & \cdots & z_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & z_{imp,str} \end{bmatrix} \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} \tag{5.12}$$

Standard notation gives the following equation (5.13).

$$d = Ce = CSx = CSLy = CS(I - A)^{-1}y \tag{5.13}$$

Further, to understand how the different processes contribute to the various impact categories we can calculate D_{pro}, the total impacts matrix per process. The calculation in shown in (5.14) or with standard notation in (5.15).

$$D_{pro} = \begin{bmatrix} d_{11} & \cdots & d_{1,pro} \\ \vdots & \ddots & \vdots \\ d_{imp,1} & \cdots & d_{imp,pro} \end{bmatrix} = \begin{bmatrix} c_{1,1} & \cdots & z_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & z_{imp,str} \end{bmatrix} \begin{bmatrix} e_{11} & \cdots & e_{1,pro} \\ \vdots & \ddots & \vdots \\ e_{str,1} & \cdots & e_{str,pro} \end{bmatrix} \tag{5.14}$$

$$D_{pro} = CE = CS\hat{x} = CS\widehat{Ly} = CS(I - \widehat{A)^{-1}}y \tag{5.15}$$

With the same logic, but diagonalizing the e-vector we can find D_{str}, the total impacts matrix per stressor - which stressors contribute to the various impact categories. The calculation shown in (5.16) or with standard notation in (5.17).

$$D_{pro} = \begin{bmatrix} d_{11} & \dots & d_{1,str} \\ \vdots & \ddots & \vdots \\ d_{imp,1} & \dots & d_{imp,str} \end{bmatrix} = \begin{bmatrix} c_{1,1} & \dots & z_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \dots & z_{imp,str} \end{bmatrix} \begin{bmatrix} e_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e_{str} \end{bmatrix} \tag{5.16}$$

$$D_{str} = C\hat{e} = C\hat{S}x = C\widehat{SLy} = CS(\widehat{I-A})^{-1}y \tag{5.17}$$

The D_{pro} and D_{str} matrices cannot provide the full picture because they do not include the impact from the background processes to the foreground processes. Processes in the background system are the processes gathered from a generic inventory database. However, foreground processes are the ones established for the study of a specific case. Because a significant part of emissions often come from background processes, it is necessary to include them in the analysis.

In order to include the background processes, the A-matrix can be expanded, as seen in (5.18). A_{ff} will be identical to the A-matrix presented earlier in equation (5.3). A_{fb} describes the requirements from the foreground processes to the background processes, but it should be noted that this one will in most cases be zero because of unidirectional flow. A_{bf} describes the requirements from the background processes to the foreground processes. A_{bb} describes the requirements between the background processes. The corresponding stressor matrix will be as shown in (5.19). S_f and S_b describe the foreground and background stressors, respectively.

$$A_{ij} = \begin{bmatrix} A_{ff} & A_{fb} \\ A_{bf} & A_{bb} \end{bmatrix} \tag{5.18}$$

$$S_j = \begin{bmatrix} S_f & S_b \end{bmatrix} \tag{5.19}$$

The output of the processes in the foreground system, x_f, must be found, as seen in (5.20). This can then be used to calculate the demand placed on the background processes for each of the foreground processes, as seen in (5.21). This can in turn be used in equation (5.22) to find the output of different background processes as instigated by each foreground process.

$$x_f = (I - A_{ff})^{-1} y_f \tag{5.20}$$

$$M_{bf} = A_{bf} \hat{x}_f \tag{5.21}$$

$$X_{bf} = (I - A_{bb})^{-1} M_{bf} = (I - A_{bb})^{-1} A_{bf} \hat{x}_f \tag{5.22}$$

Now, we can look at the impacts. First, the impact potential of the foreground processes are calculated (in (5.23)), then the impact potentials generated in the background system are calculated (in (5.24)). When adding these two together we get the total contribution of impacts associated with the individual processes in the foreground system (equation (5.25)).

$$D_{pro,ff} = Cs_f \hat{x}_f \tag{5.23}$$

$$D_{pro,bf} = CS_b X_{bf} = CS_b (I - A_{bb})^{-1} M_{bf} = CS_b (I - A_{bb})^{-1} A_{bf} \hat{x}_f \tag{5.24}$$

$$D_{pro,f} = D_{pro,ff} + D_{pro,bf} \tag{5.25}$$

5.1.4 Interpretation Phase

This phase consists of interpreting the results from the LCI and LCA phase. It should be investigated if the results are consistent with the goal and scope defined [17].

The interpretation is made with respect to the potential environmental effects and does not consider the risks associated with the project. The interpretation phase should include reflections on the results and can conclude with recommendations consistent with the defined goal and scope.

5.2 SimaPro

SimaPro is the LCA software used in this thesis. It is a widely used LCA software that enables comprehensive analysis of the environmental impacts of products and systems throughout their life cycle [24]. It allows users to assess the environmental effects of various processes and products based on impact categories such as GHG emissions, energy consumption, water usage, and waste generation [24].

SimaPro offers a potent life cycle inventory data database, including information on raw materials, energy inputs, emissions, and waste outputs [24]. It includes different LCI databases, including ecoinvent [24]. The software supports different LCA methodologies, including ISO standards, and provides tools for sensitivity analysis, scenario comparison, and reporting [24]. In this thesis, the impact assessment method mentioned earlier in this chapter, namely ReCiPe, will be utilized, which is conveniently available in SimaPro software.

Chapter 6

Risk Assessment as a Method

Risk assessments, in general, have some essential steps regardless of the specific methods chosen for the assessment. The first step is hazard identification to figure out what can go wrong. And next, why the hazards happen. Knowing the reason makes it possible to prevent the hazards by applying barriers. If it is a quantitative analysis, the next step is frequency analysis to determine how often it happens. This is essential to evaluate whether safeguards, barriers, or mitigating measures will be necessary. Next, it is essential to determine the development of different accident scenarios. This will help define where mitigating measures should be placed and whether they are necessary.

6.1 Hazard Identification

It is necessary to perform hazard identification to understand the elements or processes that need to be assessed from a risk standpoint. Several methods exist for this purpose, namely checklist and brainstorming, JSA, FMECA, HAZOP, SWIFT, MLD, and change analysis [25].

Not all hazard identification methods will be helpful in the case of installing novel technologies on a ship. Checklist methods are, for instance, not an ideal choice for this. The checklist is limited to previous experience and cannot anticipate hazards in new designs. JSA is not covering because it is meant for specific work tasks or procedures, not relevant to this type of problem. HAZOP and SWIFT heavily depend on experience and knowledge [25].

Change analysis is a hazard identification method that focuses on finding the potential effects of modifications to a system [25]. This method is beneficial for comparing the new (changed) system to the basic (known) system. The basic procedure is to identify the critical differences between the new and basic systems, evaluate the possible effects of the difference (positive or negative), determine the risk impact, then examine essential issues in more detail [25]. The complete workflow of this method is shown in Figure 6.1.

Some advantages of the method are that it will allow for systematically exploring all the differences that could introduce significant risk and is a practical, proactive risk assessment for changing situations[25]. However, this method does not quantify the risk levels, so another method must be used to create quantitative risk estimates [25].

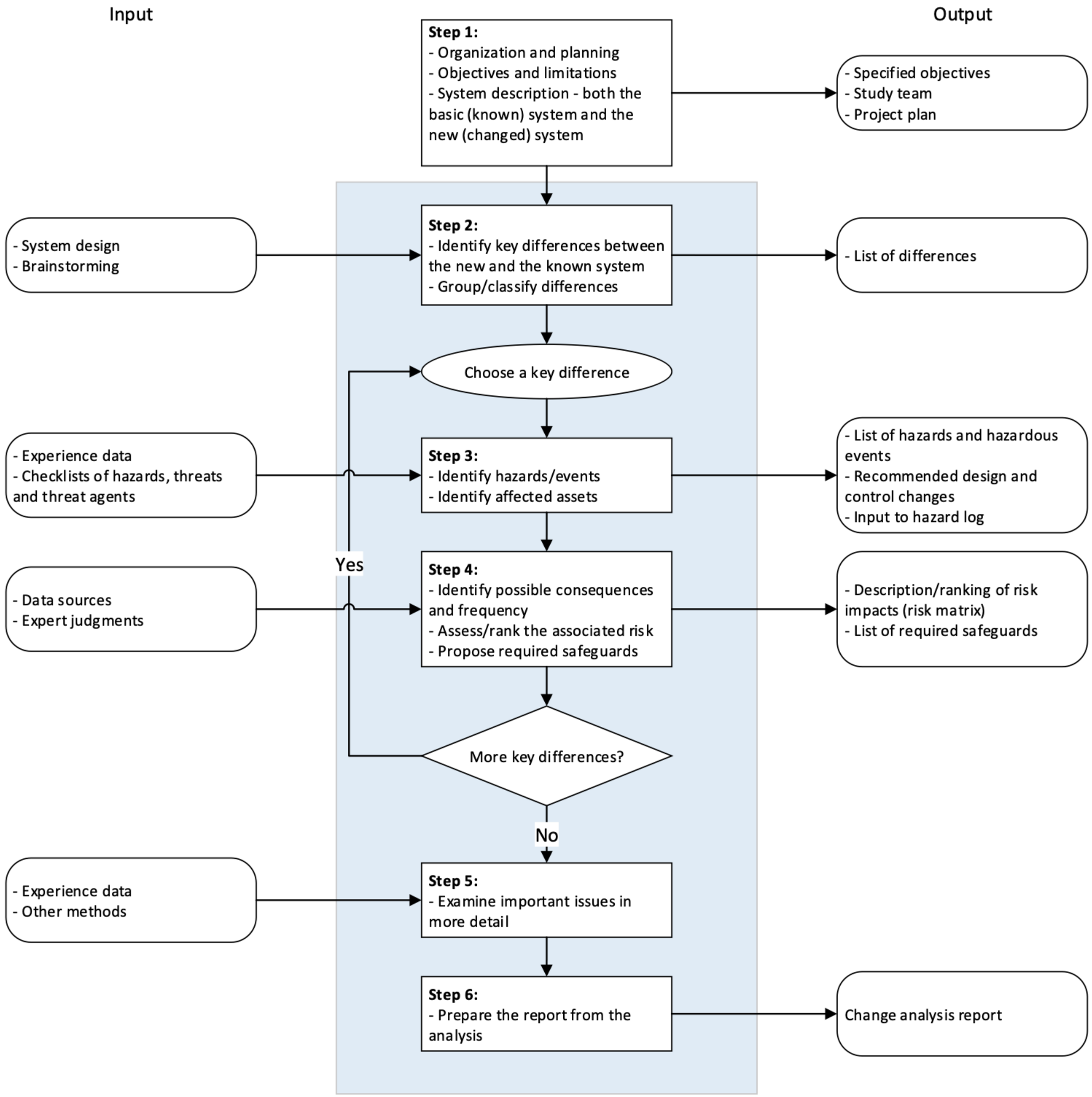


Figure 6.1: Analysis workflow for change analysis [25]

Step 5 of the change analysis (see Figure 6.1) is to examine critical issues in more detail. If issues needing further analysis are found, they can be analyzed with other risk assessment tools. Different tools may be practical depending on the classification of the issue or hazard. For example, an FMECA may be a good tool for technical failures and faults. FMECA looks at failure modes for the system; it allows looking at each component in a very detailed manner and can identify how it can conceivably fail. A drawback is that it is necessary with very detailed knowledge of the system and preferably ample experience.

6.2 Causal and Frequency Analysis

In order to figure out the frequency or probability of an unwanted event happening, frequency analysis is vital. Frequency analysis often goes hand in hand with causal analysis because we must also know why to determine how often a hazardous event happens. Some standard methods used are *cause and effect diagrams*, *fault tree analysis*, *Bayesian networks*, and *Markov analysis*. Cause and effect diagrams do not provide quantitative answers. Bayesian networks provide quantitative answers; however, the data collection workload will increase exponentially with each new node, making it quite time-consuming for larger systems. Fault tree analysis is very commonly used and well documented; however, it may be difficult for dynamic systems or systems with complicated maintenance. Markov analysis is not appropriate for an initial causal analysis of hazardous events; however, it compensates for some of the weaknesses of fault tree analysis [26]. Both fault tree analysis and Markov analysis give quantitative answers.

6.2.1 Fault Tree Analysis

Fault tree analysis (FTA) is meant to identify the basic events that may result in hazardous events, find the probability of the event, and identify aspects of the system that need improvement [26]. It may be performed both quantitatively and qualitatively. There exist standards for performing FTA, with the leading international standard being IEC 61025 (2006) [27].

The method is deductive, meaning that we start with the hazardous event (in this case, the TOP event) and work backward in the causal sequence. The procedure is continued until a suitable level of detail is achieved, and the last level of events will be *basic* events. It is a binary analysis - all the events either happen or not - there are no intermediate states. A separate FTA must be conducted for each TOP event.

Through FTA, minimal cut sets can be identified, making it easy to know what basic events must happen for the TOP event to occur. This could also help find the relevant places to place barriers.

After an FTA, a sensitivity analysis will help determine how much the TOP event probability changes when one or more input parameters are changed. This is interesting to know how the uncertainty in the input parameters will influence the TOP event probability.

6.3 Development of Accident Scenarios

Developing accident scenarios is a natural next step after causal and frequency analysis. We now know why and how often a hazardous event will happen, and what remains is to figure out the consequences of the hazardous event. Event tree analysis is a highly regarded method for this and allows for good integration with fault trees.

6.3.1 Event Tree Analysis

While FTA finds the causes of a hazardous event, event tree analysis (ETA) identifies the accident scenarios given a hazardous event and the consequences. The combination of the two is often called the bow-tie structure [28].

The goals of ETA are to identify the accident scenarios, identify barriers, assess the applicability and reliability of these barriers, identify internal and external events that may influence the event sequences, determine the frequency of each scenario, and determine and assess the consequence spectrum. Barriers are measures that prevent or mitigate the harmful effects of accident scenarios [28].

The starting point of the ETA will be one of the hazards identified from the change analysis and used in the FTA. Further, the tree will branch out around pivotal events that result in different end scenarios. Finally, the probability for each end event (accident scenario) can be calculated with input data for each pivotal event and the hazardous event. The workflow is explained in more detail in Figure 6.2.

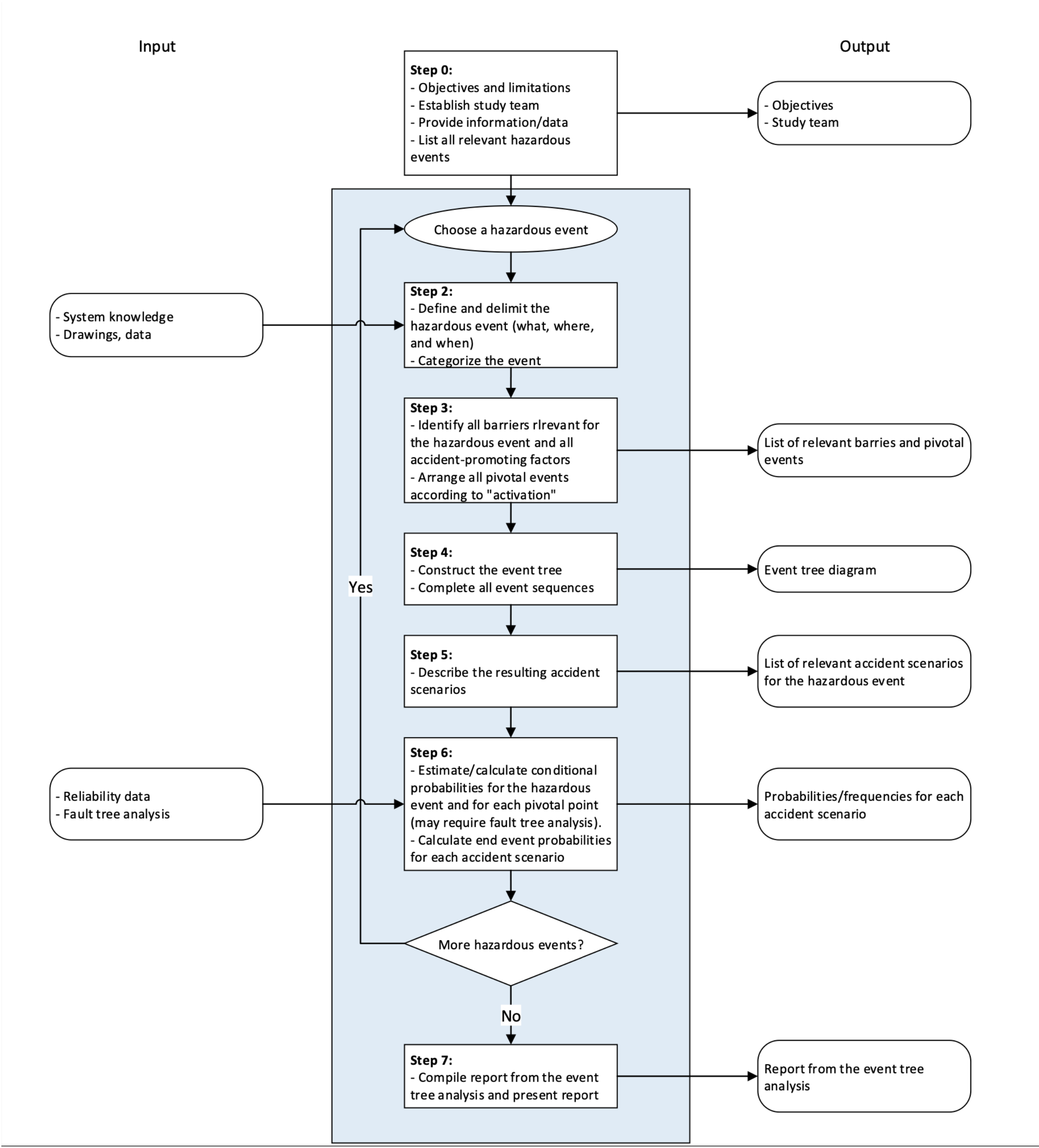


Figure 6.2: Analysis workflow for ETA [28]

ETA has some limitations; it has no standard graphical layout and requires that the hazardous events be analyzed separately, making it time-consuming. Additionally, it requires that the sequence of pivotal events be known in advance, and it does not allow the incorporation of partial successes or failures. Despite the drawbacks, it is widely used and clearly represents the event sequence after a hazardous event [28].

6.4 Human Reliability Analysis

Human errors are claimed to account for 60-90% of all accidents [29]. It is, therefore, vital to determine human reliability. This can be done with human reliability analysis (HRA) which is a systematic identification and evaluation of the possible errors that operators, maintenance personnel, and other personnel in the system may make [29].

The main steps to do a quantitative HRA are identifying critical operations, analyzing the tasks and breaking them down, identifying the human error modes, and determining the HEPs for each error mode.

Human error probability (HEP) is the probability that an error will occur when a given task is performed [29]. HEP can be estimated with Equation (6.1). The HEP is assumed to be independent of time because humans do not experience wear and need maintenance as machines do.

$$HEP = \frac{Z}{n} = \frac{\text{number of errors}}{\text{number of opportunities for error}} \tag{6.1}$$

Human reliability is not likely to be a significant issue with rotor sail operations because they primarily operate autonomously.

6.5 Explosion Risk Assessment

In an explosive atmosphere, there already exist two of the three parts to a "fire triangle." There is oxygen, and there is a combustible. What is missing is heat or ignition. For this reason, the equipment used in a dangerous zone is regulated. For a proper explosion to occur, the five elements of an "explosion pentagon" must be fulfilled. That means that additionally to oxygen, combustible, and ignition, we need dispersion and confinement. Dispersion means that the combustible or fuel is mixed with the air in the right proportions, meaning that the fuel concentration is between the lower and upper explosive limits [14]. Confinement propagates as the temperature and pressure increase. Without confinement, the event may be classified as a flash fire, which can be just as detrimental as an explosion because of secondary fire or explosion risk. In conclusion, an explosion risk assessment must cover three aspects: the probability of explosion hazard to be present, the probability of triggering the explosion hazard, and the likely outcome of an explosion [14]. When introducing new components to a ship, it is advantageous to consider if this will change the risk picture concerning explosion risk.

An explosion risk assessment considers the following questions:

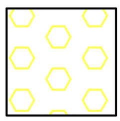
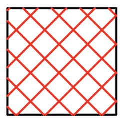
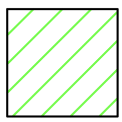
- How likely is it that an explosive atmosphere will occur?
- How likely is it that an ignition source will be present and become active and effective?
- What are the anticipated effects and consequences?

6.5.1 Likelihood of Explosive Atmosphere Being Present - Zone Classification

The zone classification of dangerous areas is helpful as a guide. Not all areas in a dangerous zone will have the same level of exposure to gas, so a zone classification means that the strictest rules do not have to be observed in all parts of the area. The zones are divided by the frequency and duration of the occurrence of the explosive atmosphere [14]. There are different classifications for gas and dust zones. However, only gas zones will be considered here.

The gas zones are divided into zone 0, 1, and 2, with decreasing degrees of likelihood. Each zone's explanation and symbol are shown in Table 6.1. The definitions are stated in ATEX Workplace directive 1999/92, and it is essential to note that the classifications are only applicable during regular operation and minor failures and not in case of catastrophic failure [14].

Table 6.1: Definition of explosion zones [30]

Zone 0	area in which an explosive gas atmosphere is present continuously, or for long periods, or frequently	
Zone 1	area in which an explosive gas atmosphere is likely to occur occasionally in normal operation	
Zone 2	area in which an explosive gas atmosphere is not likely to occur in normal operation, but, if it does occur, will exist for a short period only	

Each zone definition is vague because it does not include specific numbers to understand what is meant by "continuously," "long period," and so on. The legislation leaves it very much to the employer's judgment to make the appropriate safety measures decision. However, there is general consensus on the numbers presented in Table 6.2, where T is the estimated time period with the explosive atmosphere present.

Table 6.2: Estimated time period with explosive atmosphere present for each explosion zone

Zone	Duration/frequency guidance
Zone 0	T > 1000 h/year or T > 1 h/shift
Zone 1	10 h/year < T < 1000 h/year
Zone 2	1 h/year < T < 10 h/year and T < 1min/shift

The ship owner performs the division of spaces on the ship into different zones, and it is common to have internal guidelines for what is regarded as each zone. However, there is a general procedure that can be observed if there are no initial guidelines [14]:

1. Obtain process information, such as temperature, pressure, concentrations, plant design, and material explosions risk parameters, such as flash point, limits of explosion, and layer ignition temperature.
2. Determine internal zone classifications as appropriate.
3. Identify release points and assign grades of release.
4. Consider relevant effects of ventilation.
5. Determine zone numbers and zone extents.

As seen from the general procedure above, several vital factors exist in the division of zones, not just the substances present and their handling. Factors such as temperature, pressure, and concentration are crucial. Furthermore, considering that the area is onboard a ship exposed to weather and climate fluctuations, this warrants special and careful consideration.

In addition to considering the estimated time with the explosive atmosphere being present, different release grades can be considered to help decide what zone to use in a space. For example, even though there is no direct relation between the zone classifications and the grades of release, in open air, continuous grade of release will usually result in zone 0 classification, primary grade leads to zone 1, and secondary grade leads to zone 2 [14]. See further explanation of the release grades in Table 6.3.

Table 6.3: Definition of grades of release

Grade of release	Definition	Time guidance [h/year]
Continuous grade	A release that is continuous or is expected to occur frequently or for long periods	T > 1000
Primary grade	A release that can be expected to occur periodically or occasionally during normal operation	10 < T < 1000
Secondary grade grade	A release that is not expected to occur in normal operation and, if it does occur, is likely to do so only infrequently and for short periods	1 < T < 10

Substances

Materials with the possibility of creating an explosive atmosphere are often divided into four groups: flammable gasses, flammable liquids, flammable mist, and flammable dust. The ships we are considering in this thesis are chemical tankers, and they carry only liquid cargo. However, some cargoes have a low boiling point, so they are transported under pressure. So the most relevant groups, in this case, are flammable liquids and gases.

- **Flammable liquids** – often hydrocarbon compounds. These can often change into vapor near the surface, even at room temperature, which creates an explosive atmosphere. Most other liquids would require higher temperatures to do the same.
- **Flammable gases** – often compounds of carbon and hydrogen; however, hydrogen and ammonia also belong to this group. These gases generally only require a small amount of energy to initiate a reaction with oxygen in the atmosphere.

Substances can also be divided into classes based on flash points, fluid categories, and gas groups. Additionally, there are temperature classes for equipment. The flash point of substances present will decide the necessary temperature class. However, the specifics of these will be discussed elsewhere.

Limits of flammability

Even if flammable substances are present in the atmosphere, it does not mean that they will be ignitable. The concentration in the air has to be between Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL)[14]. LEL is the minimum concentration of a given substance that must be present for flame propagation following ignition. UEL is the maximum concentration of a given substance that can be present for flame propagation to happen following ignition [14].

6.5.2 Likelihood of an Effective Ignition Source - Ignition Hazard Assessment (IHA)

Equipment

When explosive atmospheres cannot be eliminated, the risk must be mitigated by avoidance of possible ignition sources. Therefore, the equipment used in the various gas zones must adhere to the equipment selection rules of Annex II, Sect. B of ATEX Workplace directive 1999/92 [14]. If the equipment used within a given zone is within the regulations, the risk is considered sufficiently minimized [14]. Equipment to be used is generally organized into three categories, depending on the zone(s) they can be used.

- **Category 1** – the highest level of protection. Can be used in zone 0 (and all others) [14].

- **Category 2** – high level of protection. Can be used in zone 1 (and zone 2) [14].
- **Category 3** – normal level of protection. Can be used in zone 2 [14].

Sometimes, the required equipment does not possess the adequate category (sufficiently low level of ignition sources) but is still essential to the operation. In this case, the risk must be accepted, and mitigating measures can be implemented to reduce consequences.

Detailed information on the equipment is required to decide the likelihood that an ignition source will become active and effective. One must know the probabilities of failures that will cause friction resulting in heat or sparks. And in equipment with circuit boards, the switches should be isolated.

Different kinds of ignition sources

- **Hot surfaces** – Occurs either from equipment operation or from heat exposure (typically sun exposure). If the surface temperature reaches the atmosphere's ignition temperature, it can be a possible ignition source. Some malfunctions may cause hot surfaces, such as moving parts that overheat because of inadequate lubrication. Slow moving parts typically do not need protections from frictional heating.
- **Open flames and hot gasses** – are one of the most effective ignition sources. In addition will hot gasses, especially with hot or glowing particles ignite explosive atmospheres.
- **Mechanical sparks** – typically develop from friction between components, impact or abrasion. Especially friction between light metals (aluminum, magnesium, titanium), their alloys and rusty steel can produce sparks. Oxidizable particles torn off that become hot can react further with oxygen and reach high(er) temperatures.
- **Electrical sparks** – may occur even at low voltages, and typically happen when making or breaking circuits, at loose connections and at stray electric currents. This can be a source of ignition both inside electrical apparatus and in cabling onboard.
- **Static electricity** – charges through contact and separation, because of the negative and positive charges moved in this process. If not grounded, the charge will build up to a point where it can discharge with a static arc. The static arc may provide an ignition source. Some hydrocarbon gases have minimum ignition energies as low as 0.1 mJ, while a person walking on a carpeted floor can build up a potential difference large enough for a 40 mJ discharge. This proves that static electricity is an ignition source that should be taken very seriously.
- **Chemical reactions** – happen when different gasses or substances react with each other. With an exothermic reaction where the rate of heat generation exceeds the rate of heat loss to the surroundings it can become an ignition source.
- **Lightning** – is very high energy and can easily ignite an explosive atmosphere or cause stray currents that give of sparks that can be ignition sources.
- **Stray electric currents and cathodic corrosion protection** – can cause both electric sparks and heating in their path. Both of these can be ignition sources.

- **Radio frequency waves** – can give off powerful fields that under certain circumstances can cause ignition.
- **Optical radiation** – might be a source of ignition when concentrated. For instance, sunlight. It can be focused by different objects - especially glass. Additionally, laser radiation may become an effective ignition source because of its concentrated high energy.
- **Ionizing radiation** – can come from certain equipment with nuclear elements. It can ignite an explosive atmosphere by self-heating, chemical reaction and absorption.
- **Adiabatic compression and shock waves** – because rapid compression of gas has negligible heat loss and very high heat generation. Further when high pressure gas is released into pipes it can generate shock waves and temperature rises high enough to be a source of ignition.

6.5.3 Anticipated Consequences

A fire or explosion's consequences can range from minor to catastrophic. It can cause both material damage and human injuries or death. The main consequences relevant to this case are:

- Injury or death of humans
- Material damage to the ship
- Emissions of chemicals or fuel to surrounding environment
- Economic losses from damage/loss of cargo

The crew onboard will be the most exposed in case of an explosion or fire at sea. While if something were to happen in port, close to other ships, or while sailing in a narrow channel/river, other humans may also be affected. The injuries can be, for example, burns, blast injuries, inhalation injuries, lacerations, and projectile penetration wounds.

Material damage will, similar to before, only affect the ship itself if at sea but can also affect surrounding infrastructure if at port or close to land. The damages can vary depending on the severity, from minor stains or bulges to the ship capsizing or sinking. Material damage to the tanks and hull can lead to another significant consequence; emissions of fuel or chemicals. A chemical tanker will carry a large volume of chemicals that can harm the surrounding environment and wildlife. Poisoning of the environment is a serious issue and something that the company's image can suffer significantly from.

A less severe but still profound consequence is the economic losses to the ship owner from damage to or loss of cargo. If the ship is harmed, this may impede the ship's ability to keep a certain pressure or temperature in the tanks.

6.5.4 Explosion Prevention and Mitigating Measures

The main actions to prevent an explosion are avoiding an explosive atmosphere and eliminating all ignition sources if that is impossible. The three ways to avoid creating an explosive atmosphere are avoiding flammable material, keeping conditions outside the flammable range, or removing oxygen content.

In the case of a chemical tanker, we cannot avoid the flammable material because it is the cargo. Keeping conditions outside the flammable range (i.e., between LEL and UEL) keeps the atmosphere nonexplosive, but this will not be possible for all substances. However, ventilation that keeps the gas/vapor lower than LEL is ideal in cases where it is possible. Removing oxygen in the open air is not possible either. What then remains is to eliminate ignition sources.

Because of the issues with some of the avoidance tactics of explosions, mitigating measures are often implemented to kick in should an accident happen. Typically these will be, for example, explosion-resistant design - meaning that the structure can handle an explosion's increased pressure or pressure shock. It can also be injecting suppressing chemicals or preventing flame and explosion propagation with physical barriers.

Chapter 7

Cost Assessment

Cost assessments, or LCC, are a necessary step in any evaluation of novel technologies. It should be used to evaluate the total costs associated with the entire life cycle of a ship or piece of technology. This includes its design, construction, operation, maintenance, and disposal. When ship owners invest in novel technologies to reduce emissions, they must consider the upfront costs and the long-term financial implications. This chapter examines the importance of LCC assessment for ship owners and highlights the significance of incorporating future costs, such as potential CO_2 taxes, in the assessment process. Additionally, it explores the calculation of Net Present Value (NPV) as a critical financial metric and its relevance in evaluating investment options within the context of LCC assessment.

For energy-saving devices specifically, the fuel price will be essential to the long-term financial implications. The rate at which it is possible to pay back the investment of any energy-saving device will depend on the fuel price. If the cost is high, the investment payback period will be shorter than when the fuel price is low.

Their contribution is difficult to estimate because fuel prices fluctuate and are nearly impossible to predict. Fuel costs constitute a substantial portion of operational expenses and significantly impact different technology options' overall life cycle costs. The fuel savings generated from energy-saving devices tell us how much can be potentially saved in fuel, but the fuel price tells us how much that will be in monetary value.

With the increasing focus on environmental sustainability and the global commitment to reducing GHG emissions, ship owners must anticipate potential future costs associated with carbon dioxide (CO_2) or other emission taxes. As these can also influence the payback period of an energy-saving device on a ship. These were also discussed earlier in chapter 4. By incorporating these future costs into the cost assessment, ship owners can better understand the long-term financial implications of technology investments and make informed decisions to mitigate risks and maximize returns. However, this additional cost may be incorporated into customer contracts. So, in the end, the customers will be the ones to pay the emission taxes. Nevertheless, even if the ship owners do not directly pay the emission taxes, the customers will be incentivized to choose providers with lower emissions because of lower prices.

In conducting a cost assessment of implementing new technologies on board, the ship owner must consider several factors contributing to overall costs. The initial investment will include equipment, installation, retrofitting expenses, and possibly infrastructure modifications.

Additionally, possible loss of income due to installation time must be considered. Then, increased maintenance costs must be accounted for. If the installed technology has any residual value at the end of the ship's lifetime, that should be considered as well.

Net Present Value (NPV) is a widely used financial evaluation method. It enables, for instance, ship owners to assess the profitability of investments. One of its main advantages is that it considers the time value of money. This is done by discounting future cash flows to their present value. This is essential because money in the future will not have the same value as today, so calculations without discounting will not give an accurate picture of a financial investment over time. Including NPV calculations in the cost, analysis helps ship owners make informed decisions.

NPV can be simply summarized as *Present Value of Cash Outflow* subtracted from *Present Value of all Cash Inflows*

So a positive NPV indicates that the investment is expected to generate more value than the initial investment. And conversely, a negative NPV will indicate that the investment is unlikely to generate sufficient returns to cover the costs. Sometimes it is interesting to perform several calculations to compare different technology options or input values. For example, in the case of ships with energy-saving devices, different calculations with different fuel price cases are especially interesting.

When using NPV as a financial evaluation method, one must determine an appropriate weighted average cost of capital (WACC). The WACC should reflect the time value of money and account for inflation, interest rates, and investment risk profiles.

Part II

Operational Life Cycle Assessment of Rotor Sail Implementation

Chapter 8

Goal, Scope, Boundaries and Functional Units

The goal and scope of the study set the base for what should be answered by the analysis and what the analysis should include. It will set boundaries and demands for what data should be included in the inventory analysis. However, as an LCA requires interpretation throughout the study, the inventory and impact assessment phases can also change the scope of the study.

8.1 Goal of the Study

The main goal is to determine whether installing rotor sails on an existing tanker vessel is beneficial by analyzing the ship's operation. In this thesis, an *existing vessel* will be defined as a ship that was in operation before the rotor sail installation and is not explicitly designed to implement WASPs.

The main goal is divided into several sub-goals. The most high-level sub-goals are described in Figure 8.1, finding the emissions and costs in both cases. This will create the basis on which a comparison and conclusion can be made as to whether the implementation is beneficial or not.

The intended audience is part of the study goal to understand the prior level of knowledge of the reader. In this thesis, we collaborate with Odfjell, an interested party in the study's results. Other than that, the relevant audience will be students and academicians. For this reason, the study will be written at an academic level, though many principles and methods are explained.

8.2 Scope

As previously described, it is essential to define the scope so that the results from the LCA fulfill the goal of conducting the LCA. In this case, where the goal is to compare two different ways of operating the ship, it is essential to set the scope and boundaries such that the analysis makes a fair comparison.

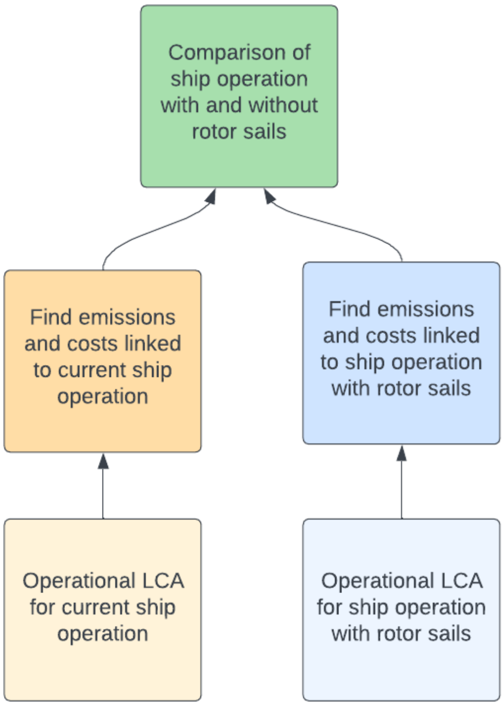


Figure 8.1: Diagram describing most high-level subgoals

The analysis aims to compare the ship's operation with and without rotor sails. Therefore, the analysis will only include processes from 2025 until recycling, which is assumed to be in 2045. This is further described in section 8.3. Outside the scope will be the ship's construction and previous ship operation. Recycling of the ship and rotor sails is also excluded from the scope. This means that the ship's operation (from now until recycling) will be the only part of the ship's lifetime considered. The reasons for only considering the operation are described in subsection 8.2.3.

The rotor sails are only operating when sailing at sea. Data from the ship owner describes that the ships are operating 50% of the time at sea and 50% of the time in port. As the rotor sails are not operating when in port, the operation in port is excluded from the analysis. The operation in port will be the same if the ship has rotor sails or not, and will therefore not give any differences in the comparison of the two operational modes. The operation in port is excluded by only including ship speeds above 8 knots.

In order to find the difference in emissions and costs for the two operational cases, it is necessary to conduct four analyses: Environmental analysis for the ship's operation with and without rotor sails and cost analysis for the two operational modes. The two operational modes will be modeled in SimaPro with operational values and costs and then analyzed with the ReCiPe and LCC methods. The ReCiPe method is already well-implemented, while no LCC methods are already implemented in SimaPro. The costs will be calculated in SimaPro by creating our own analysis model, and the results will be used in a separate LCC calculation.

8.2.1 System Boundaries

The system considered is the ship as a whole. For the analysis with rotor sails, the system considered is the ship as a whole with installed rotor sails.

8.2.2 Process Flow

Illustrating the process flows in the scope and system boundaries helps get an overview of what is included and excluded. It is essential to be aware of what is excluded from the scope and to determine if the assumptions of excluding processes make the analysis reliable and adequate to answer the goal.

The process flow diagram for regular ship operation is shown in Figure 8.2, and for operation with rotor sails in Figure 8.3. The construction and recycling phase, operation at the port, and rotor sail fabrication and installation are outside the scope. This is further explained in the following sections. The diagram only includes the foreground processes, as the background processes, such as maintenance, transportation, electricity, and fuel, are unnecessary to get an overview of the scope.

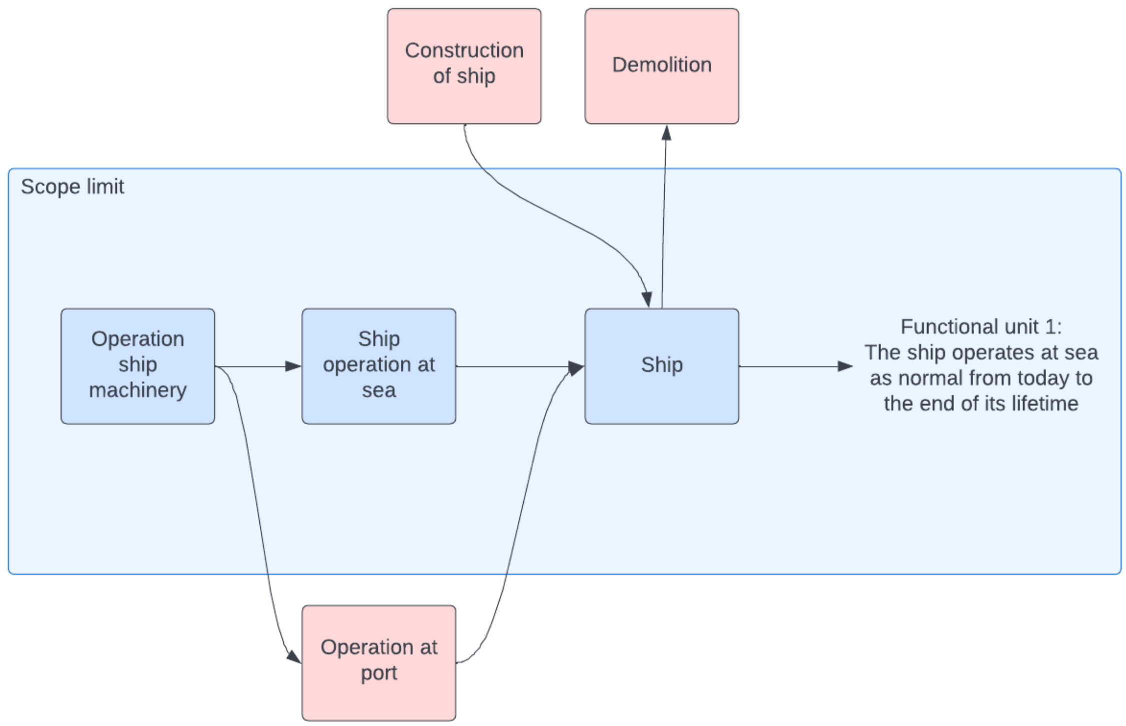


Figure 8.2: Process flow with scope limits for normal operation

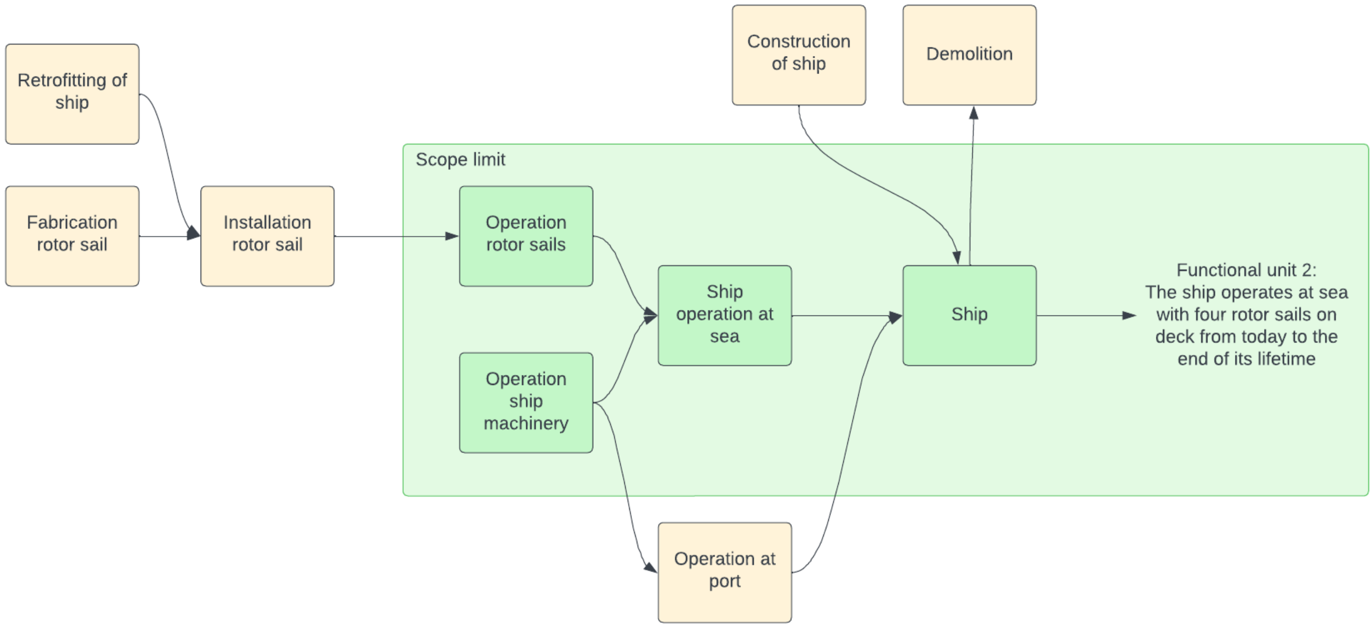


Figure 8.3: Process flow with scope limits for operation with rotor sails

8.2.3 The Case for an Operational LCA

A proper LCA according to the ISO-standards should include the entire life cycle of the ship, from the raw materials used in its construction to the resources used for scrapping the used vessel. However, in our goal of comparing operations with and without rotor sails, the ship construction and scrapping will remain the same in both cases. Several studies have proven that the vast majority of emission contributions from ships come from operations.

A study by Chatzinikolaou and Ventikos that considered a Panamax tanker ship's total life cycle emissions found that the ship operation contributes to the highest emission production [31]. Carbon dioxide, carbon monoxide, methane, nitrogen oxide, particulate matter, and sulfur dioxide were considered emissions. Ship operation had the highest contribution in all categories. For example, the share of emissions attributed to the operation of carbon dioxide and carbon monoxide was 96% and 71%, respectively [31].

Additionally, two other articles confirm the findings. A study considering a Panamax bulk carrier found that fuel consumption in operation is the primary emissions contributor, resulting in more than 90 % of emissions for the entire life cycle [32]. Furthermore, a study considering different ships for crude oil transport found that operation makes up 91% of all carbon emissions [33].

In contrast, only a small part comes from construction or recycling procedures. For this reason, it is fair to exclude the ship's construction and recycling from this thesis's scope. The goal is to find whether rotor sails will be worthwhile for these ships when considering differences in emissions, risks, and costs. Construction and recycling operations will not be affected by the change and will take time to calculate, while they don't contribute much to the result. In conclusion, this thesis will only consider the ship's operational life within the scope of the LCA.

8.2.4 Functional Unit

As mentioned, the analysis requires two models of the system in order to compare them. One analysis for the ship with rotor sails and one without rotor sails. This results in two functional units for the LCA.

- **Functional unit 1:** The ship operates at sea as usual from 2025 to the end of its lifetime (2045).
- **Functional unit 2:** The ship operates at sea with four rotor sails on deck from 2025 to the end of its lifetime (2045).

To make sure the two analyses are comparable, the processes of the analyses and the functional unit should ensure that the results are comparable. The two functional units for this analysis are essentially the same. We will use the same route data and assumptions for the analysis, but one will have four rotor sails as an addition.

The operation, until the rotor sails are implemented (in 2025), is identical in both cases. When the goal is to find out if it is beneficial to install the rotor sails to the specific ship or not, it is not interesting to implement the impacts from the processes already performed. Moreover, the ships we are considering in this thesis are relatively new, with the majority of their lifetime still ahead of them. The reason for not including construction and recycling is explained in subsection 8.2.3.

8.3 Assumptions

It is necessary to make a series of assumptions to perform an analysis such as this. Some of them are previously mentioned and explained in this chapter, but the following list summarizes these assumptions and mentions new ones to get an overview. Some of the new assumptions come from the concepts described in the next chapter.

- **Construction and recycling** – The construction and recycling of the ship and rotor sails will contribute little, as shown in previous literature and studies, and are excluded.
- **Lifetime ship** – The ship's lifetime is assumed to be 25 years. Many ship owners are considering lifetime extensions. Nevertheless, considering lifetime extensions in this thesis will further complicate the analysis and widen the scope, so we have decided only to consider the initially planned lifetime of the ship.
- **Lifetime rotor sails** – The lifetime of the rotor sails is 25 years as well, as stated by providers [4]. Considering that the sails will be installed on a ship already in operation, they will not reach their entire lifetime on one ship. We assume it can be sold or moved to another ship if the original ship is recycled. However, we will not consider the rotor sails saving effects on the next ship or the potential monetary savings of selling it.
- **Operational time** – Considering that the ships were built in 2019 and 2020, with an expected lifetime of 25 years, we assume that the rotor sails will be implemented in

2025. This means that 20 years remain of the expected lifetime and is the amount of time we will consider for the study. The analysis will also only analyze the operation at sea, which is about 50% of the time during regular operation.

- **Operational speed** – The LCA will be conducted assuming that the ship with rotor sails will sail with the same operational speeds as previous operation. This means that the engine has to be throttled back and adapted at all times when the rotor sails are giving a lift. This is a complex process as the propeller is fixed pitch, and the engine is a two-stroke diesel/HFO engine. However, we assume the engine can be adjusted to fit the current propulsive power from the rotor sails.
- **Auxiliary engines** – It is assumed that the ship owner will use one of the auxiliary engines with the highest capacity when sailing with rotor sails. This avoids starting an additional auxiliary engine when sailing without rotor sails. This is further explained in subsection 9.2.2.
- **Aerodynamic resistance** – The Matlab code considers that the rotor sails are tilted when not operating. In subsection 9.1.1, we say that the rotor sails will be installed without a tilting system. This implies that aerodynamic resistance will not be accounted for when the ship is sailing without the rotor sails operating. For this case, we have assumed that we can neglect these aerodynamic drag forces.
- **Interference between rotor sails** – We assume that the distance between the rotor sails is large enough to neglect the interference. According to a study by G.Bordogna et al [34], the interference is close to none when the distance between two sails is 15 times the diameter of the rotors. In our case, the distance between the rotor sails are 7 times the diameter crosship and 6 times the diameter longship. This means that there will be aerodynamic interference between the rotor sails that is not accounted for in the calculations.

Chapter 9

Inventory Analysis - LCI Phase

The data collected in the LCI phase mainly consists of ship-specific data, wind data, and power savings calculations. The ship owner provides the historical data for the ships and the ship's specifications. Wind data are gathered from Copernicus Marine, and the power savings are calculated from the ship and wind data. The power savings processes and calculations are quite comprehensive, and are illustrated in a simplified flow chart in Figure 9.1. This chapter further describes the processes in this flow chart and will explain what data are put into the SimaPro software and how they are gathered or calculated.

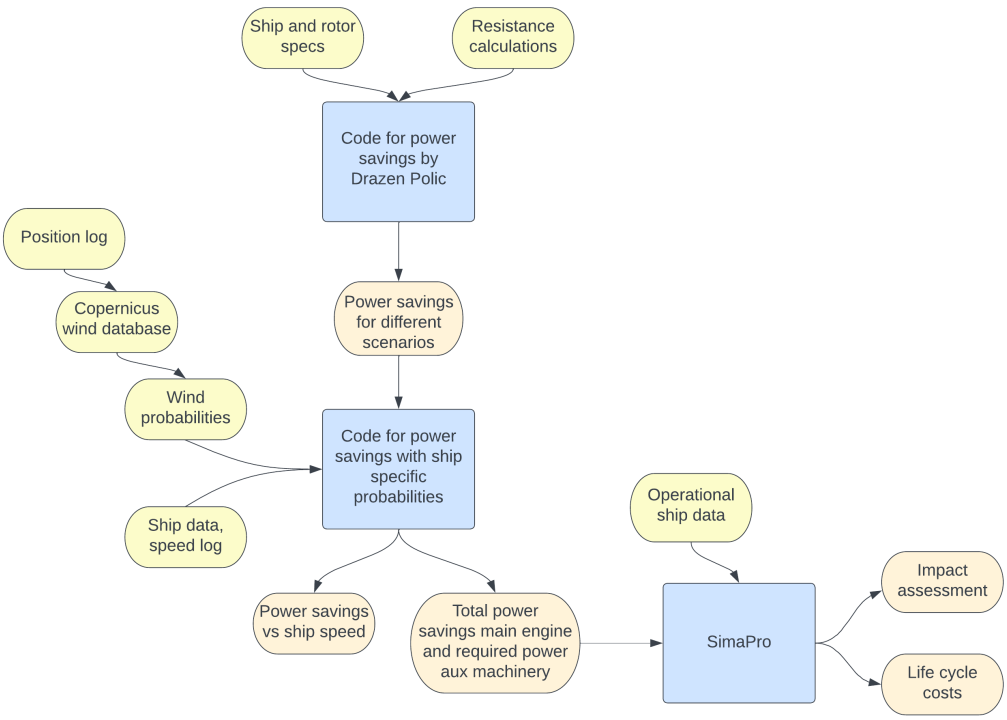


Figure 9.1: Flow chart of processes for calculating input data for SimaPro

9.1 Data for Power Savings

In order to estimate the power savings from the rotor sails as accurately as possible, considering the available time for this thesis, a program developed by postdoc researcher Dražen Polić at NTNU has been used. The program is written in Matlab and is developed and described in a study focusing on using energy efficiency measures, specifically rotor sails, on reaching the IMO 2050 GHG targets [2].

Our thesis focuses on a specific group of tankers from Odfjell and therefore differs from the mentioned study that focuses on newbuilt dry bulk ships. However, the code that calculates the power savings will import the data related to the ships for this thesis, and the result will be a reasonable estimation of the power savings for these ships.

To estimate the power savings from the rotor sails, dimensions, and raw data from the ship owner are provided to Dr. Polić. The results from the code are then used with historical wind data for the ship route from Copernicus with a code developed in Python for this thesis (see Appendix I). The Python code is developed to return the total power savings in different ways. One method, later named *Method A*, is developed to return the average power consumption from the rotor sails and the average power savings for the main engine. The results of method A are returned to be used in the LCA in SimaPro. The other method, *Method B*, returns the power savings for different speeds to understand when the ship saves the most. The input data, Matlab code from Dr. Polić, and the Python code are further described below.

9.1.1 Input Parameters Matlab Code

The input data include ship dimensions, ship resistance at multiple ship speeds and drafts, propeller dimensions and efficiency, and rotor sail dimensions and locations. An overview of these values is shown in a spreadsheet in Appendix A.1.

Values for the ship dimensions come from the general arrangement of the ships. The ship drafts, LCB, and displacement for the different drafts are found in a powering performance model tests report for the ships. The ship specifications are shown in Table 9.1 together with propeller dimensions that come from a report for the finished design of the rudder for the shipowner.

Table 9.1: Ship and propeller specifications for Matlab code

Ship specs	Scantling draft	Design draft	Ballast draft
L_{OA} [m]		182.9	
Breadth [m]		32.2	
Keel to main deck [m]		20.2	
Draft midship [m]	13.2	11	7.5
LCB [m]	2.53	4.29	2.91
Propeller specs			
Efficiency	0.75	0.766	0.783
Diameter [m]		7	

The resistance values for calm sea are extracted from model testing, while the resistance values for waves are estimations done by assuming head waves of 3 meters. Dr. Polić calculated the resistance estimations using the empirical method STAwave-2 [35]. If the mean wave height were calculated from the historical wind conditions for the ship, it would be 1.2 meters, shown in Appendix B. Therefore, the method used to estimate the resistance with 3 meter head waves gives a conservative result. The two cases of resistance are used separately to calculate the power savings in the Matlab code. The Python code will then combine the values of the power savings as 50% calm sea and 50% sea with 3 meter head waves. From now on, the 50/50 combination will be called *average sea*, the calm sea will still be *calm sea*, and 3 meter head waves will be called *heavy sea*. A similar practice is used in Lindstad et al. [36] to capture all three sea states.

The rotor sail dimensions are gathered from the two suppliers Anemoi[4] and Norsepower[6] and are shown in Table 9.2. The specifications of the rotor sails determine some of the constraints of the Matlab code, which is described in subsection 9.1.3. The rotor sails and foundation height is set to be as high as possible but not higher than the ship's highest point. This is to extract as much power from the sails as possible without the need for tilting or rail systems, which would require a more complicated integration process and would be more expensive. As mentioned in section 8.3, having fixed sails will lead to some aerodynamic forces which are neglected for this thesis.

Table 9.2: Rotor sail specifications for Matlab code

Rotor sail specs	
Rotor diameter [m]	3.5
Rotor height [m]	24.5
End plate diameter [m]	7
Base height [m]	2
Installed power [W]	80 000
Max rpm	265
Max bearing load [kN]	175
Max operational wind speed [m/s]	35
Number of devices	4

The deck of a tanker consists of a nest of pipes and includes several explosion zones that must be avoided, which is further explained in chapter 13. The location of the rotor sails are based on discussions with the ship owner, and shown in Figure 9.2. The Matlab code does not consider interference between the rotor sails. We are here assuming that the distance between the rotor sails is big enough to neglect the interference, even though interference will occur as described in section 8.3.

9.1.2 Discretized Data

In the Matlab code, deciding on pre-defined discretized values for ship speed, ship draft, true wind speed, and true wind angle relative to the ship's heading is necessary. All possible combinations of these discretized values make up *bins*, and the code returns power savings and other relevant data for each bin. The most relevant data returned from the code for this case are how much propulsion power the rotor sails generate and how much electrical power the rotor sails consume.

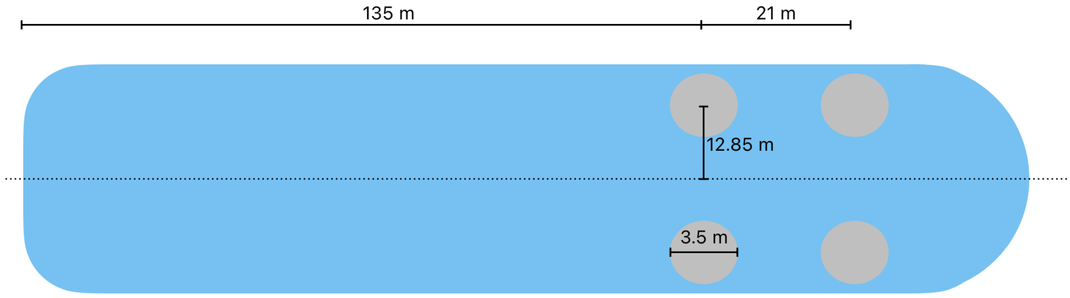


Figure 9.2: Placement of rotor sails seen from above with measurements (not representative of scale).

The increments of the discretized values for ship speed, true wind speed, and true wind angle are decided based on the gathered historical values for these parameters, the computational time of the Matlab code, and the wanted accuracy of the results. The chosen values are shown in Table 9.3 and explained below.

Table 9.3: Data discretization of values for Matlab code

Parameter	**Min value**	**Max value**	**Increments**	**Values**
Ship speed	8 kn	16 kn	1	9
True wind speed	2.5 m/s	25 m/s	2.5	10
True wind angle	0°	180°	5	37

Ship speed discretization is done by looking at the historical data of the ships. In the scope, it is decided not to include ship speeds below 8 knots; therefore, the discretization starts at 8 knots. The maximum ship speed is decided during conversations with the ship owner. Some of the ship speed data includes velocities above 16 knots (as seen in Figure 9.3), but the ship owner states that this might be errors in the measurements and that a maximum sailing speed of 16 knots should be assumed.

The true wind speed is discretized with increments of 2.5 and goes from 2.5 to 25. This is decided based on the historical wind data. How the data is found is further described in subsection 9.1.5.

True wind angle discretization includes wind between 0 and 180 degrees with a step length of 5. Not including 180 to 360 degrees is because the system is assumed to be symmetrical, making the computational time lower. This again allows having shorter increments which give more accurate results.

The ship drafts are not discretized with equal increments but are based on the ship's three specified ship drafts; design draft of 11 meters, ballast draft of 7.15 meters, and the scantling draft of 13.2 meters. The probabilities of having the different drafts from the raw data are shown in Figure 9.4. To later calculate the power savings, the drafts are rounded to the nearest specified draft. This means that the drafts below 9 meters are rounded to 7.15 meters, the drafts between 9 and 12 meters are rounded to 11 meters, and the ones above 12 meters are rounded to 13.2 meters.

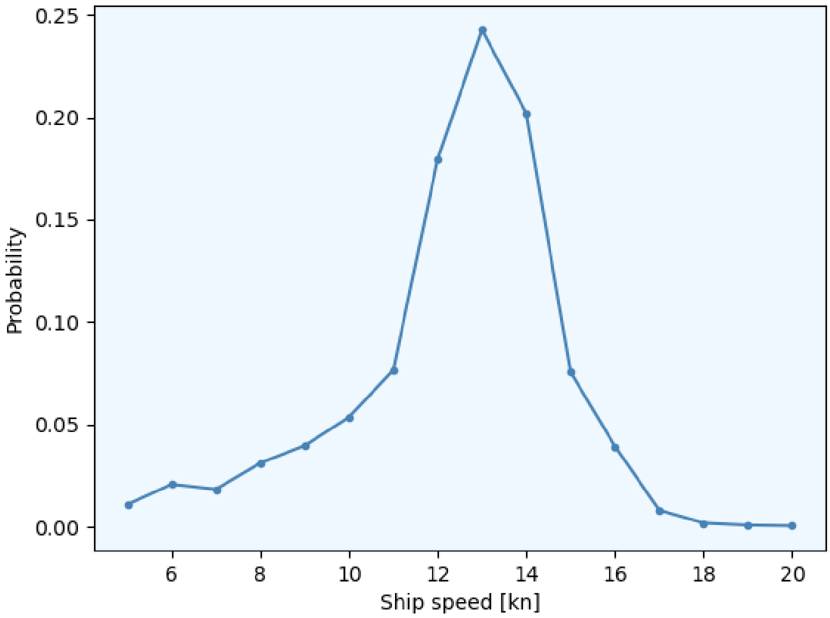


Figure 9.3: Probability of average ship speed from raw data

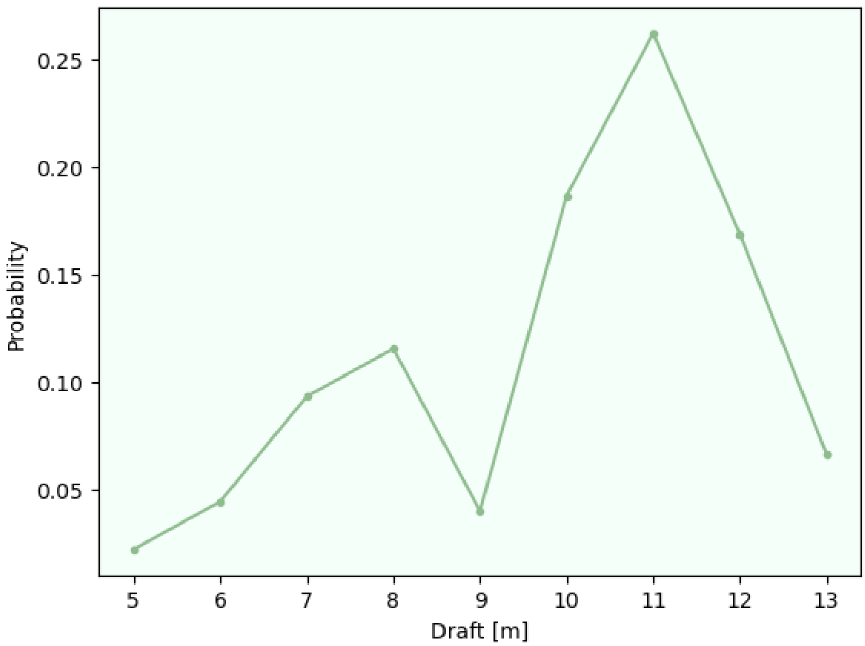


Figure 9.4: Probability of different ship drafts from raw data

9.1.3 Calculations Matlab Code

By using the input data described in subsection 9.1.1 and the discretized data in subsection 9.1.2, the code estimates the power savings and consumption for each of the unique bins of true wind speed, true wind angle, ship speed, and draft. The output also includes other data that are not relevant to this thesis. An example of one of the spreadsheet provided by Dr. Polić is attached in Appendix C, where it is shown what data are returned.

The thrust and side force of the rotor sails are determined using lift and drag coefficients provided by Tillig and Ringsberg [37]. These coefficients are validated using full-scale and model-scale data for a rotor sail design with specific rotor sail geometric parameters (24 meter height and 4 meter diameter). The spin ratio, which compares the local apparent wind speed with the rotor sail speed, is used as a basis for expressing the coefficients. A spin range of 1 to 3 is suggested for accurate calculations. However, Tillig and Ringsberg obtained a good agreement between lift and drag coefficients with full-scale data for a spin ratio range of 1-5 [37].

The calculation of aerodynamic thrust and side force involves employing a strip theory and quasi-steady approach. This approach considers the apparent wind speeds and angles, rotor sail spin ratio, and corresponding lift and drag coefficients for each strip of the rotor. The derived aerodynamic forces are then converted into thrust and side force vectors by summing the contributions from all strips. Additionally, to compensate for significant aerodynamic side forces, wind-assisted ships deviate downwind, resulting in a drift angle, β. Hydrodynamic lift and drag forces are produced by the ship's speed and drift angle, and an empirical method proposed by Kijima et al is used to estimate the lift coefficient, taking into account various hydrodynamic derivatives and maneuvering coefficients [38]. The equation for the lift coefficient is shown in Equation (9.1).

$$c_L = Y_\beta \beta + Y_r r + Y_{\beta\beta}\beta|\beta| + Y_{rr}r|r| + \left(Y_{\beta\beta r}\beta + Y_{\beta rr}r\right)\beta r \tag{9.1}$$

The Y values are conventional maneuvering coefficients or hydrodynamic derivatives, while the r values are the normalized yaw angular speeds. For these calculations, only two of the hydrodynamic derivatives, Y_β and $Y_{\beta\beta}$ are considered, as the four other derivatives will have r equal to zero [2]. Y_β and $Y_{\beta\beta}$ are given in Kijima et al [38]. The lift coefficient c_L is also reduced to 25% of the calculated value because of the observations from Tillig and Ringsberg [37].

Predicting wind-induced drag at small drift angles presents significant challenges. Computational Fluid Dynamics (CFD) simulations are computationally expensive for such calculations. Consequently, in the absence of precise computations or measurements, an assumption is made that the added wind-induced hydrodynamic drag, $R_{add,wind}$, is proportional to the product of the lift coefficient, c_L, the drift angle, β, and a correction factor of 1.2 [2]. This is shown in Equation (9.2)

$$R_{add,wind} = -1.2 \cdot |c_L \cdot sin\beta| \tag{9.2}$$

The power savings for each bin are calculated as shown in Equation (9.3). P_{noWASP} is the required power for the ship without rotor sails. T_{prop} is the necessary thrust from the propeller,

u is the surge velocity, and η_p is the efficiency of the propeller. $P_{req,WASP}$ is the power required for the rotor sails to spin, and η_e is the power efficiency from the engine to the electrical drive in the rotor sails. Shortly explained, the power saved is found by subtracting the required power for the ship with rotor sails and the required power for the rotor sails from the required power without rotor sails.

$$P_{\mathrm{s}} = P_{\mathrm{noWASP}} - \left(\frac{T_{\mathrm{prop}}\, u}{\eta_p} + \frac{P_{\mathrm{req}\ ,WASP}}{\eta_e} \right) \tag{9.3}$$

Constraints

The input parameters are not only used for calculating the power output but also for defining the constraints. Table 9.2 provides an overview of constraint values primarily related to rotor sails. The different constraints set limits to the operational cases of the rotor sails. Power savings are determined by utilizing values within these limits. The code iterates from the lowest to the highest limit, and the returned value for power saving corresponds to the highest achievable savings that fall within the defined limits.

- **RPM** – This constraint is related to the maximum revolutions per minute (RPM) of the rotors. The code will start with an RPM that gives a spin ratio of 1, and calculate with increments of 5 until the maximum RPM given. When you change the RPM you also change the area of the sail, in other words, the trim of the sails.
- **Spin ratio** – This constraint is about the spin ratio, also known as the velocity ratio, which plays a crucial role in determining the occurrence of vortex shedding from the rotors. The spin ratio is valid between 1 and 5.
- **Power requirement** – The next constraint is about the power requirements for operating the rotor sails. The rotational motion of the rotors demands a certain amount of power, and the electrical drive in the rotors has a maximum capacity. The code is using the minimum value as 20% of the installed power, while the maximum value is the installed power.
- **Thrust force** – This constraint delimits the maximum thrust capacity of the rotors. Its maximum value is set based on the maximum bearing load.
- **Side force** – The constraint relates to the longitudinal side force exerted from the rotor sails on the hull.
- **Drift angle** – This constraint regards the maximum permissible side force acting on the rotors. The maximum drift angle is 3°, which is low compared to similar codes [39]. This can make the result more conservative.
- **Wind speed** – The maximum wind speed allowed to give power savings is the maximum operational wind speed of the rotor sails. For this case it is 35 m/s which is given by Norsepower and DNV [6] [40].

9.1.4 Results Matlab Code

After giving the input parameters described in subsection 9.1.1 to Dr. Polić, he provided spreadsheets of the power savings amongst other data, an example of this is shown in Appendix C. One file contains the power savings for resistance values with no waves and the other for resistance values with head waves of 3 meters. These results are further used in the Python code described in the following sections.

9.1.5 Calculations Python Code

Wind data are collected from a historical weather database from Copernicus using the coordinates over one year (2022) from one of the ships sailing a typical route. The route is plotted on a map as seen on Figure 9.5 and shows several passages over the Atlantic Ocean.

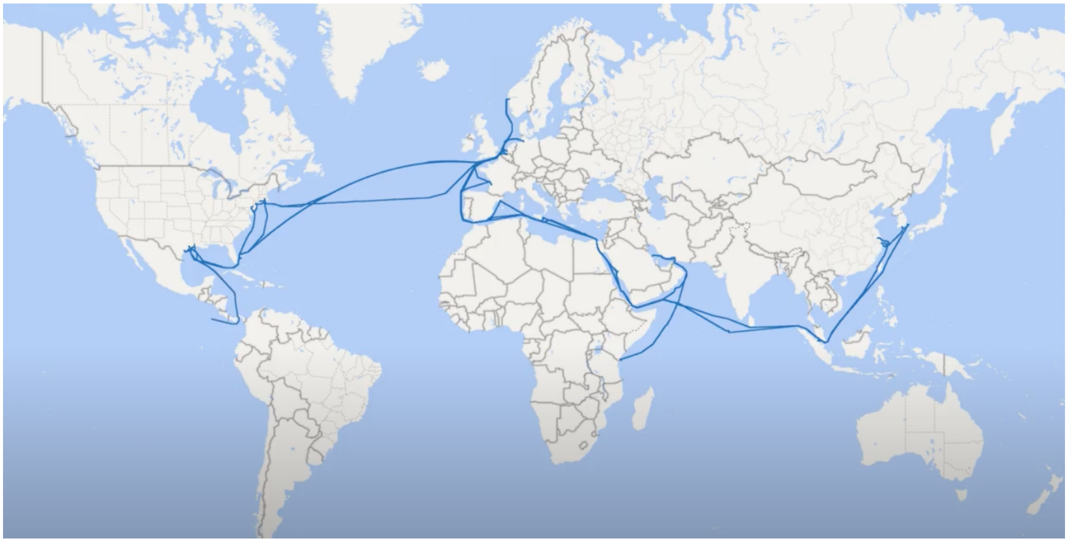


Figure 9.5: Historical route by one of the ships

Copernicus Marine Environment Monitoring Service (CMEMS) has developed an application [41] which makes it possible to download weather data for given locations by uploading a file with the time and wanted locations. The input given to the application for this case is a file with time, latitude, and longitude coordinates from the historical ship route of 2022 supplied by the ship owner. Then the product, dataset, and wanted variables were chosen. The chosen product was "WIND_GLO_PHY_L4_NRT_012_004" [42] with the variables northward wind and eastward wind. The product gives the historical wind values based on scatterometer observations and operational numerical weather predictions. The values are corrected to represent wind from 10 meters above the sea surface. This makes it possible to use the wind data without corrections for disturbance from the sea surface.

The application then provides a csv file with the wind speed from the south, the wind speed from the west, and the time. The TWS and TWA in the Matlab code are relative to the ship heading. In order to use the values from the downloaded csv file, the Python code that calculates the power savings for this case also contains conversion of the wind.

The Python program takes northward wind and eastward wind from Copernicus and converts this into wind angle and wind speed separately. Then the wind angle is converted to where the wind comes from, not where it goes. The wind speeds, and direction for the location of the ship route are plotted as a polar plot in Figure 9.6. The different colors represent the different wind speeds, and the direction of the bars shows the wind direction.

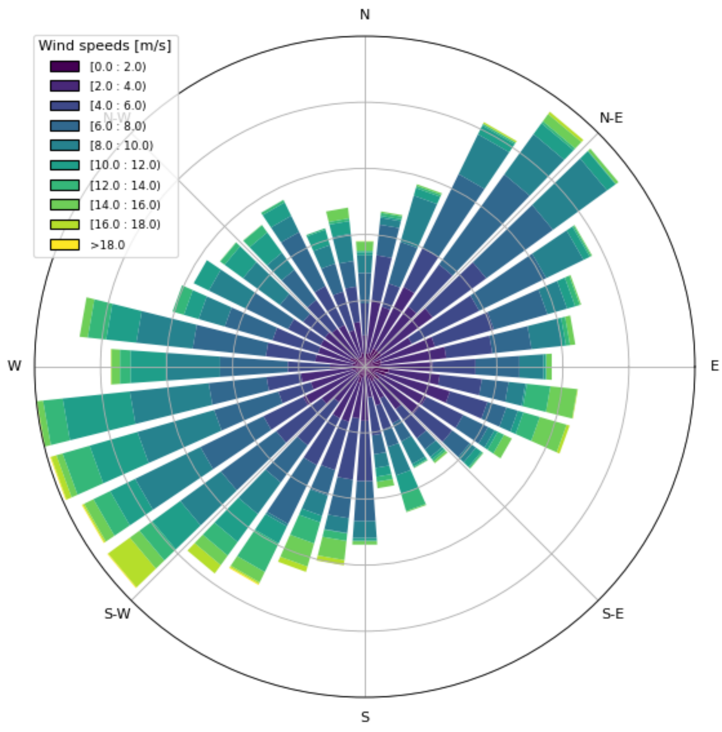


Figure 9.6: Polar plot of wind speed and wind angle for the given route

The wind direction has to be combined with the ship heading to use the wind probabilities with the results from the Matlab code. This gives the TWA and TWS relative to the ship and is shown in Figure 9.7. The degrees marked on the graph illustrate wind direction in relation to the ship heading. The probabilities for TWS and TWA relative to the ship are used together with the results from the Matlab code to calculate the total power savings in the Python code. The Python code is shown in Appendix I with equations and a detailed explanation of the conversion.

To ensure that the historical wind data for the ships are representative, the wind speeds are compared to IMO wind probabilities. The IMO wind probabilities are based on the average wind conditions on the leading global shipping routes [43]. The approximated true wind speed for the IMO wind data and the wind data from the ship route is plotted in Figure 9.8.

The IMO wind speed probabilities are based on considerable amounts of data over several years, which makes the graph smooth. Ours pertains to only one route during one year, so the data points are limited. Because of this, it is natural that it is not as smooth. It still has a similar shape, with only a few deviations, making us feel confident using it for calculations.

IMO has also provided a plot of the distribution of wind angles in relation to the ships based on the leading global shipping routes. This is shown in Figure 9.9, and the ship heading

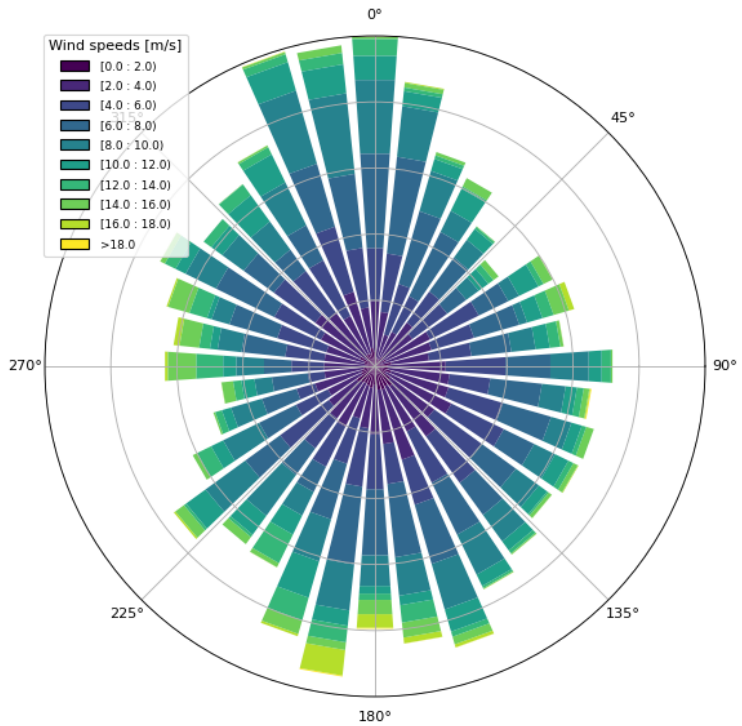


Figure 9.7: Polar plot of TWS and TWA relative to the ship

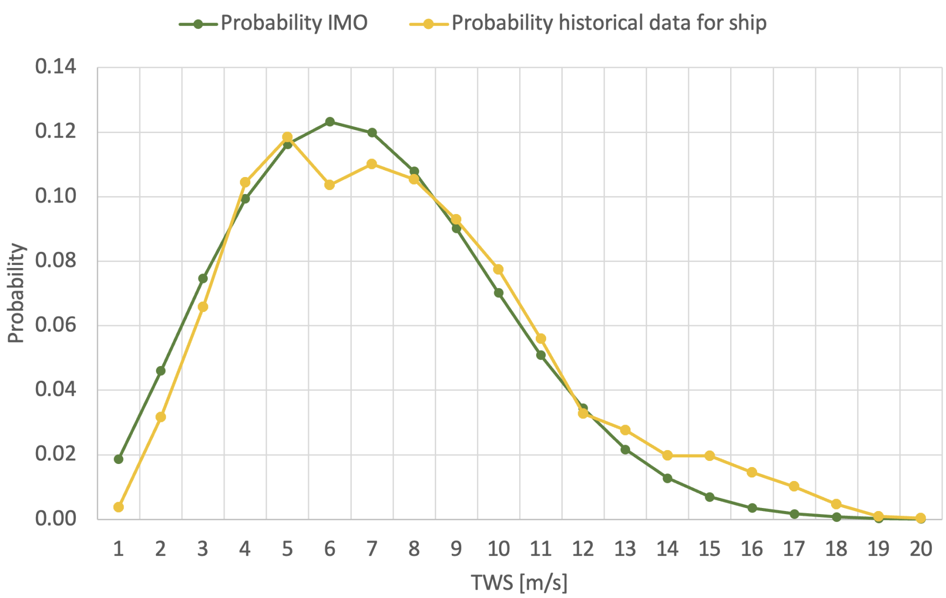


Figure 9.8: Approximated TWS probability IMO vs ship data

goes towards the right. When we compare it with our data for TWA in Figure 9.7, we can recognize the shape except for some jagged peaks in our graph. Both tend to have more wind coming towards the bow and stern. However, as for the wind speed data, IMO has collected more data over a more extended time period which makes it smoother.

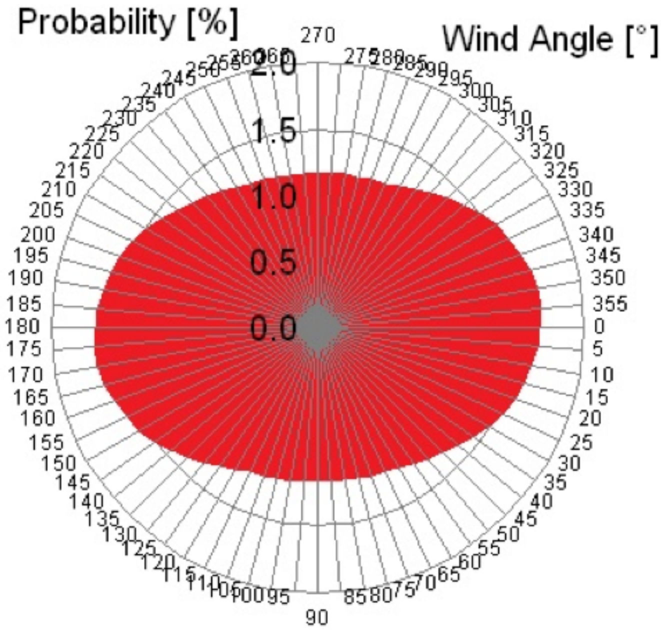


Figure 9.9: Probability of TWA relative to ship heading from IMO [43]

Method A

The principle of this method is to calculate the total power savings for the ship with the given historical route. It is done by calculating the probability of each bin (each combination of ship speed, draft, true wind speed, and true wind angle). The probability of each bin is multiplied by the power savings for each bin $P_{s,bin}$ and then summed up and divided by the sum of the probability of each bin multiplied with the required power for each bin, $P_{req,bin}$. This gives the total power savings, $P_{s,tot}$, shown in Equation (9.4).

$$P_{s,tot} = \frac{\sum P_{s,bin} \cdot \text{prob of bin}}{\sum P_{req,bin} \cdot \text{prob of bin}} \tag{9.4}$$

To make the results relevant to the processes of the LCA, the average power consumption from the rotor sails and the total power savings (in percentage) from the main machinery are calculated.

The average power consumption, $P_{cons,sail}$, is calculated by summing the required auxiliary power for the rotor sails, $P_{req,sail,bin}$, multiplied by the respective probabilities for the bins. This is shown in Equation (9.5).

$$P_{cons,sail} = \sum P_{req,sail,bin} \cdot \text{prob of bin} \tag{9.5}$$

Power savings for the main machinery, $P_{s,mainmach.}$, is calculated by the sum of the required power for the rotor sails, $P_{req,sail}$, and the total saved power, $P_{s,ship}$, divided by the required power the ship without rotor sails, $P_{req,ship}$. This is shown in Equation (9.6).

$$P_{s,main\,mach.} = \frac{P_{req,sail} + P_{s,ship}}{P_{req,ship}} \tag{9.6}$$

Method B

This method estimates power savings for each ship speed. This is done by calculating the probability for each combination of TWS and TWA. The power savings from each speed, $P_{s,shipspeed}$, is found by multiplying this probability with power savings from the unique bin, $P_{s,bin}$, and then summed up for all the scenarios of a specific ship speed, divided by the probability multiplied with the total required power, $P_{req,bin}$, summed up for the specific ship speed (Equation (9.7).

$$P_{s,shipspeed} = \frac{\sum_{shipspeed} P_{s,bin} \cdot prob\,of\,wind}{\sum_{shipspeed} P_{req,bin} \cdot prob\,of\,wind} \tag{9.7}$$

9.1.6 Results Pyhton Code

Method A

The results from the Python code for method A are presented in Table 9.4. When calculating ship resistance, the highest power savings and the lowest auxiliary power consumption occur when calm sea is assumed. The lowest power savings and the highest power consumption occurs at heavy sea, when the resistance calculations are based on 3 meter head waves. The combination of the two states gives the results for average sea, which is further used in calculations in SimaPro.

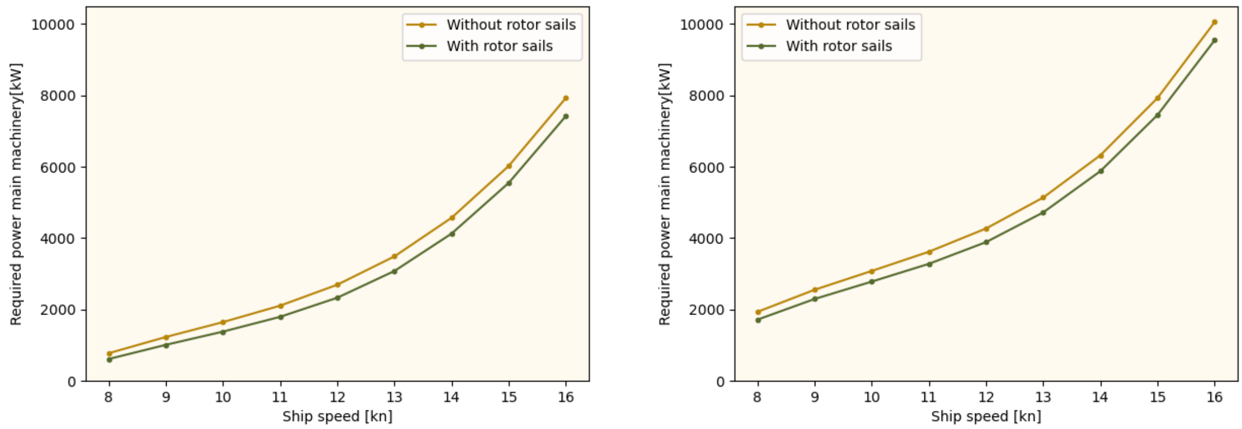
Table 9.4: Power savings results Method A

	P_s total	P_s main machinery	P_{req} rotor sail average
Calm sea	10,8 %	12,3 %	52,2 kW
Heavy sea	7,6 %	8,7 %	55,1 kW
Average sea	9,2 %	10,5 %	53,7 kW

The results are within the expected range of power savings stated by Norsepower and Anemoi, which is 5-30% [7][3]. The power savings are significant, especially considering that rotor sails were not considered in the ship's design and operation. Whether the savings are enough for the implementation to be beneficial has to be considered in conjunction with the environmental and economic results from the LCA and the risk assessment.

Method B

The required power from the main machinery with and without rotor sails for the different speeds is illustrated below. The required power for calm sea is shown in Figure 9.10a and with heavy sea in Figure 9.10b. These two cases combined give the average required power in Figure 9.11.



(a) Calm sea (b) Heavy sea

Figure 9.10: Required power main machinery with and without rotor sails

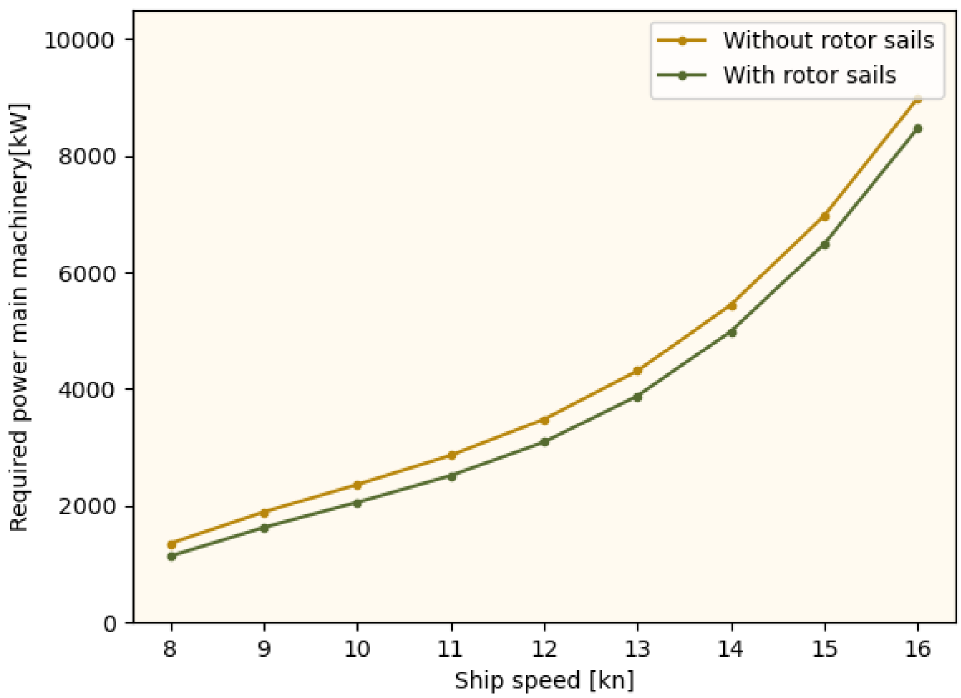
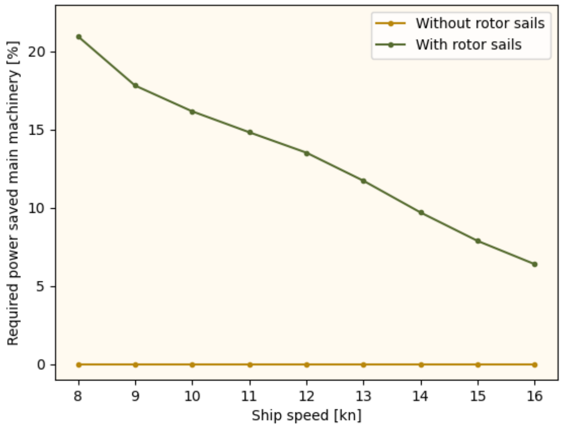
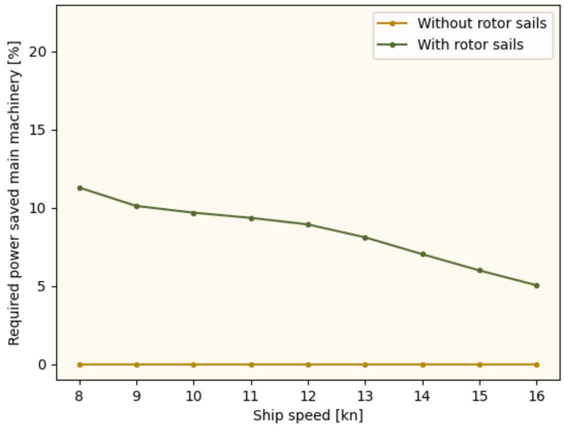


Figure 9.11: Average required power main machinery with and without rotor sails

The percentage of required main machinery power is shown for calm and heavy sea in Figure 9.12 respectively, and the average of these results are shown in Figure 9.13



(a) Calm sea



(b) Heavy sea

Figure 9.12: Power main machinery compared to operation without rotor sails for different speeds

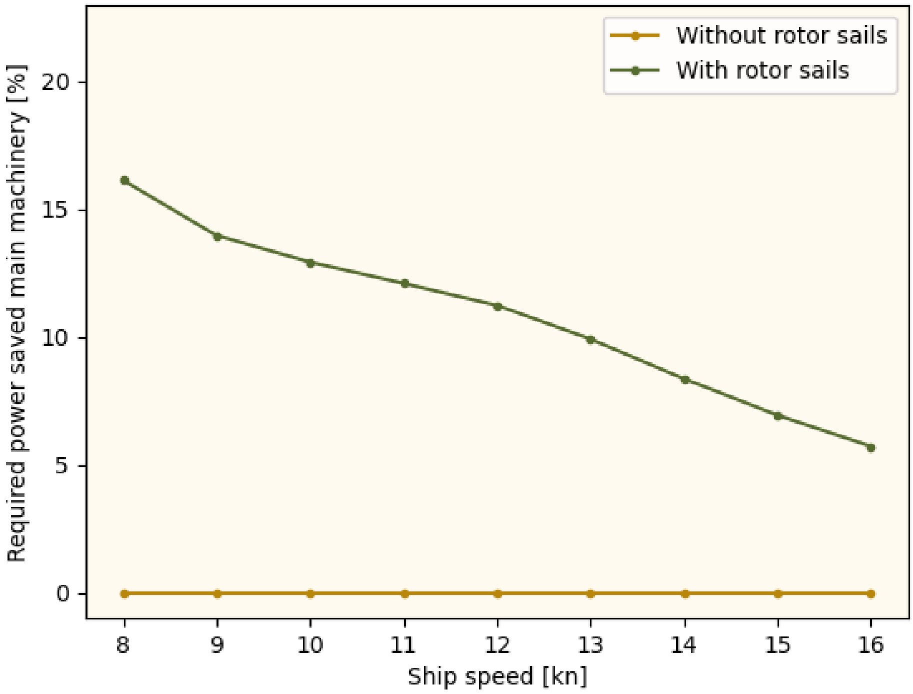


Figure 9.13: Average main machinery power saved compared to operation without rotor sails for different speeds

The results from method B are not used in SimaPro, but they are presented to better understand the ship's operation with rotor sails.

In general, the percentage of power saved when sailing in calm sea (Figure 9.12a) is higher than in heavy sea (Figure 9.12b). This is probably due to added resistance from the waves, which requires more power from the engine and the sails to maintain the same speed as without waves. However, the absolute power saved is higher for heavy sea than calm sea. This is probably due to the rotor sails' drift force and capacity. The drift force will be slightly more prominent when there are no waves; hence the lift force will be slightly lower. The other reason is that sometimes the rotor sails will generate enough power for the ship not to use the main engine at a given speed. This means that in some cases with favourable wind conditions, the rotors can give more propulsion than what is required for the specific speed. When there are waves and higher resistance, this excess power can be utilized, and the rotor sail can therefore provide more power in heavy sea in some cases.

When combining the sea states, the power savings curve gets smoother. At first, it decreases steeply before decreasing slightly less, then decreases almost linearly with increasing ship speed.

9.2 Data for SimaPro

The results for power savings on the main machinery and power consumption for the auxiliary engines with rotor sails in method A are used together with historical ship data to calculate the inputs for SimaPro. The different parameters for the different processes are set to be over one year, and SimaPro will adjust the result to be over 20 years. A simplified illustration of the flow of the processes is shown in Figure 9.14. All the data for input to SimaPro is presented in a spreadsheet in Appendix D, and how the values are found are described in the sections below.

9.2.1 Fuel Oil Cost

The cost of fuel oil is a fluctuating variable, and future prices are challenging to estimate. Regulations and policies can change the taxes and prices of fuel directly or indirectly. It can, to a certain level, be predicted as it takes time to implement regulations, but at the same time, it is not certain if and when such regulations will be implemented. Other tricky things to predict are incidents such as conflicts and wars, natural disasters, low access to oil in certain areas, and other incidents that can change the fuel price. There are several articles on the topic, and their results differ a lot [44].

For this thesis, it is decided not to predict the future but make a simplified approach by using three different predictions on the fuel price; low, medium, and high. We have decided to choose the low, medium, and high fuel prices by looking at the fuel costs for the last ten years. The fuel prices are illustrated in Figure 9.15, and from this, the price is assumed low at 200 USD/t, medium at 500 USD/t, and high at 1200 USD/t. 500 USD/t looks like a reasonable value for medium cost as the fuel oil price while writing this thesis is around 500 USD/t.

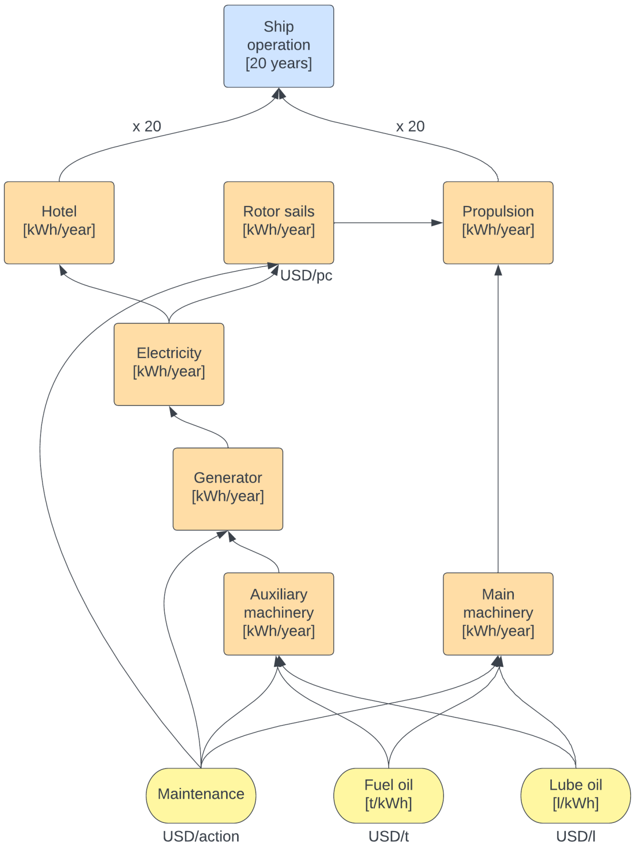


Figure 9.14: Simple illustration of the process flow

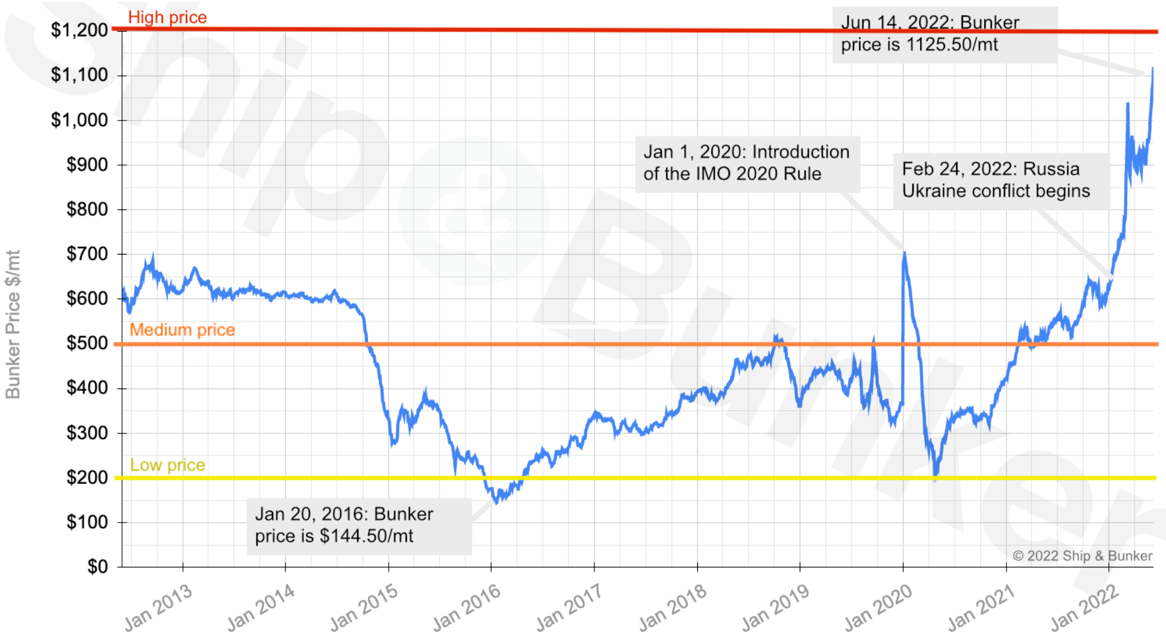


Figure 9.15: Fuel prices over the 10 last years [45]

Even though it is difficult to predict the fuel price, most reports estimate the fuel oil price will increase. One of these predictions based on a techno-economic assessment from Lloyd's Register is shown in Figure 9.16, where we can see that from now to 2040-2050, the fuel cost of fuel oil has more than doubled. We can then assume that the medium and high prices considered in this thesis are more probable than the low price.

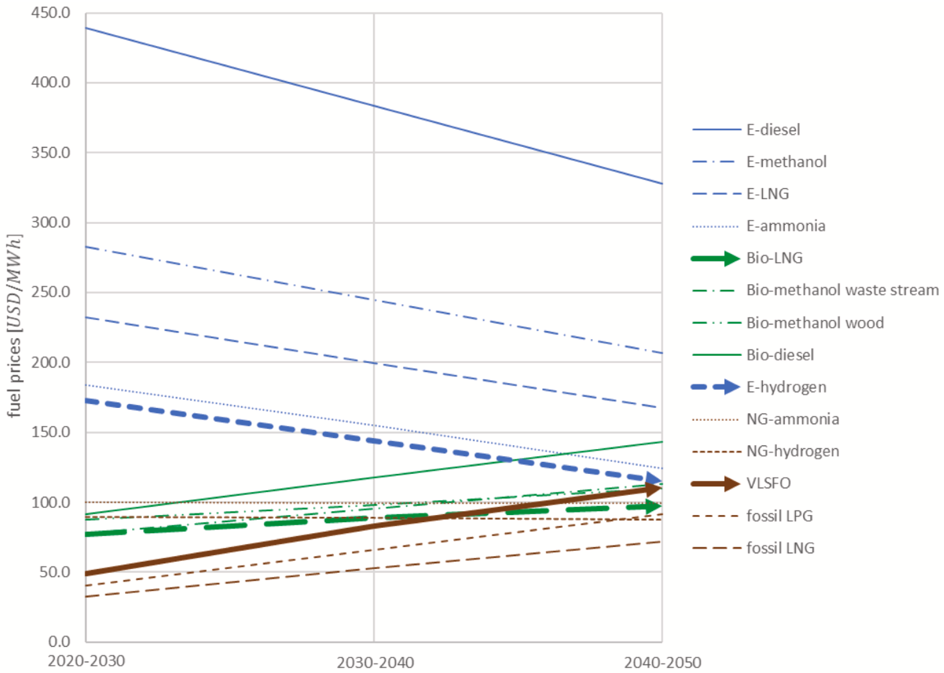


Figure 9.16: Predicted fuel prices over future time periods based on Lloyd's register and UMAS [46][47]

9.2.2 Auxiliary Machinery Data

The different parameters for the auxiliary machinery are calculated with regard to operation over one year. The inputs are presented in Table 9.5 and further described below, and the calculations are shown in the spreadsheet in Appendix D.

Running hours, lube oil, and fuel oil

The running hours of the auxiliary engines are estimated by using the average running hours at sea per day for the ships multiplied by the average days at sea per year. The ship has four auxiliary engines, two with a capacity of 1050 kW and two with 1320 kW. Most of the time at sea, the ship uses only one engine with the lowest capacity.

A passage over the Pacific Ocean has been studied to find the running hours with rotor sails. We made a code in Python to find out how often the ship sails with one or two auxiliary engines in operation. The code is shown in Appendix H. The results from the Python code with the data from the Pacific passage show that only one engine, with 1050 kW capacity, is used 94% of the time, while an additional auxiliary engine is running 6% of the time. In order to minimize the cases where another of the auxiliary engines has to be started to run the

Table 9.5: Input values to SimaPro for auxiliary machinery

Parameter	**w/o rotor sails**	**w/ rotor sails**
Maintenance		
Average invoice cost [USD]	1 320	1 320
Average invoices per ship	11	11
Lube oil		
Cost [USD/l]	2.1	2.1
Consumption [l/year]	3 942	3 942
Fuel oil		
Cost [USD/t]	500	500
Cons [t/year]	675	738
Power consumption		
Power consumption [kWh/year]	3 140 698	3 434 705
Emissions		
N_2 [t/year]	15 860	17 345
O_2 [t/year]	2 984	3 263
CO_2 [t/year]	1 853	2 026
H_2O [t/year]	974	1 065
SO_x [t/year]	31	34
NO_x [t/year]	28	31
CO [t/year]	1.9	2.1
HC [t/year]	2.2	2.4

rotor sails, the ship should sail with one auxiliary engine of 1320 kW as the main electricity supply when using rotor sails and adding the power needed for the rotor sails in the same code results in the same amount of running hours. This way, there are no additional costs for starting up a new engine, only extra fuel costs because of higher power consumption.

The lube oil consumption is found by multiplying the running hours per year with the specific lube oil consumption. The ship owner gives the value for the specific lube oil consumption and the cost of lube oil per liter. There is no difference in the lube oil consumption with and without rotor sails because the running hours of the auxiliary engines are the same. This is because we have assumed that when the rotor sails are installed, the ship will use the auxiliary engine with the highest capacity as a primary auxiliary engine.

Fuel oil consumption is found by multiplying the power consumption over a year with the SFOC. The SFOC comes from the ship owner, and the power consumption is calculated by multiplying the average power from the auxiliary engines at sea with the average running hours at sea per year.

Maintenance for auxiliary machinery operation

The spare parts and maintenance cost for the auxiliary machinery is estimated by taking all the spare parts and maintenance costs over one year for the six ships with four auxiliary engines each and dividing them by the number of spare part invoices. This way, we have the average cost of spare parts for each maintenance action. The data comes from the ship owner's log of maintenance of auxiliary engines for the six ships during 2022.

Overhauls on the major piston and turbocharger are performed every 20 000 running hours. Connecting rod bearings, thrust bearings, and main bearings are replaced every 40 000 running hours. As the running hours for the auxiliary machinery are the same with and without rotor sails, these costs are excluded as they will not make a difference in the comparison.

9.2.3 Main Machinery Data

The input values to SimaPro for the main machinery are shown in Table 9.6. Calculations are shown in Appendix D, and further information about the values are described below.

Table 9.6: Input values to SimaPro for main machinery

Parameter	w/o rotor sails	w/ rotor sails
Maintenance		
Average invoice cost [USD]	2 529	2 529
Average invoices per ship	9	9
Lube oil		
Cost [USD/l]	1.5	1.5
Consumption [l/year]	2 190	2 190
Fuel oil		
Cost [USD/t]	500	500
Cons [t/year]	3 629	3 248
Power consumption		
Power consumption [kWh/year]	22 263 540	19 925 868
Emissions		
O_2 [g/kWh]	25 336	22 676
CO_2 [g/kWh]	11 354	10 162
H_2O [g/kWh]	7 058	6 317
SO_2 [g/kWh]	0.07	0.06
NO_x [g/kWh]	265	237
HC [g/kWh]	5	4

Running hours, lube oil, and fuel oil

The running hours are found by knowing that the ship is sailing at sea half of the year and that the running hours at sea are 24 hours per day, both for operation with and without rotor sails.

The lube oil consumption is given by the shipowner and multiplied by the running hours per year to find the total consumption per year. The shipowner also gives the cost of the lube oil.

The value for SFOC comes from a shop test of the ship with the main machinery. The total fuel consumption for one year is found by multiplying the SFOC with the total power consumption. Power consumption per year is calculated from the average power from the engine with the running hours per year.

Maintenance for main machinery

The maintenance activities and costs for the main machinery are found in the same way as for the auxiliary machinery. The numbers come from the average of the six ships over year 2022.

Overhauls and replacements are also excluded from calculating the main machinery costs, as the ship will have the same running hours with and without rotor sails.

9.2.4 Rotor Sail data

Input values to SimaPro for the rotor sails are shown in Table 9.7. There are four rotor sails in total, and the cost of one rotor sail is set to 500 000 USD each. This cost is assumed to include assembly and installation and comes from other studies with similar rotor sail dimensions [48]. The rotor sails will be installed at already planned dry-docking; therefore, we have not estimated any loss of income due to time off-hire.

The energy consumption and energy saved by the main machinery come from the results of method A in the Python code presented in Table 9.4, the electrical efficiency, and the historical energy data for the ships. The calculations are shown in Appendix D.

Table 9.7: Input values to SimaPro for rotor sails

Parameter	**Value**
Units [pcs]	4
Cost [USD/pc]	500 000
Energy consumption from ax machinery [kWh/year]	270 465
Energy saved to main machinery [kWh/year]	3 272 740

Chapter 10

Impact Assessment - LCIA phase

As described in the theory about impact assessment, the ReCiPe method is used to calculate the impacts from the ship operation. SimaPro generates extensive data as output, and we have selectively exported the most pertinent information for this case. The results we have chosen are divided into midpoint and endpoint indicators and are presented and discussed in this chapter.

Midpoint indicators

The results of the ReCiPe midpoint indicators for the ship operating for 20 years with and without rotor sails are presented in Table 10.1. The values in the table, together with a graphical comparison of the midpoint indicators characterized in Figure 10.1, show that all the impact categories are improved by operating with the rotor sails. Figure 10.1 shows reductions for the different impact categories between 8% and 13% when operating the ship with rotor sails.

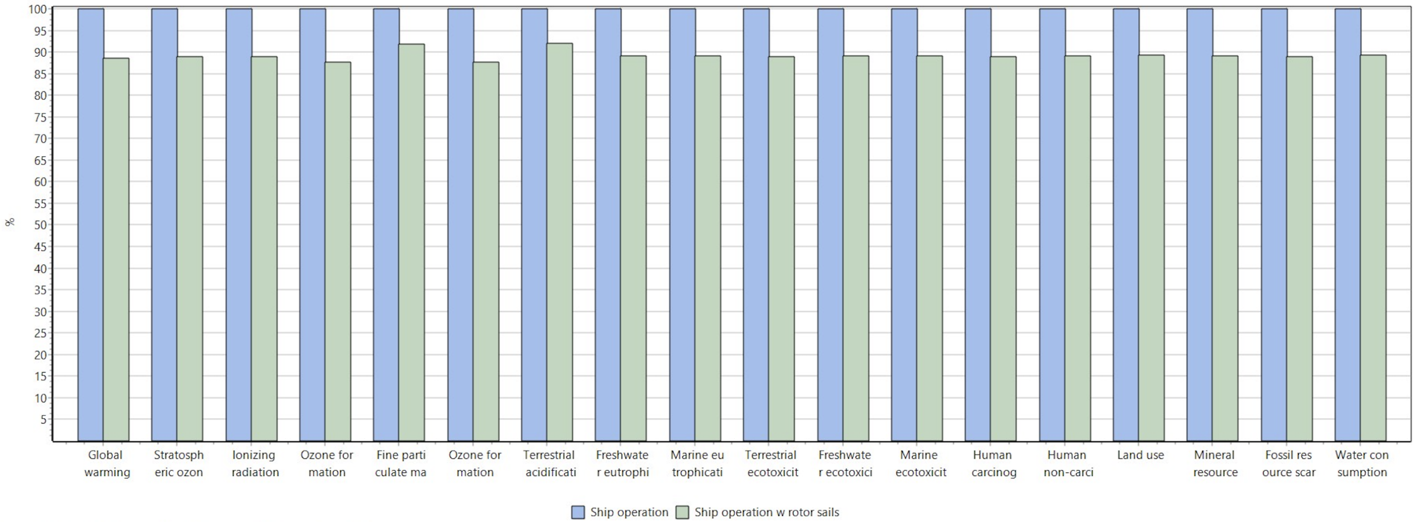


Figure 10.1: Characterized comparison for midpoint indicators

As mentioned in the literature study, the GWP is one of the most discussed indicators in

Table 10.1: Characterized midpoint indicators for operation with and without rotor sails

Impact category	Unit	Normal operation	Operation with rotor sails
Global warming	kg CO_2 eq	$2,96 \cdot 10^8$	$2,62 \cdot 10^8$
Stratospheric ozone depletion	kg CFC11 eq	68,5	61
Ionizing radiation	kBq Co-60 eq	$2,56 \cdot 10^6$	$2,27 \cdot 10^6$
Ozone formation, Human health	kg NO_x eq	$6,03 \cdot 10^6$	$5,28 \cdot 10^6$
Fine particulate matter formation	kg PM2.5 eq	$9,25 \cdot 10^5$	$8,49 \cdot 10^5$
Ozone formation, Terrestrial ecosystems	kg NO_x eq	$6,04 \cdot 10^6$	$5,29 \cdot 10^6$
Terrestrial acidification	kg SO_2 eq	$3,02 \cdot 10^6$	$2,78 \cdot 10^6$
Freshwater eutrophication	kg P eq	$3,16 \cdot 10^3$	$2,81 \cdot 10^3$
Marine eutrophication	kg N eq	279	249
Terrestrial ecotoxicity	kg 1,4-DCB	$8,18 \cdot 10^7$	$7,28 \cdot 10^7$
Freshwater ecotoxicity	kg 1,4-DCB	$4,75 \cdot 10^5$	$4,23 \cdot 10^5$
Marine ecotoxicity	kg 1,4-DCB	$7,78 \cdot 10^5$	$6,93 \cdot 10^5$
Human carcinogenic toxicity	kg 1,4-DCB	$7,95 \cdot 10^5$	$7,08 \cdot 10^5$
Human non-carcinogenic toxicity	kg 1,4-DCB	$1,28 \cdot 10^7$	$1,14 \cdot 10^7$
Land use	m^2 a crop eq	$1,65 \cdot 10^6$	$1,48 \cdot 10^6$
Mineral resource scarcity	kg Cu eq	$7,2 \cdot 10^4$	$6,41 \cdot 10^4$
Fossil resource scarcity	kg oil eq	$9,11 \cdot 10^7$	$8,1 \cdot 10^7$
Water consumption	m^3	$2,63 \cdot 10^4$	$2,34 \cdot 10^4$

today's discussion about climate change. The graph in Figure 10.2 presents the contribution to global warming from the different processes of ship operation with and without rotor sails. This contribution does not only include the direct emissions from burning the fuel in the engines but also the life cycle of the fuel and lube oil. The rotor sails considerably reduce emissions from the main machinery concerning global warming. The emissions from the auxiliary machinery are slightly increased as the rotor sails require some power to operate. The emissions from the main engine and auxiliary engines are the most considerable, and they come from the emissions of burning the fuel. HFO and lube oil include the whole life cycle from when it is extracted, transported, and used.

With the exact values from Table 10.1, the total reduction of GWP is 34 000 000 kg CO_2 equivalents, which equals a reduction of global warming potential of 11.5% . The avoided greenhouse gas emissions by using rotor sails for 20 years is equivalent to the GHG emissions from 7 566 gasoline-powered passenger vessels driven for one year [49]. The reduced emission of GHG with rotor sails is also equivalent to GHG emissions avoided by operating ten wind turbines with an average capacity of 1.82 MW over one year. This equals the electricity use for 6 616 homes for a year [49].

Taking into account all six ships, as opposed to just the one examined in this thesis, a substantial reduction of 204,000 tonnes of CO2 equivalents can be anticipated. When comparing these emissions, it becomes evident that this reduction is equivalent to the GHG emissions avoided by operating 57 windmills with a capacity of 1.82 MW each for an entire year. Additionally, it can be likened to the emissions produced by approximately 2 701 tanker trucks filled with gasoline.

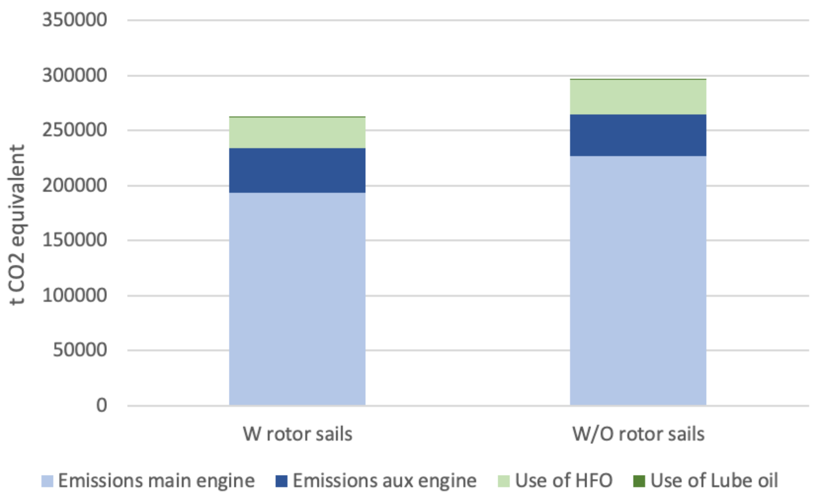


Figure 10.2: GHG contribution to GWP for the different processes

Endpoint indicators

A comparison of the contribution to the ReCiPe endpoint indicators for the ship operating for 20 years with and without rotor sails are shown normalized in Figure 10.3. The model is normalized according to the ReCiPe normalizing factors[20].

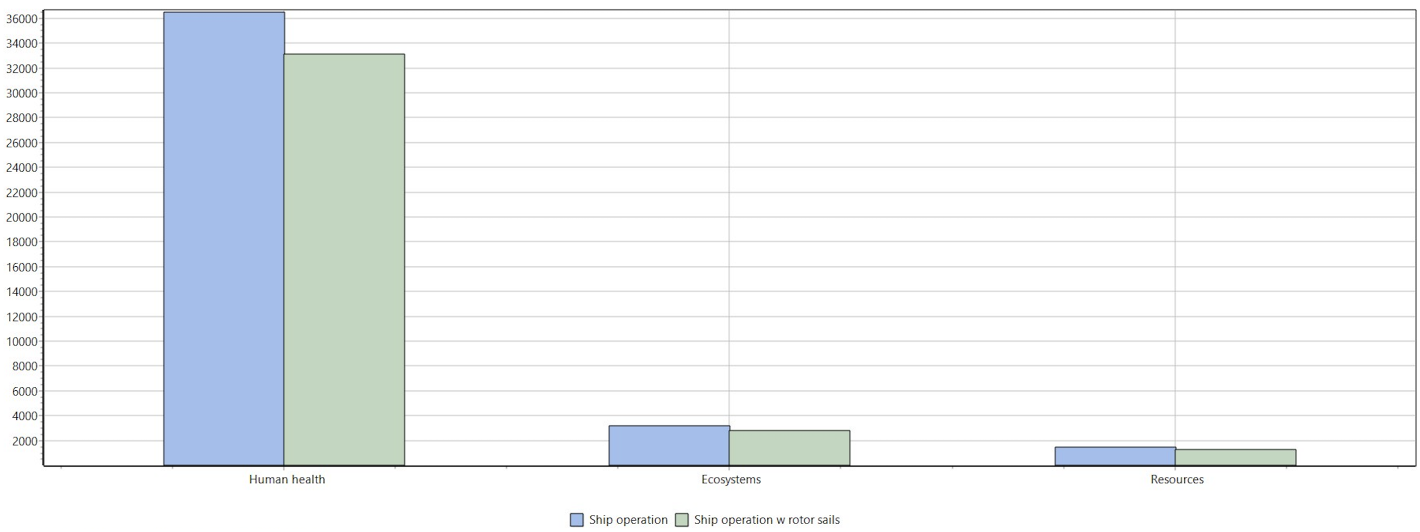


Figure 10.3: Normalized comparison for endpoint indicators

As we can see in Figure 10.3, the ship operation affects human health the most amongst the endpoint indicators. Therefore we have exported data to see what contributes most to the human health indicator. This is presented in Table 10.2 and Figure 10.4. The graph in Figure 10.4 shows what categories within human health are most affected by the ship operation. This graph shows that fine particulate matter formation and global warming for human health are the most significant contributors to the negative effect on human health.

Figure 10.5 shows the contribution from the different processes of the ship operation to fine particulate matter impacts on human health. The effect on humans from global warming

Impact category	Unit	Normal operation	Operation with rotor sails
Fine particulate matter formation	DALY	581.3	533.8
Global warming (human health)	DALY	275.5	243.3
Human carcinogenic toxicity	DAlY	2.6	2.4
Human non-carcinogenic toxicity	DALY	2.9	2.6
Ionizing radiation	DALY	0.02	0.02
Ozone formation	DALY	5.5	4.8
Stratospheric ozone depletion	DALY	0.04	0.03
Water consumption	DALY	-0.03	-0.02
Total	DALY	866.8	786.9

Table 10.2: Impact categories for human health for operation with and without rotor sails

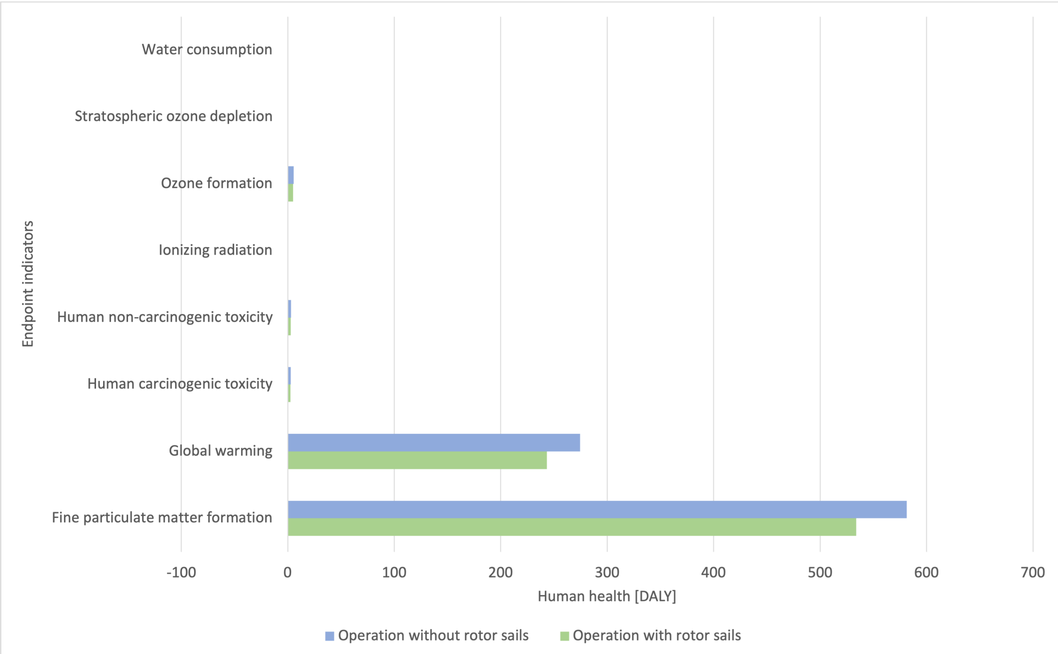


Figure 10.4: Human health with categories for operation with and without rotor sails

is shown in Figure 10.6. What we can see in those two graphs is that the percentage of the contribution for the auxiliary machinery is significantly higher for fine particulate matter formation than global warming. This is most likely because the auxiliary machinery is not as optimized as the main machinery when it comes to exhaust.

The total effect for operation with rotor sails over 20 years contributes with 787 DALYs, while operation without rotor sails over 20 years results in 867 DALYs. Implementing rotor sails can therefore save the equivalent of 80 years of full health.

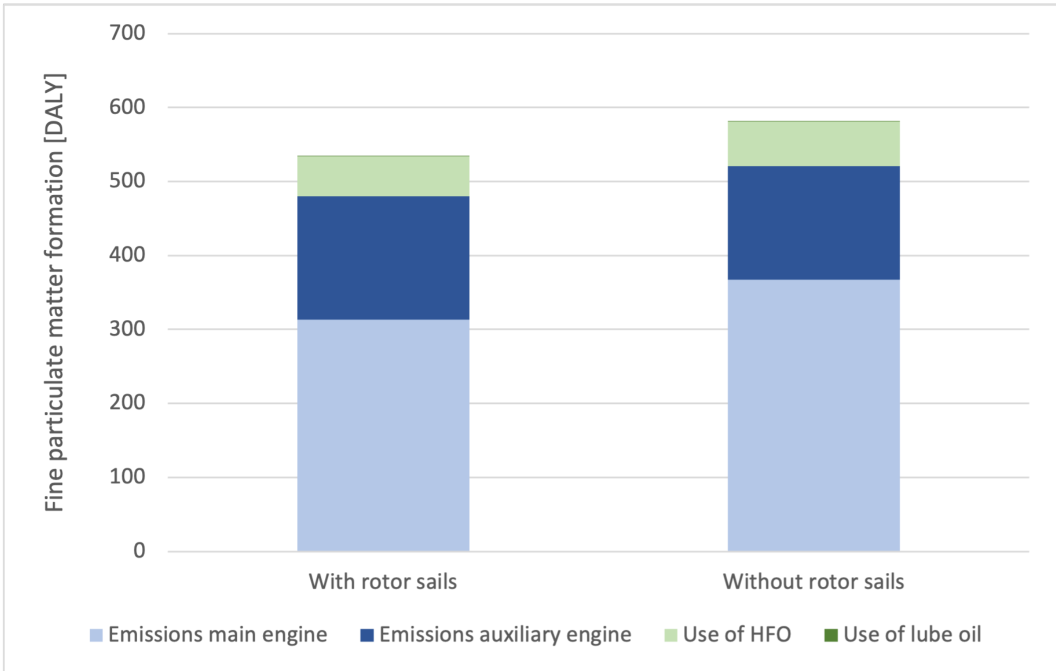


Figure 10.5: Fine particulate matter formation for the different processes for operation with and without rotor sails

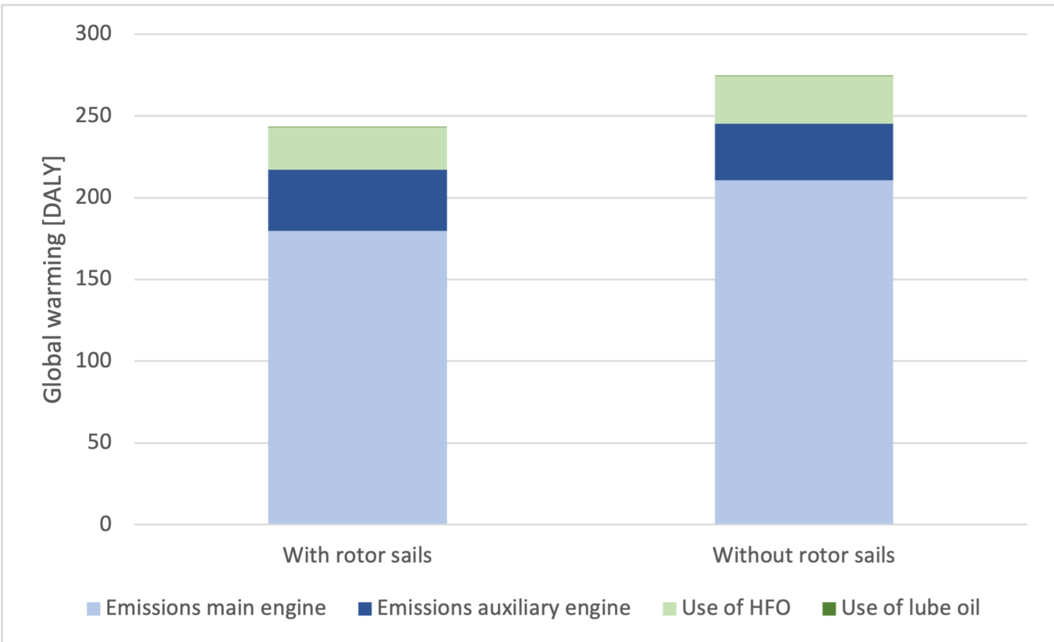


Figure 10.6: Global warming (human health) for the different processes for operation with and without rotor sails

Chapter 11

Cost Analysis

11.1 LCC SimaPro

The cost analysis in SimaPro returns the cost for the different processes over 20 years. However, the fuel costs are only based on sailing conditions and not on fuel used in port or other operations. The fuel costs are calculated with a fuel price of 500 USD/t, 200 USD/t, and 1200 USD/t.

It is important to note that the expenses and savings calculated in SimaPro are not adjusted for inflation or the time value of money. Therefore the savings are not *real* because the investment becomes more expensive the longer it takes to pay it off. Nevertheless, these values can be instrumental in examining the distribution of expenses and how they change after rotor sail implementation.

The costs for the operation with and without rotor sails are shown in Tables 11.1, 11.2, and 11.3. These tables show monetary savings when the fuel price is 500 USD/t and 1200 USD/t. When the fuel price is 200 USD/t, there are negative savings, meaning that the expenses outweigh the savings from implementing the rotor sails.

Figures 11.2, 11.4, and 11.6 illustrate the distribution of operational expenses in million USD that is gathered from the tables. Obviously, the total costs will be significantly higher with the higher fuel price, especially considering that fuel cost is the main contributor in all cases. Here we can also see that the operation with rotor sails is only economically beneficial when the fuel price is 500 and 1200 USD/t. For 200 USD/t, the operation without rotor sails is more beneficial from an economic perspective.

Table 11.1: Costs for 20 years with fuel price 500 USD/t

Category	Without rotor sails	With rotor sails	Saved
HFO aux machinery	6 750 000	7 380 000	-630 000
HFO main machinery	36 289 580	32 479 160	3 810 420
Lube oil aux machinery	146 664	146 664	0
Lube oil main machinery	65 700	65 700	0
Maintenance aux machinery	290 400	290 400	0
Maintenance main machinery	455 220	455 220	0
Rotor sails	0	2 000 000	-2 000 000
Total	43 997 564	42 817 144	1 180 420

Table 11.2: Costs for 20 years with fuel price 200 USD/t

Category	Without rotor sails	With rotor sails	Saved
HFO aux machinery	2 700 000	2 952 000	-252 000
HFO main machinery	14 515 832	12 991 664	2 133 852
Lube oil aux machinery	146 664	146 664	0
Lube oil main machinery	65 700	65 700	0
Maintenance aux machinery	290 400	290 400	0
Maintenance main machinery	455 220	455 220	0
Rotor sails	0	2 000 000	-2 000 000
Total	18 173 816	18 901 648	-727 832

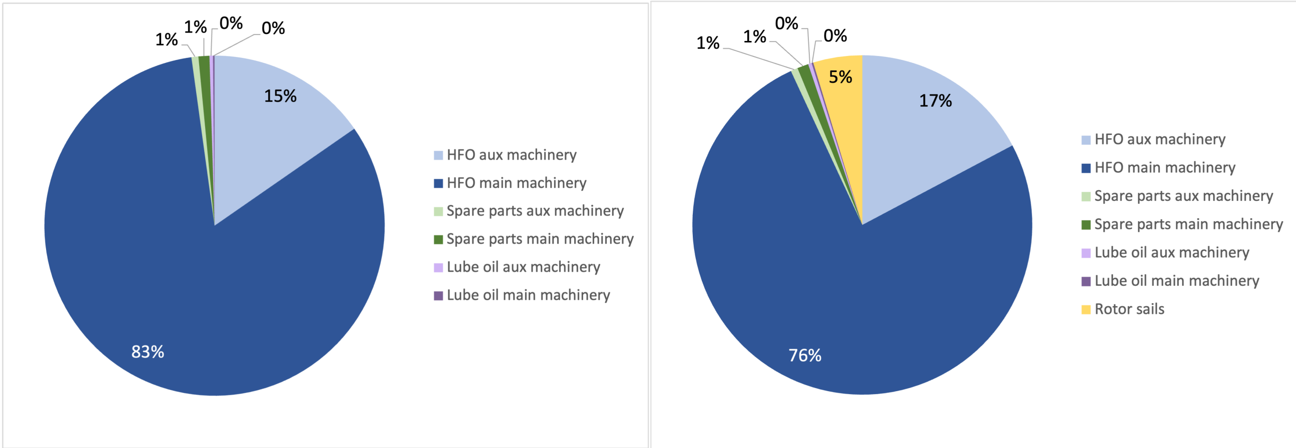
Table 11.3: Costs for 20 years with fuel price 1200 USD/t

Category	Without rotor sails	With rotor sails	Saved
HFO aux machinery	16 200 000	17 712 000	-1 512 000
HFO main machinery	87 094 992	77 949 984	9 145 008
Lube oil aux machinery	146 664	146 664	0
Lube oil main machinery	65 700	65 700	0
Maintenance aux machinery	290 400	290 400	0
Maintenance main machinery	455 220	455 220	0
Rotor sails	0	2 000 000	-2 000 000
Total	104 252 976	98 619 968	5 633 008

In Figures 11.1, 11.3, and 11.5, the percentage distribution of the different cost categories is shown. When the fuel price is higher, the costs associated with fuel for the main and auxiliary machinery will naturally be higher, making up a higher percentage of the total expense distribution.

For the auxiliary machinery, the percentage increases further when the rotor sails are implemented. In all fuel price cases, the *HFO aux machinery* category increases after implementation. The reason is that the rotor sails will take their power from the auxiliary machinery. Thus, it will have higher power and fuel consumption.

The lube oil and maintenance costs are unchanged when rotor sails are implemented. This is because the running hours for the main and auxiliary engines will remain the same after implementation. Exceptions from this will be if the rotor sails require more power than the auxiliary engine can give and a new engine has to be started.



(a) Without rotor sails (b) With rotor sails

Figure 11.1: Cost distribution expressed with percentages - fuel price 500 USD/t

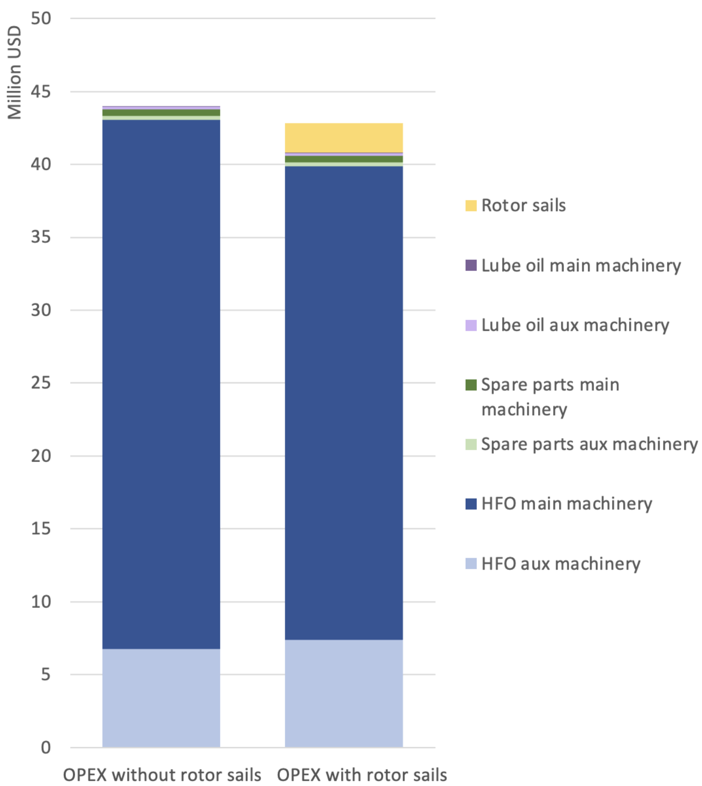
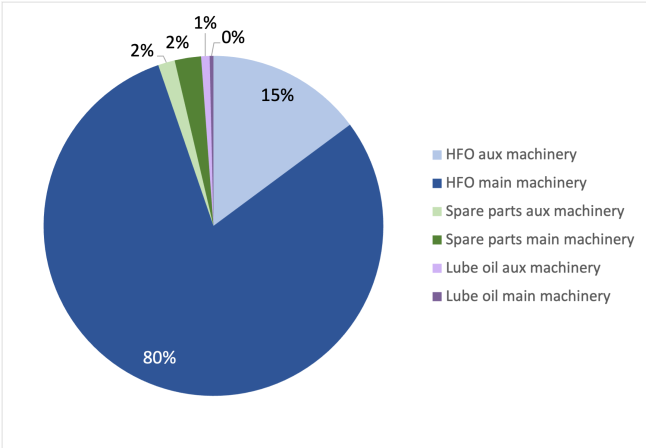
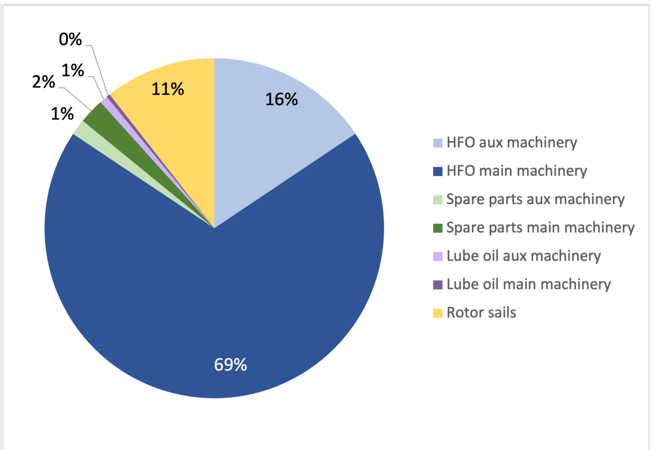


Figure 11.2: Cost distribution expressed in million USD - fuel price 500 USD/t



(a) Without rotor sails



(b) With rotor sails

Figure 11.3: Cost distribution expressed with percentages - fuel price 200 USD/t

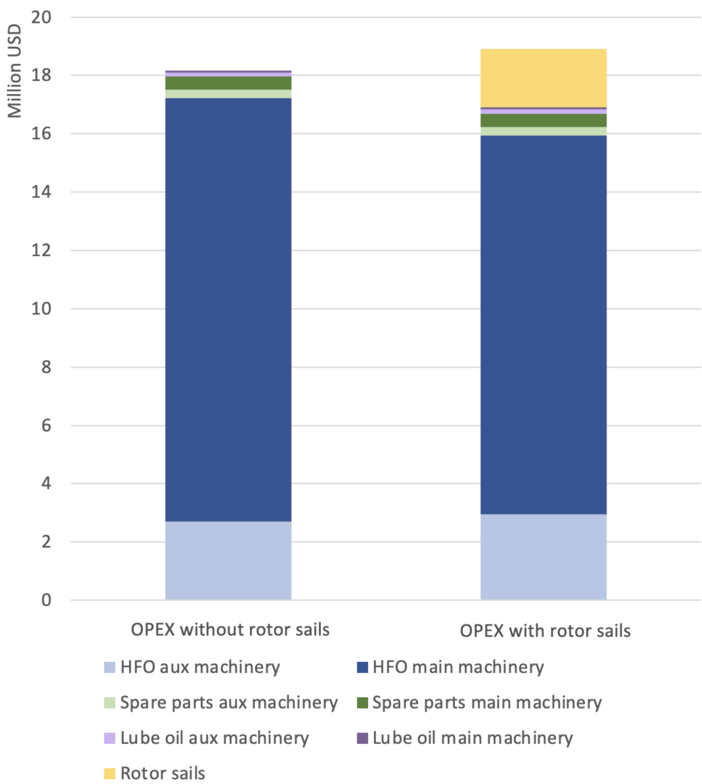
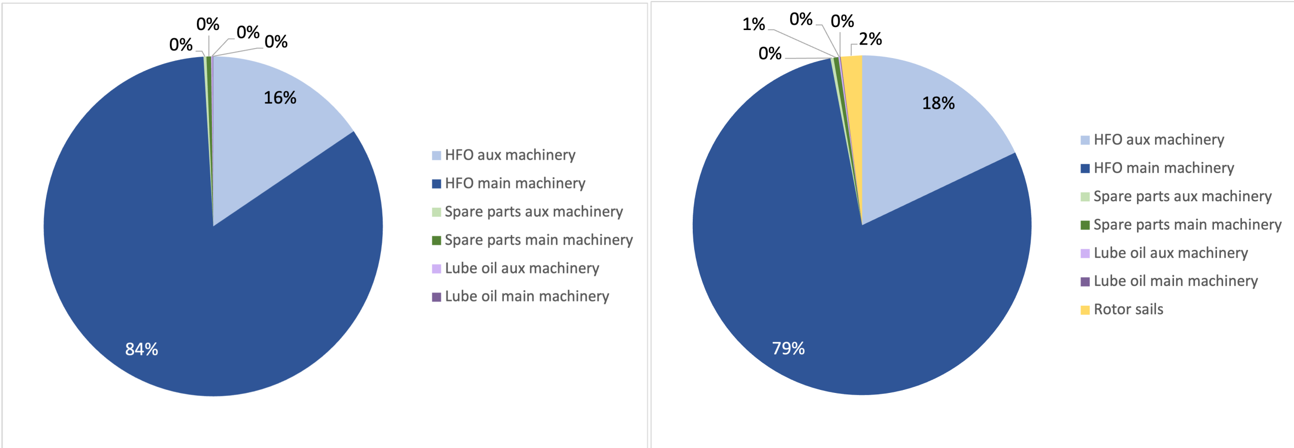


Figure 11.4: Cost distribution expressed in million USD - fuel price 200 USD/t



(a) Without rotor sails

(b) With rotor sails

Figure 11.5: Cost distribution expressed with percentages - fuel price 1200 USD/t

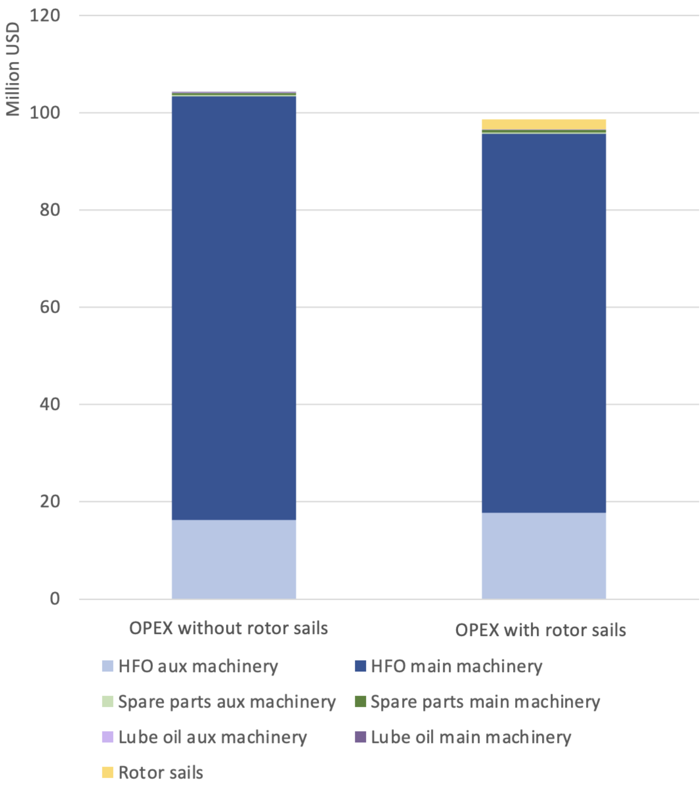


Figure 11.6: Cost distribution expressed in million USD - fuel price 1200 USD/t

11.2 Payback Period

As mentioned, the LCC from SimaPro does not consider the time value of money. It does not consider discounts or investment rates, and the calculations are, therefore, imprecise concerning the payback period. We have used net present value (NPV) with the weighted average cost of capital (WACC) for each year to estimate the rotor sails' payback period for each fuel price presented earlier.

The previous section also shows that the costs for lube oil and maintenance are the same before and after implementation. To figure out whether it is profitable to install the rotor sails from an economic perspective, it is therefore only necessary to consider the fuel costs and the costs of buying the rotor sails. The calculations are shown in Appendix E.1, and the results are illustrated in Figure 11.7.

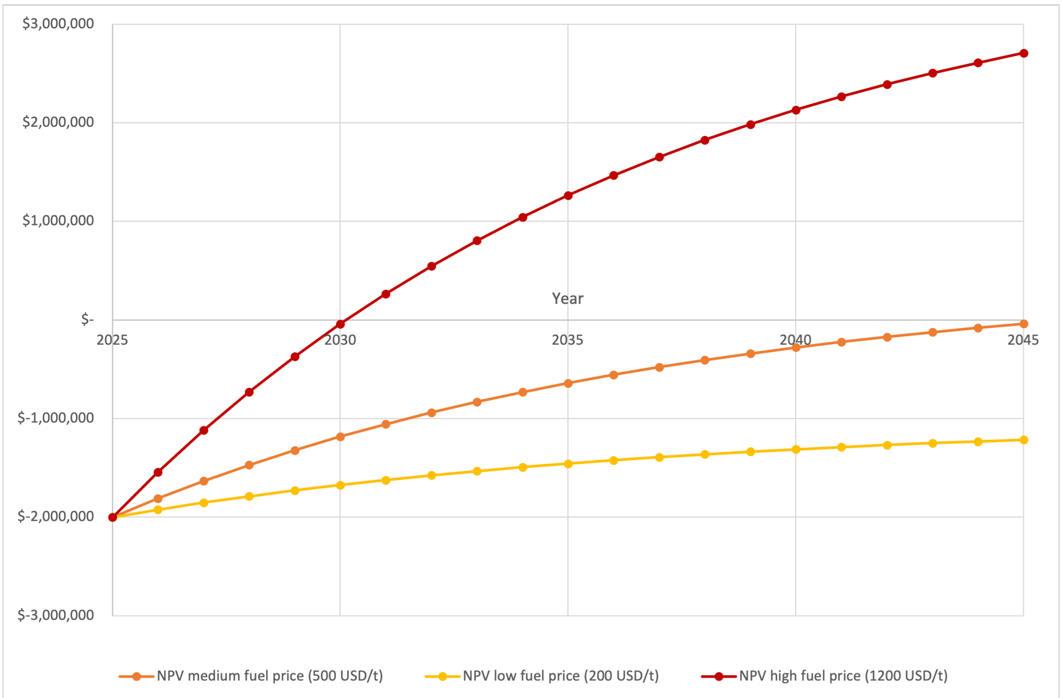


Figure 11.7: Rotor sail payback period based on NPV calculations

From Figure 11.7, we can see that if the fuel price is 200 USD/t, installing the rotor sails is not economically profitable. The NPV after the rotor sail lifetime of 25 years is still negative. The payback period will be long for the 500 USD/t fuel price as well. In fact, it will just break even by the estimated recycling of the ship. However, the rotor sails still has another five years of their lifetime. The expected payback period for the highest fuel price is five years after installation.

In essence, this means that the profitability of implementing the rotor sails is exceedingly dependent on the level of the fuel price.

Part III

Risk Assessment of Rotor Sail Implementation

Chapter 12

Change Analysis

Installing the rotor sails on a ship will entail changing the already established system onboard. Change analysis of the system will allow us to see how the risk picture will change due to the installation. The change analysis method described in section 6.1 is used for this.

12.1 Step 1: Objectives, Limitations, System Description

The objective of conducting a risk assessment for implementing the rotor sails is to determine whether these changes to the system will increase the risks. For this assessment, only the risk connected to the ship's regular operation with rotor sails will be considered. A general risk assessment for the entire ship will not be carried out. Outside of the scope is also the installation process of the rotor sails and the availability and reliability of the rotor sails.

The system is a chemical tanker ship. Its primary purpose is to move cargo between destinations within a timely frame and cost-efficiently. Without rotor sails, the propulsion relies entirely on the main engine with propeller. The implementation of rotor sails will split the propulsion load so that it will be reliant on rotor sails with supply from the auxiliary engines and the propeller with supply from the main engine.

12.2 Step 2: Key Differences

The key differences between the new and the old system are presented in the lists below. They are grouped by their expected effects. Many aspects will change when implementing a new component on a ship, and the most important ones for this case have been mentioned here. However, not all of these will be explored in this thesis. Highlighted in bold are the points we will look into further.

Changes that may directly impact the crew and their work:

- **New blind sectors caused by rotor sails**
- Decreased available space on the main deck because of rotor sail foundations

- More air turbulence on deck because of pressure differences from rotor sails
- **Maintenance of rotor sails on deck**
- Fast spinning cylinder on deck

Changes that may impact the machinery:

- Increased load on auxiliary machinery
- Possibly decreased load on the main machinery

Changes that may impact the stability of the ship:

- Increased height at the front of the ship
- Increased weight at the front of the ship
- Higher center of mass
- Increased side effects from rotor sails in the wind

Changes that may impact explosivity on the ship:

- **More air turbulence on deck because of pressure differences from rotor sails**
- **Spinning machinery on deck in an area that usually does not contain a lot of moving machinery**
- **New cabling for power supply to rotor sails**
- **Necessary maintenance operations on rotor sails**

Decreased visibility, increased crew risk due to more maintenance activities on deck, and increased risk linked to fire and explosion are the risks that will be considered in this thesis.

Increased load on the auxiliary machinery will not be considered. As can be seen in earlier calculations in subsection 9.2.2, the increase in the average load of the auxiliary machinery when using rotor sails is from 637 kW to 691 kW. This is an increase of 7.8% and equals an average load on 52% of MCR. This might actually be net positive because the engine will run at a more optimal speed. The decrease in the main machinery will not be considered either because it is likely not a sufficiently significant reduction for the motor to be troubled with low-load issues. As mentioned in section 3.4, the load should be less than 40% SMCR or be low over an extended amount of time without pauses of running it at higher loads for it to be a big issue. Neither of these is likely to happen in this case.

As the weight of the rotor sails are most likely not more than 0.1% of the ship's dwt, we assume that they will not contribute to a significant vertical increase of the ship's center of mass. Additionally, they are installed symmetrically to avoid moving the crosship center of gravity. Impacts on the stability will not be considered in this thesis.

12.3 Blind Sectors, Step 3 and 4

Hazards

The main hazard of blind sectors in the bridge view is difficulties in maneuvering. Blind sectors can also be problematic for seeing other ships or obstacles and ensuring the lights on the ship are visible to other ships.

Consequences and probability

There are regulations that decide how big a blind sector can be not to impair visibility or maneuvering. SOLAS Chapter V, regulation 22 explains the rules regarding the issue of obstacles in the way of bridge view. The rule states:

"No blind sector, caused by cargo, cargo gear or other obstructions outside of the wheelhouse forward of the beam which obstructs the view of the sea surface as seen from the conning position, shall exceed 10°. The total arc of blind sectors shall not exceed 20°. The clear sectors between blind sectors shall be at least 5°. However, in the view described in .1, each individual blind sector shall not exceed 5 °." [50]

The angles of obstructed view have been calculated to be 2.97° per side, with a total of 5.93° for the two blind sectors. This is within the safety limits presented in SOLAS. The calculations can be seen in Appendix F.

We then conclude that loss of visibility is not an issue and is within the given regulations. There is no need for measures, and the hazard will not be explored further.

12.4 Maintenance of Rotor Sails, Step 3 and 4

Hazards

Maintenance on the rotor sails will likely occur on the main deck during sailing or while in port. Especially while sailing, the ship can have unpredictable movements, which can be hazardous to people conducting maintenance on the rotor sails. It can also be hazardous to maintenance personnel as they have to pass the barriers surrounding the rotor sails. The rotor sails could start to rotate when not in operation, either from a technical failure or human error. If the maintenance involves heat from friction or sparks, such as welding, it can lead to an explosion, as described in section 6.5.

Consequences and frequency

We do not have information about the reliability or availability data of the rotor sails. For this reason, it is difficult to quantify the risk that faces the crew when they maintain the rotor sails. Anemoi and Norsepower state that their rotor sails require little maintenance, and we, therefore, assume that the rotor sails require minimal maintenance in their given lifetime (25 years) [3][7]. We also assume that the crew is used to conducting operations on the main deck, and since it is a chemical tanker, they already have well-developed routines and guidelines.

Welding operations could cause sparks that are problematic concerning explosion risk. However, the rotor sails will already be installed, and no new welding operations will be necessary.

Conclusion: the hazards linked to maintenance will not be very prevalent and will not be explored further in this thesis.

12.5 Explosivity, Steps 3 and 4

Hazards

The rotor sails are spinning objects driven by an electric drive with a low-voltage power supply. Considering that their regular operation will be within an area very close to gas zones on the ship, their ability to be a source of ignition must be considered. Therefore the main hazards are all faults that may cause heat and mechanical or electrical sparks. Some examples of what can cause ignition:

- Mechanical issues cause too much friction in rotation → heat and/or sparks
- Mechanical issues inside the electric drive cause too much friction in rotation → heat and/or sparks
- Weak couplings between components, bad cables, electrical issues → electrical sparks

Consequences and frequency

The consequences of ignition from the rotor sails may be none, but it can also cause fire or explosion on board if an explosive atmosphere is present. The risks linked to explosions on board because of rotor sails will be explored further in chapter 13.

12.6 Step 5: Examination of Important Issues in More Detail

We have found that the most critical issue to consider is the explosion risk. An explosion risk assessment is conducted in chapter 13.

Chapter 13

Explosion Risk Assessment

From the change analysis in chapter 12, we found that explosion risk was the most relevant risk to consider. On tanker vessels such as those in this thesis, there are stringent regulations about safety regarding explosion risk. For this reason, the ship is divided into different zones, protecting the ship and crew. Explosions or fires pose a genuine risk when in an atmosphere of potentially flammable gas.

13.1 Likelihood of Explosive Atmosphere Being Present - Zone Classification

The ship is divided in a way that separates the accommodation (at the back) from the tanks (everything in front of the wheelhouse). This division is roughly illustrated in Figure 13.1 with a *safe* and a *dangerous* zone, where the safe zone is an area where an explosive gas atmosphere should not occur. The safe zone is generally where the crew is unless they are engaged in operations on deck. The dangerous zone is divided into explosion zones 0, 1, and 2, as explained earlier in section 6.5 and summarized below.

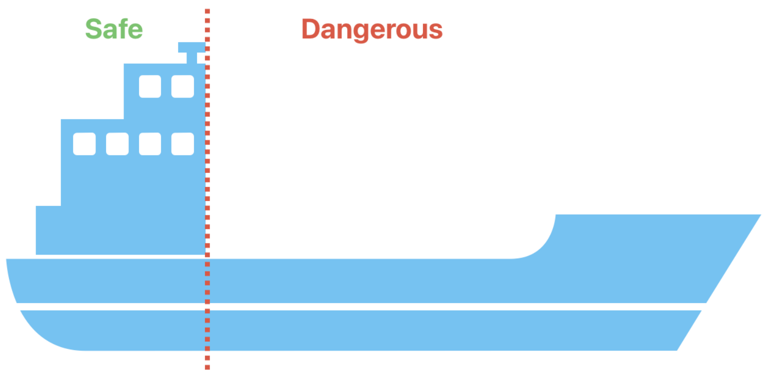
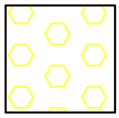
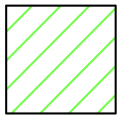


Figure 13.1: Division between safe and dangerous zones on a ship

The rotor sails are to be placed in the dangerous zone, so considering the possibly increased risk of explosion is crucial. There is an illustration of where the different zones are located on the ship. The overview is given on the general arrangement (GA) with the different zones marked with colors and lines/circles. It shows the ship from the side, front, and different decks. A recap of the different zones is shown in Table 13.1. Some of the illustrations are shown in Figures 13.2, 13.3, and 13.4 for the main deck, forecastle deck, and a side view. There are no zone 0 areas on these decks, as zone 0, in this case, only applies to the inside of tanks, pipeworks, and venting systems (see Figure 13.4).

Table 13.1: Summary of explosion zone definitions

Zone	Description	Duration/frequency guidance	Symbol
Zone 0	area in which an explosive gas atmosphere is present continuously, or for long periods, or frequently	T > 1000 h/year or T > 1 h/shift	
Zone 1	area in which an explosive gas atmosphere is likely to occur occasionally in normal operation	10 h/year < T < 1000 h/year	
Zone 2	area in which an explosive gas atmosphere is not likely to occur in normal operation, but, if it does occur, will exist for a short period only	1 h/year < T < 10 h/year and T < 1min/shift	

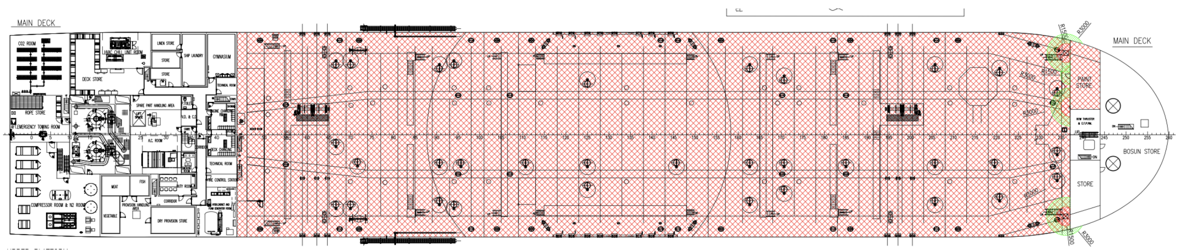


Figure 13.2: Main deck explosion zones

When placing the rotor sails on the ship, we must adhere to the limitations of the explosion zones on board. In short, this will mean lifting them from the main deck because, as seen in Figure 13.2, the entire main deck is a zone 1 environment. Odfjell's internal policies state that the zone 1 environment is valid up to 2.4 m above the deck. Accordingly, the rotor sails must be installed at least 2.4 m above the main deck. While for the next deck up, meaning the forecastle and poop deck and the catwalk, the spaces we want to place the rotor sails are

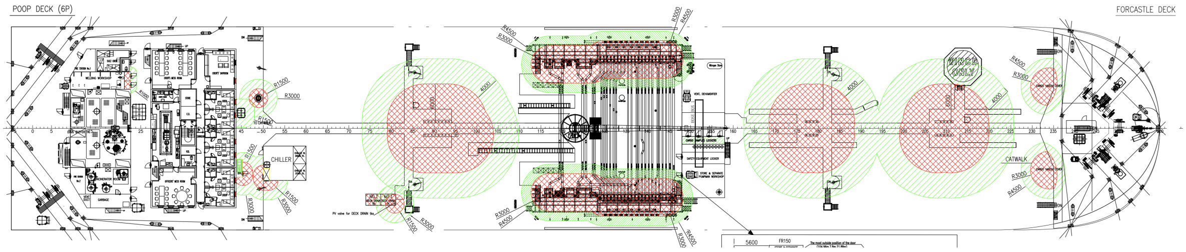


Figure 13.3: Forecastle and poop deck explosion zones

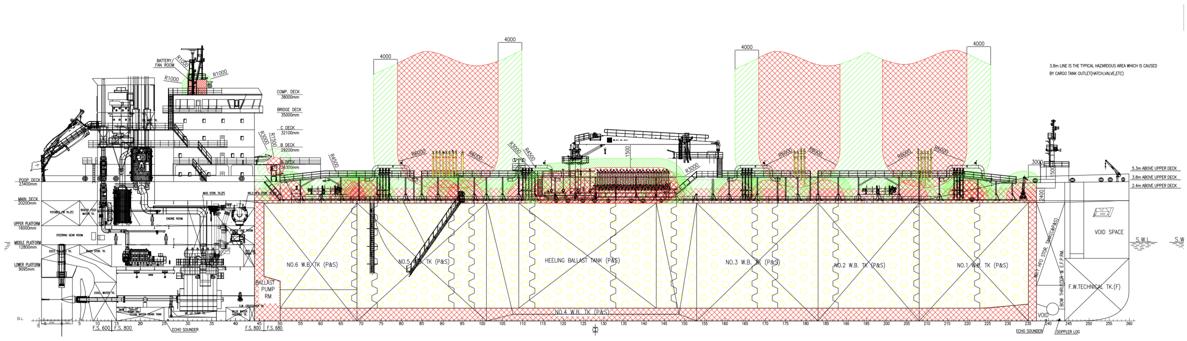


Figure 13.4: Explosion zones from side view

not within any of the zones. Therefore, all that must be considered is the height above the main deck necessary.

When observing Figure 13.3, we can see that the explosion zones a few meters above the main deck are only around the points of potential releases. The three big zone 1 areas are where the pressure vacuum masts (PV masts) are located. Their point is to regulate the pressure in the tanks, opening to release if pressure is too high and opening to let air enter if pressure is too low. As seen in Figure 13.4, their zone classification is valid several meters up in the air and the area around. In the middle of the ship, at each side, is the chemical manifoil, which is where the cargo is on- and off-loaded.

Considering that we plan to place the rotor sails forward of the manifoil area, the central zones we need to avoid are the two PV mast release points at the front. As already explained, the zone 1 and 2 restrictions last several meters up in the air. So, the rotor sails must be placed entirely outside of the zone 1 and 2 areas, as seen from above.

The likelihood of an explosive atmosphere being present depends on the zone where you are located. In this case, we will use the frequency guidance as given by Torben Jepsen in *ATEX—Explosive Atmospheres: Risk Assessment, Control and Compliance* [14]. These values are also given in Table 13.1.

13.2 Likelihood of Ignition Sources Being Present and Effective

13.2.1 Fault Tree Analysis

The chosen strategy for finding the frequency at which an ignition source will be present and active is fault tree analysis (FTA). Using FTA, we were able to find the basic events that can result in the hazardous TOP event. The method is explained in subsection 6.2.1.

The chosen TOP event is *Rotor sails as a source of ignition.* What we want to find with this TOP event is the frequency at which either rotor sail can act as an ignition source.

As mentioned, the rotor sails will be placed outside of any of the classified zones. However, there will be several classified zones within close range. The rotor sails can be delivered with an electric drive that is either ATEX compliant or not. It is reasonable to assume that an ATEX-compliant electric drive will come at a higher cost than a normal one. Unfortunately, it is not stated by the manufacturer what is meant by ATEX compliant and what zones the rotor sail can be used. However, it must have a low probability of creating sparks and heat. An ATEX-compliant electric drive on this ship is not obligatory because the rotor sails are placed outside any classified zone.

A separate fault tree has been created for each case, with and without ATEX-compliant electric drive. Naturally, the risks associated with a non-compliant rotor sail are higher than in the opposite case. The main differences in the two cases are clearly shown in the fault trees presented in Figure 13.5 and Figure 13.6. The risks associated with operational friction and electrostatic discharge are unchanged when ATEX-compliant, while the spark from the electric drive is substantially reduced. Before introducing the compliant drive, we can see that the electric drive has the highest contribution to the TOP-event frequency. It is double that of electrostatic discharge and friction. However, with an ATEX-compliant device, the risk reduces to a much lower number, making the two other contributors more appreciable. The results and the frequency expressed in hours for the two cases are shown in Table 13.2.

Table 13.2: FTA results

TOP event	TOP event frequency[h^{-1}]	Frequency in hours
Rotor sails as a source of ignition (no ATEX compliant electric drive)	$1.6564 \cdot 10^{-4}$	6037
Rotor sails as a source of ignition (with ATEX compliant electric drive)	$8.1531 \cdot 10^{-5}$	12265

The fault trees consist of 7 or 4 basic events. In Figure 13.5, there are seven basic events that describe the main assumed failures that can lead to sparks. Expert judgment has been used to decide how the rotor sail might create ignition sources. There is minimal information available, and some assumptions had to be made. The fault tree with ATEX compliancy only has four basic events. That is because the specific reduction in each of the basic events from the previous tree is hard to estimate. So an assumption has been made that the frequency of sparks from the electric drive is $1 \cdot 10^{-10}$ when it is ATEX compliant.

For the basic event *electrostatic discharge*, which appears in both event trees, the frequency is set to $1 \cdot 10^{-5}$ for each rotor sail. The rest of the failure data is gathered from *Nonelectronic*

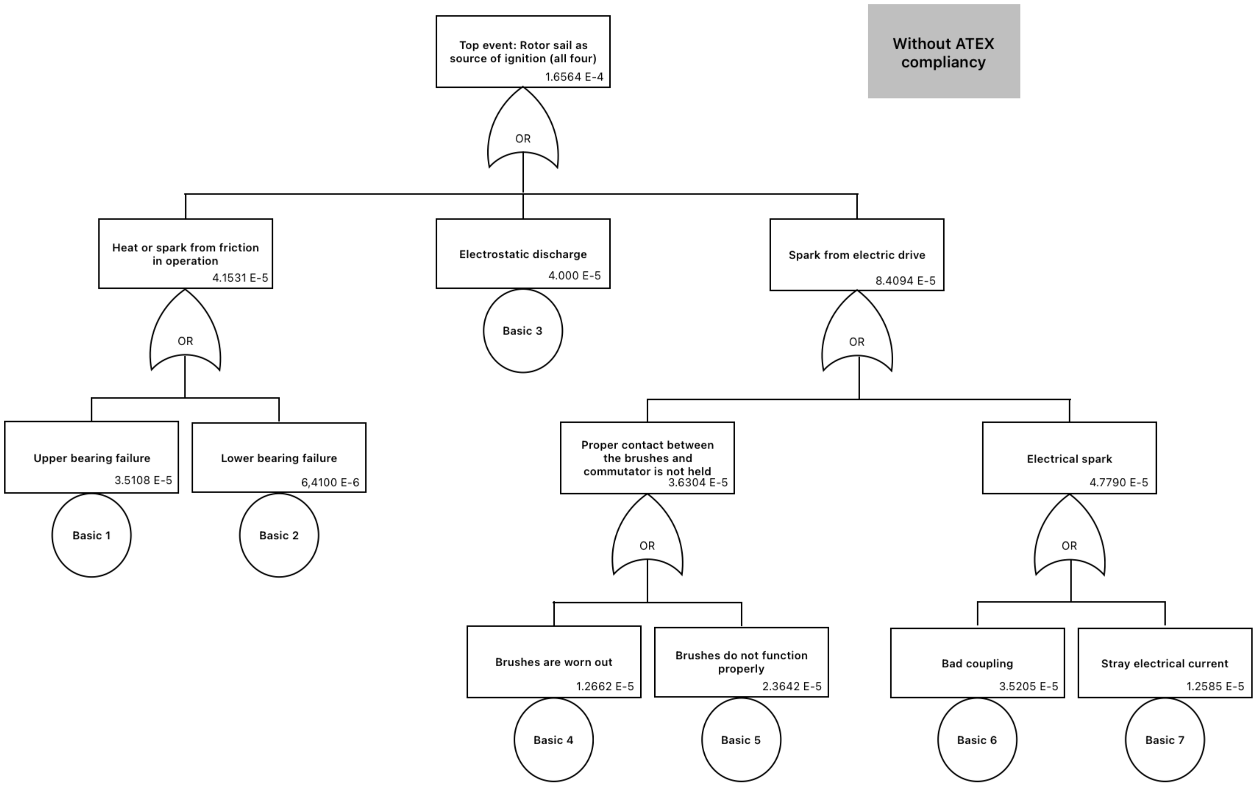


Figure 13.5: Fault tree considering risk of ignition from four rotor sails when electric drive is not ATEX compliant. Frequencies per hour of operation.

Parts Reliability Data by the Reliability Analysis Center [51]. It contains failure data for various components relevant to the ones we want to study. All the failure frequencies in the FTA are per hour operation.

Sources of error

Quantifying the basic events is based on a mix of sources and expert judgment. Unfortunately, we only know very basically the inner workings of the rotor sails because we have not been able to collect pertinent data from the providers. For this reason, some very rough assumptions and estimates had to be made, which means that a sensitivity analysis is instrumental. If better data is available, the assessment can be redone to give a more accurate answer.

The failure data used in the FTA are from *Nonelectronic Parts Reliability Data* by the Reliability Analysis Center [51]. It should be noted that this was published in 1991, and the data is relatively old. Additionally, it has not been possible to know precisely what components to use for finding the failure data, considering that we do not have access to detailed information about the construction of the rotor sail. Due to the lack of detailed information about the different components, the numbers used come from general categories of

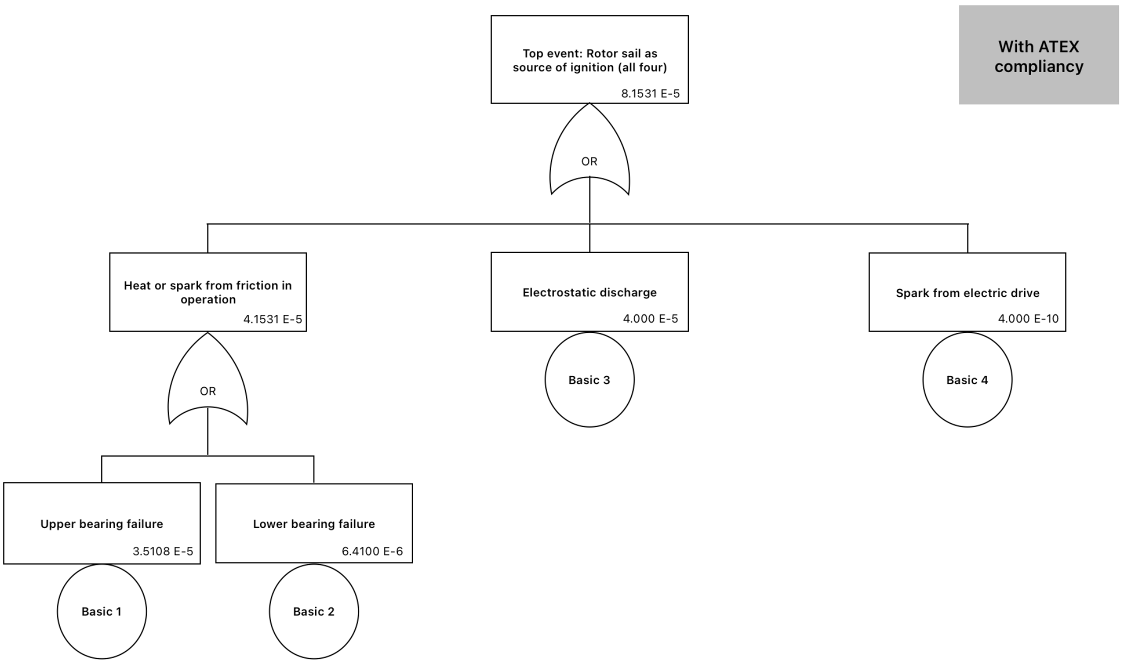


Figure 13.6: Fault tree considering risk of ignition from four rotor sails when electric drive is ATEX compliant. Frequencies per hour of operation.

the components. The general categories contain average data for all the specific components within this category. This way, we avoid using too high or too low failure rates when we do not know the specific component. For electrostatic discharge, an estimate based on knowledge was used. The materials that make up the rotor sail can possibly create an electrostatic charge because of fast movement in the air. However, it is tough to know whether the estimate is accurate.

13.3 Likelihood of Explosive Atmosphere and Active Ignition Being Present Simultaneously

Ignition sources or explosive environments are not generally an issue as long they do not appear simultaneously. For example, storing flammable substances in a tank is not problematic because the inside environment is without ignition sources. In order to explore the explosion frequency and the possible consequences, the event tree assessment (ETA) method has been used as explained in subsection 6.3.1.

13.3.1 Event Tree Assessment

The event tree allows us to explore the frequency of each outcome, given that we have the frequency of the TOP event from the FTA and the probabilities of each new event happening.

Initiating event

Using ignition as initiating event allows us to consider the probability of ignition and explosive atmosphere in conjunction with each other rather than using explosion as the initiating event and only looking at the consequences of that.

The event tree starts with a hazardous/initiating event - ignition. In this case, ignition from any of the rotor sails. The frequency of the event is taken from the FTA in the previous section. However, as explained previously, the ship's sailing time is assumed to be about 50 % of the time. We will assume that the rotor sails are always in operation during sailing. The annual frequency of ignition from the FTA must be divided by two to ensure that the rotor sails are only in operation half the time. Another essential change is that the frequency in the fault tree is per hour, while in the event tree it is per year. So the hourly frequency is multiplied by hours in a year to give annual frequency before input to the event tree.

The event tree calculations do not include the general risk of explosion on the ship, only if it is caused by ignition from one of the rotor sails.

Pivotal events and probabilities

Data from Sea-web [52] has been used to find the probabilities of the different outcomes. The search criteria are described in Table 13.3. From the search, we gathered the numbers shown in Table 13.4, which form the basis of the probabilities in the ETA.

Table 13.3: Search criteria used in Sea-web

Ship type	TANKERS
Deadweight	30 000 - 50 000
Timeframe	January 1st 2000 - January 1st 2020
Casualty type	Fire / Explosion

The first pivotal event is (1) explosion. It is assumed that an explosion will happen if there is ignition and if there is an explosive atmosphere. We cannot use the general explosion risk calculated from the Sea-web data because we are looking for the probability of an explosive atmosphere and not an explosion. The rotor sails are placed outside any of the classified zones. However, we have decided to judge them as if they were in a zone 2 environment. The reason is that it is uncertain whether the air turbulence from the rotor sails could affect the spread of gasses from release points.

As stated in Table 13.1, it is expected that there is an explosive atmosphere for up to 10 h/year in a zone 2 environment. This is used to calculate the probability of an explosive atmosphere for the first pivotal event.

Nevertheless, it is practical to know the general risk of explosion on the ship because we can find the relative increase after implementation. However, a full explosion risk assessment will not be conducted in this thesis, and we will instead use an approximation based on the accidents of similar ships. The numbers used are from the data extracted from Sea-web. From Equation (13.1), we can see that the general explosion accident frequency is 0.00175 or once every 571 years.

Table 13.4: Data from Sea-web used in ETA

Ships active in period	1881
Fire/explosion events in period	66
Serious events	53
Non-serious events	13
Reported hull damage	27
Reported pollution	3
Reported human injury/death	18
Reported total loss of ship	11

$$\text{Explosion accident frequency} = \frac{\text{Explosion accidents}}{\text{Shipyears}} = \frac{66}{37620} = 0.00175 \tag{13.1}$$

For the subsequent four pivotal events; (2) constructional damage, (3) oil/chemical spill, (4) capsizing or sinking, and (5) human injuries, we have used the information as given in Table 13.4. It is sometimes challenging to get correlational data or to know what happened first in Sea-web, and additionally, hull and machinery damage are filed in the same category, so it is difficult to know whether an accident concerns the hull or the machinery. More about the issues with data can be found under Sources of error.

The probabilities are based on the historical data gathered from Sea-web but are distributed to the pivotal events using expert judgment. For instance, it is thinkable that there is a higher chance of human injuries when the ship has capsized or sunk than when it floats. Another example is if the damage to the ship is severe enough to cause spills, it is at higher risk for capsizing or sinking than when there are no spills.

Event trees, resulting accident scenarios, and frequencies

The ETAs without and with ATEX-compliant electric drive are shown in Figures 13.7 and 13.8, respectively. Bigger versions can be seen in Appendix G. The classification and consequences of the various end events are shown in Figure 13.9.

From the event tree annual frequency results, we can see that the annual frequencies for all the outcomes involving explosion are very low (less than $3.6 \cdot 10^{-3}$ or once every 278 years). See the summary of results in Table 13.5.

The next column (outcome percentage) is not a standard parameter but an interesting parameter. It shows the percentage probability of each outcome given that ignition has happened. That means that given ignition (from rotor sail), 99.8858% of the time, the outcome will be no explosion. Conversely, there will be an explosion given ignition from rotor sails 0.1142% of the time.

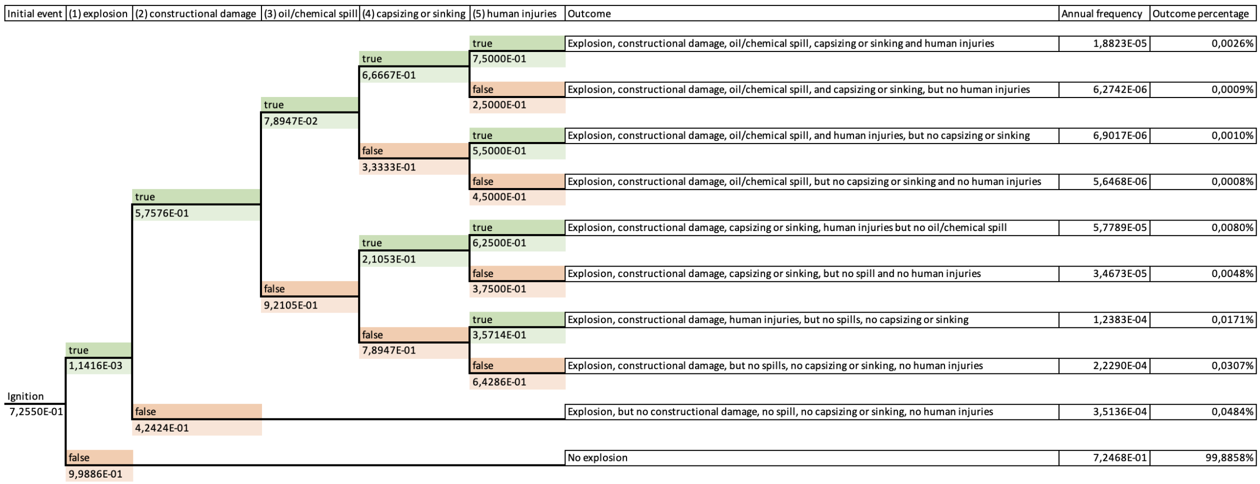


Figure 13.7: Event tree considering the consequences of possible ignition without ATEX compliant electric drive

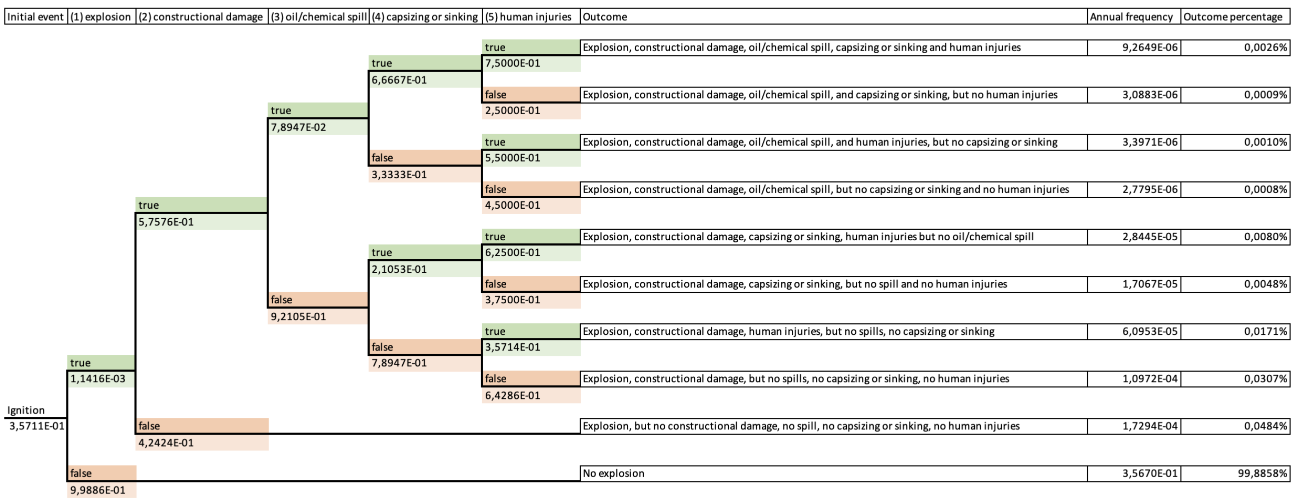


Figure 13.8: Event tree considering the consequences of possible ignition with ATEX compliant electric drive

Table 13.5: Summary of ETA results for cases with and without ATEX compliant rotor sail

	w/o ATEX compliancy	w/ATEX compliancy
Annual frequency, all explosion outcomes given ignition from rotor sails	$8.2820 \cdot 10^{-4}$	$4.0766 \cdot 10^{-4}$
Annual frequency, ignition from rotor sails but no explosion	0.7247	0.35670
Percentage of outcomes that include explosion, given ignition from rotor sails	0.1142%	0.1142%
New general explosion risk after adding rotor sails	$2.5826 \cdot 10^{-3}$	$2.1620 \cdot 10^{-3}$
Percentage increase in general explosion risk	47.2074%	23.2363%

Figure 13.9 classifies the severity of each end event in the ETA. The categories loss of life, material damage, and environmental damage classify the different outcomes. As illustrated, the category with the most severe consequences is environmental damage. This is because an explosion can lead to serious spills, sunken ships, and distribution of materials and debris. The most severe consequences naturally belong to the end events with the most upward turns in the event tree.

Sources of error

As mentioned, the data source for constructing the ETA relies heavily on Sea-web. A big issue with this is under-reporting. Not all relevant casualties will be reported, and because of this, the probabilities for each pivotal event will likely be lower than the actual numbers. Another problem is the variety of details in the reports. Some reports clearly state the chronological sequence of the incidents, while others do not. It is, therefore, difficult to determine the conditional probabilities of each event happening, and it is assumed that all the collected accident data happened in the same order as used in the event trees.

Another problem that we noticed when analyzing the data is that most of the accidents reported in the *Fire/Explosion* casualty category were accidents that had happened during maintenance and not sailing. This means that many of the accidents will not be representative of the type of accidents we are considering here. The actual rate of explosions and fires while sailing may be lower than implied in this chapter. Nevertheless, under-reporting could mean it should be higher, so it is difficult to know how the results have been affected.

End event description	Loss of life				Material damage				Environmental damage			
	0	1-5	6-10	> 10	Negligible	Low	Medium	High	Negligible	Low	Medium	High
Explosion, constructional damage, oil/chemical spill, capsizing or sinking and human injuries												
Explosion, constructional damage, oil/chemical spill, and capsizing or sinking, but no human injuries												
Explosion, constructional damage, oil/chemical spill, and human injuries, but no capsizing or sinking												
Explosion, constructional damage, oil/chemical spill, but no capsizing or sinking and no human injuries												
Explosion, constructional damage, capsizing or sinking, human injuries but no oil/chemical spill												
Explosion, constructional damage, capsizing or sinking, but no spill and no human injuries												
Explosion, constructional damage, human injuries, but no spills, no capsizing or sinking												
Explosion, constructional damage, but no spills, no capsizing or sinking, no human injuries												
Explosion, but no constructional damage, no spill, no capsizing or sinking, no human injuries												
No explosion												

Figure 13.9: Classification of end events from the ETA and their consequences

13.4 Sensitivity Analysis

Because of the error sources listed above for both the FTA and the ETA, it is necessary to perform a sensitivity analysis on the input data. This will allow us to explore whether the end results will differ significantly when the input failure rates are different.

The TOP event frequency gathered from the fault tree is quite low, so for good measure, we calculated the TOP event frequency if all the failure rates were 50% higher. See Figure 13.10.

As seen in Figure 13.10, the new TOP event frequency is $2.4845 \cdot 10^{-4}$, or every 4025 hours which is a 66% increase from previously.

When we do the same for the case with an ATEX compliant electric drive Figure 13.12, we find that the new TOP event frequency is $1.1510 \cdot 10^{-4}$, or every 8688 h of operation which is a 41% increase from previously.

Implementing the new TOP event frequencies into the event tree gives the new event trees shown in Figure 13.11 and Figure 13.13.

We have decided not to increase the probabilities of the pivotal events in the event tree because, as discussed in subsubsection 13.3.1, there are factors that could both increase and decrease the probabilities of each pivotal event.

The main results, compared with the results from the sensitivity analysis, are presented in Table 13.6.

Table 13.6: Explosion risk assessment results, summarized

	TOP event frequency [h^{-1}]	Initial event annual frequency	General explosion risk increase	New general explosion annual frequency
Without ATEX compliancy	$1.6564 \cdot 10^{-4}$	0.72550	47.2074%	0.002583
Without ATEX compliancy + 50% failure rate	$2.4845 \cdot 10^{-4}$	1.0882	70.8083%	0.002997
With ATEX compliancy	$8.1531 \cdot 10^{-5}$	0.3571	23.2363%	0.002162
With ATEX compliancy + 50% failure rate	$1.1510 \cdot 10^{-4}$	0.5041	32.8035%	0.002330

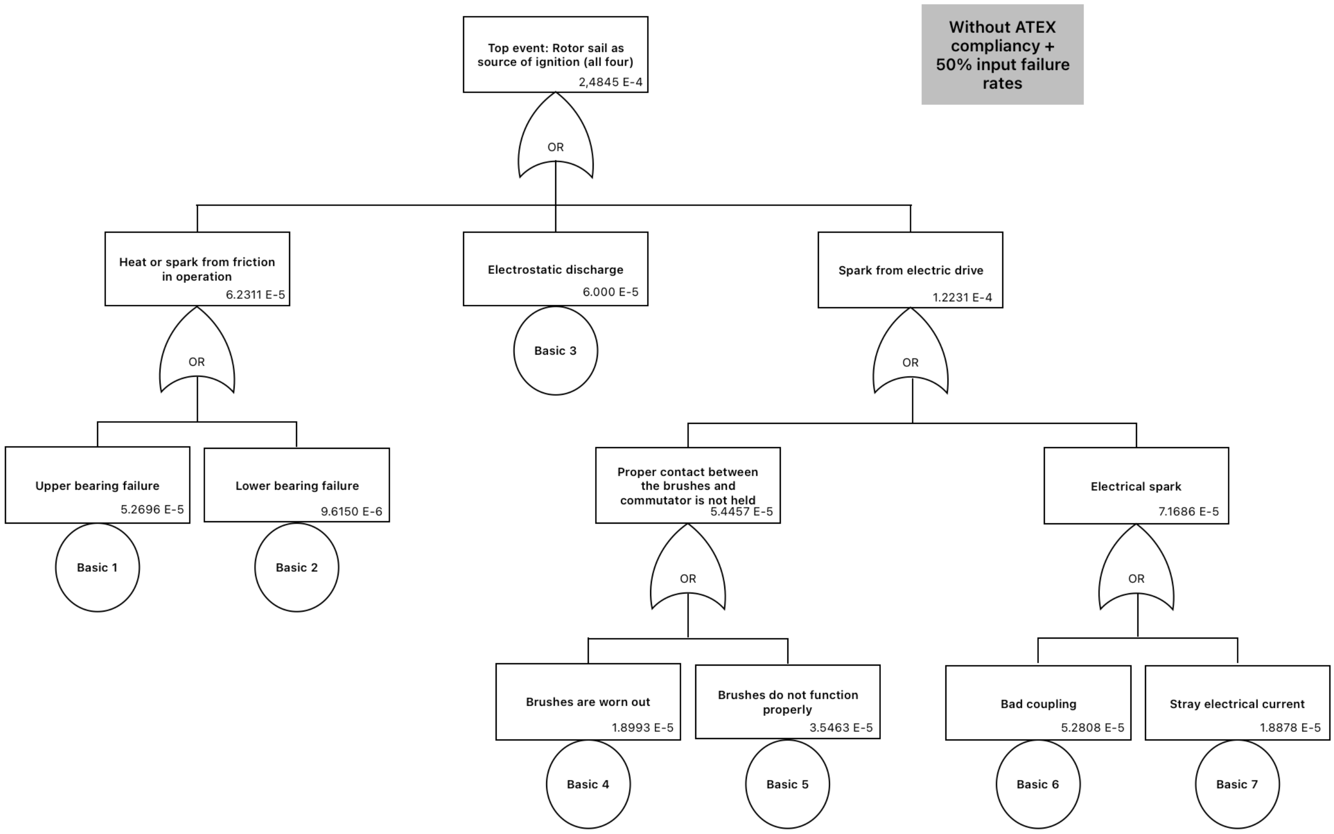


Figure 13.10: Fault tree considering risk of ignition from four rotor sails when electric drive is not ATEX compliant and input failure rates are 50% higher. Frequencies per hour of operation.

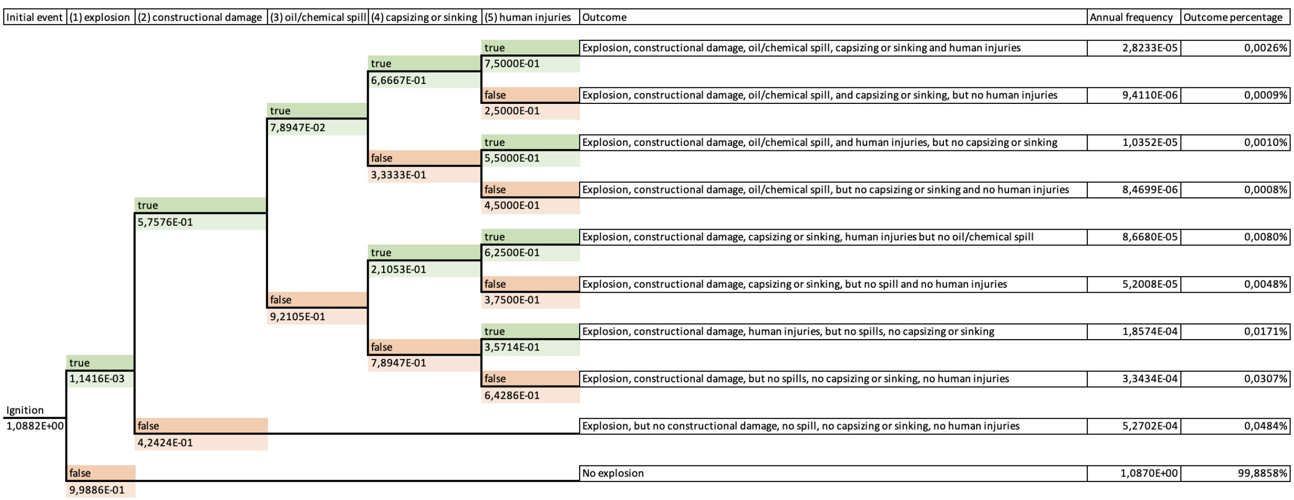


Figure 13.11: Event tree considering the consequences of possible ignition without ATEX compliant electric drive for increased TOP event frequency

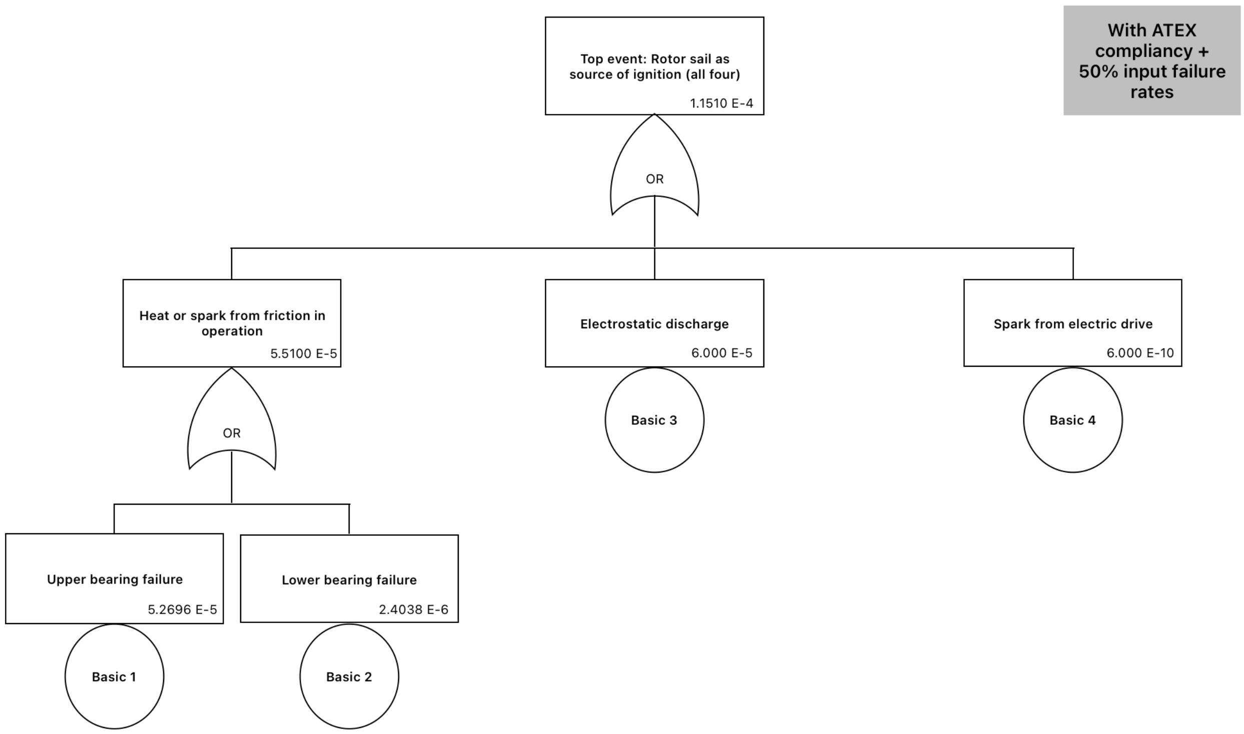


Figure 13.12: Fault tree considering risk of ignition from four rotor sails when electric drive is ATEX compliant and input failure rates are 50% higher. Frequencies per hour of operation

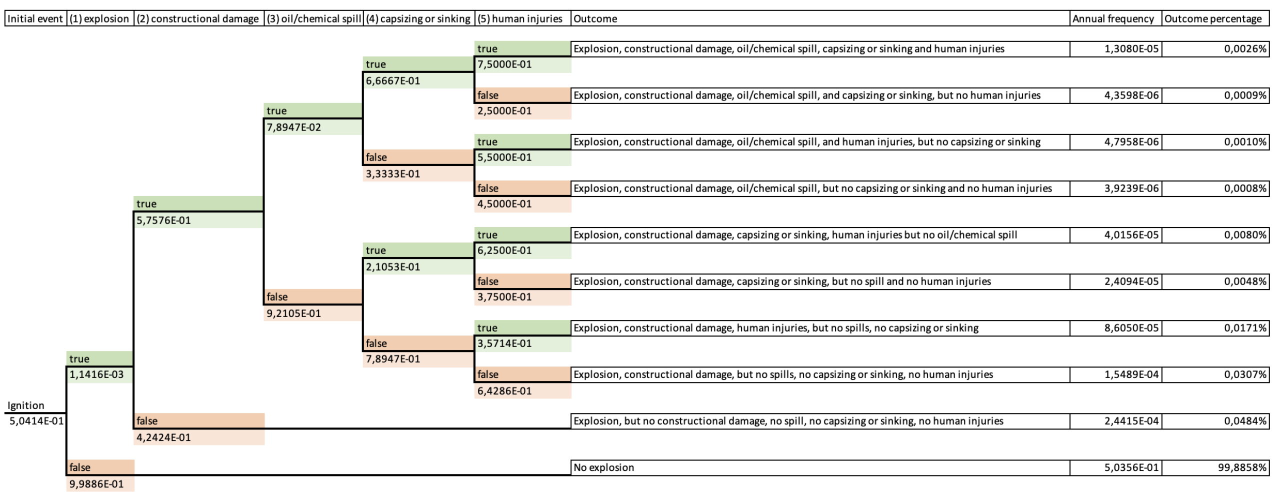


Figure 13.13: Event tree considering the consequences of possible ignition with ATEX compliant electric drive for increased TOP event frequency

Part IV

Discussion and Conclusions

Chapter 14

Discussion

14.1 Life Cycle Analysis

The implementation of rotor sails resulted in the reduction of all impact categories. The lift generated by the rotor sails effectively reduces emissions from the main engine to a greater extent than the emissions generated by powering the rotor sails. Global warming potential is the most discussed impact indicator today, and the life cycle analysis results show a reduction of 11.5%, which is a significant amount of GHG reduction over 20 years. The human health category is expected to improve the most among the endpoint indicators. Operating the ship with rotor sail is expected to save 80 years of full health compared to normal operation.

Considering all of the six ships instead of just the one analyzed in this thesis, a reduction of 204 000 tonnes kg CO_2 equivalents is expected. To put this into perspective, it is equivalent to the GHG emissions avoided by operating 57 wind turbines with a capacity of 1.82 MW each for an entire year. It is also equivalent to 2 701 tanker trucks' worth of gasoline.

As transparency is an essential part of LCA, it is important to mention that the whole life cycle was not included. The previous ship operation was excluded because it would be equal for both operation with and without rotor sails in the future. One thing that could be different for the two cases, which were not included in this assessment, is the cradle-to-grave effects of the rotor sails. Construction, transportation, and installation of the rotor sails are not included and would likely increase the impacts from the ship with the rotor sails. However, we have found that the operation part contributes to about 90% of the impacts for many ships. As the rotor sails are smaller and less complicated structures, it was a fair assumption to neglect the construction and installation phase. Regarding transportation, the ship can install the rotor sails where they are produced, as the ship sails worldwide.

The inventory analysis is an extensive part, especially regarding power saving calculations. The results from the power savings are not only interesting to use in the LCA model but also interesting to study to better understand the operation of the ships with rotor sails. We see that the lower the ship speed is, the higher power savings in percentage we get. This can make it necessary to reconsider the operational ship speed in order to save more power. The total expected power savings are 9.2% and 10.5% saved for the main machinery. The power savings are significant, considering the ships still have a long lifetime left and that rotor sails were not considered when designing the ships. The calculated power savings for the ships are within the expected savings stated by the rotor sail suppliers. The power savings calculations have been done by neglecting some parameters, such as aerodynamic interference between the sails. However, there are also made several assumptions that make the results more conservative. All this makes us confident that the ships will have sufficient power savings to reduce the emissions significantly.

The power savings are calculated based on historical wind data with the ships sailing without rotor sails. If rotor sails are to be implemented, not only the ship speed could be reconsidered, but also the ship route. As the rotor sails utilize the wind for propulsion, sailing a route with more favorable wind conditions might be more beneficial.

14.2 Cost Analysis

The operational costs vary with the fuel costs. We see that for fuel prices lower than around 500 USD/t, which is today's price, the installation and operation of rotor sails will not be beneficial from an economic perspective.

If we look at different studies about the prediction of future fuel oil costs, most show an increasing trend in the fuel price. If the fuel price is higher than today's, which is probable according to some studies, the investment of the rotor sails should be beneficial.

If the operational ship speed and route are changed to utilize more favorable wind conditions, such that the power savings are increased, it will also change the costs. If the power savings increases sufficiently, the economic benefit of implementing rotor sails can increase enough to make the implementation beneficial for lower fuel costs.

14.3 Risk Assessment

The change analysis uncovered visibility, maintenance, and fire/explosion risk as the main risk issues when considering rotor sail implementation on the ship. Reduced visibility was calculated to be within the SOLAS regulations and not an issue. The maintenance activities on rotor sails are assumed to be within the scope of regular work on deck and, therefore, not considered. This point should be considered again when more specific technical information is available. For fire/explosion risk, an explosion risk assessment with fault tree analysis and event tree assessment as the primary methods were performed.

The general explosion annual frequency increase varies for the cases with and without ATEX compliance. Nevertheless, the highest percentage increase is 47.2% for four rotor sails without ATEX compliancy. The increase brings the general explosion annual frequency up to 0.002583, which is once every 387 years. Before introducing the rotor sails, the original value was 0.00175, or once every 571 years. The increase in annual frequency is relatively modest. An explosion/fire event on the ship was improbable to happen before implementing the rotor sails, and after their implementation, it is still quite unlikely even though the risk has been noticeably increased.

If the rotor sails are ATEX compliant, the general explosion risk has a lower increase of 23.2% to 0.002162 or every 462 years. Clearly, that is significantly better than without ATEX compliance. Whether the better choice is to implement with or without ATEX compliance has to be evaluated in conjunction with the increased cost in a cost-benefit study.

The data used in the risk assessment are arguably unreliable because of several factors discussed; age, limited technical knowledge of the rotor sails, under-reporting, and lack of search specificity in Sea-web. Because of this, the assessment has been performed conservatively by selecting higher failure data for the FTA and performing a sensitivity analysis with 50% higher input failure rates. With this, it was shown that the general explosion annual frequency changed only moderately, even with a significant increase in the input failure frequencies.

Human errors were not considered as a part of the risk assessment. The TOP events chosen were not suitable for including human errors. Human errors in the production or installation of the rotor sail could affect the chances of failure, but they will be reflected in component failure data.

14.4 Further work

When implementing wind assistant ship propulsion to a ship, changing the route where the wind is more likely to give more beneficial wind conditions should be considered. Even if the route is longer, it can save more power by utilizing the wind speed and direction in a better way. If the implementation of rotor sails is decided, the ship route and speed should be reconsidered.

Given the significant influence of fuel prices on the profitability of implementing rotor sails, conducting a thorough investigation into fuel price dynamics becomes crucial. Performing a comprehensive analysis to predict future fuel prices would provide valuable insights. Additionally, it is essential to assess the associated risks of potential economic losses, taking into account the findings from the fuel price analysis.

Chapter 15

Conclusion

Implementing four rotor sails on the deck of the chemical tanker vessel considered in this thesis does not impact the risk levels on the ship in a significant matter to which it should be advised against. Nevertheless, a clear and informed decision should be made to decide whether the rotor sails should be ATEX compliant or not. The implementation of rotor sails will lead to reduced emissions, benefiting both human health and the environment. In terms of operational costs, the economic advantages depend on the fluctuation of fuel prices. If the fuel price increases, the implementation of rotor sails will be advantageous. Considering that costs are directly tied to fuel prices, the decision to adopt rotor sails should be carefully evaluated in relation to the risk of fuel costs.

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Appendices

Appendix A

Data for Power Savings Calculations

A.1 Input Data to Matlab Code

DATA FOR POWER SAVINGS				
Hull data				
Keel to main deck [m]	20.2			
LOA [m]	182.9			
LPP [m]	179.43			
Breadth [m]	32.2			
Draft midship [m]	13.2	11	7.15	
Displacement [m^3]	61480.4	49682.2	30221.2	
LCB	1.41%	2.39%	1.62%	
LCB [m]	2.53	4.29	2.91	
Rudder				
Height [m]	7.1			
Width [m]	5.2			
Aspect ratio	1.34			
Area [m^2]	37.57			
Location with respect to the hull [m]	0.15	from keel to bottom of rudder. 2,74m from AP		
Max rudder angle [deg] (expected stall angle of the rudder)	45	both ways		
Propeller				
Diameter [m]	7			
Draft midship [m]	13.2	11	7.15	
Propeller efficiency	0.75	0.766	0.783	
Flettner rotor location				
No. FR	**1**	**2**	**3**	**4**
From aft perpendicular [m]	135	156	135	156
From center line [m]	12.85	12.85	-12.85	-12.85
Flettner rotor				
Rotor diameter [m]	3.5			
Rotor height [m]	24.5			
End plate diameter [m]	7			
Base height [m]	2			
Installed power [W]	80000			
Typical h over deck [m]	26.5			
Max rpm	265			
Max bearing load [kN]	175			
Max apparent wind speed [m/s]	70			
Number of devices	4			
Polynomial constants resistance(P_E)	**a3**	**a2**	**a1**	**a0**
No wind no waves, ballast t=7,15m	35617.71	-417960.37	2075961.59	-3401870.42
No wind no waves, design t=11m	85993.18	-1288700.04	7049995.56	-12602227.99
No wind no waves, scantling t=13,2m	94010.72	-1360539.98	7308296.06	-12822107.36

Figure A.1.1: Data for power savings calculations

A.2 Effective Power from Model Tests

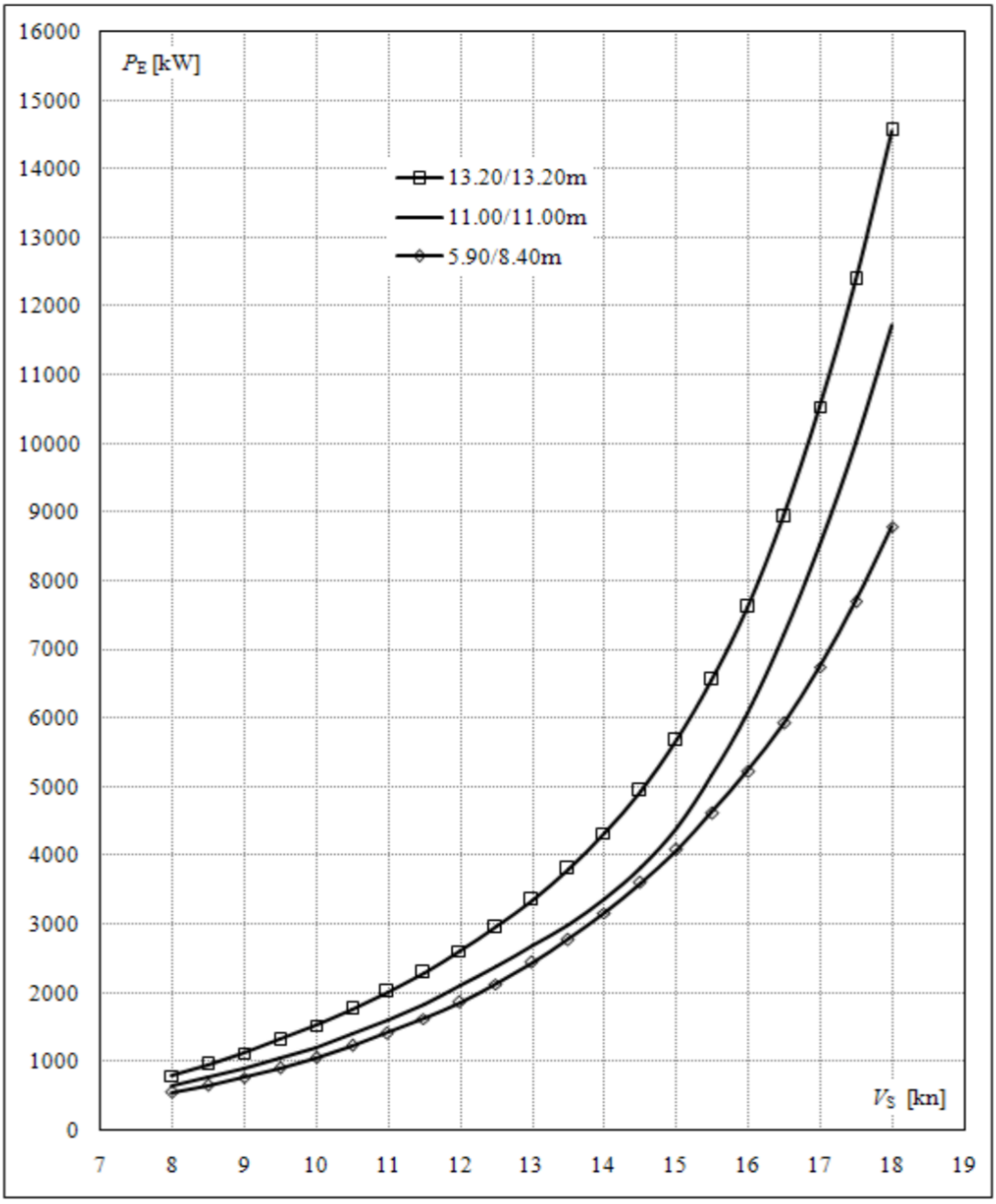
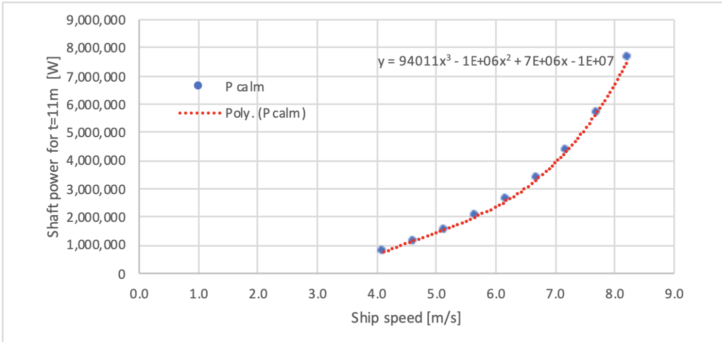


Figure A.2.1: Effective power for different drafts

A.3 Resistance Values from Model Tests - Calculating Polynomial Constants

Power curve from sea trial (no wind, no waves), scantling t=13,2m

Vs knots	Vs m/s	P calm W
8.0	4.1	801700
9.0	4.6	1128200
10.0	5.1	1532500
11.0	5.7	2022000
12.0	6.2	2612200
13.0	6.7	3357600
14.0	7.2	4330800
15.0	7.7	5688300
16.0	8.2	7624900



Polynomial constants plot out by equations

	a3	a2	a1	a0
P calm	94010.72236	-1360539.979	7308296.057	-12822107.36

Figure A.3.1: Effective power for different drafts

	A	B	C	D	E	F
1						
2			Power curve from sea trial (no wind, no waves), design draft t=11m			
3						
4						
5	Vs	Vs	P calm			
6	knots	m/s	W			
7	8	=A7*0.514444444	644000			
8	9	=A8*0.514444444	866000			
9	10	=A9*0.514444444	1211000			
10	11	=A10*0.514444444	1588000			
11	12	=A11*0.514444444	2166000			
12	13	=A12*0.514444444	2722000			
13	14	=A13*0.514444444	3388000			
14	15	=A14*0.514444444	4422000			
15	16	=A15*0.514444444	6166000			
16						
17						
18						
19						
20						
21						
22						
23		Polynomial constants plot out by equations				
24			a3	a2	a1	a0
25	P calm		=LINEST(C7:C15,B7:B15^{1,2,3})			

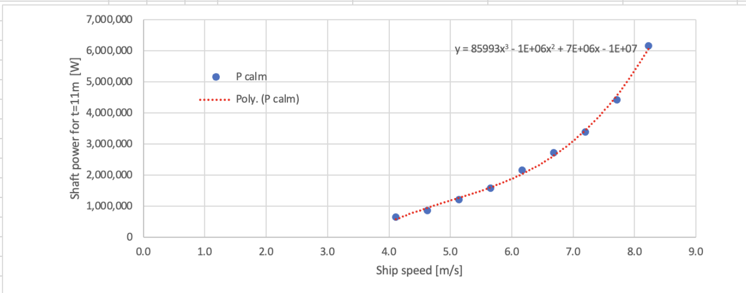
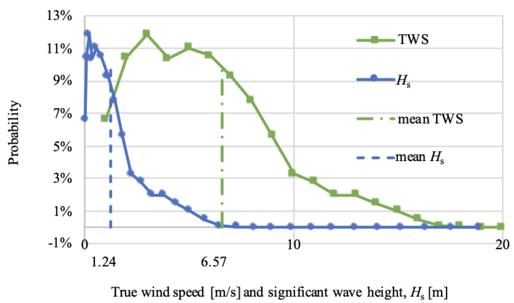


Figure A.3.2: Effective power for different drafts with formulas

Appendix B

Calculations Mean Wave Height

TWS curve	cw			11.3											
parameters	kw			2.2											
	TWS		m/s	1	2	3	4	5	6	7	8	9	10	11	12
wave height	H_s		m	0.022426096	0.089704383	0.201834862	0.358817533	0.560652396	0.80733945	1.098878695	1.435270133	1.816513761	2.242609582	2.713557594	3.229357798
TWS probabi	Probability			0.03165174	0.06581801	0.10447902	0.1184347	0.10363036	0.11013673	0.10539054	0.09288072	0.07738488	0.05601132	0.03275185	0.02762848
	Mean wave height														
		1.243592109	m	0.000709825	0.005904164	0.021087509	0.042496447	0.05810061	0.088917727	0.115811419	0.133308923	0.140570699	0.125611523	0.088874031	0.089222247
	Mean TWS														
		6.57450912	m/s	0.03165174	0.13163602	0.31343706	0.4737388	0.5181518	0.66082038	0.73773378	0.74304576	0.69646392	0.5601132	0.36027035	0.33154176
				0	0.1	0	0.1								
				1.243592109	1.243592109	6.57450912	6.57450912								



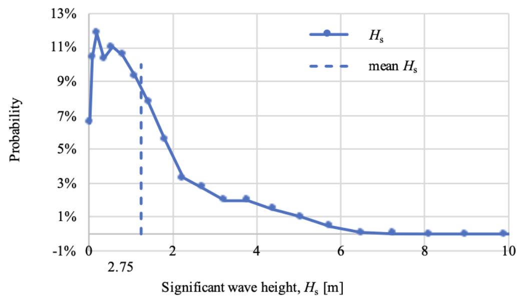
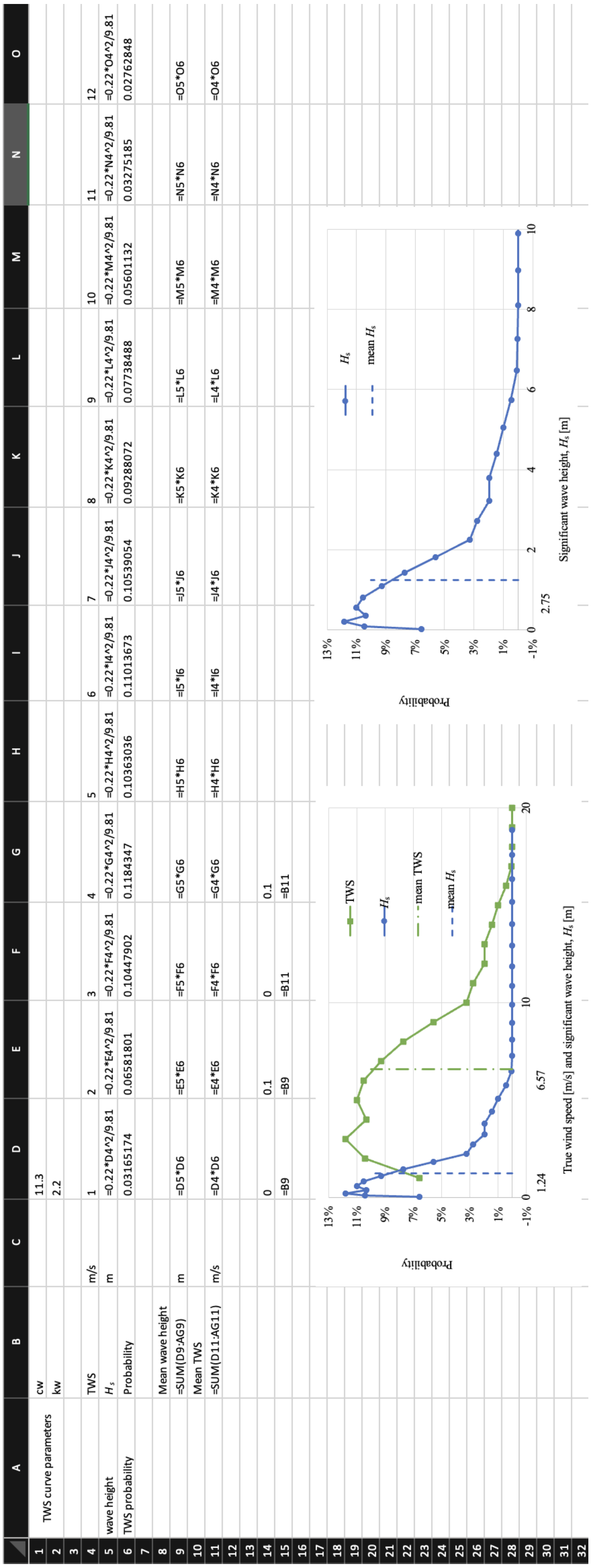


Figure B.0.1: Calculations of mean wave height



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	TWS curve parameters	cw		11.3											
2		kw		2.2											
3															
4		TWS	m/s	1	2	3	4	5	6	7	8	9	10	11	12
5	wave height	H_s	m	=0.22*D4^2/9.81	=0.22*E4^2/9.81	=0.22*F4^2/9.81	=0.22*G4^2/9.81	=0.22*H4^2/9.81	=0.22*I4^2/9.81	=0.22*J4^2/9.81	=0.22*K4^2/9.81	=0.22*L4^2/9.81	=0.22*M4^2/9.81	=0.22*N4^2/9.81	=0.22*O4^2/9.81
6	TWS probability	Probability		0.03165174	0.06581801	0.10447902	0.1184347	0.10363036	0.11013673	0.10539054	0.09288072	0.07738488	0.05601132	0.03275185	0.02762848
7															
8		Mean wave height													
9		=SUM(D9:AG9)	m	=D5*D6	=E5*E6	=F5*F6	=G5*G6	=H5*H6	=I5*I6	=J5*J6	=K5*K6	=L5*L6	=M5*M6	=N5*N6	=O5*O6
10		Mean TWS													
11		=SUM(D11:AG11)	m/s	=D4*D6	=E4*E6	=F4*F6	=G4*G6	=H4*H6	=I4*I6	=J4*J6	=K4*K6	=L4*L6	=M4*M6	=N4*N6	=O4*O6
12															
13															
14				0	0.1	0	0.1								
15				=B9	=B9	=B11	=B11								

Figure B.0.2: Calculations of mean wave height with formulas

Appendix C

Output from Matlab Code

'Ship speed [kn]'	'Rotor height [m]'	'True wind speed [m/s]'	'True wind angle [deg]'	'Wind probability [-]'	'Constraint limit rpm[-]'	'Constraint limit SR[-]'	'Constraint limit WASP power[-]'	'Constraint limit thrust[-]'	'Constraint limit side force[-]'	'Constraint limit drift[-]'	'Constraint limit trim sails[-]'	'Constraint limit windy[-]'	'Drift [deg]'	'I
8	24.5	2.5	0	0.005053502	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	5	0.005032354	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	10	0.004971082	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	15	0.004875672	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	20	0.004754554	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	25	0.004616967	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	30	0.004471597	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	35	0.004325736	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	40	0.004184985	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	45	0.004053316	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	50	0.003933341	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	55	0.00382663	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	60	0.003734017	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	65	0.00365585	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	70	0.003592181	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	75	0.00354291	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	80	0.003507876	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	85	0.003486927	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	90	0.003479957	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	95	0.003486927	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	100	0.003507876	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	105	0.00354291	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	110	0.003592181	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	115	0.00365585	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	120	0.003734017	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	125	0.00382663	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	130	0.003933341	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	135	0.004053316	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	140	0.004184985	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	145	0.004325736	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	150	0.004471597	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	155	0.004616967	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	160	0.004754554	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	165	0.004875672	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	170	0.004971082	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	175	0.005032354	0	0	0	0	0	0	0	0	0	
8	24.5	2.5	180	0.005053502	0	0	0	0	0	0	0	0	0	
9	24.5	2.5	0	0.005053502	0	0	0	0	0	0	0	0	0	
9	24.5	2.5	5	0.005032354	0	0	0	0	0	0	0	0	0	
9	24.5	2.5	10	0.004971082	0	0	0	0	0	0	0	0	0	

Figure C.0.1: Output from Matlab code showing first half of the parameters

'Drift difference [deg]'	'Rudder angle [deg]'	'Effective thrust [N]'	'Added resistance [N]'	'Side force [N]'	'Yaw moment WASP [Nm]'	'Yaw moment WASP [Nm]'	'Effective rotor power [W]'	Required power WASP [W]	Required power ship [W]	Saved power ship[W]	'Installed power [W]'
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	1719962.413	0	0
0	0	0	0	0	0	0	0	0	2117240.757	0	0
0	0	0	0	0	0	0	0	0	2117240.757	0	0
0	0	0	0	0	0	0	0	0	2117240.757	0	0

Figure C.0.2: Output from Matlab code showing second half of the parameters

Appendix D

Data for SimaPro

AUX MACHINERY		
Maintenance		
Total invoice cost [USD]	88440	
n ships	6	
n invoices per year	67	
Avg invoice cost [USD]	1320	
Avg invoices per ship	11	
Avg invoice cost [USD/ship/year]	14740	
Lube oil		
SLOC [g/kWh]	1	
SLOC [l/h]	0.8	
Cost [USD/l]	2.1	
Cons [l/year]	3942	
Cost [USD/year]	8278	
Density [g/ml]	0.922	
Cost [USD/kg]	22.8	
Cons [kg/year]	363	
Cost [USD/year]	8278	
Fuel oil		
SFOC [g/kWh]	215	
Avg fuel oil cons at sea [t/day]	3.7	
Cost [USD/t]	500	
Cons [t/year]	675	
Cost [USD/year]	337625	
Running hours and power cons		
Avg running hours at sea [h/day]	27	
Assumed days at sea [day/year]	182.5	
Avg power from aux engines [kW]	637	
Electrical efficiency	0.9	
Avg el power cons [kW]	574	
Eng power cons [kWh/year]	3140698	
El eng power cons [kWh/year]	2826628	
Emissions	**[g/kWh]**	**[t/year]**
N2	5050	15860.52326
O2	950	2983.662791
CO2	590	1853.011628
H2O	310	973.6162791
SOx	10	31.40697674
NOx	9	28.26627907
CO	0.6	1.884418605
HC	0.7	2.198488372

MAIN MACHINERY		
Maintenance		
Total invoice cost [USD]	139091	
n ships	6	
n invoices per year	55	
Avg invoice cost [USD]	2529	
Avg invoices per ship	9	
Avg invoice cost [USD/ship/year]	23182	
Lube oil		
SLOC [l/h]	0.5	
Cost [USD/l]	1.5	
Cons [l/year]	2190	
Cost [USD/year]	3285	
Density [g/ml]	0.89	
Cost [USD/kg]	16.9	
Cons [kg/year]	195	
Cost [USD/year]	3285	
Fuel oil		
SFOC [g/kWh]	163	
Cost [USD/t]	500	
Cons [t/year]	3629	
Cost [USD/year]	1814479	
Running hours and power consumption		
Avg running hours at sea [h/day]	24	
Assumed days at sea [day/year]	182.5	
Avg power engine [kW]	5083	
Propeller efficiency	0.76	
Avg propulsive power [kW]	3863	
Eng power cons [kWh/year]	22263540	
Total propulsive power [kWh/year]	16920290.4	
Emissions Tier II	**[g/kWh]**	**[t/year]**
O2	1138	25335.9085
CO2	510	11354.4054
H2O	317	7057.54218
SO2	0.003	0.06679062
NOx	11.92	265.381397
		0
HC	0.21	4.6753434

ROTOR SAILS	
Power savings	0.105
Average power consumption [kW]	53.7
Average running hours [h/day]	27
Sailing at sea [days/year]	182.5
Time with power savings [h/year]	4927.5
Energy cons rotor sails [kWh/year]	264606.75

AUX MACHINERY w/rotor sails		
Maintenance		
Total invoice cost [USD]	88440	
n ships	6	
n invoices per year	67	
Avg invoice cost [USD]	1320	
Avg invoices per ship	11	
Avg invoice cost [USD/ship/year]	14740	
Lube oil		
SLOC [g/kWh]	1	
SLOC [l/h]	0.8	
Cost [USD/l]	2.1	
Cons [l/year]	3942	
Cost [USD/year]	8278	
Fuel oil		
SFOC [g/kWh]	215	
Avg fuel oil cons at sea [t/day]	3.7	
Cost [USD/t]	500	
Cons [t/year]	738	
Cost [USD/year]	369231	
Running hours and power cons		
Avg running hours at sea [h/day]	27	
Assumed days at sea [day/year]	182.5	
Avg power from aux engines [kW]	697	
Electrical efficiency	0.9	
Avg el power cons [kW]	627	
Eng power cons [kWh/year]	3434705	
El eng power cons [kWh/year]	3091235	
Emissions	**[g/kWh]**	**[t/year]**
N2	5050	17345.2611
O2	950	3262.96992
CO2	590	2026.47605
H2O	310	1064.7586
SOx	10	34.3470517
NOx	9	30.9123466
CO	0.6	2.0608231
HC	0.7	2.40429362

MAIN MACHINERY w/rotor sails		
Maintenance		
Total invoice cost [USD]	139091	
n ships	6	
n invoices per year	55	
Avg invoice cost [USD]	2529	
Avg invoices per ship	9	
Avg invoice cost [USD/ship/year]	23182	
Lube oil		
SLOC [l/h]	0.5	
Cost [USD/l]	1.5	
Cons [l/year]	2190	
Cost [USD/year]	3285	
Fuel oil		
SFOC [g/kWh]	163	
Cost [USD/t]	500	
Cons [t/year]	3248	
Cost [USD/year]	1623958	
Running hours and power consumption		
Avg running hours at sea [h/day]	24	
Assumed days at sea [day/year]	182.5	
Avg power engine [kW]	4549.285	
Propeller efficiency	0.76	
Avg propulsive power [kW]	3457	
Eng power cons [kWh/year]	19925868.3	
Total propulsive power [kWh/year]	15143659.9	
Emissions Tier II	**[g/kWh]**	**[t/year]**
O2	1138	22675.6381
CO2	510	10162.1928
H2O	317	6316.50025
SO2	0.003	0.0597776
NOx	11.92	237.51635
		0
HC	0.21	4.18443234

Figure D.0.1: Input data for SimaPro

	B	C	D	F	G	H
2	**AUX MACHINERY**			**MAIN MACHINERY**		
3	**Maintenance**			**Maintenance**		
4	Total invoice cost [USD]	88440		Total invoice cost [USD]	139091	
5	n ships	6		n ships	6	
6	n invoices per year	67		n invoices per year	55	
7	Avg invoice cost [USD]	=C4/C6		Avg invoice cost [USD]	=G4/G6	
8	Avg invoices per ship	=C6/C5		Avg invoices per ship	=G6/G5	
9	Avg invoice cost [USD/ship/year]	=C8*C7		Avg invoice cost [USD/ship/year]	=G7*G8	
10	**Lube oil**			**Lube oil**		
11	SLOC [g/kWh]	1				
12	SLOC [l/h]	0.8		SLOC [l/h]	0.5	
13	Cost [USD/l]	2.1		Cost [USD/l]	1.5	
14	Cons [l/year]	=C27*C28*C12		Cons [l/year]	=(8760/2)*G12	
15	Cost [USD/year]	=C14*C13		Cost [USD/year]	=G14*G13	
16	Density [g/ml]	0.922		Density [g/ml]	0.89	
17	Cost [USD/kg]	=C13/(C16*100/(1000))		Cost [USD/kg]	=G13/(G16*100/(1000))	
18	Cons [kg/year]	=C16*100/1000*C14		Cons [kg/year]	=G16*100/1000*G14	
19	Cost [USD/year]	=C18*C17		Cost [USD/year]	=G17*G18	
20	**Fuel oil**			**Fuel oil**		
21	SFOC [g/kWh]	215		SFOC [g/kWh]	163	
22	Avg fuel oil cons at sea [t/day]	3.7				
23	Cost [USD/t]	500		Cost [USD/t]	500	
24	Cons [t/year]	=C32*C21/1000000		Cons [t/year]	=G32*G21/1000000	
25	Cost [USD/year]	=C24*C23		Cost [USD/year]	=G23*G24	
26	**Running hours and power cons**			**Running hours and power consumption**		
27	Avg running hours at sea [h/day]	27		Avg running hours at sea [h/day]	24	
28	Assumed days at sea [day/year]	=365/2		Assumed days at sea [day/year]	=365/2	
29	Avg power from aux engines [kW]	=C22*1000/((C21/1000)*C27)		Avg power engine [kW]	5083	
30	Electrical efficiency	0.9		Propeller efficiency	0.76	
31	Avg el power cons [kW]	=C29*C30		Avg propulsive power [kW]	=G29*G30	
32	Eng power cons [kWh/year]	=C29*C27*C28		Eng power cons [kWh/year]	=G29*G27*G28	
33	El eng power cons [kWh/year]	=C32*0.9		Total propulsive power [kWh/year]	=G32*G30	
34	**Emissions**	**[g/kWh]**	**[t/year]**	**Emissions Tier II**	**[g/kWh]**	**[t/year]**
35	N2	5050	=C35*$C$32/1000000			
36	O2	950	=C36*$C$32/1000000	O2	1138	=$G$32*G36/1000000
37	CO2	590	=C37*$C$32/1000000	CO2	510	=$G$32*G37/1000000
38	H2O	310	=C38*$C$32/1000000	H2O	317	=$G$32*G38/1000000
39	SOx	10	=C39*$C$32/1000000	SO2	0.003	=$G$32*G39/1000000
40	NOx	9	=C40*$C$32/1000000	NOx	11.92	=$G$32*G40/1000000
41	CO	0.6	=C41*$C$32/1000000			=$G$32*G41/1000000
42	HC	0.7	=C42*$C$32/1000000	HC	0.21	=$G$32*G42/1000000

	I	J	L	M	N	P	Q	R
2	**ROTOR SAILS**		**AUX MACHINERY w/rotor sails**			**MAIN MACHINERY w/rotor sails**		
3	Power savings	0.105	**Maintenance**			**Maintenance**		
4	Average power consumption [kW]	53.7	Total invoice cost [USD]	88440		Total invoice cost [USD]	139091	
5	Average running hours [h/day]	27	n ships	6		n ships	6	
6	Sailing at sea [days/year]	=365/2	n invoices per year	67		n invoices per year	55	
7	Time with power savings [h/year]	=J6*J5	Avg invoice cost [USD]	=M4/M6		Avg invoice cost [USD]	=Q4/Q6	
8	Energy cons rotor sails [kWh/year]	=J7*J4	Avg invoices per ship	=M6/M5		Avg invoices per ship	=Q6/Q5	
9			Avg invoice cost [USD/ship/year]	=M8*M7		Avg invoice cost [USD/ship/year]	=Q7*Q8	
10			**Lube oil**			**Lube oil**		
11			SLOC [g/kWh]	1				
12			SLOC [l/h]	0.8		SLOC [l/h]	0.5	
13			Cost [USD/l]	2.1		Cost [USD/l]	1.5	
14			Cons [l/year]	=M27*M28*M12		Cons [l/year]	=G14	
15			Cost [USD/year]	=M14*M13		Cost [USD/year]	=G15	
16								
17								
18								
19								
20			**Fuel oil**			**Fuel oil**		
21			SFOC [g/kWh]	215		SFOC [g/kWh]	163	
22			Avg fuel oil cons at sea [t/day]	3.7				
23			Cost [USD/t]	500		Cost [USD/t]	500	
24			Cons [t/year]	=M32*M21/1000000		Cons [t/year]	=Q32*Q21/1000000	
25			Cost [USD/year]	=M24*M23		Cost [USD/year]	=Q23*Q24	
26			**Running hours and power cons**			**Running hours and power consumption**		
27			Avg running hours at sea [h/day]	27		Avg running hours at sea [h/day]	24	
28			Assumed days at sea [day/year]	=365/2		Assumed days at sea [day/year]	=365/2	
29			Avg power from aux engines [kW]	=M22*1000/((M21/1000)*M27)+J4/M30		Avg power engine [kW]	=5083*(1-J3)	
30			Electrical efficiency	0.9		Propeller efficiency	0.76	
31			Avg el power cons [kW]	=(M29)*M30		Avg propulsive power [kW]	=Q29*Q30	
32			Eng power cons [kWh/year]	=M29*M27*M28		Eng power cons [kWh/year]	=Q29*24*Q28	
33			El eng power cons [kWh/year]	=M32*0.9		Total propulsive power [kWh/year]	=Q32*Q30	
34			**Emissions**	**[g/kWh]**	**[t/year]**	**Emissions Tier II**	**[g/kWh]**	**[t/year]**
35			N2	5050	=M35*$M$32/1000000			
36			O2	950	=M36*$M$32/1000000	O2	1138	=Q36*$Q$32/1000000
37			CO2	590	=M37*$M$32/1000000	CO2	510	=Q37*$Q$32/1000000
38			H2O	310	=M38*$M$32/1000000	H2O	317	=Q38*$Q$32/1000000
39			SOx	10	=M39*$M$32/1000000	SO2	0.003	=Q39*$Q$32/1000000
40			NOx	9	=M40*$M$32/1000000	NOx	11.92	=Q40*$Q$32/1000000
41			CO	0.6	=M41*$M$32/1000000			=Q41*$Q$32/1000000
42			HC	0.7	=M42*$M$32/1000000	HC	0.21	=Q42*$Q$32/1000000

Figure D.0.2: Input data for SimaPro with formulas

Appendix E

Economic Calculations

E.1 NPV Calculations

General data		
Avg fuel use per day [tons]		9.94
Fuel use per year main mach [tons]		3629
Additional fuel use per year aux mach [tons]		58
Fuel price per ton	$	500
Fuel expenses main machinery per year	$	1,814,479
Additional fuel expense aux mach per year	$	29,075
WACC		8.5 %

Expenses for operation with rotor sails				
Initial investment rotor sails	$ 2,000,000		Fuel savings main machinery	14.7 %
Extra fuel expense aux machinery	$ 29,075		Fuel savings main mach per year	$ 266,728
Net Present Value (NPV)				
Year	Negative	Positive		
0	$ -2,000,000			$ -2,000,000
1	$ -29,075	$ 266,728	NPV (1 year)	$ -1,780,965
2	$ -29,075	$ 266,728	NPV (2 years)	$ -1,579,089
3	$ -29,075	$ 266,728	NPV (3 years)	$ -1,393,028
4	$ -29,075	$ 266,728	NPV (4 years)	$ -1,221,543
5	$ -29,075	$ 266,728	NPV (5 years)	$ -1,063,493
6	$ -29,075	$ 266,728	NPV (6 years)	$ -917,825
7	$ -29,075	$ 266,728	NPV (7 years)	$ -783,568
8	$ -29,075	$ 266,728	NPV (8 years)	$ -659,829
9	$ -29,075	$ 266,728	NPV (9 years)	$ -545,784
10	$ -29,075	$ 266,728	NPV (10 years)	$ -440,674
11	$ -29,075	$ 266,728	NPV (11 years)	$ -343,797
12	$ -29,075	$ 266,728	NPV (12 years)	$ -254,511
13	$ -29,075	$ 266,728	NPV (13 years)	$ -172,219
14	$ -29,075	$ 266,728	NPV (14 years)	$ -96,374
15	$ -29,075	$ 266,728	NPV (15 years)	$ -26,470
16	$ -29,075	$ 266,728	NPV (16 years)	$ 37,957
17	$ -29,075	$ 266,728	NPV (17 years)	$ 97,336
18	$ -29,075	$ 266,728	NPV (18 years)	$ 152,064
19	$ -29,075	$ 266,728	NPV (19 years)	$ 202,505
20	$ -29,075	$ 266,728	NPV (20 years)	$ 248,994

Figure E.1.1: NPV calculations

	A	B	C	D	E	F	G	H	I	J
1										
2										
3										
4		**General data**			**Expenses for operation with rotor sails**					
5		Avg fuel use per day [tons]	=C6/365		Initial investment rotor sails	2000000			Fuel savings main machinery	0.147
6		Fuel use per year main mach [tons]	=Sheet1!G24		Extra fuel expense aux machinery	=C10			Fuel savings main mach per year	=$C$9*J5
7		Additional fuel use per year aux mach [tons]	=Sheet1!M24-Sheet1!C24		**Net Present Value (NPV)**					
8		Fuel price per ton	500		Year	Negative	Positive			
9		Fuel expenses main machinery per year	=C8*C6		0	=-(F5)				=F9
10		Additional fuel expense aux mach per year	=C8*C7		1	=-$F$6	=J6		NPV (1 year)	=F9+NPV($C$11,F10)+NPV($C$11,G10)
11		WACC	0.085		2	=-$F$6	=J6		NPV (2 years)	=F9+NPV($C$11,F10:F11)+NPV($C$11,G10:G11)
12					3	=-$F$6	=J6		NPV (3 years)	=F9+NPV($C$11,F10:F12)+NPV($C$11,G10:G12)
13					4	=-$F$6	=J6		NPV (4 years)	=F9+NPV($C$11,F10:F13)+NPV($C$11,G10:G13)
14					5	=-$F$6	=J6		NPV (5 years)	=F9+NPV($C$11,F10:F14)+NPV($C$11,G10:G14)
15					6	=-$F$6	=J6		NPV (6 years)	=F9+NPV($C$11,F10:F15)+NPV($C$11,G10:G15)
16					7	=-$F$6	=J6		NPV (7 years)	=F9+NPV($C$11,F10:F16)+NPV($C$11,G10:G16)
17					8	=-$F$6	=J6		NPV (8 years)	=F9+NPV($C$11,F10:F17)+NPV($C$11,G10:G17)
18					9	=-$F$6	=J6		NPV (9 years)	=F9+NPV($C$11,F10:F18)+NPV($C$11,G10:G18)
19					10	=-$F$6	=J6		NPV (10 years)	=F9+NPV($C$11,F10:F19)+NPV($C$11,G10:G19)
20					11	=-$F$6	=J6		NPV (11 years)	=F9+NPV($C$11,F10:F20)+NPV($C$11,G10:G20)
21					12	=-$F$6	=J6		NPV (12 years)	=F9+NPV($C$11,F10:F21)+NPV($C$11,G10:G21)
22					13	=-$F$6	=J6		NPV (13 years)	=F9+NPV($C$11,F10:F22)+NPV($C$11,G10:G22)
23					14	=-$F$6	=J6		NPV (14 years)	=F9+NPV($C$11,F10:F23)+NPV($C$11,G10:G23)
24					15	=-$F$6	=J6		NPV (15 years)	=F9+NPV($C$11,F10:F24)+NPV($C$11,G10:G24)
25					16	=-$F$6	=J6		NPV (16 years)	=F9+NPV($C$11,F10:F25)+NPV($C$11,G10:G25)
26					17	=-$F$6	=J6		NPV (17 years)	=F9+NPV($C$11,F10:F26)+NPV($C$11,G10:G26)
27					18	=-$F$6	=J6		NPV (18 years)	=F9+NPV($C$11,F10:F27)+NPV($C$11,G10:G27)
28					19	=-$F$6	=J6		NPV (19 years)	=F9+NPV($C$11,F10:F28)+NPV($C$11,G10:G28)
29					20	=-$F$6	=J6		NPV (20 years)	=F9+NPV($C$11,F10:F29)+NPV($C$11,G10:G29)

Figure E.1.2: NPV calculations with formulas

Appendix F

Angle Calculations for Rotor Sail Blind Sectors

The calculations for the blind sectors caused by placing the rotor sails are shown in Figure F.0.1 and their corresponding formulas in Figure F.0.2. The explanation of angles x, u and v are illustrated in Figure F.0.3.

RS1 and RS3		
v	83,83	degrees
u	81,90	degrees
angle obstructed	1,92	degrees

RS2 and RS4		
v	84,87	degrees
u	83,26	degrees
angle obstructed	1,61	degrees

Angle of vision between two rotor sails on same side		
v	83,26	degrees
u	83,83	degrees
angle between	-0,56	degrees

Considering two RS on same side as ONE blind sector	2,97	degrees per side
	5,93	degrees total

Distances		
Bridge from AP	32,4	m
RS1 and 3 from AP	135	m
RS2 and 4 from AP	156	m
Bridge to RS1 and 3	102,6	m
Bridge to RS2 and 4	123,6	m
CL to RS	12,85	m
CL to RS inner	11,1	m
CL to RS outer	14,6	m
Rotor sail diameter	3,5	m

Figure F.0.1: Excel calculation of blind sectors

	A	B	C	D	E	F	G
1	RS1 and RS3				Distances		
2	v	=ATAN(F5/F8)*360/(2*PI())	degrees		Bridge from AP	32,4	m
3	u	=ATAN(F5/F9)*360/(2*PI())	degrees		RS1 and 3 from AP	135	m
4	angle obstructed	=B2-B3	degrees		RS2 and 4 from AP	156	m
5					Bridge to RS1 and 3	=F3-F2	m
6					Bridge to RS2 and 4	=F4-F2	m
7	RS2 and RS4				CL to RS	12,85	m
8	v	=ATAN(F6/F8)*360/(2*PI())	degrees		CL to RS inner	=F7-F11/2	m
9	u	=ATAN(F6/F9)*360/(2*PI())	degrees		CL to RS outer	=F7+F11/2	m
10	angle obstructed	=B8-B9	degrees				
11					Rotor sail diameter	3,5	m
12							
13	Overlap of blind sectors between two rotor sails on same side						
14	v	=ATAN(F6/F9)*360/(2*PI())	degrees				
15	u	=ATAN(F5/F8)*360/(2*PI())	degrees				
16	angle between	=B14-B15	degrees				
17							
18							
19	Considering two RS on same side as ONE blind sector	=B16+B10+B4	degrees per side				
20		=B19*2	degrees total				

Figure F.0.2: Excel calculation of blind sectors - showing formulas

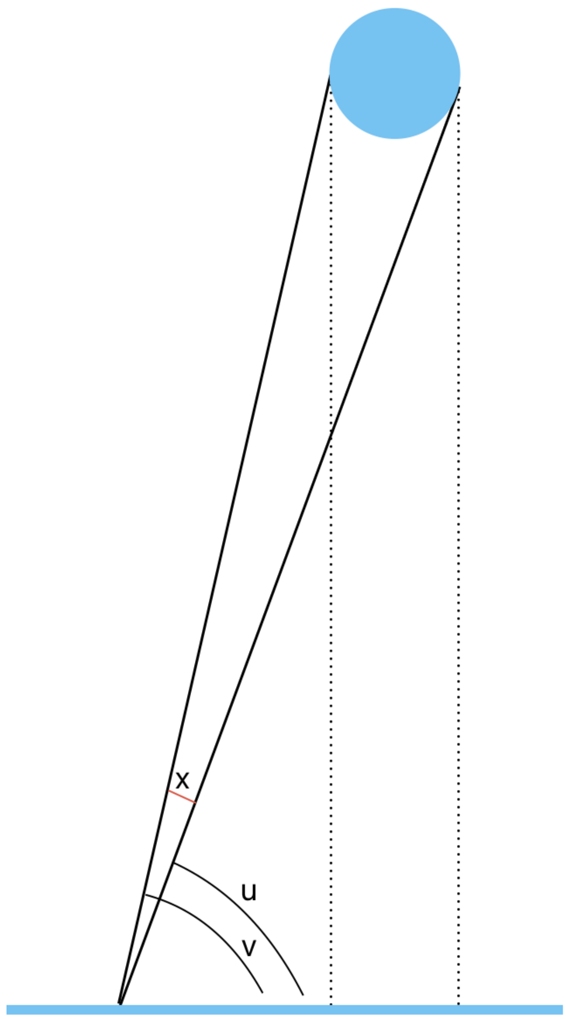


Figure F.0.3: Angles

Appendix G

Event Trees

G.1 Event Tree with ATEX Compliant Electric Drive

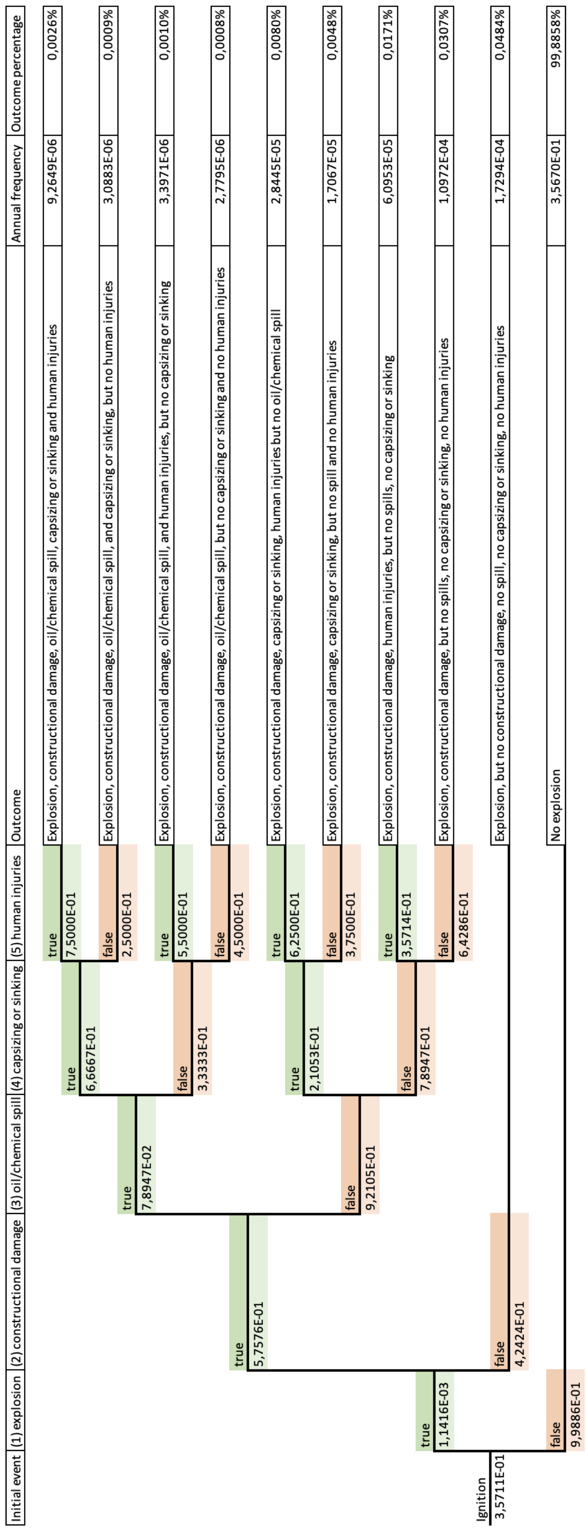


Figure G.1.1: Event tree considering the consequences of possible ignition with ATEX compliant electric drive

G.2 Event Tree without ATEX Compliant Electric Drive

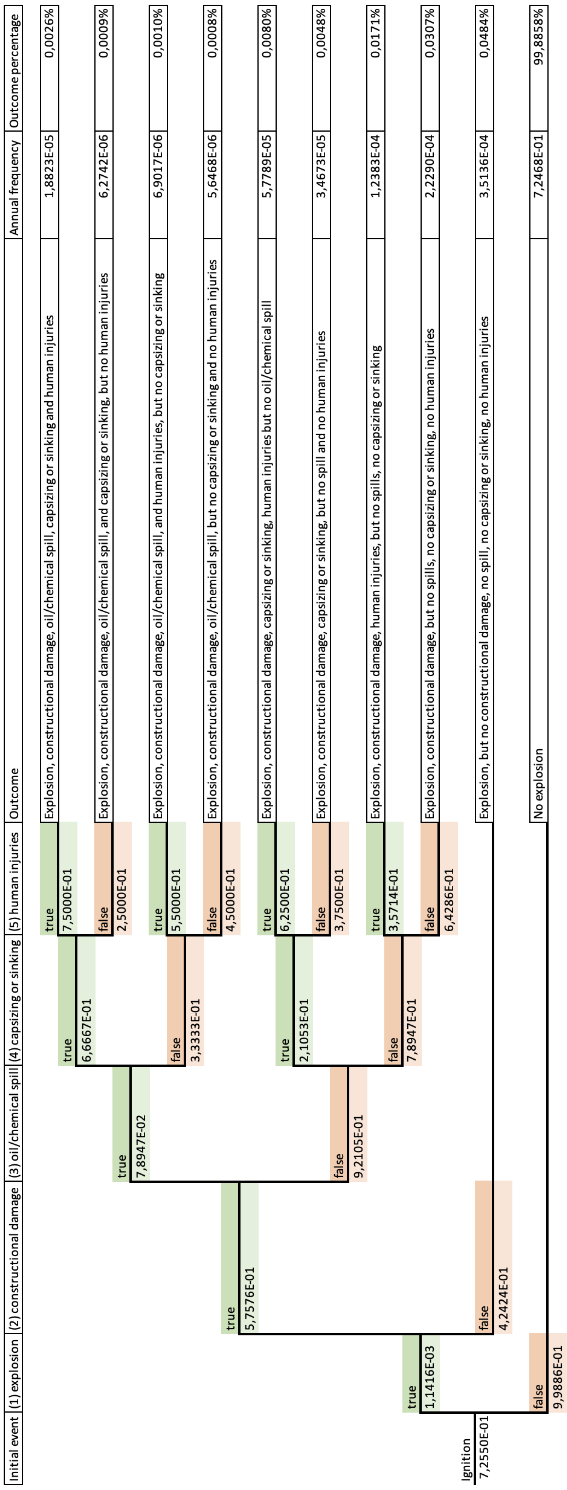


Figure G.2.1: Event tree considering the consequences of possible ignition without ATEX compliant electric drive

G.3 Event Tree with ATEX Compliant Electric Drive + Increased Initial Event Frequency

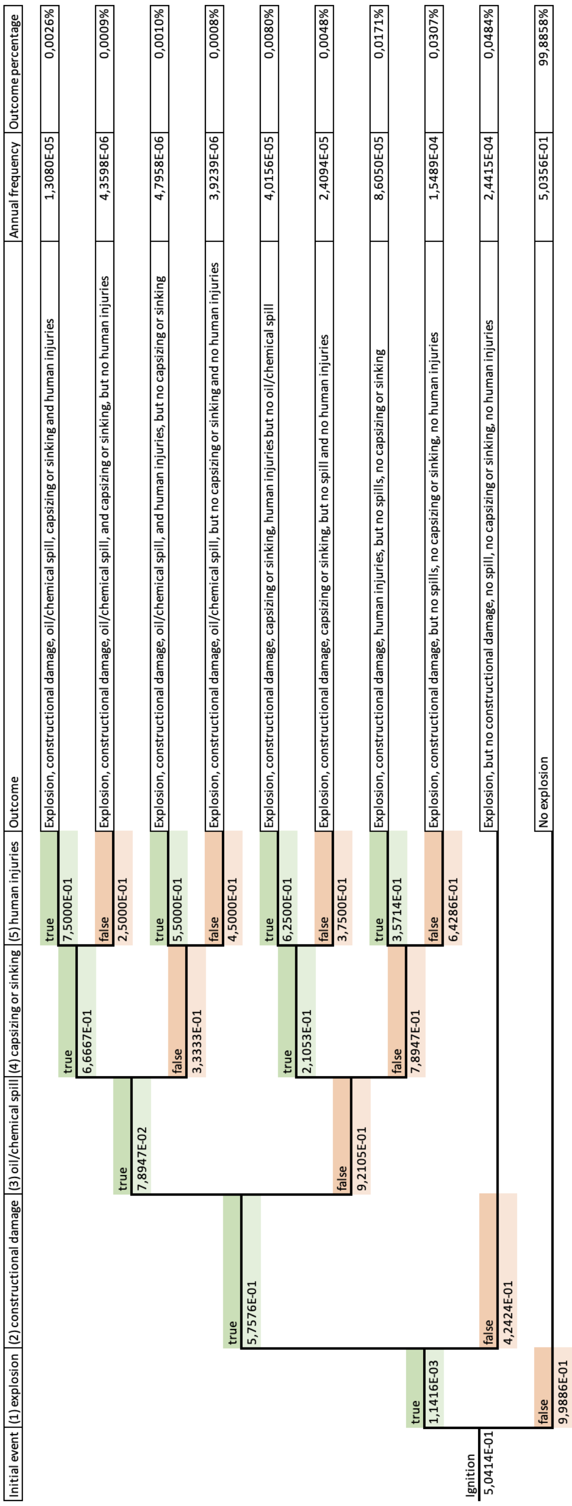


Figure G.3.1: Event tree considering the consequences of possible ignition without ATEX compliant electric drive for increased TOP event frequency

G.4 Event Tree Without ATEX Compliant Electric Drive + Increased Initial Event Frequency

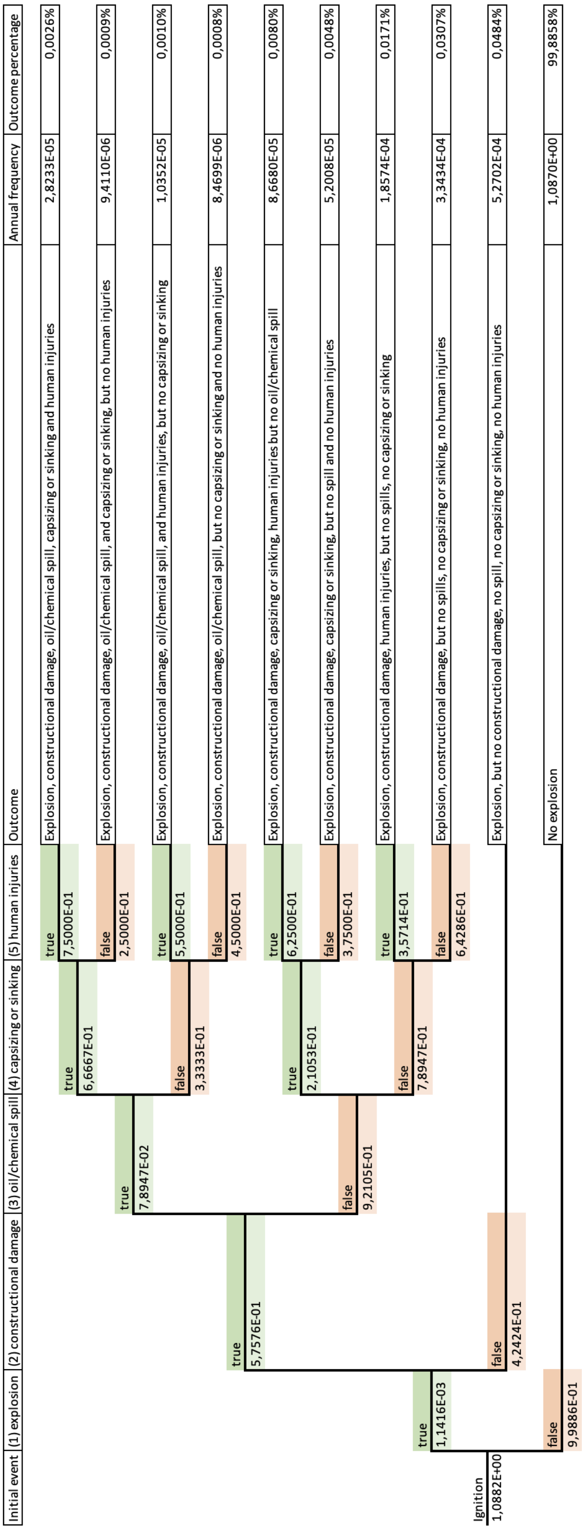


Figure G.4.1: Event tree considering the consequences of possible ignition without ATEX compliant electric drive for increased TOP event frequency

Appendix H

Auxiliary Engine Calculations Python

[1]:
```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import copy
np.set_printoptions(suppress=True)
```

[2]:
```
# Excel sheet to dataframe
df = pd.read_excel('Export_aux_eng.xlsx')

# Arrays of time, relevant power, and total load
P_av = df['MSBO-AVA-POW(kW)'].to_numpy()
L_tot = df['MSBO-TOT-LOD(kW)'].to_numpy()
t = df['Sample time'].to_numpy()

# Making an array with total power
P_tot = np. add(P_av,L_tot)
```

Finding how often two engines are used

If the total power is bigger than what one engine can produce, the count adds one to the variable for two engines. If it is lower, the count adds one to the variable for one engine. Then the percentage of these two are found.

[3]:
```
# Finding how often one or two aux engines are used
one_eng = 0
two_eng = 0

for i in range (0,len(P_tot)):
    if P_tot[i] < 1320:
        one_eng += 1
```

```
    if P_tot[i] > 1320:
        two_eng += 1

one_eng_part = one_eng/(two_eng+one_eng)
two_eng_part = 1-one_eng_part

print('Time using one engine:',np.round(one_eng_part,3),'Time using two␣
 ↪engines:', np.round(two_eng_part,3))
```

```
Time using one engine: 0.935 Time using two engines: 0.065
```

Total load with rotor sails

The total power to the rotor sails are added to the total load. The calculations shows that the average power consumption from the rotor sails are 53,7 kW. The code is also tested for the total maximum power the rotor sails can consume by using the maximum installed power 80 kW. The power consumption of the rotor sails are divided by 0.9 which is the efficiency of the mechanical power from the engine to the electrical grid.

[4]:
```
# Power to rotor sails
P_rs = (53.7)
P_rs_max = 80*4/0.9

# Finding total load with rotor sails
L_tot_rs = np.zeros(len(L_tot))
L_tot_rs_max = np.zeros(len(L_tot))
for i in range (0,len(L_tot)):
    L_tot_rs[i] = L_tot[i] + P_rs
    L_tot_rs_max[i] = L_tot[i] + P_rs_max
```

Finding how often two engines are used with rotor sails

The same procedure as for without rotor sails is used, except now the required power for the rotor sails are added to the total power, and the margin for when to start up a new engine is increased. The reason for this is that it is assumed that the auxiliary engine with the highest capacity is used. The limit for when to start a new engine is when the running engine is at a capacity of 90%, which in this case is 90% of 1320 kW, which gives a limit of 1188 kW.

[5]:
```
# Finding the value or margin where a new engine is started
two_eng_rs = copy.copy(two_eng)
one_eng_rs = copy.copy(one_eng)

two_eng_rs_max = copy.copy(two_eng)
one_eng_rs_max = copy.copy(one_eng)

for i in range (0,len(P_tot)):
```

```
    if L_tot_rs[i] > 1188 and P_tot[i] < 1320:
        two_eng_rs += 1
        one_eng_rs -= 1
    if L_tot_rs_max[i] > 1188 and P_tot[i] < 1320:
        two_eng_rs_max += 1
        one_eng_rs_max -= 1

one_eng_part_rs = one_eng_rs/(two_eng_rs+one_eng_rs)
two_eng_part_rs = 1-one_eng_part_rs

one_eng_part_rs_max = one_eng_rs_max/(two_eng_rs_max+one_eng_rs_max)
two_eng_part_rs_max = 1-one_eng_part_rs_max

print('Time using one engine with rotor sails:',np.round(one_eng_part_rs,␣
↪3),'Time using two engines with rotor sails:', np.
↪round(two_eng_part_rs,3))
print('Time using one engine with rotor sails on max power cons:',np.
↪round(one_eng_part_rs_max, 3),'Time using two engines with rotor sails:
↪', np.round(two_eng_part_rs_max,3))
```

```
Time using one engine with rotor sails: 0.935 Time using two engines with␣
↪rotor
sails: 0.065
Time using one engine with rotor sails on max power cons: 0.924 Time using␣
↪two
engines with rotor sails: 0.076
```

Appendix I

Python Code Power Savings

[1]:
```
import pandas as pd
import copy
import numpy as np
import matplotlib.pyplot as plt
np.set_printoptions(suppress=True)
```

Discretised data

In order to combine the results for power savings from the Matlab code from Drazen Polic, the probability for all the possible cases from the raw data must be found. The Matlab code uses discretised data, and the raw data must be compared with the same discretized data with the same increments. The block under sets up the discretised data that are used in the Matlab code. They are then put in a matrix such that the unique bins later can be compared with the raw data to find the probabilities.

[2]:
```
# Creating arrays of the discretized values for the relevant parameters
v_s_disc = np.arange(8,17,1) # ship speed
tws_disc = np.arange(2.5,27.5,2.5) # true wind speed
twa_disc = np.arange(0,185,5) # true wind angle
d_disc = [7.15, 11.0, 13.2] # draft

# Calculating number of unique bins
n_bins = len(v_s_disc)*len(tws_disc)*len(twa_disc)*len(d_disc)

# Creating arrays of the relevant parameters with the length of unique bins
v_s = np.arange(n_bins)
twa = np.arange(n_bins)
tws = np.arange(n_bins, dtype=float)
d = np.arange(n_bins, dtype=float)

# Inserting values in the arrays to create unique bins
for k in range (len(d_disc)):
```

```
    for i in range (len(tws_disc)):
        for j in range(len(v_s_disc)):
            for l in range(len(twa_disc)):
                position = l+j*len(twa_disc)+i*len(twa_disc)* \
                len(v_s_disc)+k*len(v_s_disc)*len(twa_disc)*len(tws_disc)
                v_s[position] = v_s_disc[j]
                tws[position] = tws_disc[i]
                twa[position] = twa_disc[l]
                d[position] = d_disc[k]

# Creating matrix of the unique bins
bins_matrix = np.zeros(shape=(len(v_s), 4))
for i in range (len(v_s)):
    bins = np.array([v_s[i],tws[i],twa[i],d[i]])
    bins_matrix[i] = bins
```

Reading from raw data file

The first block uses the pandas package to read the relevant columns from an excel file that contains wind data from copernicus, time, ship position, ship speed, ship heading, and draughts.

[3]:
```
# Excel sheets to dataframe
df = pd.read_excel('Discretization.xlsx')
df2 = pd.read_excel('Bow Optima 2022.xlsx')

# Creating arrays of the relevant values
v_s_raw = df['ship_speed[kn]'].to_numpy()
course_s = df['ship_course[°]'].to_numpy()
east_w = df['eastward_wind'].to_numpy()
north_w = df['northward_wind'].to_numpy()
df['just_date'] = df['date'].dt.date
df2['just_date'] = df2['Date'].dt.date
t_pos_report = df['just_date'].to_numpy()
t_daily_report = df2['just_date'].to_numpy()
draught = df2['AverageMeanDraft'].to_numpy()
draught[np.isnan(draught)] = 0

# Deepcopy done to plot the ship speed later. It has nothing to do with␣
↪the calculations of the power savings
vsraw=copy.deepcopy(v_s_raw)
```

Finding the true wind speed and true wind angle relative to the ship heading

The wind data are gathered for the time and location of the ship. The wind data are exported as eastward wind and northward wind. - First step is to convert the eastward wind and northward wind into wind angle and wind speed. - The wind speed is found by pythagoras: square root of eastward wind squared and northward wind squared - The wind angle is found by using trigonometric considerations - Second step is to change the wind angle definition to go the opposite direction, changing the angle with 180 degrees. E.g. from "northward" to "from south". - This is done to easier combine the wind speed with the heading of the ship - It is done by substracting 180 degrees from the existing angle. If the wind angle turns out negative, 360 degrees are added to make it a positive value because the ship headings are given from 0 to 360 degrees - Third step is to find the true wind angle relative to the ship heading. - True wind angle is found by substracting the ship heading from the wind angle. - If the true wind angle is more than 180 or less than -180, they are substracted or added by 360 degrees respectively. This is to make sure that the definition of the angles are from -180 degrees to 180 degrees.

[4]:
```
# Finding the wind speed as one variable
tws_raw = np.zeros(len(east_w))
wa = np.zeros(len(east_w))
for i in range (0,len(tws_raw)):
    tws_raw[i] = np.sqrt(east_w[i]**2 + north_w[i]**2)

# Finding the wind angle as one variable(where the wind is going to)
for i in range (0,len(wa)):
    if north_w[i]<0 and east_w[i]<0:
        wa[i] = np.arctan(east_w[i]/north_w[i]) * (180/np.pi) + 180
    if north_w[i]<0 and east_w[i]>0:
        wa[i] = np.arctan(-north_w[i]/east_w[i]) * (180/np.pi) + 90
    if north_w[i]>0 and east_w[i]>0:
        wa[i] = np.arctan(east_w[i]/north_w[i]) * (180/np.pi)
    if north_w[i]>0 and east_w[i]<0:
        wa[i] = np.arctan(north_w[i]/(-east_w[i])) * (180/np.pi) + 270

# Changing definition of wind direction. E.g. from "northward" to "from␣
↪south"
for i in range (0,len(wa)):
    wa[i] -= 180
    if wa[i] < 0:
        wa[i] += 360

# Deepcopy done to plot the wind later. It has nothing to do with the␣
↪calculations of the power savings
windspeed=copy.deepcopy(tws_raw)


# Finding true wind angle relative to ship heading
twa_raw = np.zeros(len(wa))
for i in range (len(twa_raw)):
    twa_raw[i] = wa[i]-course_s[i]
    if course_s[i] <= 180 and twa_raw[i] > 180:
        twa_raw[i] -= 360
    elif course_s[i] >= 180 and twa_raw[i] < -180:
```

```
        twa_raw[i] += 360
    twa_raw[i] = abs(twa_raw[i])

# Deepcopy done to plot the wind later. It has nothing to do with the␣
 ↪calculations of the power savings
winddir = copy.deepcopy(twa_raw)
```

Estimating the draught for each scenario

The data for draught only excists as average mean draught per day. These data needs to be combined with the day for each scenario to estimate the draught for each scenario.

[5]:
```
draught_raw = np.zeros(len(t_pos_report))
for i in range (0,len(t_daily_report)):
    for j in range (0,len(t_pos_report)):
        if t_pos_report[j] == t_daily_report[i]:
            draught_raw[j] = draught[i]
        if draught_raw[j] < 7:
            draught_raw[j] = 11
```

Rounding variables to fit the discretised data

As the raw data are measurements, there will be many values that are not equal to the discretised data. The raw data are therefore rounded to the value closest to the discretised value for each category.

[6]:
```
# Rounding raw data for draughts to match the discretized data
for i in range (0,len(draught_raw)):
    if draught_raw[i] <= d_disc[0]+(d_disc[1]-d_disc[0])/2:
        draught_raw[i] = d_disc[0]
    elif draught_raw[i] >= d_disc[1]+(d_disc[2]-d_disc[1])/2:
        draught_raw[i] = d_disc[2]
    else:
        draught_raw[i] = d_disc[1]

# Rounding raw data for ship speeds to match the discretized data
v_s_raw = np.rint(v_s_raw)


for i in range (0,len(v_s_raw)):
    if v_s_raw[i] < v_s_disc[0]:
        v_s_raw[i] = v_s_disc[0]

# Rounding true wind angle to match the discretized data
def deg_discr(deg_input, d_min, d_max, d_step):
    d_discr = np.arange(d_min + d_step/2, d_max + d_step*3/2, d_step)
```

```
    for i in range (len(deg_input)):
        for j in range (len(d_discr)):
            if d_discr[j] <= deg_input[i] <= d_discr[j+1]:
                deg_input[i] = d_discr[j+1] - d_step/2
        if d_discr[-1] <= deg_input[i] or deg_input[i] <= d_discr[0]:
            deg_input[i] = d_min

deg_discr(twa_raw, 0, 185, 5)

# Rounding the true wind speed to match the discretized data
def speed_discr(v_input, v_min, v_max, v_step):
    v_discr = np.arange(v_min-v_step/2, v_max+v_step*v_step/2, v_step)
    for i in range (len(v_input)):
        for j in range (0,len(v_discr)):
            if v_discr[j] <= v_input[i]<= v_discr[j+1]:
                v_input[i] = v_discr[j+1]-v_step/2
        if v_input[i] <= v_min:
            v_input[i] = v_discr[1]-v_step/2
        if v_input[i] >= v_max:
            v_input[i] = v_discr[-1]-v_step/2

speed_discr(tws_raw, 2.5, 27.5, 2.5)
```

Finding probability of having each unique combination of bins

The rounded raw data are furst put into a matrix. Then the unique combinations are put into a matrix and the raw data compared to find how often these unique combinations occures. Then the probability of each of the unique combinations are found.

[7]:
```
# Putting rounded raw data for ship speed, true wind speed, relative true␣
↪wind angle, and draught in matrix
raw_matrix = np.zeros(shape=(len(v_s_raw), 4))
for i in range (len(v_s_raw)):
    raw = np.array([v_s_raw[i],tws_raw[i],twa_raw[i], draught_raw[i]])
    raw_matrix[i] = raw

# Finding the unique rows of the raw data and counting how many cases of␣
↪each unique row
unique_rows = np.unique(raw_matrix, axis=0)

count = np.zeros(len(unique_rows))
for i in range (len(unique_rows)):
    for j in range (len(raw_matrix)):
        if unique_rows[i,0] == raw_matrix[j,0] and unique_rows[i,1] ==␣
↪raw_matrix[j,1] and unique_rows[i,2] == raw_matrix[j,2] and␣
↪unique_rows[i,3] == raw_matrix[j,3]:
            count[i] += 1
```

```python
# Finding probability of having each unique combination of ship speed,␣
↪wind speed, and true relative wind angle from the raw data
prob = np.zeros(len(unique_rows))
for i in range (len(prob)):
    prob[i] = count[i]/np.sum(count)
```

Probabilities with the discretised bins

The probabilities from the raw data for the unique rows are put together with the discretised bins. The reason for this is that the discretised bins from the Matlab code is put in a specific order, and the probabilities for the bins needs to match the bins from the Matlab code.

[8]:
```python
# Putting the unique rows from raw data with the probability
v_s_df = np.zeros(len(prob))
tws_df = np.zeros(len(prob))
twa_df = np.zeros(len(prob))
draught_df = np.zeros(len(prob))

for i in range (len(prob)):
    v_s_df[i] = unique_rows[i,0]
    tws_df[i] = unique_rows[i,1]
    twa_df[i] = unique_rows[i,2]
    draught_df[i] = unique_rows[i,3]

unique_bins = np.zeros(shape=(len(prob), 4))
for i in range (len(prob)):
    r = np.array([v_s_df[i],tws_df[i],twa_df[i],draught_df[i]])
    unique_bins[i] = r

# Putting the probabilities of the rows from the raw data to the general␣
↪discretized bins
bins_prob = np.zeros(len(bins_matrix))
for i in range (len(bins_matrix)):
    for j in range (len(unique_bins)):
        if bins_matrix[i,0] == unique_bins[j,0] and bins_matrix[i,1] ==␣
↪unique_bins[j,1] and bins_matrix[i,2] == unique_bins[j,2] and␣
↪bins_matrix[i,3] == unique_bins[j,3]:
            bins_prob[i] = prob[j]
```

Total power savings

The total power savings are found by importing the results for required power for ship with rotor sails and power savings from the Matlab code. The total required power for the ship with rotor sails are found by summing the required power with their respective probabilities. The required power for the ship without rotor sails are found by summing the power saved and required power for ship with rotor sails, and again multiplied with the probability for the respective bins. The total power savings are then found by substracting the required power with rotor sails from the required power without rotor sails, and then divided by the required power without rotor sails.

[9]:
```
# Importing results for power savings from Matlab

xls = pd.ExcelFile('Students_results_07_06_23.xlsx')

df4 = pd.read_excel(xls, 'draft 7.15 with 3m waves')
df5 = pd.read_excel(xls, 'draft 11 with 3m waves')
df6 = pd.read_excel(xls, 'draft 13.2 with 3m waves')
'''
# Code below is used to calculate for no waves. If the average is to be␣
↪calculated, the df has to be changed to df7, df8, and df9
df4 = pd.read_excel(xls, 'draft7.15m no waves')
df5 = pd.read_excel(xls, 'draft 11m no waves')
df6 = pd.read_excel(xls, 'draft 13.2m no waves')
'''
# Creating arrays of the relevant values
req_p_fr_7 = df4['Required power WASP [W]'].to_numpy()
req_p_ship_7 = df4['Required power ship [W]'].to_numpy()
p_s_7 = df4['Saved power ship[W]'].to_numpy()

req_p_fr_11 = df5['Required power WASP [W]'].to_numpy()
req_p_ship_11 = df5['Required power ship [W]'].to_numpy()
p_s_11 = df5['Saved power ship[W]'].to_numpy()

req_p_fr_13 = df6['Required power WASP [W]'].to_numpy()
req_p_ship_13 = df6['Required power ship [W]'].to_numpy()
p_s_13 = df6['Saved power ship[W]'].to_numpy()
'''
# Code below is used to calculate the average between power savings for no␣
↪waves and 3m head waves
req_p_fr_71 = df7['Required power WASP [W]'].to_numpy()
req_p_ship_71 = df7['Required power ship [W]'].to_numpy()
p_s_71 = df7['Saved power ship[W]'].to_numpy()

req_p_fr_111 = df8['Required power WASP [W]'].to_numpy()
req_p_ship_111 = df8['Required power ship [W]'].to_numpy()
p_s_111 = df8['Saved power ship[W]'].to_numpy()

req_p_fr_131 = df9['Required power WASP [W]'].to_numpy()
req_p_ship_131 = df9['Required power ship [W]'].to_numpy()
p_s_131 = df9['Saved power ship[W]'].to_numpy()


# Code below is used to calculate the average between power savings for no␣
↪waves and 3m head waves
```

```
req_p_fr_7 = (req_p_fr_7 + req_p_fr_71)/2
req_p_ship_7 = (req_p_ship_7 + req_p_ship_71) /2
p_s_7 = (p_s_7 + p_s_71)/2

req_p_fr_11 = (req_p_fr_11+req_p_fr_111)/2
req_p_ship_11 = (req_p_ship_11+req_p_ship_111)/2
p_s_11 = (p_s_11+p_s_111)/2

req_p_fr_13 = (req_p_fr_13+req_p_fr_131)/2
req_p_ship_13 = (req_p_ship_13+req_p_ship_131)/2
p_s_13 = (p_s_13+p_s_131)/2
'''
req_p_ship_fr = 0
req_p_ship_no_fr = 0

for i in range (0,len(p_s_7)):
    req_p_ship_fr += req_p_ship_7[i] * bins_prob[i] + req_p_ship_11[i] *␣
 ↪bins_prob[i+len(p_s_7)] + req_p_ship_13[i] *␣
 ↪bins_prob[i+len(p_s_7)+len(p_s_11)]
    req_p_ship_no_fr += (req_p_ship_7[i]+p_s_7[i]) * bins_prob[i] +␣
 ↪(req_p_ship_11[i]+p_s_11[i]) * bins_prob[i+len(p_s_7)] +␣
 ↪(req_p_ship_13[i]+p_s_13[i]) * bins_prob[i+len(p_s_7)+len(p_s_11)]
print('Total power savings for 3m head waves:
 ↪',(req_p_ship_no_fr-req_p_ship_fr)/req_p_ship_no_fr)
```

```
Total power savings for 3m head waves: 0.0761783718842071
```

Required power sails and power savings main engine

The required power for the sails are found by summing the required power for WASP and multiplied with the probability of the bin. It is again multiplied with 0.8 which is the assumed loss in the Matlab code between the engine and the rotor sail. For this case we have a different efficiency, and the code will give the average power consumption for the rotor sails, and not what the auxiliary engine gives to the rotor sails.

The saved power for the main engine is found by substracting the required power with rotor sails from the sum of average power consumption for rotor sails and required power for the ship without rotor sails, and then divided by the required power for the ship without rotor sails.

[10]:
```
# Finding the required power for the rotor sails
req_p_fr_avg = 0
for i in range (0,len(p_s_7)):
    req_p_fr_avg += req_p_fr_7[i] * bins_prob[i] + req_p_fr_11[i] *␣
 ↪bins_prob[i+len(p_s_7)] + req_p_fr_13[i] *␣
 ↪bins_prob[i+len(p_s_7)+len(p_s_11)]
print('Average power consumption rotor sails:',req_p_fr_avg)
```

```
# Power savings main engine
p_s_main = (req_p_fr_avg + req_p_ship_no_fr - req_p_ship_fr)/
↪req_p_ship_no_fr
print('Power saved main engine:',p_s_main)
```

```
Average power consumption rotor sails: 55137.13599024678
Power saved main engine: 0.08728088933685746
```

I.0.1 Method B - power savings as a function of ship speed

Probabilities

In order to find the power savings for the different speeds, the probability of having the different combinations of true wind speed and true wind angle is found, and the probability of having the different draughts.

[11]:
```
# Putting true wind speed and relative true wind angle in matrix
disc_matrix = np.zeros(shape=(len(tws_raw), 2))
for i in range (len(tws_raw)):
    d = np.array([tws_raw[i],twa_raw[i]])
    disc_matrix[i] = d

uniqueRows = np.unique(disc_matrix, axis=0)

# Finding probability of having each unique combination of wind speed and␣
↪true relative wind angle
count = np.zeros(len(uniqueRows))
for i in range (0,len(uniqueRows)):
    for j in range (0,len(disc_matrix)):
        if uniqueRows[i,0] == disc_matrix[j,0] and uniqueRows[i,1] ==␣
↪disc_matrix[j,1]:
            count[i] += 1

prob = np.zeros(len(uniqueRows))
for i in range (len(prob)):
    prob[i] = count[i]/np.sum(count)

# Probability draught
n=[0,0,0]
p=[0,0,0]
for i in range (0,len(draught_raw)):
    if draught_raw[i] == d_disc[0]:
        n[0] +=1
    elif draught_raw[i] == d_disc[1]:
        n[1] +=1
    elif draught_raw[i] == d_disc[2]:
```

```
        n[2] +=1
p[0] = n[0]/len(draught_raw)
p[1] = n[1]/len(draught_raw)
p[2] = n[2]/len(draught_raw)
```

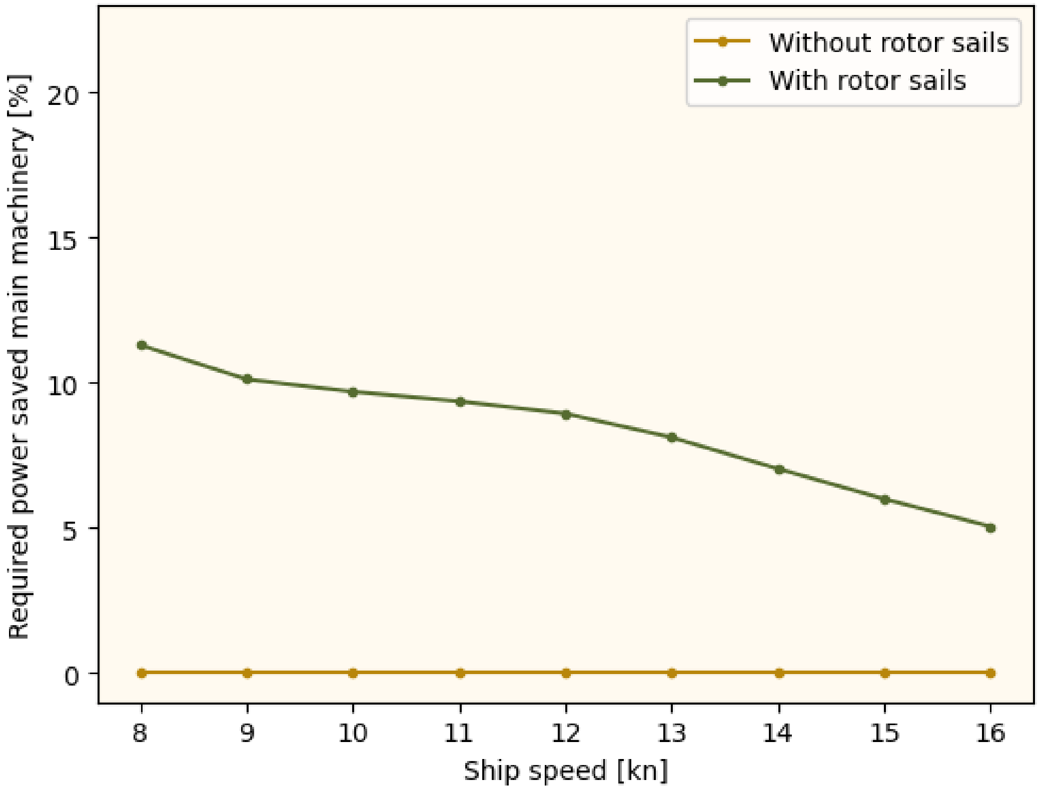
Power saved for the different speeds

First probabilities for the wind speed is added to the respective discretised bins. Then the required power with rotor sails and without rotor sails for the different speeds are found. They are found by multiplying the probability of the wind speed of the bin with the required power for all the bins for one speed. This is done for every speed. The power saved for each speed is found by substracting the required power with rotor sails from the required power with rotor sails and then divided by the required power withour rotor sails.

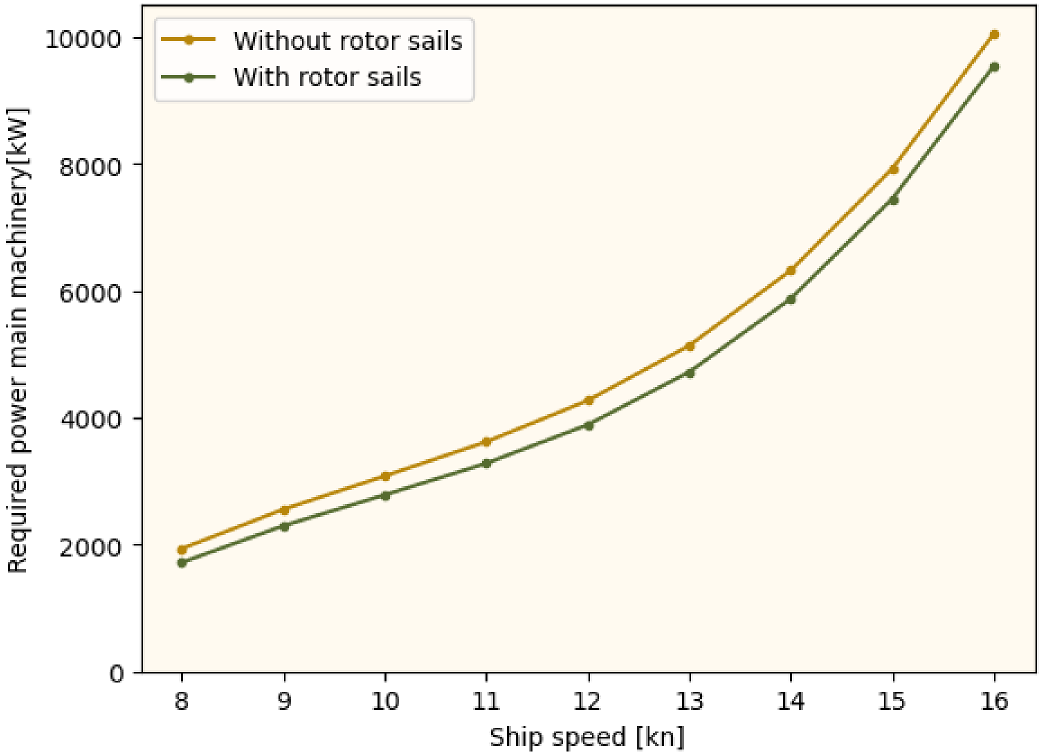
[12]:
```
# Putting the unique bins with the probability
tws_df = np.zeros(len(prob))
twa_df = np.zeros(len(prob))

for i in range (len(prob)):
    tws_df[i] = uniqueRows[i,0]
    twa_df[i] = uniqueRows[i,1]

unique_bins = np.zeros(shape=(len(prob), 2))
for i in range (len(prob)):
    r = np.array([tws_df[i],twa_df[i]])
    unique_bins[i] = r

# Putting the probabilities to the general discretized bins
bins_prob = np.zeros(len(bins_matrix))
for i in range (len(bins_matrix)):
    for j in range (len(unique_bins)):
        if bins_matrix[i,1] == unique_bins[j,0] and bins_matrix[i,2] ==␣
↪unique_bins[j,1]:
            bins_prob[i] = prob[j]

# Finding required power with rotor sails
P_req = np.zeros(len(v_s_disc))
for k in range (0,len(v_s_disc)):
    for i in range (0,len(tws_disc)):
        for j in range (0,len(twa_disc)):
            P_req[k] +=␣
↪bins_prob[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] *␣
↪req_p_ship_7[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] * p[0] +␣
↪bins_prob[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] *␣
↪req_p_ship_11[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] * p[1] +␣
↪bins_prob[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] *␣
↪req_p_ship_13[i*len(v_s_disc)*len(twa_disc)+j+len(twa_disc)*k] * p[2]
```

```
# Finding required power withour rotor sails
P_req_wo = np.zeros(len(v_s_disc))

for i in range (0,len(v_s_disc)):
    P_req_wo[i] = (req_p_ship_7[i*len(twa_disc)] + p_s_7[i*len(twa_disc)])␣
 ↪* p[0] + (req_p_ship_11[i*len(twa_disc)] + p_s_11[i*len(twa_disc)]) *␣
 ↪p[1] + (req_p_ship_13[i*len(twa_disc)] + p_s_13[i*len(twa_disc)]) * p[2]

P_s_v_B = (P_req_wo-P_req)/P_req_wo
```

[13]:
```
# Plots
ax = plt.axes()
ax.set_facecolor("floralwhite")
plt.plot(v_s_disc, [0,0,0,0,0,0,0,0,0], color = 'darkgoldenrod', label =␣
 ↪"Without rotor sails", marker = '.')
plt.plot(v_s_disc, P_s_v_B*100, color = 'darkolivegreen', label = "With␣
 ↪rotor sails", marker = '.')
plt.legend()
plt.ylim(-1,23)
plt.xlabel('Ship speed [kn]', fontsize=10)
plt.ylabel('Required power saved main machinery [%]', fontsize=10)
plt.savefig('Required power compared percentage no total.png')
#plt.title('Required power with rotor sails compared to without rotor␣
 ↪sails')
plt.show()
```



[14]:
```
ax = plt.axes()
ax.set_facecolor("floralwhite")
plt.plot(v_s_disc, P_req_wo/1000, color = 'darkgoldenrod', label =␣
 ↪"Without rotor sails", marker = '.')
plt.plot(v_s_disc, P_req/1000, color = 'darkolivegreen', label = "With␣
 ↪rotor sails", marker = '.')
plt.legend()
plt.ylim(0,10500)
plt.xlabel('Ship speed [kn]', fontsize=10)
plt.ylabel('Required power main machinery[kW]', fontsize=10)
plt.savefig('Required power compared total.png')
#plt.title('Required power for different ship speeds')
plt.show()
```

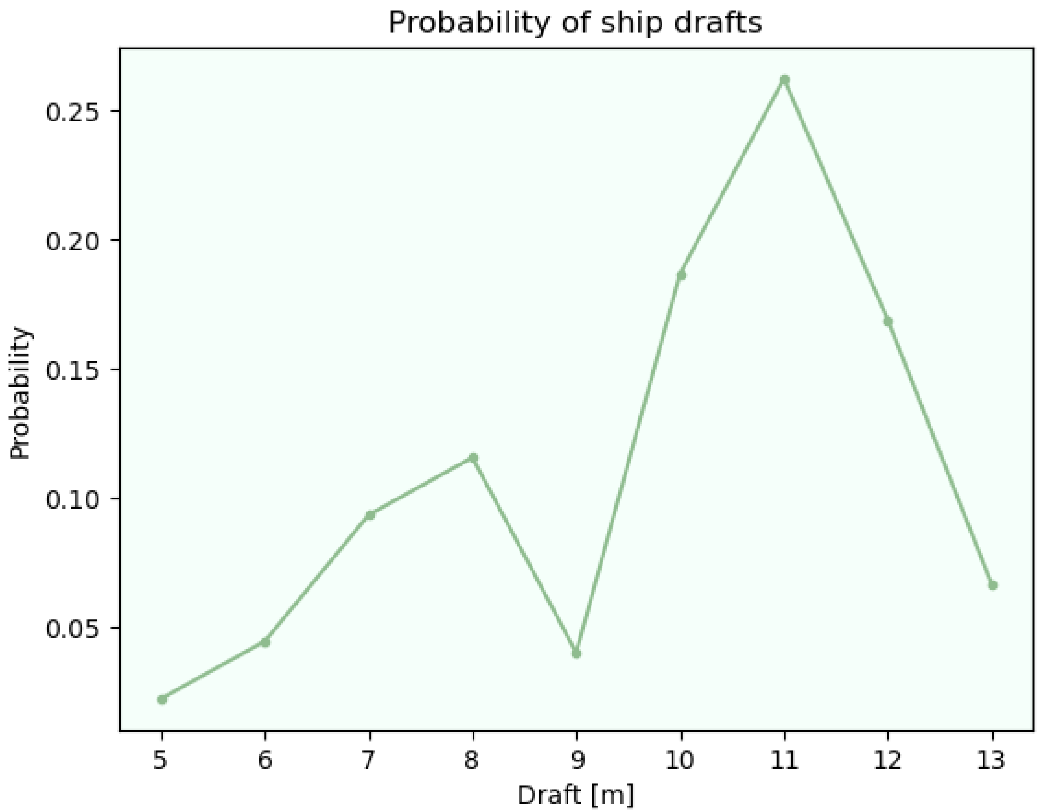


I.1 Plots

Below follows some plots to better understand the raw data that are used

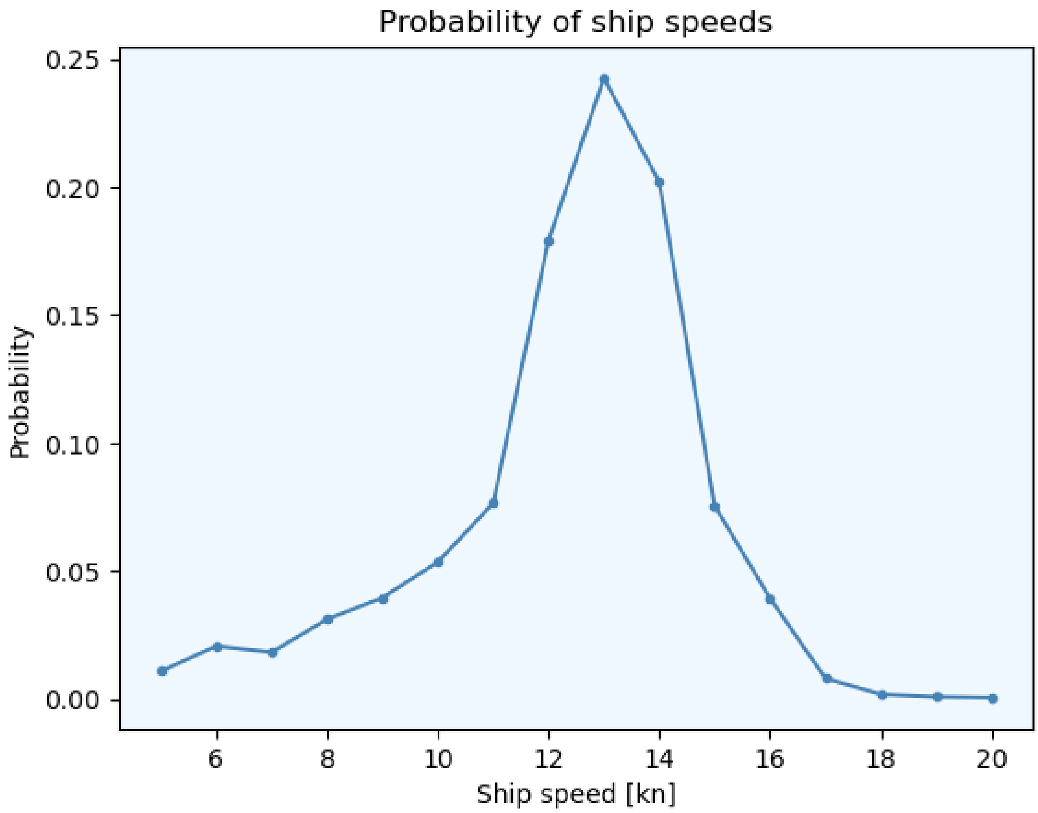
[15]:
```
# Probability of draught
dd = np.rint(draught)
d_d = []
for i in range (len(dd)):
    if dd[i] > 4:
        d_d.append(dd[i])

ddd = np.unique(d_d, return_counts=True)
d_speeds = ddd[0]

d_freque = ddd[1]
d_tott = np.sum(d_freque)
prob_dd = np.empty([len(d_speeds),1], dtype=float)
for i in range (len(prob_dd)):
    prob_dd [i] = d_freque[i]/d_tott

import matplotlib.ticker as mtick
```

```
ax = plt.axes()
ax.set_facecolor("mintcream") #linen #lavenderblush
plt.plot(d_speeds, prob_dd, linestyle = '-', marker = '.', color =␣
 ↪'darkseagreen')
plt.xlabel('Draft [m]', fontsize=10)
plt.ylabel('Probability', fontsize=10)
plt.title('Probability of ship drafts')
plt.savefig('d_plot.png')
plt.show()
```



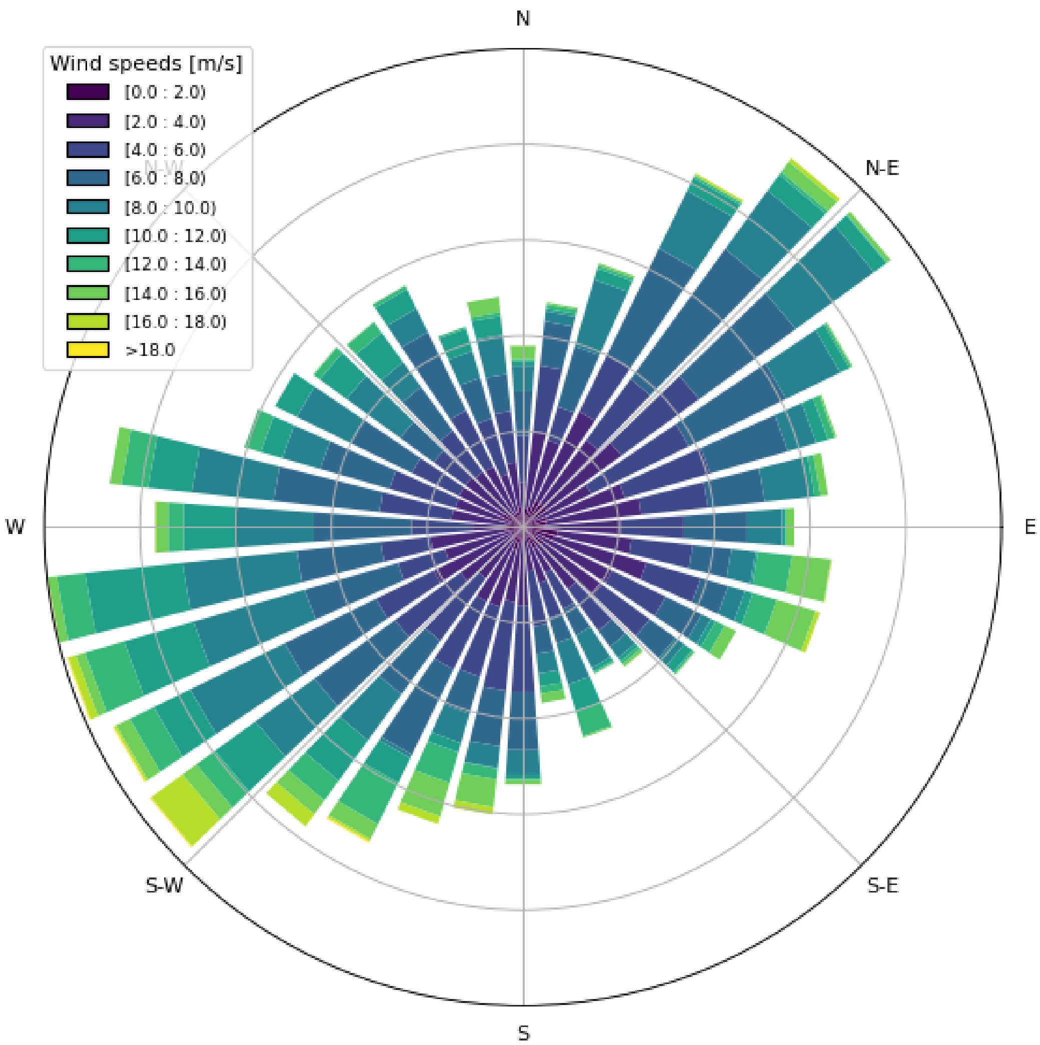
[16]:
```
# Probability of ship speeds
dd = np.rint(vsraw)
d_d = []
for i in range (len(dd)):
    if dd[i] > 4:
        d_d.append(dd[i])

ddd = np.unique(d_d, return_counts=True)
d_speeds = ddd[0]
```

```
d_freque = ddd[1]
d_tott = np.sum(d_freque)
prob_dd = np.empty([len(d_speeds),1], dtype=float)
for i in range (len(prob_dd)):
    prob_dd [i] = d_freque[i]/d_tott

import matplotlib.ticker as mtick


ax = plt.axes()
ax.set_facecolor("aliceblue") #linen #lavenderblush
plt.plot(d_speeds, prob_dd, linestyle = '-', marker = '.', color =␣
 ↪'steelblue')
plt.xlabel('Ship speed [kn]', fontsize=10)
plt.ylabel('Probability', fontsize=10)
plt.title('Probability of ship speeds')
plt.savefig('v_plot.png')
plt.show()
```



[17]:
```python
# Windrose plot
import matplotlib.cm as cm
from math import pi
from windrose import WindroseAxes
```

[18]:
```python
ax = WindroseAxes.from_ax()
ax.bar(wa, windspeed, normed=True, opening=0.8, bins=np.arange(0, 20, 2),␣
 ↪nsector=36)
ax.set_xticklabels(['E', 'N-E', 'N', 'N-W',  'W', 'S-W', 'S', 'S-E'])
ax.set_yticklabels([])
ax.set_legend(title="Wind speeds [m/s]", loc="upper left")
plt.savefig('Windrose1')
```



NTNU

Norwegian University of
Science and Technology