Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Finn Lorange

Performance analysis of Flettner rotor installations

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2022

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Det skapende universitet

Master Thesis in Marine Systems Design

Stud. techn. Finn Lorange

“Performance analysis of flettner rotor installations”

Spring 2022

Background

In the last few years there has been a shift in global focus towards the reduction of GHG emissions in all sectors. This, in combination with tightening IMO regulations, has led to an increasing interest in emission reducing technologies in the shipping industry. There exist several different concepts that all have their own advantages and disadvantages. One of the most prominent concepts in the last years has been the flettner rotor. However, these rotors are expensive to produce and install, while delivering varying fuel savings for different cases. Therefore, it is of interest to create a method that can be used commercially to determine whether the retrofitting and installation of these rotors are economically viable for a shipowner.

Overall aim and focus

The objective of the master thesis is to create a method that can be used to predict flettner rotor performance for a given vessel, given vessel and operational parameters. The method should be tested through a case study and assessed based on the experiences from this study.

Scope and main activities

The thesis should presumably cover the following main points:

1. *A short overview of the current status and important development trends related to WASP.*
2. *A relevant literature study on current and previous performance analysis methods.*
3. *Development of a method for flettner rotor performance analysis on specific vessel.*
4. *Case study utilizing the method previously described.*
5. *Discuss and Conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work

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Stein Ove Erikstad
Professor/Responsible Advisor

Abstract

After the International Maritime Organisation announced its goal to reduce greenhouse gas emissions by 50% from 2008 to 2050, an increasing focus has been drawn to implementing emission reduction measures in the shipping industry. One of the most commonly referenced measures to reduce emissions is wind-assisted ship propulsion, particularly the Flettner rotor concept. Most published research into this topic focuses on estimating the potential savings of Flettner rotors for generic ships and routes. However, this thesis aims to describe a method that any shipowner can use to determine whether Flettner rotor installation is economically viable for their specific case.

The proposed method consists of four main phases that are again divided into several steps. The first of these phases consists mostly of data gathering for the chosen vessel and potential setup. The second phase includes a rotor performance analysis and AIS and weather data gathering and processing. In phase three, the performance simulation and the weather data is combined in order to show the performance for the selected vessel and operational profile. Finally, an economic analysis is performed in order to estimate the economic payback time of the rotors given performance results from previous sections.

The method is tested in a case with a real vessel. The case investigates the bulk carrier Ma Lian Hai and attempts to estimate the savings for this vessel in the year 2020. In the second phase of the method, several external programs are used to perform the rotor savings estimation. While processing the results from this phase, several bugs were discovered in the code, leading to inaccurate simulation results. These bugs lead to the discovery of some of the method disadvantages, as well as some of the improvements that could be made in order to improve it.

The results of this thesis show that a method for performance analysis of Flettner rotor installations can be made and that it can work to assist a shipowner in decision making. It also shows that there are tools available, such as AIS and weather data, that can be used to improve the accuracy of Flettner rotor performance analysis. However, the thesis also shows that accurate performance simulation models are difficult to create and can be a bottleneck in the proposed method.

Sammendrag

I 2018 annonserte den internasjonale sjøfartsorganisasjonen sitt mål om å redusere utslippene av drivhusgasser med 50% fra 2008 til 2050. Siden dette har det vært et økende fokus på å implementere utslippsreduserende tiltak innen skipsfart. Et av disse mulige tiltakene er vindassistsert skipspropulsjon, og innenfor dette er flettner rotorer blitt det mest omtalte konseptet. Mesteparten av de publiserte studieneIdag fokuserer på å estimere potensialet for drivstoffbesparelser for generiske skip og operasjoner. Målet I denne oppgaven er å beskrive en metode som kan brukes for å avgjøre hvorvidt det er økonomisk lønnsomt å installere flettner rotorer for et gitt skip.

Den foreslåtte metoden kan hovedsaklig deles innIfire faser som igjen inneholder flere prosesser. Den første av disse fasene består av å samle data om fartøyet og om det foreslåtte opsettet av rotorer.Iden andre fasen gjøres en analyse av potensielle rotorbesparelser, samt innsamling og prosessering av AIS og værdata. Tredje fase fokuserer på å sette sammen AIS og værdatadata, med resultatene fra besparelsesanalysen, for å vise de potensielle besparelsene for fartøyets operasjoner. Til sist bør det gjøres en økonomisk analyse for å estimere den økonomiske tilbakebetalingstiden på rotorene, gitt resultatene fra de tidligere fasene.

Metoden testes i en case med et ekte fartøy. Casen undersøker bulkskipet Ma Lian Hai, og prøver å estimere besparelsene for fartøyet over året 2020.Iden andre fasen av metoden ble det brukt flere eksternt byggede programmer til blandt annet besparelsesanalysen. Da resultatene fra denne analysen skulle prosesseres ble det oppdaget en rekke feil I koden som kan lede til unøkyaktige eller urealistiske resultater. Disse feilene bidro til å oppdage noen av ulempene med den foreslåtte metoden, samt å fortå og foreslå noen av forbedringene som kan gjøres.

Resultatene fra denne oppgaven viser at en metode for å avgjøre hvorvidt flettner rotor installasjoner lønner seg er mulig å implementere, og at den kan brukes til å støtte i en skipseiers avgjørelser. Den viser også at det finnes tilgjengelige verktøy, slik som AIS og værdata, som kan brukes til å forbedre nøyaktigheten til analyser av flettner rotor besparelser. Men, oppgaven viser også at nøyaktige og pålitelige simuleringsmodeller for flettner rotor besparelser er vanskelige å lage, og kan være en flaskehals for den foreslåtte metoden.

Preface

This thesis is the culmination of 5 years working towards my Master of Science in Marine Technology at NTNU. My specialisation has been Marine Systems Design. The bulk of the work was carried out during the spring semester of 2022 at the Norwegian University of Science and Technology in Trondheim.

I would like to thank my supervisor Stein Ove Erikstad for his assistance and inspiration over the course of the semester. You were a great influence to start me down the path of this subject. Furthermore you have not only helped me complete a meaningful and interesting project, but also pushed me to become a more self-sufficent and independent engineer.

I would also like to give special thanks to postdoc Drazen Polic, who not only built the program that this thesis heavily relies on, but also spent countless ours helping me work through my issues and answering my questions, even during paternity leave and holidays. Similarly I would also give special thanks to PhD candidate Benjamin Lagemann, who has helped me greatly with large and small coding issues, as well as answer all my questions while being supportive and positive. it is safe to say that while I did not know it at the time when I started, this project would not be possible without the two of you.
A special thanks should also be given to a fellow student and friend, William Hyggen Viken, who has written his thesis in the same field as me and has helped me with several coding issues I encountered. Our discussions and talks throughout these past semesters have helped me when I am stuck and inspired me to improve my thesis.

Furthermore I want to thank my family for inspiring me and supporting me through these last 5 years as well as helping me proofread this thesis. You helped me through the moments when I thought I would not be able to complete, and always push me to do better.

Finally I would like to thank my friends here in Trondheim and in particular the guys at office C1.058, Martin G, Elias, Brage, Mathias and Martin S. You helped make every day a fun one, motivated me to go further, and made these last five years of my life unforgettable. Without you I would have never been able to complete this thesis, much less the last five years of studies. I am looking forward to keep the fun going in the years to come!

Trondheim, June 9. 2022

Finn. L

Finn Lorange

Nomenclature

Abbreviations

C_d	Drag coefficient, page 18
C_l	Lift coefficient, page 18
AIS	Automatic Identification System, tracking system for marine vessels, page 24
AWA	Apparent wind angle, page 31
AWS	Apparent wind speed, page 31
CFD	Computational fluid dynamics, page 33
CO2	Carbon dioxide, common greenhouse gas , page 21
COP26	2021 United Nations Climate Change Conference, page 3
GHG	Greenhouse gasses, page 3
IFO	Marine Diesel Oil, page 8
IMO	International Maritime Organisation, page 3
IMT	Department of Marine Technology at NTNU, page 29
JAMDA-sails	A type of rigid wing sails, page 10
MGO	Marine Gas oil, page 8
NAN	Not a number, page 34
NOx	Common name for the nitrogen oxides: N2O, NO, N2O3, NO2 and NO3 , page 21
RPM	Rotations per minute, page 30
TWA	True wind angle, page 31
TWS	True wind speed, page 31
UN	United Nations, page 7
VLSFO	Very Low Sulfur Fuel Oil, page 8
WASP	Wind Assisted Ship Propulsion, page 3

Coefficients

C_b	Block coefficient, describes the "fullness" of a vessel below the waterline, page 30
n_p	propeller efficency, page 33
$n_{c.WASP}$	sum of electrical loss between rotor and generator, page 33

Variables

β	Vessel drift angle, page 32
Δ	Displacement, page 39
ρ	Density, page 18
A	Surface area, page 18
F	Force, page 18
$P_{no.WASP}$	Required power without WASP, page 33
$P_{req.WASP}$	Required power with wasp, page 33
P_{saved}	Saved power, page 33
$R_{add.wind}$	Added wind induced hydrodynamic drag, page 33
T_{prop}	Required thrust from propeller, page 33
V	Speed, page 18
B	Beam of vessel, page 30
D	Draft of vessel, page 30
dwt	Deadweight tonnage, the total weight a ship can carry, page 22
GT	Gross Tonnage, nonlinear measure of a ship's overall internal volume, page 30
LWL	Length in the waterline of vessel, page 30

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Part I

Project introduction

Chapter 1

Introduction

1.1 Background and motivation

Last autumn, in October, COP26 was arranged in Glasgow. The climate change conference draws a considerable focus towards the implementation and development of new "green" technologies around the world. With the 2°C and 1.5°C targets of maximum increased temperature, rapid and sustained emission reductions across all industrial sectors are required. Meanwhile, there is a rapidly increasing global demand of shipping transport of approximately 4% per year since the 1990s (UNCTAD 2013). Currently, over 90% of the worlds trade is carried by sea. According to the IMO greenhouse gas study in 2020 (IMO 2021), maritime carbon dioxide emissions are expected to increase by around 90-130% between 2018 and 2050, which indicates a significant challenge to meet the carbon dioxide budgets for the shipping sector. In order to reach IMO's goal of a 50% greenhouse gas (GHG) emission reduction by 2050, significant changes within the industry are required. Shipping must work to optimize the use of each vessel and its components while also reducing emissions.

One of the many opportunities for GHG emission reductions in the shipping industry is wind-assisted ship propulsion (WASP). The main idea behind WASP is to introduce wind assistance into the propulsion systems of cargo carrier vessels in order to reduce fuel consumption. This can be done through a large variety of systems that can be either retrofitted or built into the vessel and that, when operated correctly, can lead to significant fuel savings. Most of these systems work in quite similar ways to convert the wind's kinetic energy into thrust for the ship.

While there are many studies on the potential benefits of WASP for the shipping industry and on specific cases where parametric studies have been performed to calculate performance, the implementation of WASP seems far away for most shipowners. There are multiple reasons for this, but one of the most critical is a lack of concrete evidence that the technology will lead to environmental advantages and economic benefits. Most shipowners today operate on a tight margin, and for them to consider installing WASP systems on their vessels, they will require specific performance estimates for their vessels. That is, in many ways, the goal of this thesis. Since WASP will perform very differently depending on vessel, route, and weather characteristics, it is difficult to predict performance as an outsider accurately. An attempt has been made to create a basic method that any shipowner can use to benchmark their ships and routes themselves. In this way, the performance estimates will be vessel-specific and more accurate since the shipowner has access to accurate parameters for the vessel and routes traveled.

1.1.1 Structure

While the main focus of this project is to describe a method for wind-assisted performance simulation for specific vessels, some of the general aspects of wind-assisted ship propulsion will also be covered. In order to test the method, a case study has also been performed for a real vessel, where the described method is used. In addition to this introduction, the report will therefore be structured in three parts that are further divided into chapters and sections. These parts are as follows:

Part 1 - Project introduction - This part works as a general introduction to the project, and consists of 5 smaller chapters.

- Introduction - Covers the background and motivation as well as the project structure and previous work
- Wind assisted ship propulsion - Covers the current state of technology for several wind assisted ship propulsion concepts.
- Rotor sail functionality - Gives some deeper understanding of rotor sails and how they work
- Previous studies - Covers some of the previous studies into the potential of WASP in the shipping industry
- A recipe for WASP performance modelling - Describes the proposed method for WASP performance modelling

Part 2 - Case study - This part covers the case study that was made in order to test the method, and it consists of 2 main chapters.

- Method - Describes the programs used, their functionality and some of the issues that are likely to pop up.
- Results - Describes the results of the case, with any issues encountered and conclusions drawn from the results.

Part 3 - Concluding remarks - The final part contains a discussion of the project as well as the conclusions and proposals for further work. There are two main chapters here.

- Discussion - Discusses the method, what worked, what didn't work and what can be done to improve it.
- Conclusion - Concludes the project and highlights the most important findings. Also contains some suggestions for further work.

1.1.2 Previous work

While this master thesis was written over a single semester at NTNU, it is important to recognize the work that went into the project earlier. Especially the project thesis written in the autumn of 2021 and the subject TMR11 Ocean systems simulation have been very important to the completion of this thesis and some parts of the work presented here are taken either directly or indirectly from these courses. This thesis is also heavily reliant on a set of programs made by other people. In particular, the use of a WASP performance estimation model currently in development by postdoc Drazen Polic and Ph.D. candidate Benjamin Lagemann. This program will be further detailed in their papers.

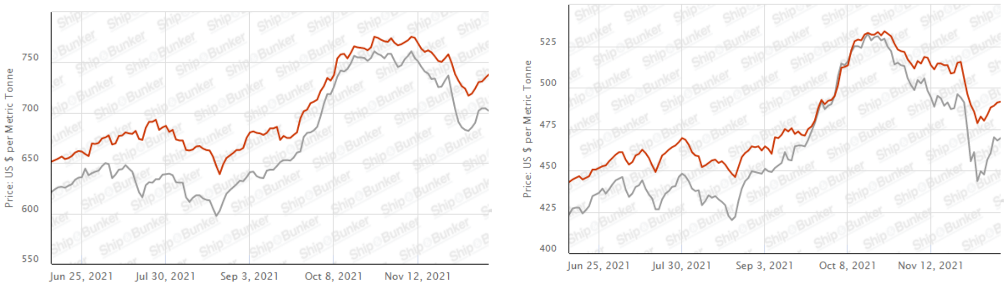
Chapter 2

Wind assisted ship propulsion

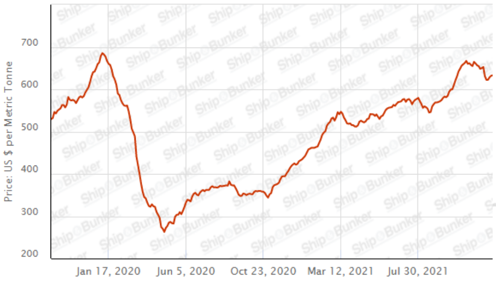
2.1 Why wind?

As far back as 3100BC, humans have relied on the wind for propulsion. Back then, the Egyptians utilized the north wind to travel south on the Nile. In the centuries since then, nearly all marine transportation has been at the mercy of the wind. Only in the late 19th century did this change with the introduction of steamships. Over the next couple of decades, the new steamships came to dominate ocean transportation completely. This was mainly a result of our ever-lasting desire for more efficient and quicker transportation. However, after more than a century of fossil fuel domination, things might be beginning to change again. As the world slowly realized the scope of global warming and the consequences of our carbon emissions, the UN finally managed to set a new course with the Paris Agreement in 2015. To align with this, the IMO launched its first-ever emission reduction strategy in 2018. This new strategy forced the industry to change, and wind power suddenly came back as an ”innovative” solution for reducing carbon emissions. The idea is that with the assistance of wind propulsion, ships could maintain the same speed as before while still using less fuel. This would be a step toward reducing emissions and allowing shipping companies to reduce their operating costs.

These reduced costs are among the other important factors that have led to the reemergence of wind-powered transportation. One of the largest cost factors for modern shipping is fuel costs. Over the last decade, fuel prices have been swinging wildly, leading to extreme uncertainty for the future of shipping. With the current status of fuel prices, it is extremely difficult for companies to plan for the future and to know what scenarios to prepare for. The graphs on the next page show the prices of three different types of ship fuel over the last year. (shipandbunker 2021)



MGO IFO



VLSFO

Figure 2.1: Global average fuel prices over the last 12 months

As seen from the graphs, the fuel prices are extremely volatile. This means that shipowners need to find a way to hedge against this volatility. Luckily WASP can potentially function to do exactly this.

While large strides have been made to make the technology commercially viable, there is still a way to go. This is mainly split into three parts. Firstly is still a limited amount of both research and empirical data regarding the technology and its efficiency. Many shipping companies are unwilling to invest a high up-front cost for the potential of long-term savings without solid evidence that the investment will pay off. This means that until the technology diffuses further into the industry and becomes more common, producers can't implement the economics of scale and reduce the upfront cost, trapping us in a negative cycle.

Secondly, another issue that ties closely into the previous one is related to the actual gains from the technology. While there are quite a few studies about the theoretical savings from different types of wind assistance, there is not nearly as much empirical proof of that efficiency. This can likely be at least partially blamed on an unwillingness to change operations in order to utilize the new technology effectively. Most empirical studies and experiments within wind-assisted propulsion see the vessels perform their same operations exactly as before. However, it is likely that the maximum gains from wind assistance can only be achieved with significant operational changes and restructuring of modern fleets and supply chains.

Finally, another factor that is also limiting the industry from implementing wind assistance is simply a lack of information. While there exists a vast amount of information about some of the alternatives, like Flettner rotors, other options have much more limited research done and much less commonly available information. This means that it is difficult for companies to realize what options they have and the advantages and disadvantages of these options. This project will therefore give an introduction to some of these technologies below, as well as discuss some of their advantages and disadvantages.

2.2 WASP systems

2.2.1 Rotor sails

Today's most commonly referenced concept for wind-assisted ship propulsion is rotor sails, also known as Flettner rotors. Flettner rotors were first developed by the German engineer Anton Flettner in the early 1900s. While the idea was initially quickly dismissed, it resurfaced again in the years after 2000 as the focus on fuel savings and emissions rose. (Menon 2021a) The sails look like large cylinders with a plate at the top and can rotate at high speeds in either direction.

The rotors utilize a phenomenon known as the Magnus effect to propel the ship forward. The Magnus effect describes a phenomenon where a sideways force is generated on a spinning cylindrical or spherical solid immersed in fluid as long as there is a relative motion between the spinning body and the fluid. The effect is named after the German physicist H.G.Magnus who discovered it while experimenting with the curvature of tennis balls and artillery shells. The effect is a peculiar manifestation of the Bernoulli theorem which states that fluid pressure decreases where speed increases. This manifests itself around spinning objects since the spinning object will drag some air around with it. The drag of the side of the object turning into the air (into the direction the ball is travelling) retards the airflow, whereas on the other side, the drag speeds up the airflow. Greater pressure on the side where the airflow is slowed down forces the ball in the direction of the low-pressure region on the opposite side, where a relative increase in airflow occurs. (Britannica 2021)

Figure 2.2: SC Connector

Source: Blog 2022

Modern adaptations

Today many different companies are producing and studying rotor sails. Modern rotor sails are adaptations of the original Flettner rotor idea and come in many different dimensions and designs. However, they all work in mostly the same way. One of the major companies producing these rotors is Norsepower. They produce rotors in various sizes and with several smart upgrades to make them easy to use and operate. The rotors can, for example, be tilted down to pass under bridges and are operated from the bridge with computers doing most of the work to optimize efficiency for different weather conditions. This, coupled with an estimated reduction in fuel consumption of around 5-20%, means that these rotors present an attractive idea to any shipowner looking to reduce emissions and save on costs. (Norsepower 2021)

Rotor sails have the potential to make a significant impact on modern ocean transportation; they are easy to retrofit, efficient, easy to use, and relatively well tested already. However, they face some significant issues as well. The initial installation cost is quite substantial, and there are still just a few companies that provide the rotors to the market. There is also the issue of space, as the rotors do take up some space that could normally be used for cargo. Even with these issues, rotor sails are looking like one of the most exciting concepts within shipping for the future. New improvements to the used technology, as well as streamlining of production and installation, could see these sails become cheaper and cheaper while also becoming more space-efficient and less of a hindrance for navigation and cargo handling.

2.2.2 Wing sails

Rigid wing sails

Similar to airplane wings, rigid wing sails have hard shells and often consist of multiple parts connected together. They often consist of two or three sails that are connected in parallel to adjust the camber. These wings have been used for a while in sailing, notably in the America's cup, but only recently have companies started looking at their use for cargo transport. The sails are highly effective aerodynamically, however there might be regulations for safety that lead to strict restrictions on their use in bad weather. Currently, YARA is one of the few companies that offer this for industry shipping. BARTech designs their sails, and the company claims the sails can reduce fuel consumption and emissions by up to 30%. While the company is obviously quite protective of their concept, they have made it clear that the efficiency is dependent on a large number of factors and that retrofits will likely not be nearly as efficient as new-builds designed explicitly for the sails.

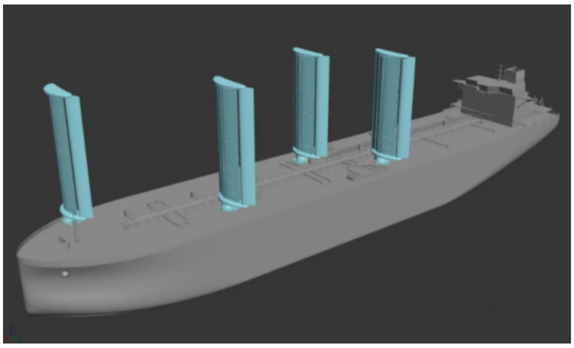


Figure 2.3: BARTech-wingsail

Source: BARTech 2021

Rigid sails have the potential to provide an auxiliary or supplementary source of propulsion on powered ships. This potential has been realized in the past with the use of JAMDA type sails in the 1980s and is therefore not entirely unproven. Ships fitted with these sails reportedly reduced their fuel consumption between 10% to over 30% under favorable conditions. It is thus easy to imagine that the fitting of rigid sails to ocean-going powered ships could significantly reduce fuel consumption and airborne emissions. In addition, they may provide other tangible and intangible benefits such as improving the health of those living near ports and shipping lanes, being a source of emergency propulsion, improving vessel stability, and enhancing the brand image and reputation of shipping companies that utilize them. However, a number of issues require further research. These issues may hinder the use of this promising technology until feasible and cost-effective solutions can be found. Some of the most critical issues are safety, economic aspects, and operational issues. There is still a long way to go within ship stability, accident prevention, and variable weather conditions. The sails also need to be an economically viable solution, meaning they need to be competitive with other emission-reducing technologies. Finally, there is also some experimenting left to do with the maintenance and reliability of the wings, which needs to be high for the wings to be a good solution for the shipowner. (Biancolini et al. 2021)(Atkinson et al. 2021)

Soft wing sails

Soft wing sails work similarly to rigid wing sails, except they are made out of modern textile sail materials, which are light and durable. This means that the sails can be reefed and furled. Recent development in sensor and software technology allows the sails to be operated fully automatically. However, little is still known about this concept since the concept is relatively new, and it is likely that it will take quite some time still before they become commercially available in the shipping industry.

2.2.3 Soft sails: DynaRig

The DynaRig, along with the original "DynaSchiff", is a trademarked name. The original concept by Prölß was for a combined rig and hull with extremely high efficiency of operation and the use of wind power to propel a large vessel across an open body of water. The modern controller for the entire ship's rig consists of a single panel operated by a single person. The masts are freestanding, the curved yards being attached rigidly to the masts. To adjust the angle of the sails, the entire mast rotates in place. When fully deployed, the sails on each mast have no gaps between them, creating a single panel to capture the wind. It is estimated to have twice the efficiency of a traditional square rig. The technology is currently mainly used on sailing yachts. Still, plans for future upgrades and expansion into the shipping industry exist and will likely be put into motion in the coming years. An example of this is the WASP ecoliner concept by Dykstra naval architects. (SouthernSpars 2021,NorthSailNews 2021,Dykstra 2021)

Figure 2.4: Wasp ecoliner by Dykstra naval architects

Source: Dykstra 2021

2.2.4 Ventilated foil systems

Another interesting wind assistance concept is ventilated foil systems. An example of this concept is the ventifoil by Econowind. The Ventifoil is a non-rotating suction wing with vents and an internal fan that uses boundary layer suction for maximum effect to generate thrust for the ship. The Ventifoil is a wing-shaped element using modern innovations in aerodynamics, creating high propelling force relative to its size. Smart suction is integrated in the wing, resulting in double the force of the Ventifoil while reefing when needed. The ventifoils come in a variety of sizes with systems allowing them to be used on all kinds of vessels. A particularly ingenious design sees two foils packed in a container, which they can be folded out of, meaning they can be placed anywhere on the vessel and not be in the way of other operations. The advantage of placing the Ventifoils solid on a vessel is mainly the opportunity to use bigger foils. Bigger foils can produce much greater forward force and thereby fuel savings. The Ventifoil can fold and rotate around its axis, meaning it can be moved around in order to always have access to other parts of the ship. (Econowind 2021)(Interreg 2021)

Figure 2.5: Vessel installed with Econowind Ventifoils

Source: Econowind 2021

2.2.5 Kites

The kite sail is another concept that has received a lot of interest recently. This rig relies on flying a gigantic kite from the bow of a ship using the traction developed by the kite to assist in pulling the ship forwards. Other concepts that have been explored were designed to have the kite rig alternately pull out and retract on a reel, driving a generator. The kite used in this setup is similar to the kites used by recreational kite-boarders on a much larger scale. This design also allows users to expand its scale by flying multiple kites in a stacked arrangement.

The idea of using kites was the most popular form of wind-assisted propulsion on commercial ships in 2012, largely due to the low cost of retrofitting the system to existing ships, with minimal interference with existing structures. This system also allows for a large amount of automation, using computer controls to determine the ideal kite angle and position. Using a kite allows the capture of wind at greater altitudes, where wind speed is higher and more consistent. This system has seen use on several ships, with the most notable in 2009 being MS Beluga Skysails, a merchant ship chartered by the US Military Sealift Command to evaluate the claims of efficiency and the feasibility of fitting this system to other ships. (cargo-partner 2021)

Figure 2.6: Concept for kites in cargo transportation systems

Source: cargo-partner 2021

2.3 Comparing systems

While all these different options have their advantages and disadvantages, there are still some clear trends. Usually, the most important factor for the success of a project is its economic viability. All the concepts except for the kite have quite high installation costs, and it is important to study the performance of the different concepts, considering this is what will make the investment pay off. In the paper (Lu and Ringsberg 2021), the performance of three WASP technologies is studied and compared. The three concepts studied are Flettner rotors, wingsails, and the DynaRig concept. The concepts are tested for an aframax oil tanker on two different routes. While all the three concepts provided fuel savings of between 5.6% and 8.9%, the Flettner rotors proved to be the most efficient while also having the smallest sail area. The study then goes on to perform a parametric study of Flettner rotors, and they come to some interesting conclusions. Most importantly, that the rotors have a significantly better performance for the smaller handysize bulk carrier. This is true even though the rotors come in different sizes, meaning that even if the rotors are scaled to the vessel, the results can vary drastically. Below is a plot showing the predicted performance for some of the different concepts in polar plots.

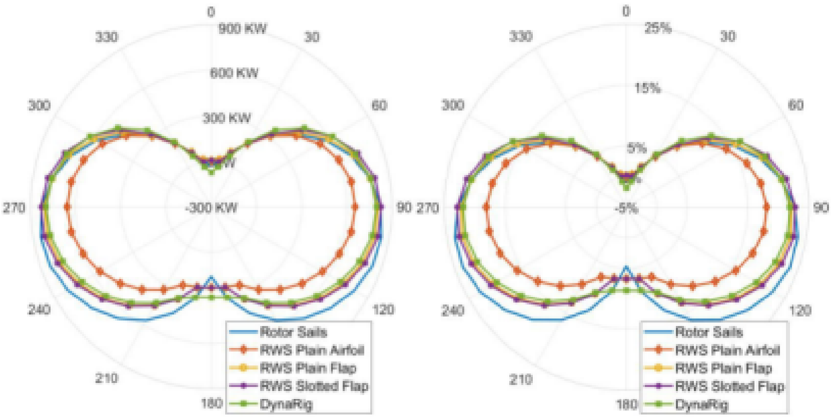


Figure 2.7: Predicted power savings for different concepts, kW to the left and savings as % of total engine power to the right

Source: Lu and Ringsberg 2021

The second most important factor when comparing the different systems is the ease of operation. This is related not only to how easy the systems themselves are to operate but also how much space they take up on board the vessel and whether they get in the way of other operations. All of these systems can generally be operated by a computer on the bridge, and the crew usually only has to turn them on and off. After this, the computer will determine everything from rotational speed to the pitch of the wings. However, there are significant differences when it comes to the space each system takes up on board the vessel. The smallest of the systems is the kite concept, which takes up nearly no space when not in use, in addition to the fact that it is generally placed in the bow of the ship where few cargo operations take place. Then come ventifoils and Flettner rotors. These systems come in a variety of sizes and configurations and can sometimes be ”folded” or ”tilted” down in order for the vessel to complete operations where the units would be in the way. The ventifoil can also come in a container where the foils are folded out of the container during use and can be folded down and moved at any time to make operations easier.

Figure 2.8: Containerized ventifoil unit

Source: Econowind 2021

Finally, the wing sails and the DynaRig are likely the systems that take up the most space. The wingsails can come in a variety of sizes and configurations, meaning it is quite flexible. However, current research seems to insinuate it is still slightly less ”convenient” than Flettner rotors. The DynaRig is more of a complete ship overhaul. With this concept, the ship uses much more space for the sails as the masts function similarly to traditional sailing masts. This means that the masts might interfere with port operations for some vessels and ports. However, this can likely be overcome as the concept is still quite new, and there are probably opportunities for the masts to be made at least a little less fragile so port operations can function normally.

2.4 Operational modes

One of the main issues regarding maximizing the efficiency of WASP is different operational modes for vessels. As described quickly in the introduction and as mentioned later in the project, the optimization of use could be quite critical for the efficiency of WASP. Different operating policies and strategies can lead to different efficiency for WASP concepts. In general, a vessel equipped with WASP would want to be in active operation nearly all the time. This means that waiting for port slots or for cargo to arrive at the port would be even more costly than for normal vessels. This is due to the high installation costs and low operating costs of WASP systems. The systems generally require very little external power and do not consume fuel on the same scale as a normal engine. This means that in order to reduce the payback period for the systems as much as possible, continuous operation is favorable.

This problem of vessel operation becomes a large issue when working to estimate vessel performance before installation. While there exists programs to estimate the potential rotor thrust for a given vessel, these programs usually do not account for the changing weather conditions around the world and during different periods of the year. This means that while it is possible to produce an estimate for potential performance over a year, this often does not accurately reflect the vessel operation and therefore does not accurately estimate vessel performance.

Chapter 3

WASP Rotor sail functionality

As described in the previous section, the most commonly used WASP technology today is rotor sails. These sails are relatively well known, and several companies produce them for the commercial market. This means that when looking to adapt WASP into their fleet, this is the technology that is the easiest to use for most shipping companies. However, most shipping companies will only be willing to adapt their vessels if the technology proves to cut costs and reduce their overall spending. For this reason, it is important to develop a method to calculate the estimated savings of a given vessel on a given route over a period, so that the companies can determine whether they believe that the initial investment is worth the cost. In order to do this, it is important to understand the rotors and how they work.

The rotors utilize a physical phenomenon known as the Magnus effect to generate the lift. The phenomenon is named after the physicist Heinrich Gustav Magnus, who discovered the effect in 1851 (Stojkovic et al. 2002). However the effect was first studied with regard to sailing when Anton Flettner patented the Flettner rotor in 1922, which utilized the effect. In order to prove the ingeniousness of his design, Flettner directed a shipyard to retrofit a 2000-ton schooner with two rotors in place of the old sailing arrangements. After the retrofitting, it was found that the new rotors outperformed the old rigging in all conditions, handled well in even the stormiest weather, and allowed for the vessel to travel upwards of 20-30°into the wind. However, even though the vessel performed well, there were only a few adaptations of the technology into shipping at the time. After the economy crashed in 1929, the concept was seemingly forgotten for a while. In the late 20th century, there was some experimenting with the rotors on smaller sailing vessels. However, there was little thought of the rotors in the shipping industry. Only recently, with the aspect of climate change and emission reductions, have the idea popped up again as a potential solution for the shipping industry. However, there are still questions about the cost-effectiveness of the rotors. This largely relates to the fact that the rotors perform very differently for different vessels and ships.

Several important factors influence the efficiency of installed rotor sails on ships. The force's direction depends on whether the rotor spins clockwise or counterclockwise and on the incoming angle of the wind. The lift force generated by the sail will point at a 90-degree angle from the incoming wind angle, and the drag force will correspond to the incoming wind angle. Due to how these angles work, the optimal apparent wind angle is slightly off 180 or 0 degrees. However, the design allows us to have extensive ranges for the optimal angle, and thus, around 1/3 of all attainable wind angles are within the optimal range.

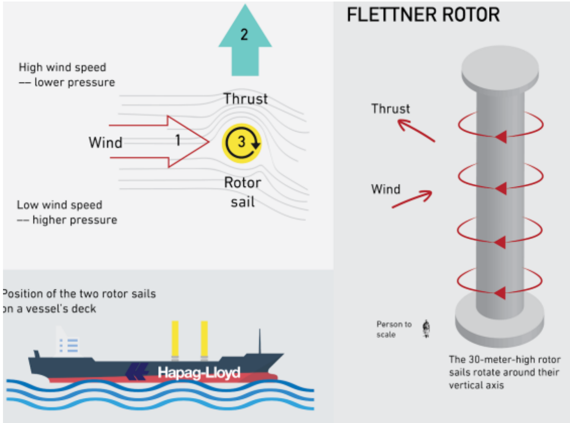


Figure 3.1: Illustration of rotor sail and functionality.

Source: Glatz 2021

In a paper by Anthony Glatz (Glatz 2021), he explains how the sails work and the relationship between wind, drag, lift, and generated power. He explains that the lift and drag forces can be calculated using the following formulas:

$$F_{lift} = \frac{1}{2} \cdot C_l \cdot \rho_{air} \cdot A \cdot V_{apparent}^2 \tag{3.1}$$

$$F_{drag} = \frac{1}{2} \cdot C_d \cdot \rho_{air} \cdot A \cdot V_{apparent}^2 \tag{3.2}$$

where the coefficients C_l and C_d are 10 and 3 respectively. These coefficients are found by utilizing the velocity ratio, which can be used to directly determine the coefficients.

These forces are applied at orthogonal angles from each other, and in order to maximize thrust, their wind angle can make the vector addition constructive in the forward direction of the vessel. The total thrust force can then be described as:

$$F_{thrust} = F_{drag} \cdot sin(\alpha) + F_{lift} \cdot sin(\alpha - 90) \tag{3.3}$$

Below are a couple of graphs describing the power generated by rotor sails

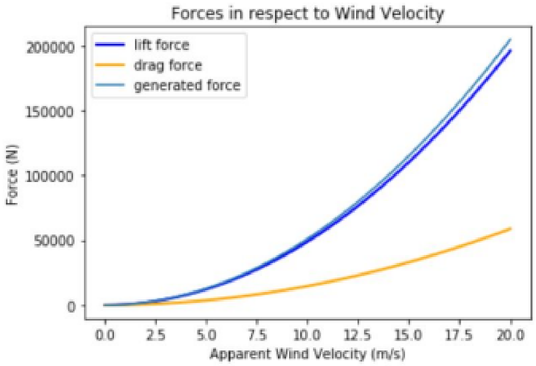


Figure 3.2: Generated forces for a rotor sail with apparent wind angle of 163,3 degrees

Source: Glatz 2021

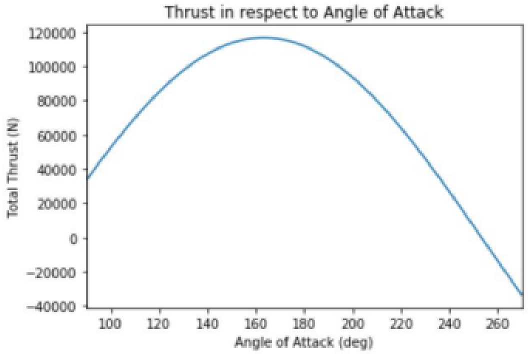


Figure 3.3: Generated forces for a rotor sail for different apparent wind angles

Source: Glatz 2021

Chapter 4

Previous studies

The first study shown here is by Ruihua Lu and Jonas W. Ringsberg (Lu and Ringsberg 2019). The paper focuses on a performance study and comparison of three different wind-assisted technologies. These are the DynaRig concept as described in section 2.4, the second is wingsails as described in 2.3, and the last is the Flettner rotor as described in 2.2. They use and aframax oil tanker as a case study on a route between Canada and Gabon. The study finds that there are significant fuel savings and that the Flettner rotor is the best performing technology out of the three. They also decide to perform a parametric study of the Flettner rotor concept on two different ships with different routes and operational profiles. Here they again found that there were significant potential savings. However, they also found that there are some requirements in order to make the rotors perform well. There needs to be a focus on selecting the Flettner rotor setup that best fits the vessel, as well as a focus on efficiently operating the rotors and vessel so that the rotors are allowed to perform in as optimal as possible conditions. A fascinating finding is that increased size does not necessarily lead to better savings, something that is important to remember when considering the installation of rotors for future vessels. All in all, this study provides a quick estimate of the potential efficiency of WASP and also covers some of the potential issues that a shipowner could face when considering implementation.

A later study by Nader R. Ammar and Ibrahim S. Seddiek (Ammar and Seddiek 2021) focuses more on the economic aspect. Similar to Lu and Ringsberg, it begins with a case study of Flettner rotors fitted to a vessel on three different routes. However, they then focus on the economic and environmental benefits more specifically. They conclude that the best possible wind angle for emission reduction is 120°/240°and that, using four Flettner rotors, the routes will have fuel consumption savings between 8.5% and 16.2%. They also conclude that this will reduce NOx and CO2 emissions of 154.3 and 5289 tonnes per year for the longest of the routes. They also look into the expected return period for the Flettner rotors finding that the rotors will have a payback period of between 7 and 13 years depending on the route. Perhaps the most important takeaway from this study, similarly to the one by Lu and Ringsberg is that the performance of the rotors is highly reliant on the operating conditions and fitting of the rotors.

In a study by DeMarco et al. 2016, a systematic approach to studying Flettner rotors and the most influential parameters on performance is taken. Through numerical simulations, they conclude that the highest uncertainty comes from the drag coefficient and that this is likely due to the limitations of the turbulence simulations. Concerning the rotor capacity to act as an auxiliary propulsion unit, they find that the lift coefficient and aerodynamic efficiency are much higher than for a normal wing of a comparable aspect ratio. They also achieve thrust magnitudes of 30% for a tanker with a couple of Flettner rotors.

Another paper by Traut et al. 2013 makes a numerical model for the performance of Flettner rotors and kites for cargo ships on five international trading routes. They find average power contributions from the Flettner rotors in the range between 193kW and 373kW. In particular, they find that on a specific route, fitting three Flettner rotors on a typical 5500 dwt, slow steaming general cargo carrier could lead to a power output from the rotors of more than 50% of the required main engine power. They also find that, compared to the kite, the Flettner rotors are more stable and provide higher average savings. The main focus of this study is to check the feasibility of wind assistance on some international trading routes, and they state specifically that future studies will have to go deeper with regard to the accuracy of the prediction models. They also specify, similarly to other papers, that more modeling has to be done with regards to different operational modes and more detailed installation processes.

A study by Talluri et al. 2018 proposes a techno-economic and environmental assessment methodology to assess the benefits of using Flettner rotors in conjunction with traditional propulsion systems. The study finds that while there is little doubt that the rotors have a positive impact on fuel consumption and GHG emissions, their economic viability is more complex. The study found that the rotors could result in up to 20% fuel and emission savings, however the economic viability is more reliant on weather conditions and the dimensions of the rotors, as well as the assumed implementation of carbon taxes and similar concepts. Another interesting finding from this study is the fact that the wind direction is more influential than the wind speed in determining the rotor efficiency.

Chapter 5

A method for WASP performance modelling

5.1 Description

While it is shown in the papers above that there are several studies on Flettner rotors already, it can be quite difficult for a shipowner to determine whether to implement rotor sails on owned vessels. There are currently two main methods that can help assess rotor sail efficiency for a vessel. These are model testing and performance simulations.

Model testing will usually be the most reliable method in order to acquire accurate results. However, this can be extremely costly, and it often does not include parameters describing the routes and operational profile of the vessel. This means that while model testing does provide very accurate performance results for a specific condition, it can be difficult to apply this to a full vessel operation or life-cycle.

Simulations are often a cheaper and more versatile tool for performance estimation. These are often heavily based on previous studies, and the methods used will often acquire similarly accurate results to model testing without the high cost. However, previous studies that have used these models rarely take into account the actual vessel operational profile and route. Instead, they will often cover "common" trading routes and operational profiles. This means that while they provide useful data, the real-life results can easily be very different when the vessel operates slightly different than the norm or on slightly different routes.

This is the reason why a general method for the shipowners that they can use to combine the common simulation methods with data from their specific vessel to make as accurate as possible performance estimates is desirable. The idea is that this method will describe the steps needed to figure out whether implementing rotor sails will be profitable for the owner or not. The model should be relatively easy to use and require only data that is relatively easy for a shipowner to gather or access from a third party.

The proposed method consists of several steps that have varying effects on the results and their usefulness. The approach used is simulation-based, meaning there are no real-life experiments involved, making the method relatively cheap to experiment with. The project can generally be split into four phasesa:

- Early planning
- Main simulations
- Comparisons and reviews
- Economic calculations

The first phase is the early planning phase. This is where the vessel or vessels to investigate are chosen. Several factors should be considered when making this decision. Firstly, most WASP performance programs require a lot of accurate data in order to achieve realistic results. This means that unless the shipowner can reliably gather positioning data and general vessel parameters, the process will be much more difficult and less accurate. Secondly, it is important to remember the factors described in the papers from the previous section. WASP will generally not perform at its best unless designed and operated in a specific way. In this phase, the reference time frame should also be decided on. There can be large differences in performance between a ship traveling the entire world over a full year and a vessel traveling only on a single route. When looking at only a specific route, this route may be particularly beneficial for WASP implementation or the opposite. Investigating a full year might get a better perspective on what the actual available savings are, both economically and environmentally. There is also an issue regarding the weather data that is to be used in the simulations. When reviewing only a single route, there might only be available data for a couple of months. This could be very important as the differences in average wind speed over the year is quite significant in some regions of the world.

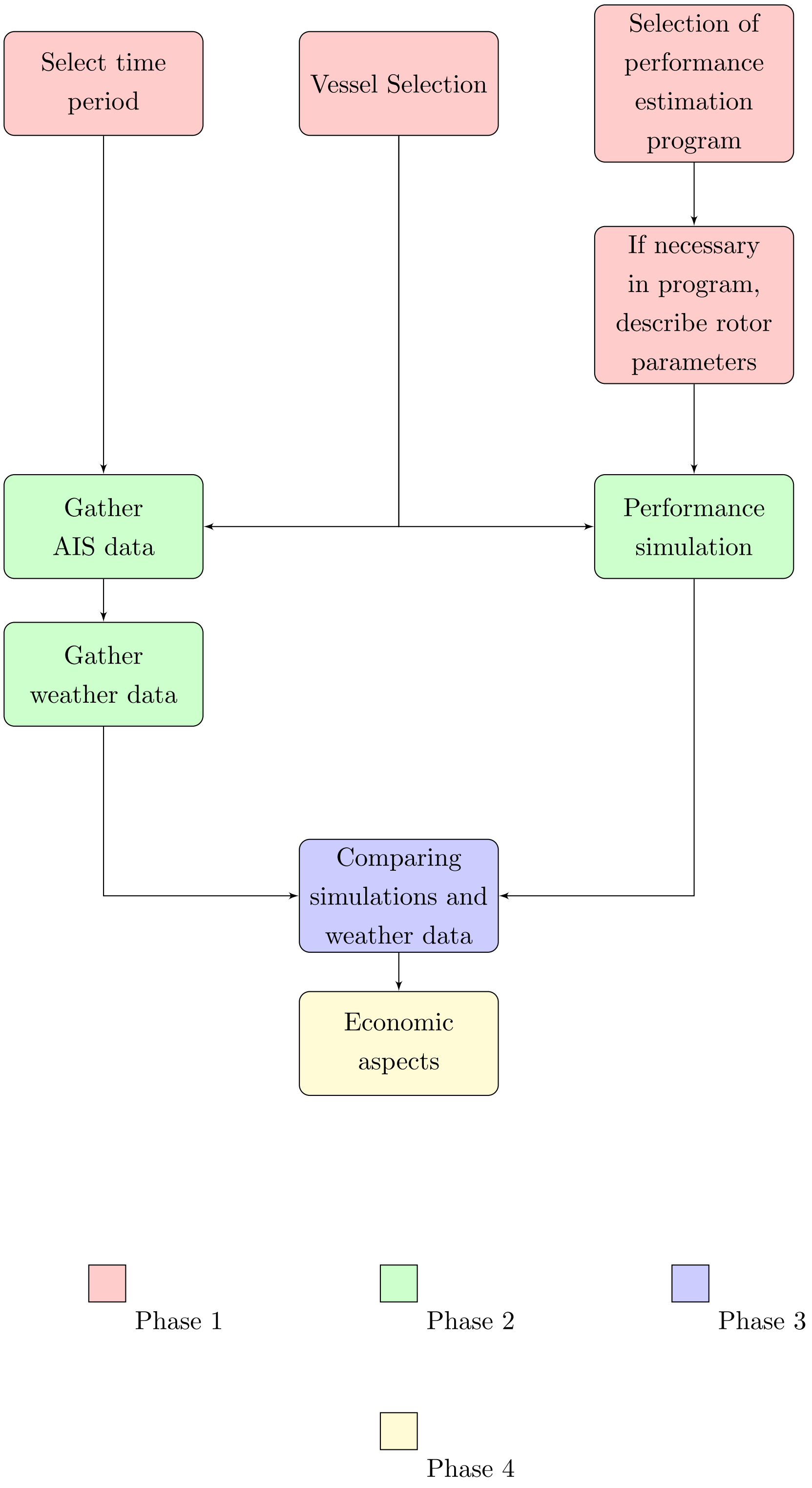
The second phase of the method is the phase where the main simulations should be run. This phase aims to complete the basic simulations for the WASP performance of the vessel, meaning the performance model of the vessel for all possible weather cases. The way this step works can vary drastically depending on what sort of performance model is used. The most basic models will require nearly all data on the rotor setups to be manually input and will print every possible case for the weather limits that are defined. With this setup, the model would likely have to be run multiple times with different rotor setups in order to find a setup that suits the vessel. However, it is also possible to make a performance model that goes a bit further than this. For example, it is possible to run a performance model that also utilizes an optimization algorithm to determine what the best possible rotor setup is. With this kind of program, there would be no need to choose a rotor setup to test, as the model would instead simply choose the best possible option for the vessel of choice. However, these models are quite complicated, and it might be difficult for a shipowner to create or acquire by other means.

In this second phase, it is also natural to collect and process the positioning data for the vessel. The most common type of positioning data used for this would be AIS data. However, a shipowner might have access to other sources of data for their ships. It is essential that this data is as accurate as possible and that it also accurately describes the amount of time spent in different regions, meaning that there is an even spread of data for all time periods. This data will be further used to collect weather data for the vessel routes. There are many ways to obtain weather data. The most basic is obviously for the vessel to be gathering data over a period, and then to use that data here. However, this might not be possible if the shipowner does not have time to wait for this data gathering. Instead, one could use data from different web pages where it is possible to download weather data from all around the world. This data can be either gathered by vessel monitoring or from satellites. However, it is important that no matter where the data is collected, some time is spent reviewing and processing it to ensure the validity and accuracy of the data.

The third phase of the method is where the main tasks from phase two are combined. The main goal here is to match every point from the weather and AIS dataset with a point from the performance simulation. This means that for every position the vessel has been on the chosen route(s), the WASP performance in the current conditions will be known. With this information, it is possible to assess the total performance over a year, as well as the performance in specific regions or areas on the routes. This part of the process should be quite simple to complete for a company as the programming required to make this comparison is quite simple. However, there is quite a bit of data-processing and results analysis involved here. One important thing to remember here is what was described in several of the articles in chapter 4, that being, the importance of operating the vessel in a way that brings out the best from the rotors. In many cases, the results from this modeling plan will lead to less optimistic results than hoped. However, these results are built on an operational profile that does not plan for wind assistance but rather wind as a hindrance. If one decides to start operating the vessel with the wind assistance in mind, it might be possible to achieve significantly better results.

Finally, an economic analysis of the case is required. With knowledge of the potential fuel and emission savings from the previous phase, it is now possible to make a cost-benefit analysis. Here it could be natural to find the economic payback time of the rotors with given installation and operating costs. The economic parameters would likely have to be provided by the rotor production companies. Again, it is important to remember that the method shows the calculated savings if the vessel is operated as it is now and potentially larger savings should the operational profile be optimized. However, it is also important to remember that the rotors do take up some space on the vessels, meaning that the cargo capacity of a vessel is likely to go down by an amount proportionally to the number and size of the rotors. All these things add up to make the economic estimates quite complex. However, this kind of cost-benefit analysis should be something that most shipping companies are quite familiar with and can perform without much issue.

5.2 Project structure diagram



Part II

Case study

Chapter 6

Method

In order to test the proposed method in section 5 a case study was performed. This case study was performed on an example vessel over an entire year. The case is to assess the potential for retrofitting Flettner rotors to the vessel but keeping the current operational profile. In this chapter, the main systems used in the different steps are covered, as well as some of the advantages and disadvantages of these systems.

6.1 WASP performance model

For the second phase of the project, a WASP performance model was needed. Creating a simulation for WASP performance that is accurate enough to be useful is a challenging task, but it is possible. The main reason for the complexity is the number of factors that can affect performance. A program needs to account for all these while still running relatively quickly and being easy to use. While it might be possible to make a sufficient program for an illustrative case, this would likely take to much time for this thesis and be less reliable than desired. However, a program currently being developed at NTNU IMT by postdoc Drazen Polic and PhD candidate Benjamin Lagemann has the required qualifications. This program was used, with some minor adaptations, in the case. The program is written in Matlab and consists of several sub-codes that work with different methods and constraints to provide as accurate as possible estimations for all relevant factors. This includes elements like the lift and drag coefficients for the rotors and there are also calculations of true wind angles and speed, effects on the engine load, and the effect of the rotor forces on the vessel drift angle.

6.1.1 Parameters

For the code to produce accurate results, the correct input parameters must be used. Below is an explanation of most of the different parameters and how they are used.

The first parameters are related to the vessel itself. These are needed to determine everything from engine power requirements at different speeds to the hull hydrodynamic derivatives and the height of the main deck. The input parameters here are very important in order to implement the different constraints for the code, as well as for estimating the savings in percent. These parameters are shown in the table below:

Parameter	Description
LWL	The vessel length at the waterline in meters
B	The beam of the vessel in meters
D	The draft of the vessel in meters
Deck height	The height of the deck above the waterline
Drift angle	The maximum hull drift angle set
GT	Gross tonnage of the vessel
Displacement	Displacement of the vessel
C_b	The vessel block coefficient, describing the ”fullness” of the vessel below the waterline
Speed	Ship speed is described as a set from v-min to v-max with a step length. An example of this would be [4:0.25:24], meaning that the program calculates performance for all speeds between 4 and 24 knots with a step length of 0.25.

Table 6.1: Description of vessel parameters

The above parameters are all related to the vessel's main particulars. However, details about the rotor setup to implement on the vessel are also required. The program used here does not optimize the number of rotors, rotor sizes, or placing of the rotors for us, so this has to be decided before the simulation starts. The main parameters required can usually be found in the brochures of the companies producing the rotors. The rotor sizes should generally be scaled up with the ship size to achieve the best possible effect. Similar to the vessel parameters, these rotor parameters serve to calculate the performance and set the standards for the constraints. Below is a list of the main rotor parameters used in the model:

Parameter	Description
Height over sea line	A description of the combined height of the deck and the rotors on top.
Height	Height of rotors
Diameter	Diameter of rotor
Base	Size of the rotor base
Count	Number of installed rotors
Installed power	Installed power for operating the rotors
Max RPM	Maximum rotations per minute for the rotors
Max thrust	Mainly relevant for safety of operation, not a description of the mathematical maximum the rotors could provide, but rather a description of how much the could ”safely”provide before they would have to be shut down because of bearing overload.

Table 6.2: Description of rotor parameters

Finally, the wind also has to be described. In order to calculate the real value of Flettner rotors, it is essential to get this right. The results could be very inaccurate if the program simply used the forecasted wind speed and calculated using that. Instead, the forecasted weather has to be converted into a ”true wind speed” at a reference height and ”a true wind angle” depending on the vessel speed in a given direction in relation to the direction of the wind. This is because the actual wind speed affecting the rotors will be very different depending on whether the vessel experiences headwind or tailwind, even if the reported wind speed is the same. This is illustrated below:

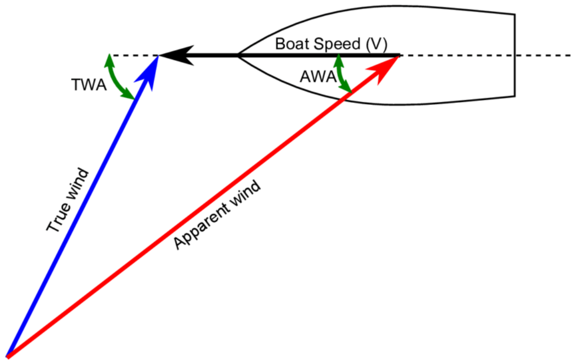


Figure 6.1: Apparent and true wind angles visualized

Source: Knudsen 2022

Both the wind speed and angles are input with three variables: maximum, minimum, and step length.

With these inputs decided, the code calculates the wind shear as well as the lift, drag, and power coefficients. For this, there are several options as to what method is used. These are accessed by importing one of several subcodes. For the wind shear, there are five options:

- Tillig (Tillig and Ringsberg 2020)
- Kramer (Torma and Kramer 2016)
- Offshore wind turbines
- DNV rules for offshore cranes
- Offshore structures

For the lift, drag, and power coefficients, there are two options:

- Tillig (Tillig and Ringsberg 2020)
- DeMarco (DeMarco et al. 2016)

As described earlier, all of the input parameters serve not only to calculate power output but also to determine the constraints. This means that there could be some surprising things in the results if these constraints are broken in some way or another. The code thus sets the value of power output to 0 if the constraints are broken, meaning that the results could show 0 power savings in places where significant power is expected. Therefore it is important to understand the constraints in depth.

6.1.2 Constraints

There are eight important constraints in the code that will cause the code to set the power output to 0, and these are further described below.

1. The first constraint is related to the wind speed and wind speed limit; the code does not allow wind speeds higher than a set limit
2. The second constraint is described by the maximum RPM of the rotors. It will trigger if the true wind speed in a specific scenario requires the rotors to rotate at a higher RPM than the maximum in order to produce the desired effect.
3. The third constraint describes the spin ratio (velocity ratio). This is important to determine the vortex shedding from the rotors, and the constraint is triggered if the spin ratio becomes too high for the Flettner rotors to handle.
4. The fourth constraint is related to the power required to run the Flettner rotors. The Flettner rotors require some power to spin, and this power is installed as described in the parameter. If the required power for a scenario is higher than the installed power, this constraint will be triggered.
5. The fifth is related to the side force on the hull and kicks in if this becomes too large
6. Next is a constraint on the maximum thrust of the rotors. As described earlier, there is a maximum thrust force that the rotors are able to create safely.
7. Similarly to the constraint for the side force on the hull, this constraint describes the maximum side force on the rotors.
8. The final constraint is again related to the power for the Flettner rotor. This constraint states that the installed power has a maximum limit.

6.1.3 Model functionality

The code functionality is described in Lindstad et al. 2022 (forthcoming), and a shortened version is shown below. The code calculates the thrust and side forces based on the lift and drag coefficients given in Tillig and Ringsberg 2020. These coefficients are backed up with full-scale testing and model-scale data. The aerodynamic lift vectors are expressed and transferred to a coordinate system as side force and thrust. To compensate for the significant side forces from wind assistance, there is the vessel drift angle β. The lift coefficient is then estimated using the method given in Kijima et al. 1990.

$$c_L = Y_\beta \beta + Y_r r + Y_{\beta\beta}\beta|\beta| + Y_{rr}r|r| + (Y_{\beta\beta r}\beta + Y_{\beta rr}r)\beta r \tag{6.1}$$

Where the Y coefficients are the hydrodynamic derivatives or manoeuvring coefficients, and r is the normalized yaw angular speed. The values for these coefficients are given in Kijima et al. 1990. Due to observations from Tillig and Ringsberg 2020 the lift coefficient c_l is reduced by 75%. Due to the cost of CFD the added wind induced hydrodynamic drag $R_{add.wind}$ is assumed proportional to drift angle, lift coefficient and a correction factor of 1.2. The power savings of the vessel is calculated as follows.

$$P_{saved} = P_{no.WASP} - (T_{prop}u/n_p p P_{req.WASP}/n_{c.WASP}) \tag{6.2}$$

Here P_{saved} is saved power, $P_{no.WASP}$ required power without WASP, $P_{req.WASP}$ WASP required power with WASP, T_{prop} required thrust from propeller, u surge velocity, n_p propeller efficiency and $n_{c.WASP}$ sum of electrical loss between rotor and generator. The last two coefficients are set to 0.7 and 0.8 respectively.

In addition to calculating the saved power and the power generated by the rotors, the code can also find the fuel consumption per voyage as given below.

$$F = n\sum_{i=0}^{n}(\frac{D_i}{v_i} \cdot ((K_f \cdot P_i) \cdot (1 + (0.7 - \frac{p_i}{p_{tot}})^2) + (k_{aux} \cdot P_{aux})) \tag{6.3}$$

After providing all these inputs and running the code, a large excel sheet with all possible cases and combinations of wind speed, wind angle, and ship speed is created. From this, it is possible to extract the data required for the specific weather and speed scenarios collected using AIS data and downloaded weather data.

6.2 AIS data and route generation

As mentioned above, the next step is to figure out which of the scenarios generated above are relevant for the specific case. This should not be very difficult for a shipowner as they have all the required data for their vessels. One form of data that can be used for this purpose is AIS data.

6.2.1 AIS - Automatic identification system

For the vessel positioning data, AIS data was used. AIS, which is short for automatic identification system, is an automated tracking system required by the IMO to be fitted on all ships with a gross tonnage above 300. The system was originally developed to avoid ship collision accidents, but the data provided allows for many other uses as well. The system offers not only the vessel position displayed in coordinates but also the vessel's speed and course. This is important because, as mentioned earlier, the relative wind angle and speed is very important for Flettner rotor performance.

While AIS data is extremely useful and easily available, there are some issues. Mainly the fact that ships can turn off their AIS transceivers when they want for a variety of reasons. This leads to some situations where datasets are incomplete or certain areas are not represented by an accurate amount of datapoints. An example of this is how many vessels turn off their AIS transceivers in the east china sea, meaning it is difficult to tell exactly where a vessel is headed in China and how the vessel has been operating along the coast. This issue is luckily not critical in the case of rotor sails, as they are most effective on the open seas, meaning that the operations close to land are not as crucial for the calculations.

In order to read and process the AIS data, a couple of external programs were used. These programs read the database and turn the data into a python pandas data frame. These data frames are an easy way to process the data further in python and are also practical due to how easy it is to write them to excel through imported python packages. This allows us to transfer AIS data, which comes in a raw db (database) format, into readable and editable data. With the data in a more understandable form, it is easier to start checking for anomalies or errors in the dataset to achieve as realistic as possible results.

6.3 Weather data

As mentioned earlier, there is also a need for weather data to be collected. In order to simulate the performance as accurately as possible real weather data collected from Copernicus Marine Data historical weather database was used. This data can be downloaded through the Copernicus web page and provides an accurate weather description for any given set of coordinates. The best way to collect this data is by using a program that requests all the desired data points and puts them into an excel file that the WASP performance program can later read. This downloading program exists already and can be found in a GitHub library. In order to collect not a single data point but instead a given set of points, as well as formatting the data in a useful way, some changes and expansions had to be made to the program. With this program installed and adapted, it was possible to collect weather data. The dataset used is called Global Ocean Wind L4 Reprocessed Monthly Mean Observations and is described by the Copernicus Marine Service as follows:

> *For the Global Ocean - The climatology refers to time series of monthly averaged wind variables calculated over the global oceans. It is estimated from daily global wind fields calculated from retrievals derived from ASCAT scatterometers onboard METOP-A and METOP-B satellites. It consists of six variables including monthly averaged wind speed, zonal and meridional wind components, wind stress amplitude and the associated components. They are calculated as arithmetic means of ASCAT daily wind analyses. The gridded daily wind and wind stress fields have been estimated over global oceans from Metop/ASCAT retrievals using the objective method. The daily analyses use standard products ASCAT L2b during the period April 2007 to present. Wind stress and the related components are estimated over swaths based on the use of Coare3.0 parameterization. The resulting daily fields are estimated as equivalent neutral-stability 10-m winds, and have spatial resolutions of 0.25° in longitude and latitude over global ocean. The objective method provides also errors characterizing the quality of each daily wind parameters at grid cell. More details about the data, the objective method, and computation algorithm may be found in (Bentamy et al, 2011. For monthly calculation purposes, only valid daily data available within each month of the period are used. The monthly winds are estimated at each grid point (0.25°x0.25°) from at least 25 daily values available at the same grid point. The associated root mean square (rms) values are*

also calculated at each grid point and used as quality control parameter. Source: CopernicusMarineService 2022

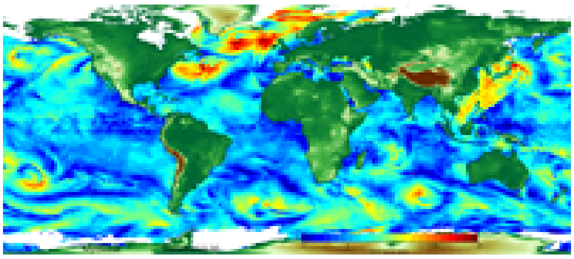


Figure 6.2: Visualization of geographical coverage

Source: CopernicusMarineService 2022

As seen from the description above, this dataset should be more than sufficient for the given case. For any chosen data point, it will interpolate between the closest data sources to create an estimate for the exact point requested. This means that all the AIS data points gathered earlier will have an exact match in the weather dataset, and it is possible to input the AIS data and get the weather for those points out. The only significant issue with this dataset is that it does not provide data for points inland, such as in the Suez and Panama canals. It also sometimes struggles to deliver accurate data for points close to land. While this isn't necessarily that problematic regarding the WASP performance, it can make the data processing quite difficult since most programs that allow large datasets' as an input struggle with "not a number" (NAN) values. This means that some changes had to be made to the programs in order to either remove all rows with NAN values in them or change all NAN values to zeros.

6.4 Combining weather data and WASP simulation

In order to compare the data from the simulation with the gathered weather data, a program was written in cooperation with some other students. This program takes in the CSV files from the simulation as well as the weather data. Since the weather data was found for all the AIS points, the heading and speed in these points is also available. This means that when comparing the simulation results with the weather data, a matching simulation point for every point in the weather dataset can be found, and this can be written into an excel sheet. With this excel sheet, it is possible to find the simulation results for all the points visited by the vessel. The potential performance for the specific route, region, or period can then be extracted, together with averages, peaks, and the mode.

6.5 Economic aspects

The final part of the project is to analyze the economic aspects. This would primarily consist of comparing the potential fuel savings of the rotors with the installation cost and the cost related to reduced cargo capacity. Considering how expensive the rotors are to install, this can be very important to understand whether or not they will pay off economically. However, this process is challenging to perform in a meaningful way without accurate economic data. The most important of these factors is the installation cost for the specific vessel. This consists of not only the cost of the rotors and installation from the rotor producers, but also the cost of not operating the vessel normally in the period it would take to install the rotors. Since this information was unavailable, it was decided that the economic analysis would not only provide little with regards to the value of this case to the project, but also require time that could be better spent on other parts of the thesis.

Chapter 7

Results

In order to show that the method described in chapter 6 works, a case study for a suitable vessel was performed with the described method. The vessel was chosen semi-randomly by looking for vessels in a certain size range that also had available AIS data of sufficient quality. It was also decided that it would be interesting to look specifically at large vessels as there have been few attempts to utilize Flettner rotors on these vessels so far, making a simulation-based approach well suited.

7.1 Vessel selection and AIS data

As described in chapter 6, there are several requirements for the vessel. However, a collection of potential candidates was found after looking at several vessels in the appropriate size spectrum. AIS data was then requested for these vessels. The data was then processed and investigated in order to decide which vessel to proceed with. Upon request, a database (db) file was received with AIS data for several vessels. The data was from 2020 and covered varying parts of the year for the different vessels. First, the data was processed and reformated into another file type that was easier to work with. This was done with a couple of lines of code that read and reformat the data of a specific vessel into a pandas data frame which could then be further modified later. Upon seeing these data frames, it also became clear that the data was not sorted by date, so it had to be sorted to get a better understanding of where the vessel was at what time. In order to get a better understanding of the data, it was visualized on a map, with every point on the map representing a single data point from the AIS data. This was done in order to check for large gaps or other issues that made the vessel unsuited for the project. After doing this several times with several different vessels, the vessel Ma Lian Hai was chosen as the best case for this study. Below is a visualization of the data for this vessel.

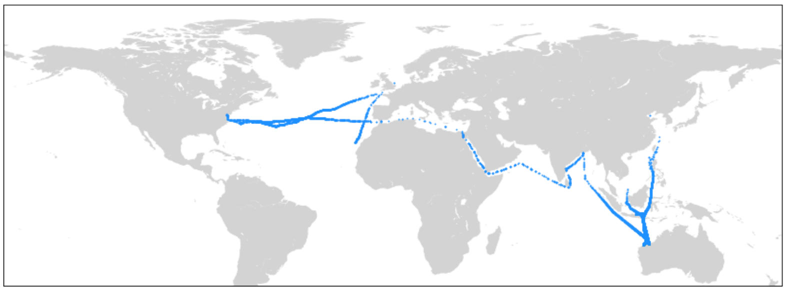


Figure 7.1: Visualized AIS data Ma Lian Hai

As seen from the map, there is a large variety in the density of the data, and there are also some holes in the Mediterranean and the east china sea. However, compared to the data from other vessels, this is quite good.

While this dataset is quite good and has a lot of data points, this can also bring some issues. The total set of AIS data for this vessel consists of 35796 rows and 8 columns, meaning that any attempt to collect weather data for every point in the set would take way too much time to be relevant in this thesis. Therefore an attempt was made to reduce the size of the dataset. There are multiple ways to do this; however, the easiest way is to only look at every x-the points in the set. For example, if only every 4th point is considered, the set would be reduced to 8949 rows. Unfortunately, even this is not small enough for the chosen weather data downloader to collect in a reasonable amount of time. Therefore, the set was cut down even more to only consider every 10th row. This gives a set of 3580 rows, which is possible to collect while running the code overnight.

Assuming the vessel is sailing in a straight course for the majority of the time in the ocean, the reduction in datapoints does not significantly affect the relevant input parameters for the WASP assessments. However, the dataset was still double-checked to see that it was not drastically altered in a way that could lead to inaccurate results. Therefore the new data was visualized as seen below.

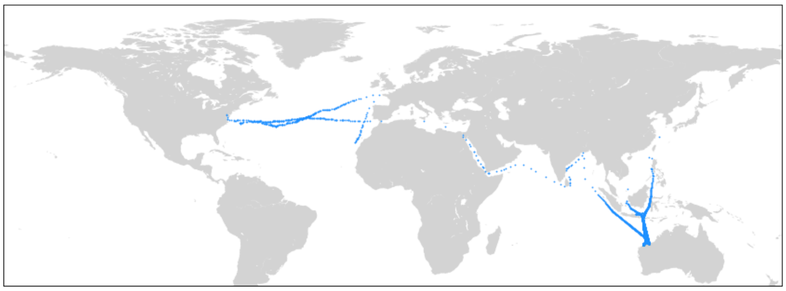
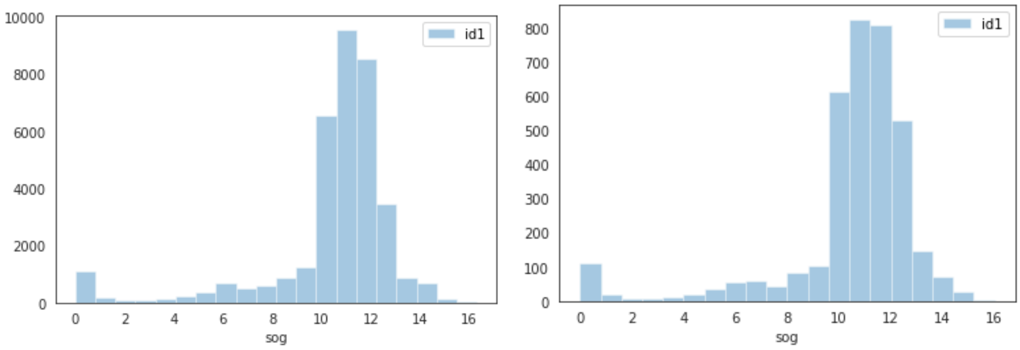


Figure 7.2: Visualized AIS data Ma Lian Hai reduced

As seen, this is clearly based on the same dataset; however, it is also clear that the distribution of the data points is not equal over the different routes. The vessel has a much larger amount of data points on certain routes and in certain regions than others. However, this is also likely to somewhat describe the amount of time spent in these regions and is therefore considered acceptable.

Another factor that is very important for the dataset is the vessel speed. If the simplifications made in the dataset significantly change the speed profile, the results could end up being very unrealistic. The vessel speed is very important to calculate the true wind speeds and thus the true effect of WASP. Therefore, the speed profiles of the original and new datasets were plotted. These are shown below.



Speed profile for original large dataset

Speed profile for new smaller dataset

Figure 7.3: Speed profiles

As seen above, the profiles are very similar in shape, and there is no problem with the distribution of speeds affecting the average vessel performance.

Now that the vessel has been decided, the vessel details need to be input into the WASP performance model. These parameters are described below:

Parameter	Value
LWL [m]	249.8
B [m]	43
D [m]	14.5
Deck height [m]	20.8-D
DWT	115297
GT	64654
Displacement	134308
C_b	0.86
Installed power [kW]	15480
Fuel consumption 14.5 knots [g/W]	167.8e-3

Source: Seaweb 2022

Table 7.1: Vessel parameter values

As the block coefficient was not available in Seaweb, it was instead calculated by hand using the equation:

$$C_b = \frac{\Delta}{LWL \cdot B \cdot T} \tag{7.1}$$

Where Δ is the volume displacement, LWL is the length in the waterline, B is the breadth, and D is the draught. The WASP performance model was then run with the wind shear from offshore wind turbines and with the lift, drag, and power coefficients from Tillig.

For the program to understand the engine and power output and requirements of the ship, the required power derivatives had to be found. These were found as the derivatives of the third-order polynomial for required power. As these were not listed in Seaweb, they were instead calculated by hand. The easiest way to do this was to use Lloyd's register Flettner savings calculator again. In this calculator, it is possible to input the parameters of the ship, and the program will calculate energy needs for different speeds. These numbers could then be used in a third-order polynomial regression analysis to determine the polynomial and its derivatives. The polynomial is:

$$g(x) = 104.15x^3 - 809.96x^2 + 2737x - 2321.27 \tag{7.2}$$

here it is easy to take out the derivatives and input them into the Matlab program.

7.2 Performance simulation

As described in chapter 6, there is also a need to input details for the Flettner rotor setup in the program. This is very important for the performance calculations; however, the choice of rotors would not be the same for all vessels. Therefore the simulation was run with three different rotor setups. Since the vessel is very large, a total of five rotors were chosen for all the setups. However, the rotors will vary in size and max rpm. The three options are shown below.

Parameter	Set 1	Set 2	Set 3
Height over sea line [m]	32.3	36.3	41.3
Rotor height [m]	26	30	35
Rotor diameter [m]	4	5	5
Foundation height [m]	2.5	3	3
Number of rotors	5	5	5
Installed power for rotors [kW]	90	115	143
Max rpm	225	180	180
Max thrust [kW]	190	300	350

Table 7.2: Rotor parameter values

These three rotor configurations are all in the upper size bracket of what is offered by most of the rotor production companies, which is natural considering the selected vessel is very large. The company brochures of several producers give the rotor details above. These producers are NorsPower, Eco Flettner, and Anemoi. The parameters in the table above contribute not only to calculating the power output of the rotors but also to describing the constraints. The effect of these constraints will be discussed more in-depth later. When the Flettner performance program is run, a solid estimate for the vessel's performance with several different rotor setups is produced.

7.2.1 Simulation results

The results from these performance simulations are saved in excel sheets that contain all the possible scenarios implemented in the model. This data can then be visualized and compared to see the performance difference between the different rotor setups. The easiest way to do this is through polar diagrams, as shown below. In order to make them easier to read they have been rotated and enlarged.

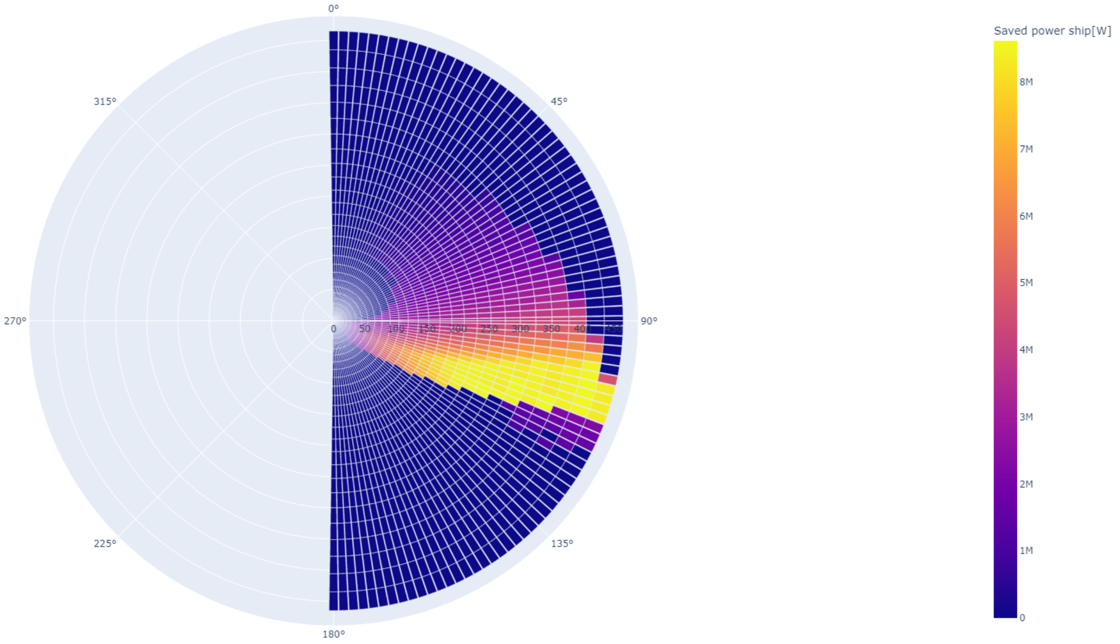


Figure 7.4: Example performance plot 11 knots

This plot shows the apparent wind angles from 0 to 180 on the top figure and the apparent wind speed increasing outwards in the diagram. The maximum wind speed in the diagram is 30 m/s, decreasing by 1 m/s per step inwards. As seen from the diagram, the effect is largest for angles between 90°and 115°, with increasing wind speeds leading to increased effect from the rotors. In the plot above, it can seem like the effect from the turbines for angles lower than 90% is almost negligible; however, this is mainly due to the way the color scheme looks in the full plot. Since the inner rings where the wind speed is lower are the most relevant, a plot with a max wind speed of 22 m/s can be created. This plot gives a much better picture of the rotors' effect in most conditions. This is shown below.

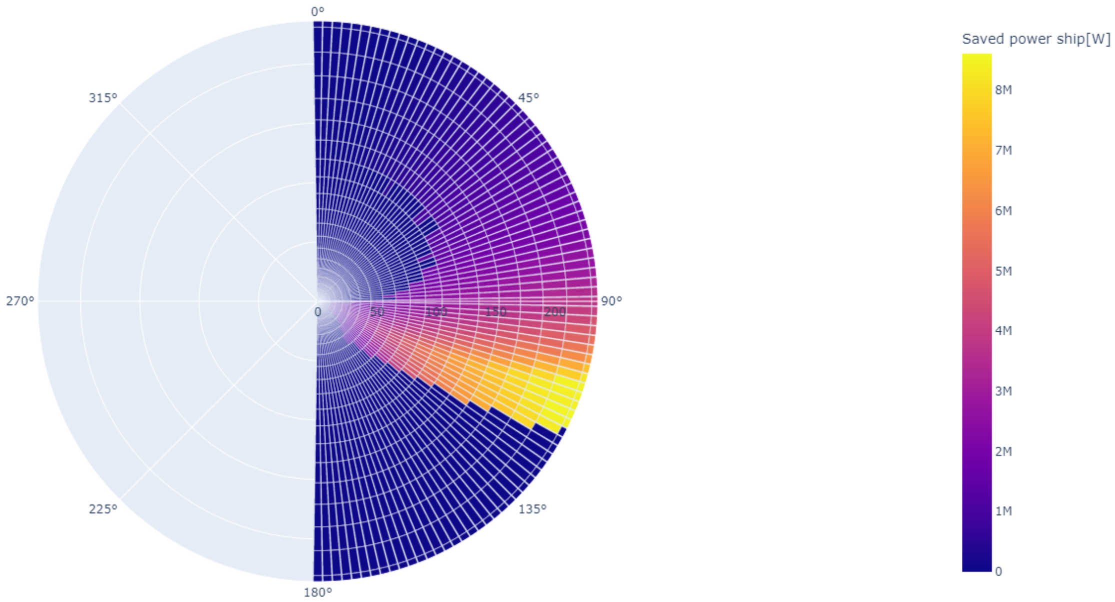
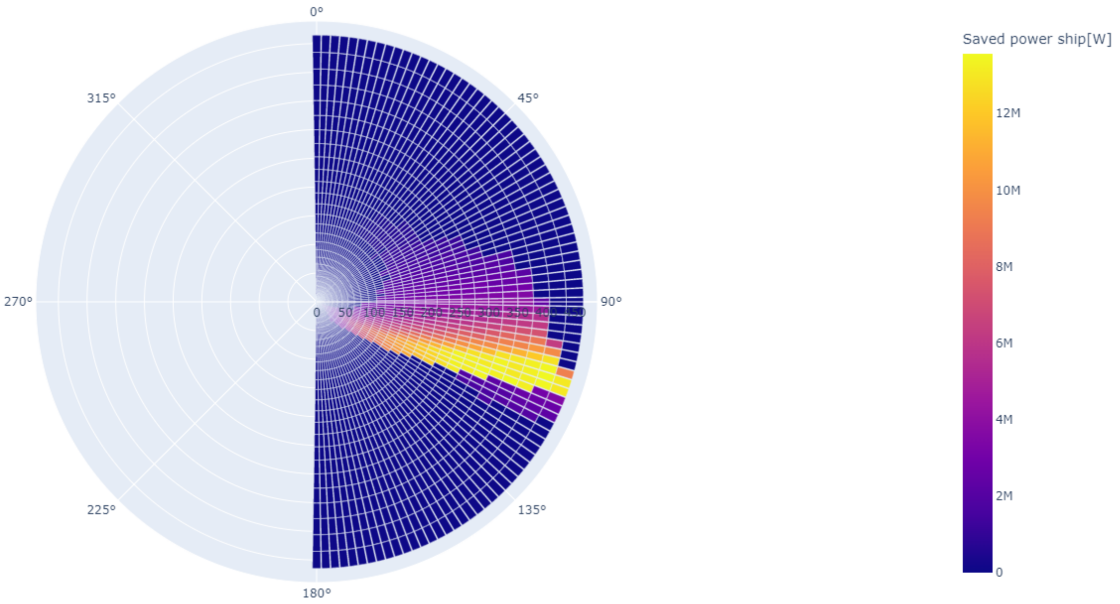


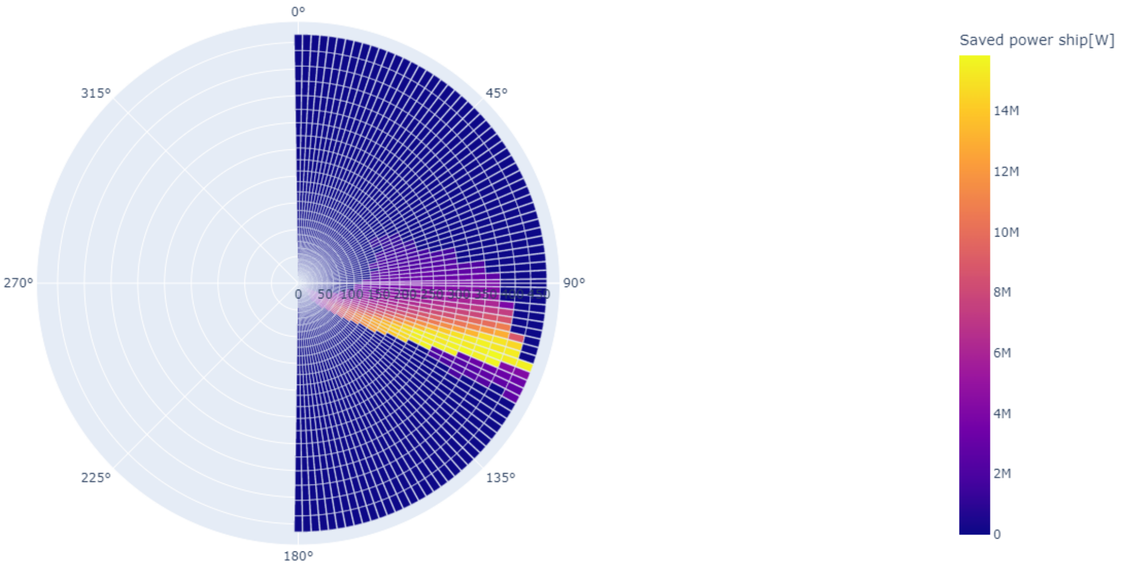
Figure 7.5: Example performance plot 11 knots 22m/s

As seen here, the rotors will produce significant savings for apparent wind angles as low as 30°. This is very important as it means the real effectiveness of the rotors is much better as they will produce an effect for an extensive amount of the possible scenarios.

The plots above are based on the smallest of the three rotor setups, with a vessel speed of 11 knots. However, the results vary significantly for the three different setups. Below are the plots for the same speed but with different setups.

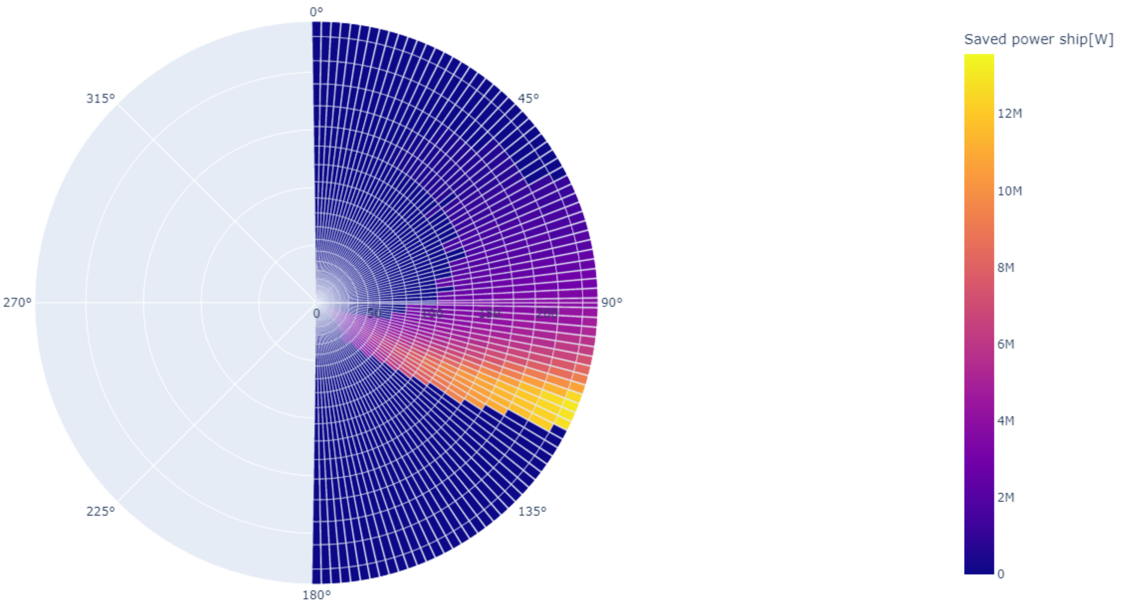


Plot 11 knots medium rotor setup

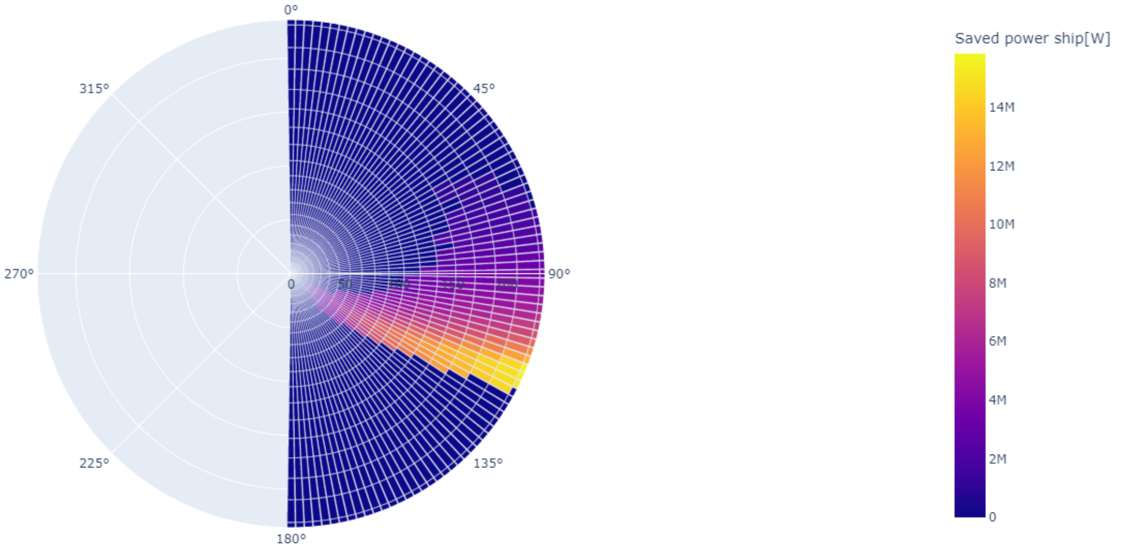


Plot 11 knots largest rotor setup

Figure 7.6: Power savings for different rotor setups



Plot 11 knots medium rotor setup max 22m/s

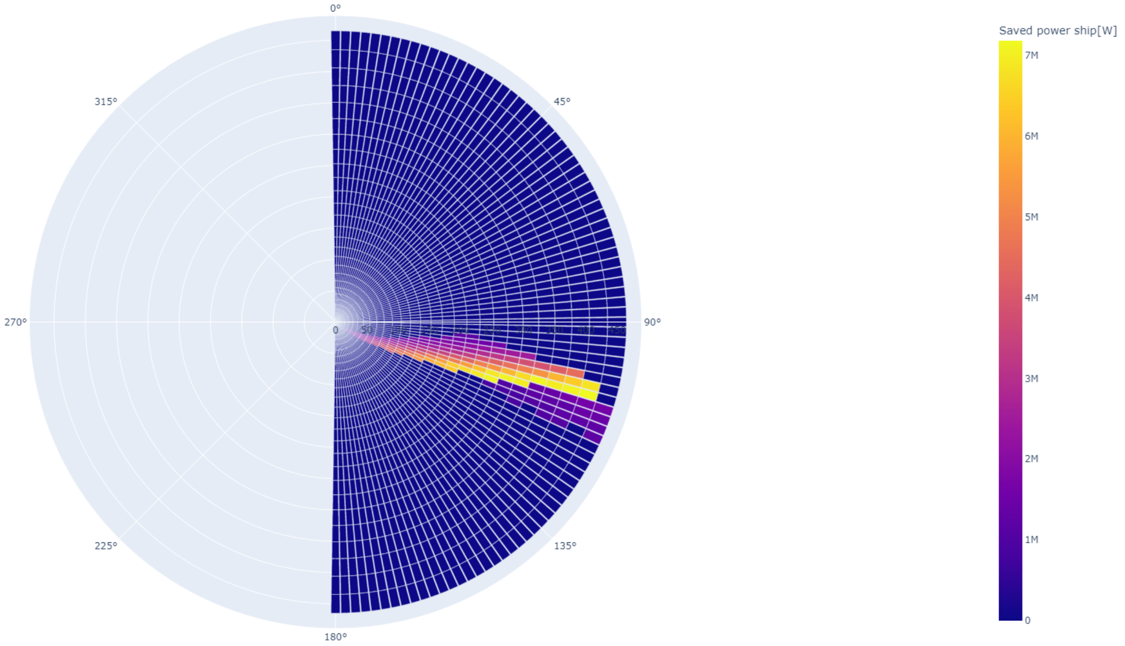


Plot 11 knots largest rotor setup max 22m/s

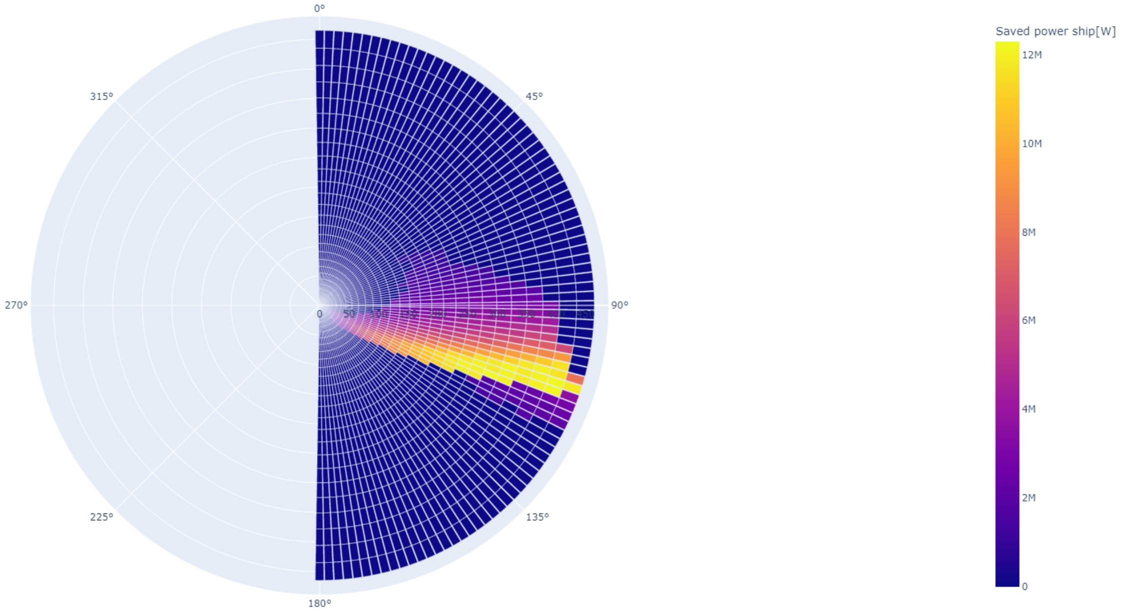
Figure 7.7: Power savings for different rotor setups max 22 m/s

The plots are quite similar; however, there are significant differences in the actual power generated. Particularly, the bars on the right describing the power generated corresponding to the colors show that the power generated is significantly larger as the rotors grow in size. However, there are few significant differences with regard to the wind angles. The highest effects still come from angles around 110°, and the power gradually fades the lower the angle gets. While it is difficult to see the effects in the lower angles, this is enhanced in the plots that are zoomed in as shown above. However, the color scheme still makes it difficult to see the effects when they get very small.

We should also look at how different ship speeds can affect the rotor performance. It is obvious that the vessel's speed will have some effect, but it can be quite surprising to see how vessel speed affects rotor performance. Below are 4 plots with the medium-sized rotor setup, but for different speeds.

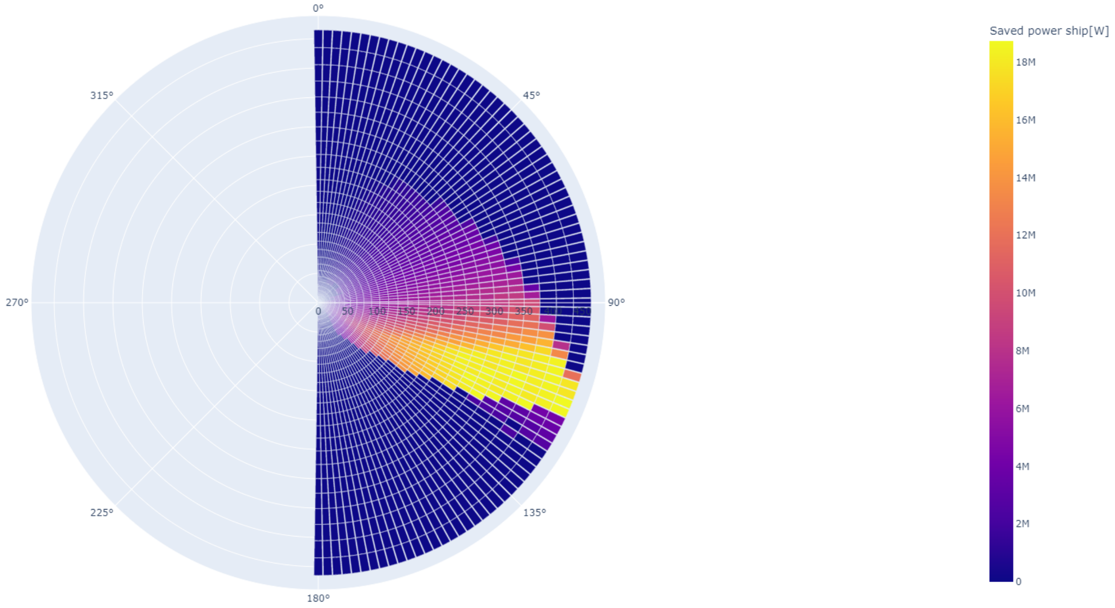


Medium rotor setup 6 knots

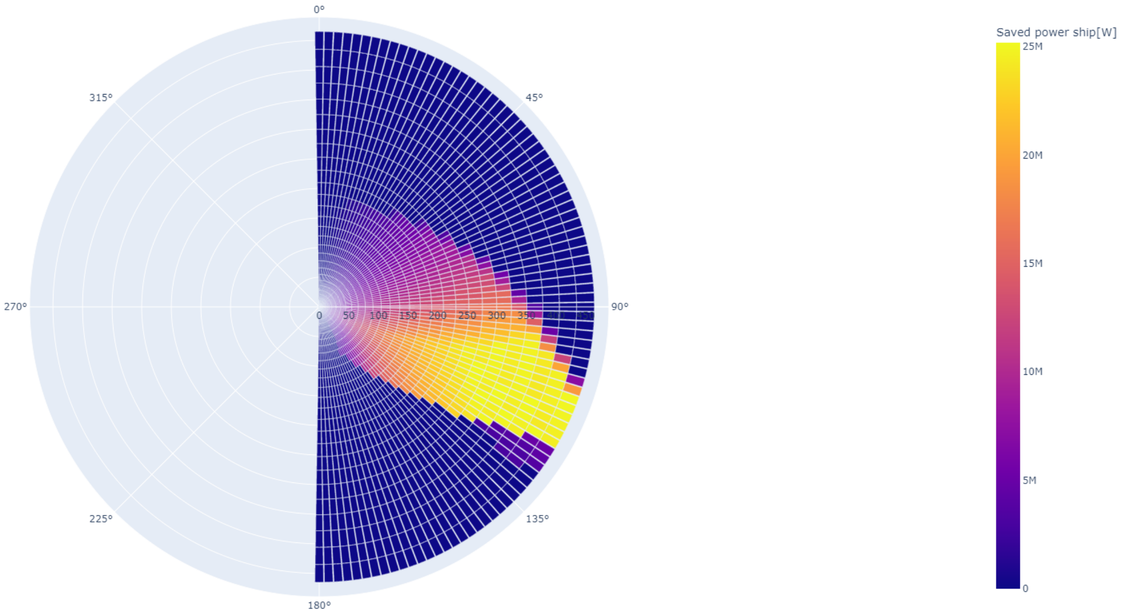


Medium rotor setup 10 knots

Figure 7.8: Power savings wind speeds 6-10 knots



Medium rotor setup 15 knots



Medium rotor setup 20 knots

Figure 7.9: Power savings wind speeds 15-20 knots

As seen, speed is essential in order to achieve good savings from Flettner rotors. Increasing ship speeds not only increases the absolute power savings, as described by the bar on the right side of the plots, but it also greatly impacts the savings from the different wind angles. This is due to the hull's limited capability of producing side force at low speeds. The obtainable thrust from the Flettner rotors is then limited for low speed due to the hull's demand for the force to be balanced. The rotors' effect will thus be larger for larger vessel speeds and also more versatile. This is further illustrated by the plot below, which is the same as the 20 knots plot above, but with a max wind speed of 22m/s.

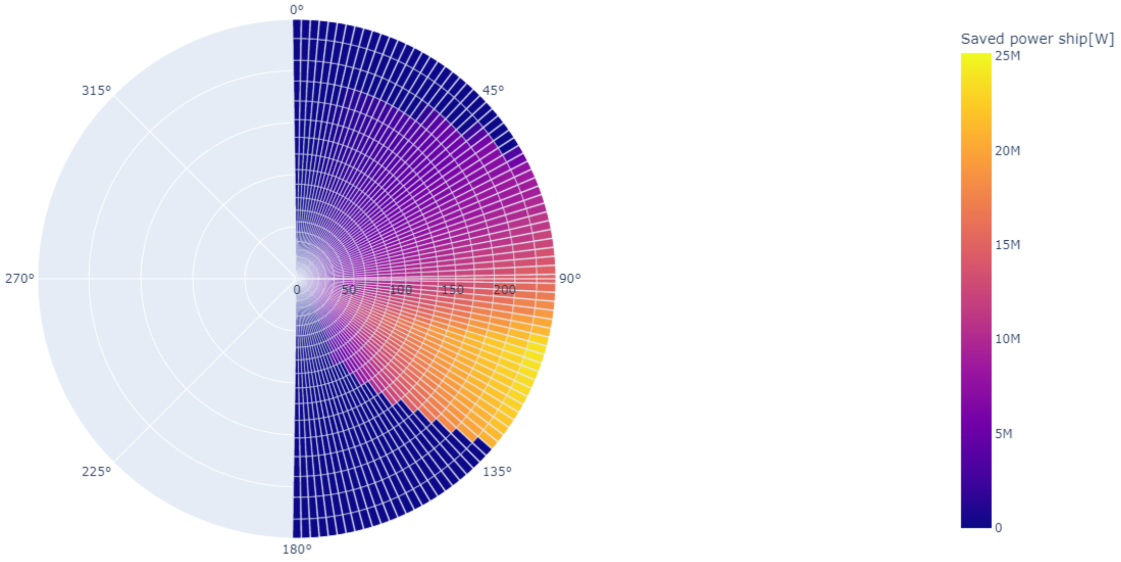
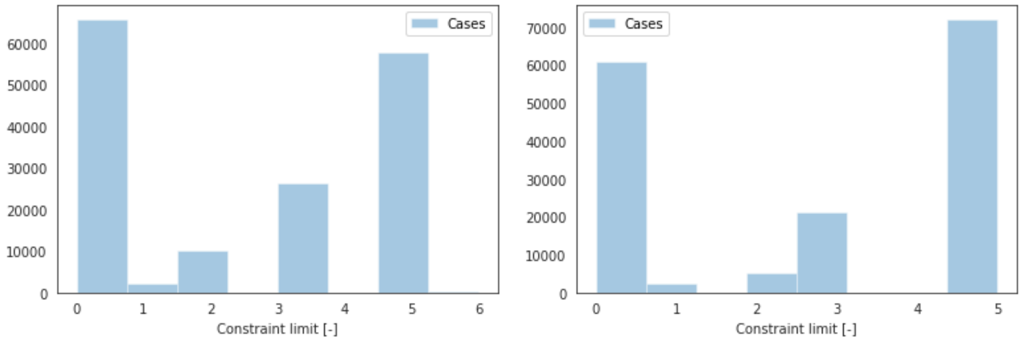


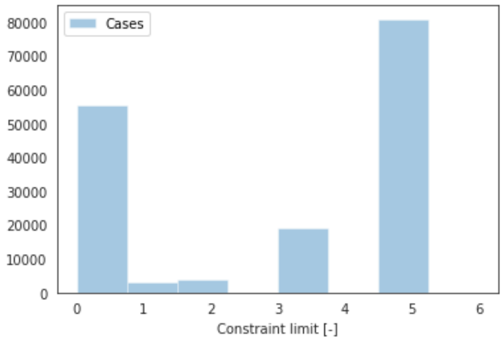
Figure 7.10: Power savings for 20 knots medium setup max 22m/s

While these results look promising, there are some surprises in the results as well. One of these is the large amount potential cases that trigger a constraint leading to a 0 value.



Constraints triggered for smallest setup

Constraints triggered for medium setup



Constraints triggered for large setup

Figure 7.11: Constraints triggered

As shown above, the constraint that is triggered the most is constraint 5 which relates to the side force on the hull. (Constraint 0 refers to cases where no other constraints are triggered). This is somewhat surprising and will be discussed a bit further later.

A short summary of the most important results from the performance simulation is found in the table below.

Parameter	Small setup	Medium setup	Large setup
Average savings [W]	2377464.98	2880552.22	3030287.59
Max Savings [W]	20999960	31376361	37304699.7
Number of cases with power savings	65770	61010	55194
Number of cases with triggered constraints	96393	101153	106964
Most common constraint triggered	5	5	5

Table 7.3: Key simulation results

This table shows that the power generated increases with rotor size and that there is a clear gap between the two larger ones and the smallest ones. However, it also shows that the larger rotors are seemingly less reliable as there are more cases without power generated the larger the rotor gets.

7.3 Collected weather data

Copernicus Marine was used for the weather data collection as described in Section 6.3. The selection of data collected is based on the AIS data for the chosen vessel. This means that the coordinates and date-time from the AIS data can be used to determine what data points to download from Copernicus Marine. This process is done through a set of python codes that downloads the data points from Copernicus. Unfortunately, the data is downloaded in single elements, meaning the code has to be ”looped” for every data point. This means that the download will take a very long time, considering the dataset consists of over three thousand points. When the data is downloaded, it is stored in an excel file that can later be used to compare with the simulation data. With the data all downloaded, it became clear that, while the original dataset had more than 3000 data points, there were only about 2500 weather points. This is mostly due to a series of constraints in the code and some errors during downloads. For example, some of the AIS data refers to points that are technically on land according to Copernicus Marine, and there is, therefore, no data for these points. This is, for example, the case with any points inside the Suez canal or in certain ports that the vessel has visited. However, 2500 points should be more than sufficient to paint a somewhat accurate picture of the real case. Some interesting things about the weather in the visited routes can also be discovered, as well as some interesting correlations between the density in AIS data and the averages for wind speeds and angles.

With the weather data saved to excel, some data processing was be done to find the key parameters for the dataset. First, the average and median wind speeds can be found. These are 4.76m/s and 4m/s, respectively. Since the median is so much lower than the average value, it is reasonable to assume that there are a significant amount of points with values in the 1 to 3 m/s region and that the points with higher values are rarer but also significantly larger than 4 and could likely range in the 8-12 area. This is further reinforced when looking at the distribution of wind speeds, as shown in the plot below.

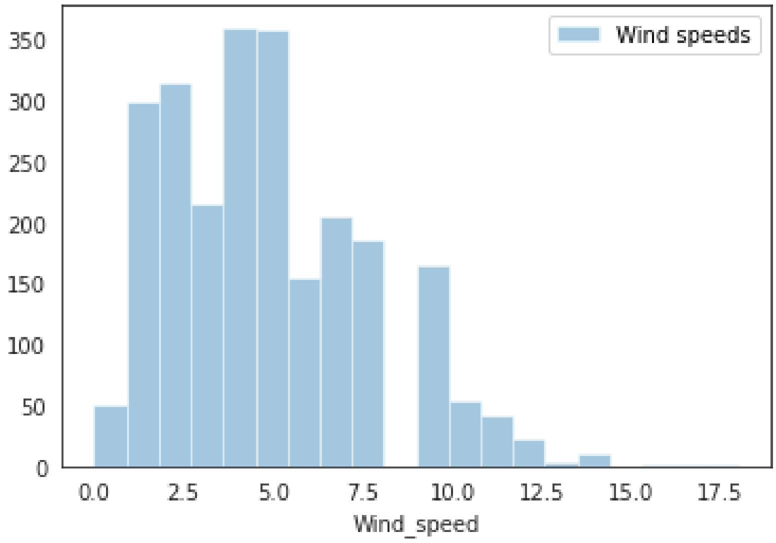


Figure 7.12:]
Wind speed distribution [m/s]

As seen from the plot, the values are spread quite evenly around the 1-5.5 region, with fewer cases of the higher values. There is a significant amount of regions with wind speeds around 6m/s and around 10m/s as well. However, it is clear that for the majority of the vessel's sailing time over a year, the wind speeds are lower than 6 m/s. Some work in excel also reveals that the maximum value for wind speed is 18m/s, and the minimum is 0. The most common value is 4m/s. What this means for the case will be further discussed later.

Another interesting aspect of the weather data is the wind angles. This is very important for the calculated effect from Flettner rotors, and difficult angles will often lead to poor performance results. Below is a windrose plot from the collected wind data.

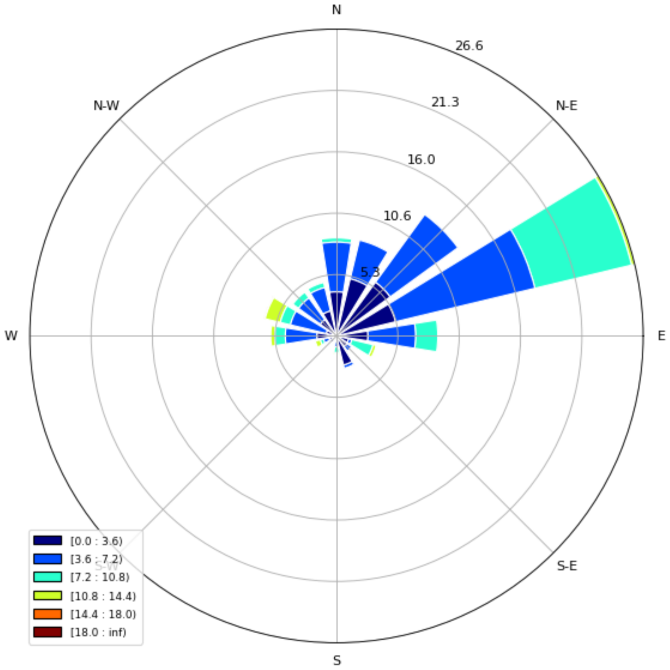
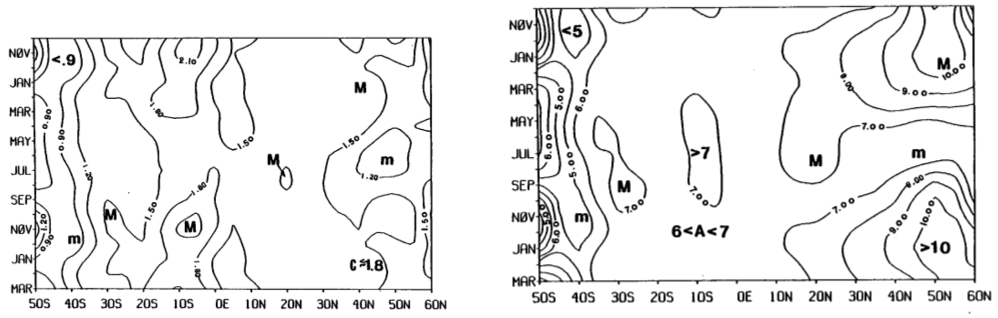


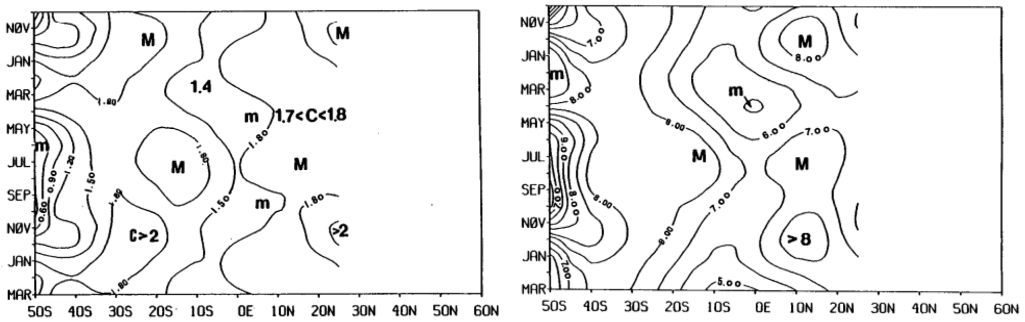
Figure 7.13: Windrose plot

As seen in the windrose plot, the wind data is not optimal for Flettner rotor efficiency. Usually, some higher angles would be desirable to achieve a good rotor effect, but here there is a large majority of angles below 80°. While it is difficult to say much before comparing the weather data with the simulation results, this could lead to poor performance results.

It is also natural to question the accuracy and validity of the data when looking at the plots above. In order to check how unusual the collected data is, it is possible to compare it to a Weibull distribution of wind speeds for some of the regions the vessel has traveled through frequently. The Weibull distribution is commonly used to describe the wind conditions in regions and usually gives a good picture of the distribution of wind speeds in a specific region. In the paper Pavia and O'Brien 1986, the authors use a series of wind observations in the world's different oceans to determine the Weibull parameters for different regions. These parameters are shown in Hovmöller diagrams with the varying parameters shown in regards to the different months in a year and the varying latitudes. Below are these plots for the Atlantic and Indian oceans as taken directly from Pavia and O'Brien 1986. Note that for all the plots M = maximum and m = minimum, as well as the fact that three months are repeated at both ends of the diagrams



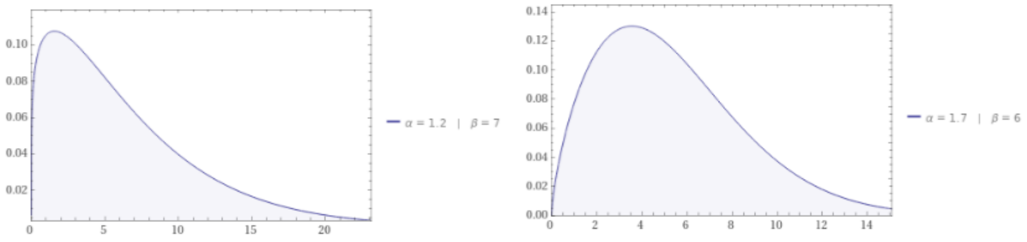
Alpha Atlantic ocean, contour interval 0.3 Beta Atlantic ocean



Alpha Indian ocean, contour interval 0.3 Beta Indian ocean

Figure 7.14: Weibull distribution parameters

If these parameters are then used to generate some Weibull distributions, they can then be compared to the datasets collected previously. This allows for an insight into how well the original data represents the statistical norm in the regions. With the assumption that the gathered wind speeds were particularly low, it was decided that the Weibull distributions would be generated with data representing the calmest period of the year. For the North Atlantic, this would be July, and for the Indian ocean, it would be around May. Below are the plotted distributions.



Weibull distribution for 40°north in the Atlantic ocean in July Weibull distribution for 0°north in the Indian ocean in May

Figure 7.15: Weibull distributions

It is now possible to find the average wind speed for this period in the north Atlantic as 6.58 with a mode of 1.57. This distribution is quite far off from the wind speeds gathered previously. However, when looking at the distribution of the Indian ocean, things are more revelatory. Here, the distribution has clear similarities with the collected data. The distribution has a mean of 5.35 and a mode of 3.56. This is quite close to what is seen in the collected data and leads to believe that the chosen vessel has spent a disproportionate amount of time in this region compared to others.

While this is not necessarily a huge problem, it can be important to remember going forward.

7.4 Combining simulation results and weather data

With all the above steps completed, it was time to combine the results from the different stages to learn how effective WASP would be in this case. This was done by comparing the weather data sheet with the simulation results sheet. A python code iterates its way through the weather data set, converting the values into whole numbers. With this done, there should be a matching data point in the simulation results for every data point in the weather data list, where the weather angles and speeds are the same so that the WASP output for any given point in the weather dataset can be found.

In order to get a better understanding of the savings produced, it was decided that the saved power should be converted into percentile fuel savings. Fuel savings is the most easy-to-understand description of WASP performance, and it is also a much more relevant statistic with respect to economic calculations and emission reduction. The code already used engine power derivatives to determine the saved power, and it was thus quite simple to adapt it to fuel savings through the specific fuel consumption of the vessel. This then allowed for plotting the power savings for a given vessel speed and different wind angles, as shown below.

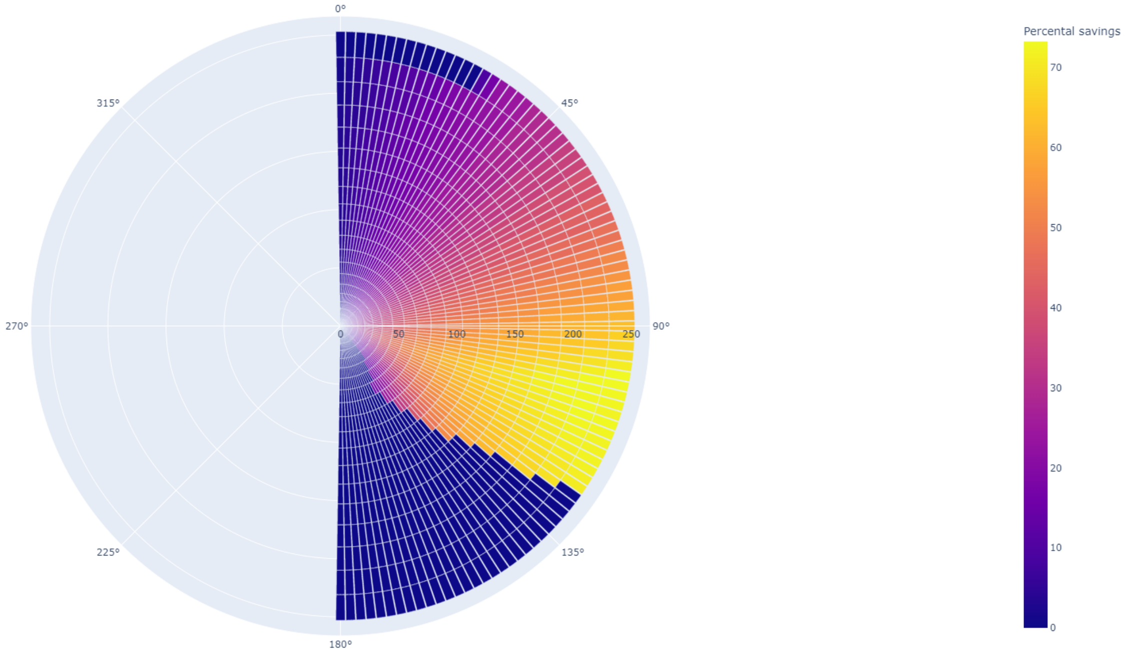


Figure 7.16: Savings in % for different wind speeds and ship speed 16 knots

This plot shows the savings in % as different colour, ranging from 70% in yellow to 0% in blue. An interesting thing to note here is the very large amount of savings generated. To have savings of over 50% would be extremely unusual and needs to be investigated further. When combined with the AIS and weather data a new excel sheet was created with only the cases that were relevant for the chosen vessel. This was then processed and the most important details were extracted and are shown in the table below for all the different rotor setups.

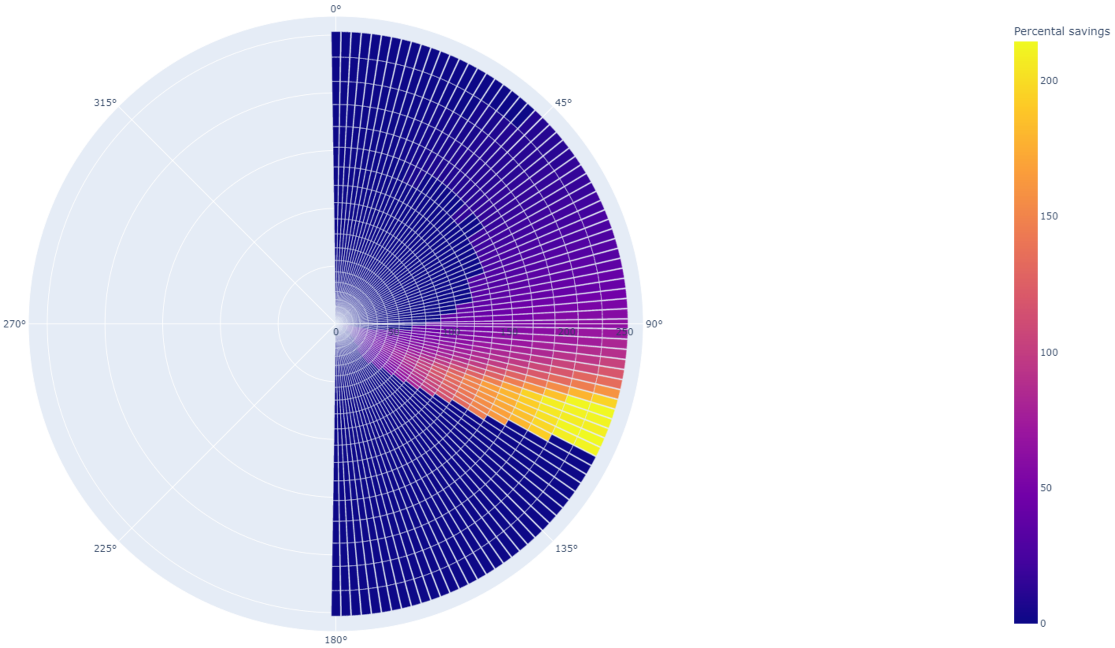
Parameter	Small setup	Medium setup	Large setup
Average savings [W]	302400.865	154227	105740.77
Max Savings [W]	3620636.93	3909666.88	4117232.38
Number of cases with power savings	295	61	46
Number of cases with 0 power savings	2141	2375	2390
Average wind speed	4.77	4.77	4.77
Average savings [%]	4.87	3.51	2.77
Max savings [%]	255.64	369.32	393.55
Total cases	2436	2436	2436

Table 7.4: Key data from the compared datasets

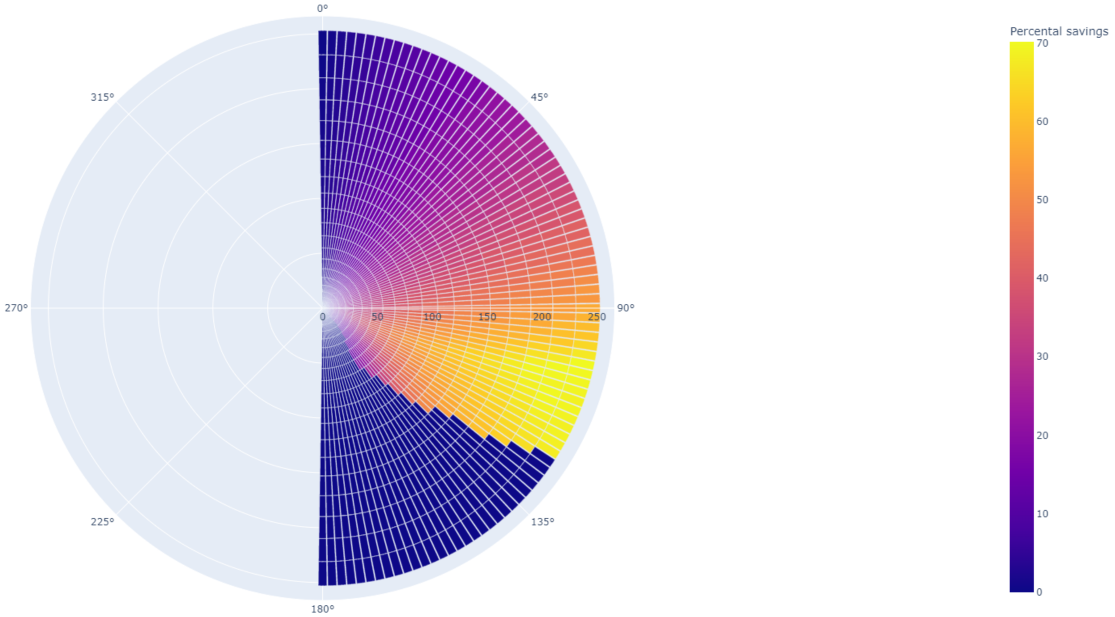
As seen in the table, the results from this case were very unlikely. Nearly all of the vessel cases have 0 generated power; however, some of the cases have fuel savings of 250+%. It is also known that a different program, for example, Lloyd's Flettner rotor savings calculator estimates 9.1% savings in global conditions for the vessel. (Lloyds 2022b) This leads to believe that there is some sort of error or bug in the performance estimation program.

7.5 Computational challenges

When processing the results for Section 7.4, it was decided to convert the saved power from the original plots and code into percentile fuel as described earlier. This was already implemented in the code; however, some small modifications had to be made to print the data. This was where some significant issues in the code were discovered. The first of these was discovered when the percentile savings for the vessel at different vessel speeds was plotted, as shown below.



Fuel savings in percent for smallest rotor setup at 10 knots

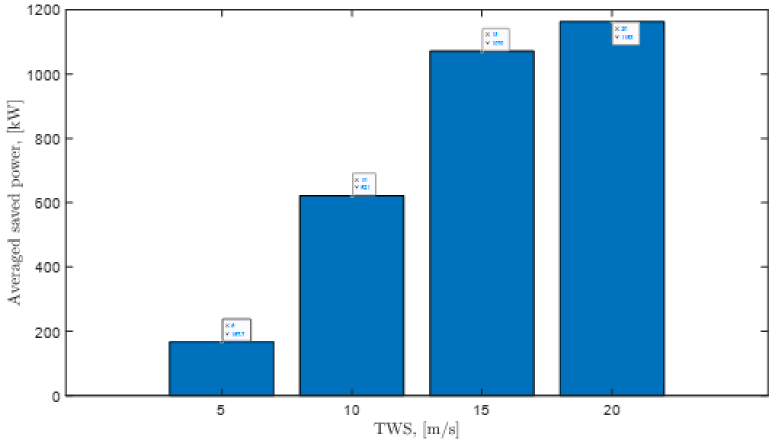


Fuel savings in percent for smallest rotor setup at 15 knots

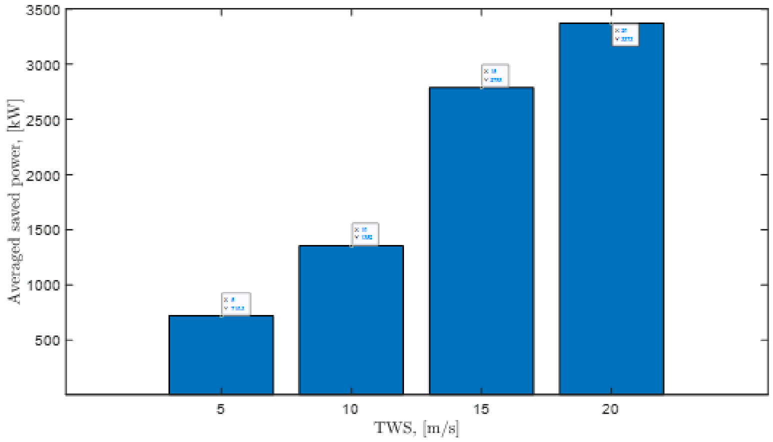
Figure 7.17: Percentile fuel savings

As seen from in Figure 7.17, there is a maximum of 200% savings for the 10 knots case. This can seemingly be fixed by setting the maximum value to 100%. However, this only fixes the issues on a surface level. The main issue here is not the specific numbers but rather the generally very high values. For the 15 knots case, the maximum is 70% savings which is still very high. As shown in section chapter 4 most studies find savings of up to 20/30%, but rarely higher. For this case, having several scenarios with savings of over 60% is strange.

While investigating this, some bugs and inaccuracies were discovered in the code. These bugs and inaccuracies include an insufficient model for hydrodynamic force generation, yaw moment balance not included, the height of the wind profile being too short, and an issue where 100% of required power can be generated with tailwind at very low wind speeds for an unknown reason. The surprising results found in my plots above are likely due to a combination of all these bugs. Drazen Polic, the postdoc who made the program originally, worked tirelessly over multiple weeks to fix the issues and get the code in working condition. Unfortunately, the project's time constraints made it impossible to complete the code on time. However, he did manage to run some of the improved iterations of the code and send some plots illustrating the differences. The top figure shows the results from the original code with fixed wind speed profile height, and the bottom figure shows the results with a new theory for hydrodynamic force generation.



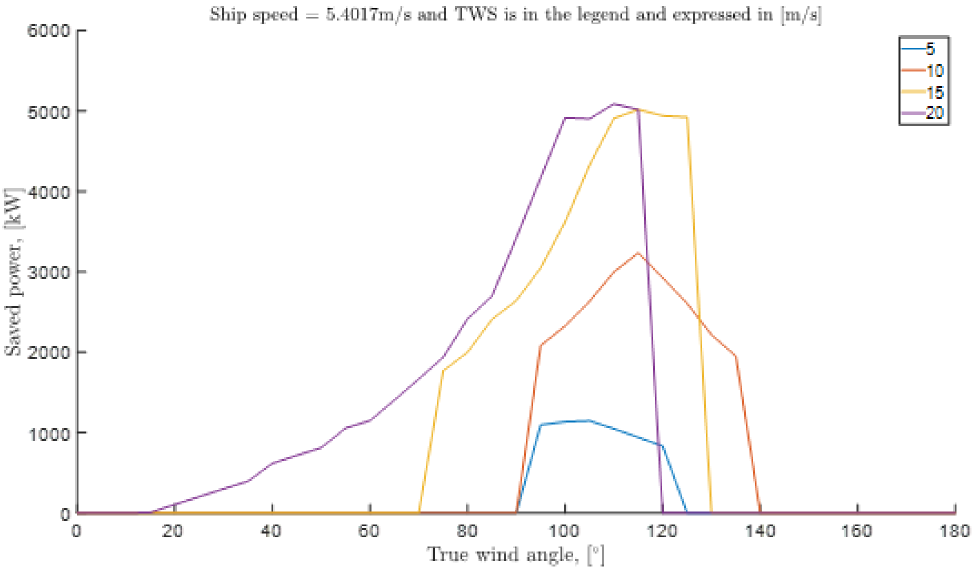
Average saved power for different wind speeds with original code with fixed wind profile height



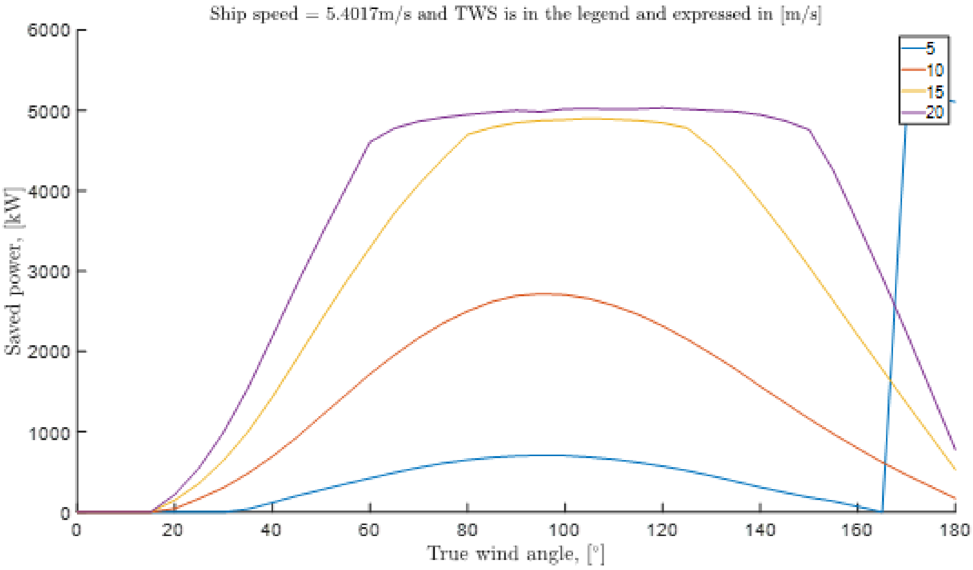
Average saved power for different wind speeds with the new hydrodynamic theory

Figure 7.18: Saved power with new and old hydrodynamic theory for different wind speeds

The figure at the bottom has a significantly higher maximum saved power and a more natural power increase interval between the different speeds. The improvements in the new model are further illustrated in the plots below, showing the saved power for different wind angles.

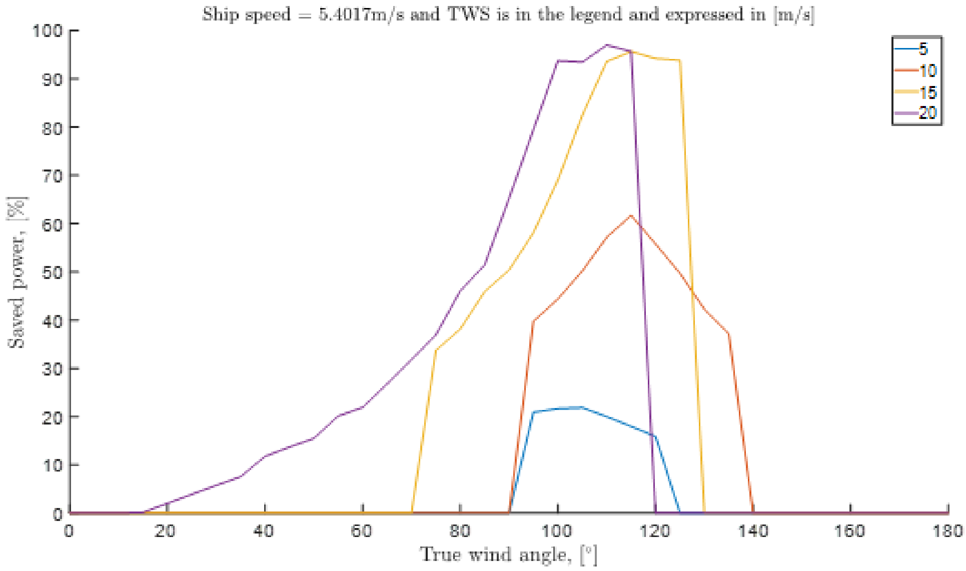


Saved power for different wind angles with a ship speed of 5.4 m/s and wind speeds in different colours using the original model

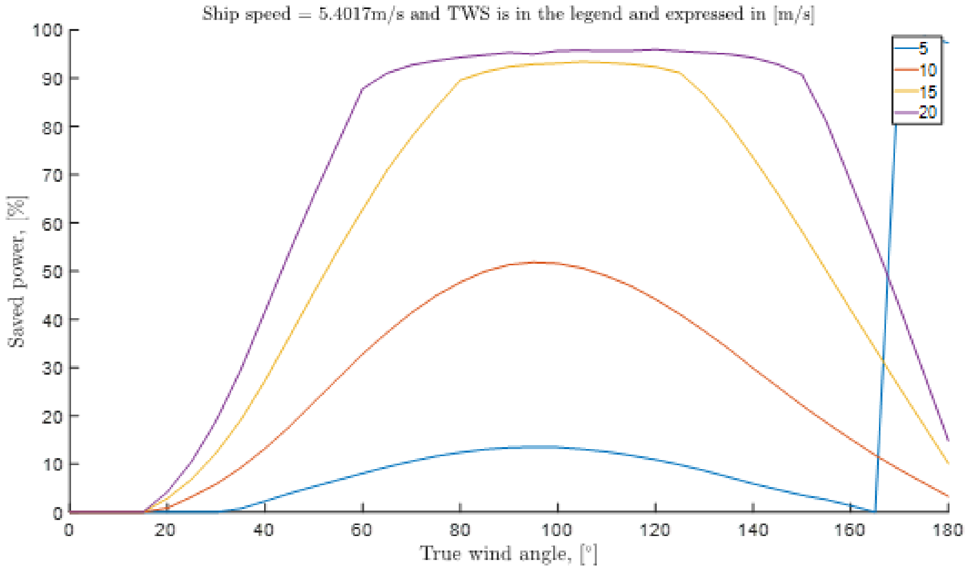


Saved power for different wind angles with a ship speed of 5.4 m/s and wind speeds in different colours using the new hydrodynamic theory

Figure 7.19: Saved power with new and old hydrodynamic in W theory for different wind angles



Percentile saved power for different wind angles with a ship speed of 5.4 m/s and wind speeds in different colours using the original model

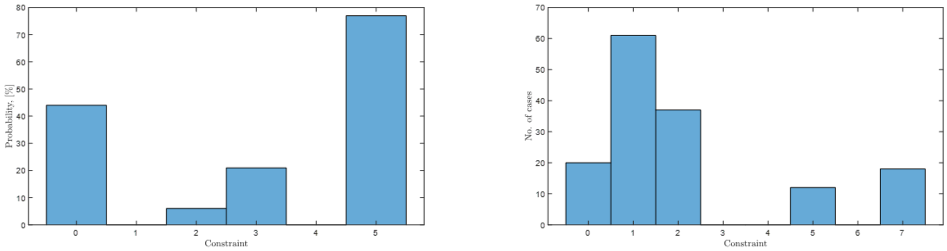


Percentile saved power for different wind angles with a ship speed of 5.4 m/s and wind speeds in different colours using the new hydrodynamic theory

Figure 7.20: Saved power with new and old hydrodynamic in % theory for different wind angles

These figures work well to illustrate how significant the errors were. The drastic drop in saved power for angles above 120°in the original model is shown. The percent having been set to max 100%, and the error with large power generated at tailwind for the graphs at the bottom can also be seen clearly. This final error with power generated at tailwind is seemingly unexplainable, and neither Drazen nor anyone else has figured out why it occurs at the time of writing this.

Additionally to the changes in power savings, the constraints were also plotted for the old and new hydrodynamic models. These show that while the old model had mostly constraint 5 (side force on hull) being triggered, the new model instead has mostly constraints 1 and 2 (max wind speed and max RPM) being triggered with a few cases of constraints 5 and 7 (max side force on rotors). This is due to the new theory leading to different hydrodynamic lift and drag. This means that the performance is now seemingly more limited by wind speeds and rotor performance than the side force on the hull as in constraint 5.



Triggered constraints with the old hydrodynamic theory

Triggered constraints with the new hydrodynamic theory

Figure 7.21: Triggered constraints for the old and new hydrodynamic theory

Part III

Concluding remarks

Chapter 8

Discussing the strategy

Using the strategy in a case study makes it possible to take this experience into account when describing the model, its disadvantages and advantages. This is very important in order to make improvements to the strategy and potentially make it more viable for commercial use.

8.1 Disadvantages

While the model has significant advantages, there are also some disadvantages to the current setup. The first of these is the model's reliance on a good performance estimation program. This was proven when just weeks before the due date of this project, several bugs were discovered in the used performance simulation program that needed to be fixed by the program's creator. For the case results to accurately reflect the method's accuracy, many of the simulations would have to be redone. Due to time constraints, this was not done; however, several plots were created to show the differences between the old and new programs. This is a large potential issue for anyone else trying to use the proposed method. Since a performance estimator has not been made specifically for this project, any shipowner wanting to use the proposed strategy would have to create or find their model. These models vary drastically in accuracy, ease of use, and error support from the provider. This problem also affects the ease of use for the strategy, as a lack of accurate models can make the proposed strategy complicated to use.

A similar problem can be found in the AIS and weather data. There are regularly significant discrepancies in AIS data compared to the real vessel routing and operations. This is mostly related to the fact that the vessel, at any point, can turn off its AIS transmitters. This is particularly common in some regions around the world, for example, the south china sea. Suppose this occurs in the dataset for the chosen vessel. In that case, the results will either be significantly less accurate and representable for the chosen vessel, or there will be a much more difficult job regarding the processing and adapting of the AIS data. This then further affects the gathering of weather data. Since the weather data is gathered based on the AIS points, a lack of AIS points in a certain region will lead to a lack of weather data for that same region. This means that a vessel spending a significant amount of time in for example, the south china sea might have performance estimates that do not take the weather of this region into account but instead accounts for only trans-pacific travel.

It should also be mentioned that while the proposed project strategy is quite simple for someone with at least some knowledge of coding, it has some limitations that make it complicated for anyone unfamiliar with simple coding. Considering the time it takes to complete a full project like this, it should also be mentioned that there are significantly easier and less time-consuming methods that can still produce acceptable results for many cases. The Lloyd's Flettner rotor savings estimator (Lloyds 2022a) is an example of such a program that takes less than a day to use for a vessel of choice. However, this does not account for specified routes at specified times and will therefore diverge somewhat in its results if the vessel has multiple uncommon routes.

The current strategy also does not account for potential errors in the different steps, as seen in the case study. Errors that have their root in an early step are not fully discovered until much later and, in some situations, might not be discovered unless the results are thoroughly double-checked. This is because small errors in the performance estimation program can affect different vessels differently. The error became quite clear when the results were processed and investigated for the code and vessel combination used in this thesis. However, that might not be the case for other combinations. Multiple other students used the same code in their thesis and found the results to be much more realistic. This means that in order to be certain of the prediction accuracy, either a system for double-checking the results has to be set up or the programs used must be proven reliable for multiple previous cases.

8.2 Advantages

Firstly, the method shows that it has several advantages over previous methods. These have to be put into perspective when considering the other options a shipowner could have in order to determine the feasibility of WASP. The clearest advantage is that the process allows for a good combination of accuracy and value. The model should provide a much more accurate description of the potential added value of the rotors than if the generic estimates provided in previous articles for "generic" vessels and trading routes are used. With vessel positioning data, the method can accurately predict the potential for a specific vessel instead of a vessel that is only similar to the one being investigated. Considering how different several studies has found the performance to be for vessels and routes that are only slightly different, this is very important. The method is also relatively cheap, depending on how much can be done in-house and how many programs and datasets must be acquired from outside sources. Even if the acquisition of a rotor performance estimation program can be costly, it is likely not nearly as costly as model testing.

Another advantage of the model as it is set up now is that it is quite easy to use. This was one of the goals for the project as it is a large part of what separates it from previous studies. Generally, it is easier to convince shipping companies to at least check the potential if this process is quick and simple to perform. Many companies are reluctant to commit to a long-term project with uncertain results; however, if the testing process is easy and cheap, it might be easier to convince them to try it. This ease of use is obviously reliant on the programs one plans to use being available and relatively simple. Unfortunately, this is also one of the main issues with the current strategy, and some potential solutions to this are discussed in Section 8.3.

8.3 Improvements

As seen in Section 8.1, there are some issues with the current method. For the strategy to be viable for commercial use, it is important to look at some of the improvements that can be made to fix these issues. The most important of these is checking the validity of the results. It can easily become a time-consuming and expensive process and is difficult to solve. However, the easiest solution would be for the strategy to have specified programs that should be used instead of the users picking the programs themselves. For this to work, there would have to exist a commercially available program that can be recommended, which is difficult at this time. This is largely due to the fact that most WASP performance estimation programs that are currently available are still in the development phase and not yet completed. This means that there is little empirical evidence to prove their accuracy. As the interest in Flettner rotor technology grows over the coming years, this might change, and it might be possible to utilize more stable and reliable programs.

The issue of program reliability is also relevant for the other programs that have to be used during the process and the data used. For the strategy to be viable for use, it has to produce accurate results, which is only possible if the input data is accurate. Therefore, it would be advantageous for a shipowner to collect as much as possible of the data from reliable sources and use experienced programmers for the data processing. However, part of the concept behind the strategy is that it is supposed to be relatively easy to use, even with limited programming experience. An alternative could be combining multiple steps into a single program that performs the analysis without outside input beyond initiating the program. In theory, it should be possible to combine all the processes in phases two and three (see Section 5.2) of the project into a single program that only requires the user to input the vessel and operation parameters. This would eliminate the potential for human errors in data processing, making the program easier to use and more reliable.

Chapter 9

Conclusion

The purpose of this thesis was to create a method that could be used to predict Flettner rotor performance for a select vessel accurately. The background for this project was the increasing focus on emission-reducing measures in the shipping industry and the high cost of implementing these concepts. The current methods for Flettner rotor performance estimation insufficiently cover the effects of operational profiles, and it was therefore of interest to create a method that included these effects.

By investigating previous methods and adapting these, the model was created. The model consisted of four main parts summarised in the diagram below.

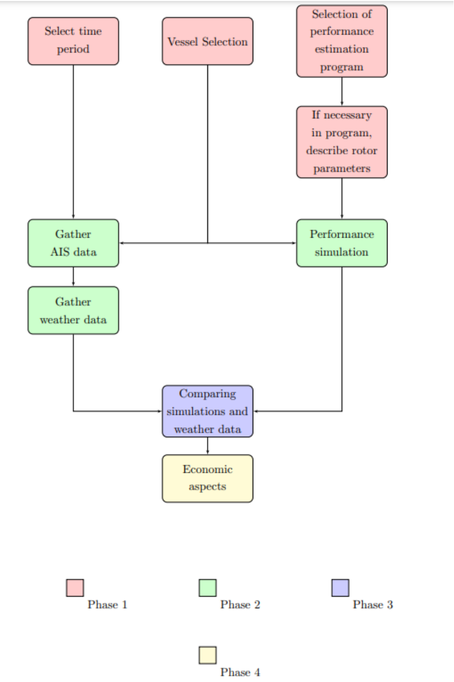


Figure 9.1: Project structure diagram

This model was then tested on a case. The case study covered the installation of 5 Flettner rotors in three different sizes for the bulk carrier Ma Lian Hai. In the case study, an externally written performance estimation program was used, and several errors were found in this program that caused the case results to become unreliable. The case study found several disadvantages and potential improvements to the original method. Mainly, the method was highly reliant on external programs that were largely untested and unreliable. The issues with these programs lead to the conclusion that the method should be updated, with specific recommendations for programs to use. If this is not possible, an extra step of result verification must be added to the model to check for potential errors.

The proposed strategy was initially intended to be easy to implement for someone with limited coding experience. However, this was not the case as it included several accounts of data processing that was more complicated than anticipated. This also highlighted the potential for human error in the phases that combine different datasets and programs, leading to the belief that an improvement to the method could be made through the combining of the different programs used into a single larger program that required less human interference and is thus not only more reliable, but also easier to use.

While the case study illustrated some of the difficulties one could encounter when performing analysis of Flettner rotor installations, it also illustrated the model functionality. The combination of AIS and weather data allowed for the estimation of vessel and rotor performance for the specific vessel case and could be adapted to any case chosen. It is also known that the method could be used to determine the economic viability of Flettner rotor installation, given vessel performance parameters.

9.1 Further work

Below are suggestions for further work that can improve the model or give better insight into Flettner rotor performance estimations.

- Improve performance estimation programs to include an optimisation algorithm that optimises rotor sizes and setups.
- Combine Flettner rotor performance estimation program with AIS and weather data downloading and processing in a single program, reducing human interference while improving reliability and ease of use. Such a program could also be further expanded on to perform nearly the entire process without interference if it were to also perform economic assessments based on current time-charter and fuel prices.
- Improve the current method by including recommendations for programs to use. This would also require the development of a reliable and easy to use program that can be recommended.

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Appendix

A Comparison code for weather, AIS and simulation results

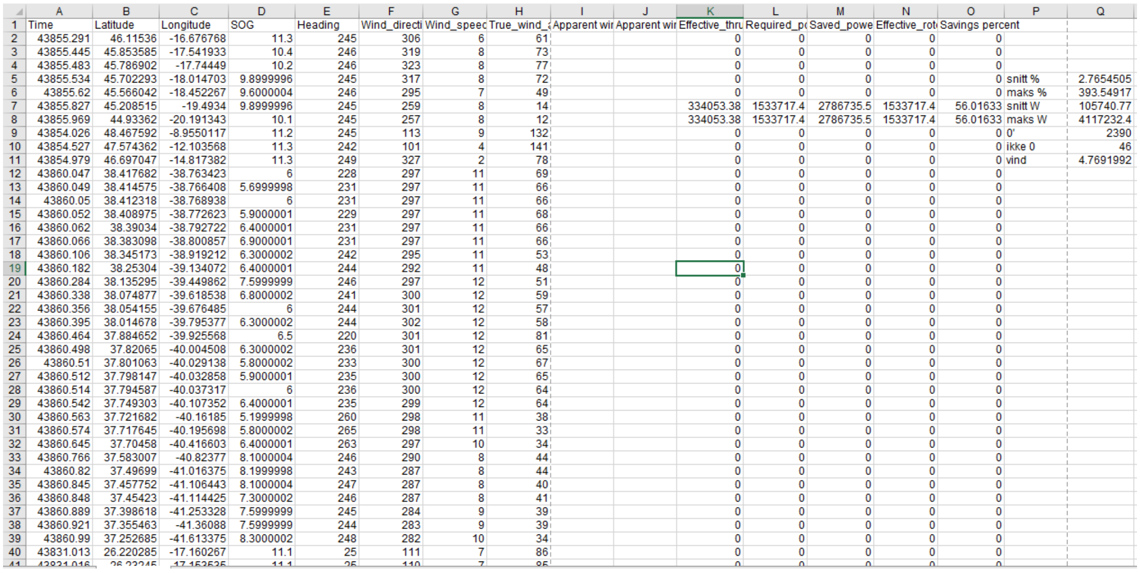
```
def WASP_Output(dataframe, wind_direction, Heading, ship_speed, wind_speed):
    #true_wind_angle = wind_direction - ship_heading  # calculating true wind angle
    true_wind_angle = wind_direction - Heading  # calculating true wind angle
    if true_wind_angle < 0:
        true_wind_angle = true_wind_angle + 360
    if true_wind_angle > 180:
        true_wind_angle = 360 - true_wind_angle

    # rounding of to nearest column value
    ship_speed_rounded = round(ship_speed * 4) / 4  # nearest 0.25 and converting to m/s
    if ship_speed_rounded < 4:  # This is temporary
        ship_speed_rounded = 4
    if ship_speed_rounded > 24:
        ship_speed_rounded = 24
    wind_speed_rounded = round(wind_speed)  # nearest integer
    if wind_speed_rounded < 1:
        wind_speed_rounded = 1
    true_wind_angle_rounded = round(true_wind_angle / 2) * 2  # nearest even number
    #print(true_wind_angle_rounded)
    #print(wind_speed_rounded)
    #print(ship_speed_rounded)
    # Finding the row corresponding to the given conditions
    corresponding_row = dataframe.loc[
        (dataframe['Ship speed [kn]'] == ship_speed_rounded) &\
             (dataframe['True wind speed [m/s]'] == wind_speed_rounded) & \
                 (dataframe['True wind angle [deg]'] == true_wind_angle_rounded)] \
                      # , 'Saved power ship[W]']
    #print(corresponding_row)
    saved_power_ship = corresponding_row['Saved power ship[W]'].values[0]
    effective_rotor_power = corresponding_row['Effective rotor power [W]'].values[0]
    required_power_ship = corresponding_row['Effective rotor power [W]'].values[0]
    effective_thrust = corresponding_row['Effective thrust [N]'].values[0]
    savings_percent = corresponding_row['Percental savings'].values[0]


    return saved_power_ship, effective_rotor_power, required_power_ship,\
         effective_thrust, savings_percent
```

B Simulation constraints descriptions

```
 % FR wind speed limit, note const_limit stays 1
        if max(v_wind)< 35
            % FR rpm is evaluated based on the mean wind speed along the FR
            v_wind_mean = mean(v_wind(h>(Deck_height+Rotor_base_height)...
                &h<(Deck_height+Rotor_base_height+Rotor_height)));
            % Aspect ratio FR
            c_AR = Rotor_height/Rotor_diameter;
            % Diameter ratio FR
            c_DR = Rotor_end_plate_diameter/Rotor_diameter;
            % Min spin ratio FR
            c_SR_min(ii,1) = 0.5;
            % FR rpm round by the factor 5
            Rotor_rpm(ii,1) = max(round(c_SR_min(ii,1)*v_wind_mean/...
                (Rotor_diameter/2)*30/pi/5,0)*5 - 5,0); % modify the last three numbers to change rou

            % iteration over FR rpms
            while Rotor_rpm(ii,1) <= (Max_rpm + 5)
                % FR rpm with increment
                Rotor_rpm(ii,1) = Rotor_rpm(ii,1) + 5;
                % Current spin ratio FR
                c_SR = (Rotor_rpm(ii,1)*pi/30*Rotor_diameter/2)./v_wind;
                c_SR(isinf(c_SR))=0; c_SR(isnan(c_SR))=0;
                % Lift, drag and power coeff vectors
                [c_L,c_D,c_P] = ...
                    c_lift_drag_power(c_AR,c_DR,c_SR,lift_drag_coeff,0);
                % Thrust, side force, and required power per FR unit
                [Thrust,Side_force,Req_power_no1] = ...
                    wind_force_power_profile(rho,Rotor_diameter,h,c_L,c_D,c_P...
                    ,alpha_bearing,alpha_wind,v_wind,0);

                % Total side force
                Total_side_force_new = sum(Side_force)*No_of_rotors;

                % List of constraints
                if Rotor_rpm(ii,1) > Max_rpm
                    const_limit(ii,1) = 2;  % 'too large rpm'
                    break
                end

                if mean(c_SR) > 3
                    const_limit(ii,1) = 3; % 'too large spin ratio for the FR'
                    break
                end
                if Req_power_no1 > Installed_power
```

```
        const_limit(ii,1)  = 4; % 'too large required power for the FR'
        break
    end
    if abs(Total_side_force_new) > abs(Max_side_force_hull)
        const_limit(ii,1)  = 5; % 'too large side force on the hull'
        break
    end
    if sum(Thrust) > Max_force
        const_limit(ii,1)  = 6; % 'too large thrust on the FR'
        break
    end
    if sum(Side_force) > Max_force
        const_limit(ii,1)  = 7; % 'too large side force on the FR'
        break
    end
    if Req_power_no1 < 0.1*Installed_power
        const_limit(ii,1)  = 8; % 'too large el motor is installed in the FR'
    end

    % FR has required power to spin
    if Req_power_no1 > 0.1*Installed_power
```

C Example of cutouts from excel sheets after comparison



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Time	Latitude	Longitude	SOG	Heading	Wind_directi	Wind_speec	True_wind_	Apparent wir	Apparent wir	Effective_thru	Required_p	Saved_powe	Effective_rot	Savings percent		
2	43855.291	46.11536	-16.676768	11.3	245	306	6	61			0	0	0	0	0		
3	43855.445	45.853585	-17.541933	10.4	246	319	8	73			0	0	0	0	0		
4	43855.483	45.786902	-17.74449	10.2	246	323	8	77			0	0	0	0	0		
5	43855.534	45.702293	-18.014703	9.8999996	245	317	8	72			0	0	0	0	0	snitt %	2.7654505
6	43855.62	45.566042	-18.452267	9.6000004	246	295	7	49			0	0	0	0	0	maks %	393.54917
7	43855.827	45.208515	-19.4934	9.8999996	245	259	8	14			334053.38	1533717.4	2786735.5	1533717.4	56.01633	snitt W	105740.77
8	43855.969	44.93362	-20.191343	10.1	245	257	8	12			334053.38	1533717.4	2786735.5	1533717.4	56.01633	maks W	4117232.4
9	43854.026	48.467592	-8.9550117	11.2	245	113	9	132			0	0	0	0	0	0'	2390
10	43854.527	47.574362	-12.103568	11.3	242	101	4	141			0	0	0	0	0	ikke 0	46
11	43854.979	46.697047	-14.817382	11.3	249	327	2	78			0	0	0	0	0	vind	4.7691992
12	43860.047	38.417682	-38.763423	6	228	297	11	69			0	0	0	0	0		
13	43860.049	38.414575	-38.766408	5.6999998	231	297	11	66			0	0	0	0	0		
14	43860.05	38.412318	-38.768938	6	231	297	11	66			0	0	0	0	0		
15	43860.052	38.408975	-38.772623	5.9000001	229	297	11	68			0	0	0	0	0		
16	43860.062	38.39034	-38.792722	6.4000001	231	297	11	66			0	0	0	0	0		
17	43860.066	38.383098	-38.800857	6.9000001	231	297	11	66			0	0	0	0	0		
18	43860.106	38.345173	-38.919212	6.3000002	242	295	11	53			0	0	0	0	0		
19	43860.182	38.25304	-39.134072	6.4000001	244	292	11	48			0	0	0	0	0		
20	43860.284	38.135295	-39.449862	7.5999999	246	297	12	51			0	0	0	0	0		
21	43860.338	38.074877	-39.618538	6.8000002	241	300	12	59			0	0	0	0	0		
22	43860.356	38.054155	-39.676485	6	244	301	12	57			0	0	0	0	0		
23	43860.395	38.014678	-39.795377	6.3000002	244	302	12	58			0	0	0	0	0		
24	43860.464	37.884652	-39.925568	6.5	220	301	12	81			0	0	0	0	0		
25	43860.498	37.82065	-40.004508	6.3000002	236	301	12	65			0	0	0	0	0		
26	43860.51	37.801063	-40.029138	5.8000002	233	300	12	67			0	0	0	0	0		
27	43860.512	37.798147	-40.032858	5.9000001	235	300	12	65			0	0	0	0	0		
28	43860.514	37.794587	-40.037317	6	236	300	12	64			0	0	0	0	0		
29	43860.542	37.749303	-40.107352	6.4000001	235	299	12	64			0	0	0	0	0		
30	43860.563	37.721682	-40.16185	5.1999998	260	298	11	38			0	0	0	0	0		
31	43860.574	37.717645	-40.195698	5.8000002	265	298	11	33			0	0	0	0	0		
32	43860.645	37.70458	-40.416603	6.4000001	263	297	10	34			0	0	0	0	0		
33	43860.766	37.583007	-40.82377	8.1000004	246	290	8	44			0	0	0	0	0		
34	43860.82	37.49699	-41.016375	8.1999998	243	287	8	44			0	0	0	0	0		
35	43860.845	37.457752	-41.106443	8.1000004	247	287	8	40			0	0	0	0	0		
36	43860.848	37.45423	-41.114425	7.3000002	246	287	8	41			0	0	0	0	0		
37	43860.889	37.398618	-41.253328	7.5999999	245	284	9	39			0	0	0	0	0		
38	43860.921	37.355463	-41.36088	7.5999999	244	283	9	39			0	0	0	0	0		
39	43860.99	37.252685	-41.613375	8.3000002	248	282	10	34			0	0	0	0	0		
40	43831.013	26.220285	-17.160267	11.1	25	111	7	86			0	0	0	0	0		

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