Master's thesis

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

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Evaluating the Potential and Viability of Wind-Assisted Ship Propulsion (WASP) for Vessels in the Norwegian Aquaculture Industry

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
Co-supervisor: Ingrid Bouwer Utne
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Master Thesis in Marine Systems Design

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"Evaluating the Potential and Viability of Wind-Assisted Ship Propulsion (WASP) for Vessel in the Norwegian Aquaculture Industry"

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Background

Norway is a leading country in sea-based aquaculture. This sector uses a variety of transport vessels, which collectively generate a large amount of transport-related emissions. With the upcoming and existing greenhouse gas reduction targets for shipping, there is increasing pressure on the industry and the need for appropriate decarbonization technologies. Wind-assisted ship propulsion (WASP) is one of the potential technologies that can lead to a significant reduction in the use of internal combustion engines and thus in a ship's greenhouse gas emissions. With this in mind, the question is whether WASP is a favourable propulsion alternative for the aquaculture sector along the Norwegian coast.

Overall aim and focus

The overall objective is to evaluate the feasibility and performance of WASP technologies in the Norwegian aquaculture sector. A performance prediction method will be developed and the fuel saving performance of such a system will be investigated in a case study. The comprehensive evaluation of the system will be completed by some safety, contextual and economic considerations.

Scope and main activities

This thesis should presumably cover the following main points:

1. Background study on aquaculture in Norway and the fleet used in this area as well as a brief introduction to WASP and the available technologies. Based on this, a recommendation on feasible combinations of aquaculture vessels and WASP technologies shall be given.
2. Performance study of a Flettner rotor installed on a fish feed transport vessel. A performance prediction method for evaluating WASP systems in coastal operations shall be developed and tested in a case study.
3. Further considerations of potential hazards associated with the use of WASP, as well as the contextual and economic aspects of such use, shall be presented for a comprehensive evaluation of the potential and viability of WASP in Norwegian aquaculture.

Modus Operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible supervisor. Professor Ingrid Bouwer Utne will be the co-supervisor of this thesis. The case study is conducted in cooperation with Egil Ulvan Rederi AS. The work shall follow the guidelines given by NTNU for the MSc Master Thesis work.

Stein Ove Erikstad
Professor/Responsible Advisor

Preface and Acknowledgments

This thesis is written a part of the master´s degree at the Department of Marine Technology (IMT) at the Norwegian University of Science and Technology (NTNU). It has a design focus and accounts for 30 ECTs. I conducted a preparation project for this thesis in the course TMR4560 during the fall semester 2021. The title of this project was "Investigation on the Influences of Wind-Assisted Ship Propulsion (WASP) on the Ship Transportation System". Parts of the introduction and background study of this thesis are taken from that project report.

As part of this thesis a case study was conducted in cooperation with Egil Ulvan Rederi AS. I would like to thank especially Ivar Chrisitian Ulvan for providing the required input parameter and information for this study. I also want to thank Stein Ove Erikstad for supervising my thesis and a lot of valuable input and thoughts. Another thanks goes to my co-supervisor Ingrid Bouwer Utne. Further, I would like to thank the WASP-group at NTNU, Benjamin Lagemann, Dražen Polić, Finn Lorange, and William Hyggen Viken, for the cooperation and exchange on our common topic. An additional thanks goes to Benjamin and Dražen for sharing their codes with.

Anna Sophia Hüllein

Sammendrag

Diskusjonen om klimaendringer, oppfyllelse av 1,5°C eller 2°C-målet og alternative energikilder er ikke ny. Først nylig, i forbindelse med FNs klimakonferanse COP26 i Glasgow, oppsto en ny debatt om fremtidens skipsfart og en tilstrekkelig energiforsyning til skipsfartsnæringen. De fleste av de pågående diskusjonene fokuserer på LNG som en overgangsløsning og hydrogen eller ammoniakk som fremtidig drivstoff for skipsfart. Vind propulsjon eller vind-assistert propulsjon (WASP) ser ut til å være ganske underrepresentert i denne sammenhengen, selv om den gir noen unike fordeler ettersom vind er fritt og rikelig tilgjengelig.
Forskningen rundt WASP fokuserer hovedsakelig på internasjonal fart i områder med gunstige vindforhold. Andre nisjer, som kysttransport og mindre fartøytyper, er mindre representert i forsknings- og gjennomføringsprosjekter. Imidlertid kan disse nisjene spille en viktig rolle i utviklingen og distribusjonen av ny teknologi. Norsk havbruk representerer en typisk nisje som det er av interesse å undersøke potensialet i vindassistert fremdrift for. Marint fiskeoppdrett er svært avhengig av skip, men også av et sunt havmiljø som grunnlag for fiskeoppdrett. Utslippene forårsaket av skip har imidlertid en negativ påvirkning på havene og det marine økosystemet. Siden norsk fiskeoppdrett ikke klarer seg uten skip, er det spesielt viktig å redusere skipsutslippene i denne sektoren og beskytte havet. Derfor oppstår spørsmålet om WASP er en passende løsning for å redusere skipsutslipp i norsk havbrukssektor. Dette spørsmålet skal besvares etter en omfattende studie med ytelsesprediksjon som hovedkriterium. Ytterligere hensyn til sikkerhet, kontekstuell situasjon og økonomi kompletterer beslutningsgrunnlaget. For ytterligere avklaring blir det utført en casestudie for et fiskefôrfartøy utstyrt med ett rotorseil.

Denne oppgaven presenterer først en detaljert bakgrunnsstudie. Historien og betydningen av norsk og internasjonal akvakultur pekes på og påvirkningene av klimaendringer og CO_2-utslipp på denne sektoren utfoldes. Det gis en kort introduksjon til WASP-systemer. I tillegg presenteres tilgjengelige systemer og det gjøres generelle vurderinger vedrørende implementering og ytelse av teknologien. Basert på den gitte informasjonen bestemmes mulige kombinasjoner av akvakultur fartøy og WASP-systemer. Bakgrunnsstudien er avrundet med en kort gjennomgang av relevant litteratur om ytelsesprediksjonsprogrammer.
Hoveddelen av oppgaven fokuserer på utvikling av en ytelsesprediksjonsmetode skreddersydd for den spesifikke nisjeanvendelsen av norsk havbruk. En casestudie, utført i samarbeid med Egil Ulvan Rederi AS, er brukt for å illustrere hvordan en slik resultatvurdering kan gjennomføres. I tillegg til beregningsmetodene er valg av inputdata og en tolkning av resultatene beskrevet i detalj. Den siste delen av vurderingen omfatter noen vesentlige sikkerhetshensyn. Den kontekstuelle situasjonen for implementering av WASP i denne sektoren vurderes ved hjelp av en SWOT-analyse. Økonomiske hensyn påpekes i en nyttekostnadsanalyse (NKA) og betraktninger om sosiale eller miljømessige NKA er gitt.

Hovedfunnene i denne oppgaven om gjennomførbarheten av WASP i akvakultursektoren er at de fleste fartøyene som brukes er for små eller ikke har nok ledig dekksareal til installasjonen. For de større fartøystypene, som lasteskip og brønnbåter, er imidlertid rotorseil og sugevinger lovende alternativer.
Ytelsesprediksjonsmetoden har fortsatt et stort forbedringspotensial. Likevel er det vist hvordan en slik metode kan skreddersys til en nisjeapplikasjon av WASP og brukes som til å estimere potensialet til et slikt system. I casestudien ble det funnet et gjennomsnittlig årlig drivstoff besparelsepotensial på 6%. Disse besparelsene skal imidlertid anses med forsiktighet. Manglende begrensninger i ytelsesprediksjonen forventes å ha ført til en overprediksjon av potensielle besparelser.
Den kontekstuelle situasjonen for implementering av dekarboniseringsteknologier i skipsfart er spesielt gunstig i øyeblikket, og WASP har sin egen spesifikke styrke når det gjelder å bruke vinden som kraftkilde. På den annen side ligger i avhengigheten av den flyktige vinden også en potensiell trussel. Det kan ikke gis noen endelig konklusjon om systemets økonomiske gjennomførbarhet , og sosiale og miljømessige faktorer er vanskelige å kvantifisere. Det kan likevel konkluderes med at bruken av WASP i norsk havbruk ser ut til å ha et lovende potensial. Ytterligere forskning på dette feltet er nødvendig og anbefales.

Summary

The discussion about climate change, meeting the 1.5°C or 2°C target, and alternative energy sources is not new. Only recently, in connection with the UN Climate Change Conference COP26 in Glasgow, a new debate arose about the future of shipping and an adequate energy supply for the shipping industry. Most of the ongoing discussions focus on LNG as a transitional fuel solution and hydrogen or ammonia as a future fuel for shipping. Wind propulsion or wind-assisted propulsion (WASP) seems to be rather underrepresented in this context, although it brings some unique benefits as wind is freely and abundantly available.
Most research focuses on deep-sea shipping in areas with favourable wind conditions. Other niches, such as coastal transport and smaller vessel types, are less represented in research and implementation projects. However, these niches can play an important role in the development and deployment of new technologies. Norwegian aquaculture represents a typical niche for which it is of interest to investigate the potential of wind-assisted propulsion. Marine fish farming is highly dependent on ships but also on a healthy marine environment as a basis for fish farming. However, the emissions caused by ships have a negative impact on the oceans and the marine ecosystem. Since Norwegian fish farming cannot operate without ships, it is particularly important to reduce ship emissions in this sector and protect the sea. Therefore, the question arises whether WASP is a viable solution to reduce ship emissions in the Norwegian aquaculture sector. This question shall be answered following a comprehensive approach using performance prediction as main criterion. Additional considerations to safety, contextual situation, and economics complete the decision base. For further clarification, a case study for a fish feed vessel equipped with one rotor sail is conducted.

This thesis firstly presents a detailed background study. The history and importance of sea-based aquaculture in Norway, as well as world-wide, is pointed out and the influences of climate change and CO_2 emissions on this sector are unfolded. A brief introduction is given to WASP systems. In addition, available systems are presented and general considerations are made regarding the implementation and performance of the technology. Based on the given information, feasible combinations of aquaculture vessels and WASP systems are determined. The background study is rounded up by a brief review of relevant literature on performance prediction programs.
The main part of the thesis focuses on the development of a performance prediction method tailored to the specific niche application of Norwegian aquaculture. A case study conducted in cooperation with Egil Ulvan Rederi AS is used to illustrate how such a performance assessment can be conducted. Besides the calculation methods, the input data selection and an interpretation of the results are described in detail.
The final part of the assessment comprises some essential safety considerations. The contextual situation for the implementation of WASP in this sector is assessed using a SWOT analysis. Economic considerations are pointed out in a cost-benefit analysis (CBA) and considerations about social or environmental CBA are given.

The main findings of this thesis about the feasibility of WASP in the aquaculture sector is that most vessels used are too small or have no free deck area for the installation available. However, for the bigger vessel types, such as cargo ships and well boats, rotor sails and suction wings are promising options.
The performance prediction method still has great potential for improvement. Nevertheless, it is shown how such a method can be tailored to a niche application of WASP and used as a way to estimate the potential and viability of such a system. In the case study, an average annual fuel saving potential of 6% was found. However, these savings shall be met with caution. Missing constraints in the performance prediction are expected to have led to an over-prediction of the potential savings.
The contextual situation for the implementation of decarbonisation technologies in shipping is especially favourable at the moment and WASP has its own specific strength in using the wind as a power source. On the other hand does the dependency on the volatile wind also represent a potential threat. No final conclusion can be given about the economic viability of the system and social and environmental factors are hard to quantify. Nevertheless, it can be concluded that the use of WASP in Norwegian aquaculture seems to have some promising potential. Further research on this topic is needed and recommended.

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Remotely Operated Vehicles

Nomenclature

AIS	Automatic Identification Systems
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CBA	Cost-Benefit Analysis
DNV	Det Norske Veritas (new)
DNV GL	Det Norske Veritas Germanischer Lloyd (old)
DOF	Degrees of Freedom
DWT	Deadweight Tonnes
ECTS	European Credit Transfer and Accumulation System
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
GT	Gross Tonnage
IMO	International Maritime Organisation
IWSA	International Windship Association
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978
MCR	Maximum Continuous Rating
MSc	Master of Science
PPP	Performance Prediction Program
ROV	Remotely Operated Vehicle
RPM	Revolutions Per Minute
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SWOT	Strengths, Weaknesses, Opportunities, Threats
TWA	True Wind Angle
TWS	True Wind Speed
UN	United Nations
UTC	Coordinated Universal Time
VPP	Velocity Prediction Program
WASP	Wind Assisted Ship Propulsion

1 Introduction

The discussion about climate change, meeting the 1.5°C or 2°C target and alternative energy sources is not new. Only recently, in connection with the UN Climate Change Conference COP26 in Glasgow, a new debate arose about the future of shipping and an adequate energy supply for the shipping industry. This clearly shows how important the issue is, and more and more regulations are being planned or put into force. MARPOL regulations, especially Annex VI, the IMO´s EEDI, EEXI, and SEEMP, emission control areas, and local regulations such as Norway´s plan to ban internal combustion engines from World Heritage-listed fjords along its coast (Nilsen 2021) are just a few examples.
Most of the ongoing discussions focus on LNG as a transitional fuel solution and hydrogen or ammonia as a future fuel for shipping. Wind propulsion or wind-assisted propulsion (WASP) seems to be rather underrepresented in this context. That is why the International Wind Ship Association (IWSA) published an open letter in March 2021 to call for the integration of wind propulsion at the heart of decarbonization considerations. The letter states: *"direct wind propulsion provides an abundant, free energy, immediately and uniquely suited to and accessible to shipping worldwide"* (IWSA 2021). In this letter, IWSA provides an outlook that up to 30% of the global fleet´s energy needs could be met by wind power and that WASP technologies, as part of a hybrid propulsion system, can help achieve said goals. (IWSA 2021)
Although the diffusion of WASP technologies in maritime transport is limited, research activities have increased in recent years. Most research focuses on deep-sea shipping in areas with favorable wind conditions. Other niches, such as coastal transport and smaller vessel types, are less represented in research and implementation projects (Chou et al. 2021). However, these niches can play an important role in the development and deployment of new technologies. They provide a shielded environment (Karslen et al. 2019) and more flexibility to experiment with innovative solutions (Mander 2017).
Norwegian aquaculture represents a typical niche for which it is of interest to investigate the potential of wind-assisted propulsion. The fish industry is Norway´s second largest export sector after oil and gas and is therefore of great importance to the Norwegian economy. In addition, the Norwegian aquaculture sector is known to be particularly focused on innovation and technology development. (Innovation Newsnetwork 2021) The solutions found here could either be exported to other countries or transferred to other sectors of the coastal marine industry. It is also crucial that ship emissions have a high impact on aquaculture. On the one hand, marine fish farming is highly dependent on ships, including for the transport of fish and fish feed. On the other hand, a healthy marine environment is the most important basis for fish farming. However, the emissions caused by ship transport have a negative impact on the oceans and the marine ecosystem (Moe et al. 2022). Since Norwegian fish farming cannot do without ships, it is particularly important to reduce ship emissions and protect the sea as the basis for the aquaculture sector. Therefore, the question arises whether WASP is a viable solution to reduce emissions from vessels used in the Norwegian aquaculture sector. This question shall be answered following a comprehensive approach using performance prediction as main criterion about the viability of the system. Additional considerations to safety, contextual situation and economics complete the decision base. For further clarification a case study for a fish feed vessel equipped with one rotor sail is conducted.

The structure of the presented thesis is as follows: The next section will provide a background study, presenting more information about Norwegian aquaculture and its importance as well as the vessel types used in this sector. Furthermore, a brief introduction to wind-assisted ship propulsion and the available systems will be given. Based on this, the feasibility of WASP for ships used in Norwegian aquaculture will be evaluated. This section concludes with a brief review of existing performance prediction programs. Section 3 gives an introduction to the case study including considerations about the rotor placement. This section finishes with a short method description. Section 4 describes the development of the performance prediction program, the input data used in the case study it then presented in Section 5. The next section presents the results of the case study focusing on the performance of the WASP system in the presented use case. An evaluation and discussion of the method is given in Section 7. To complete the comprehensive assessment of the potential and viability of WASP in Norwegian aquaculture, Section 8 presents some considerations about the safety of the system as well as a contextual SWOT and cost-benefit analysis. Section 9 comprises a conclusion and recommendations for further work.

2 Background Study

2.1 Aquaculture in Norway

Aquaculture - *"the practice of growing plants in water or farming fish for food"* as per definition in the Oxford dictionary (Oxford Learner´s Dictionaries n.d.) - plays an important role in Norway. It all started in May 1970, when two Norwegian brothers installed their first net cage to successfully farm Atlantic salmon in the sea off the coast of Norway. This first farmed salmon was the starting point for modern aquaculture not only in Norway. Ever since, the Norwegian salmon farming and aquaculture sector increased steadily. Particularly since the country offers such good conditions, with a very long coastline and good water quality. Throughout the development of salmon farming, Norway was at the forefront to find solutions for arising problems, improving fish welfare, and technical solutions to increase productivity and safety on the farms. (Norwegian Seafood Council 2020)
Today, Norway is world leading in the production of salmonids, which is considered among the most technologically advanced and profitable sectors of fish production. 35,2% of the Norwegian fish production is from aquaculture and a lot of the Norwegian fish is traded internationally. Since the early 2000s, Norway is the second major fish exporter after China. Salmon is very popular all over the world. In 2018 salmonids, especially the Atlantic salmon mostly produced in Norway, was the largest single commodity by value accounting for 19% of the value of all fish trade. (FAO 2020). The popularity of salmon comes not least from the fact that, in 1986, the Norwegian Thor Listhaug set a new trend for using salmon in sushi to increase the export rates. (Norwegian Seafood Council 2020) The high prices for salmon in the world make Norwegian fish exports particularly profitable and result in high revenues (FAO 2020). Therefore, the fish industry is Norway´s second largest export sector after oil and gas. (Innovation Newsnetwork 2021)

2.1.1 Salmon Farming

Salmon farming is a form of marine aquaculture, or mariculture, where only the grow-out phase takes place in the sea. The upstream processes take place in fresh water environments in land-based facilities. (FAO 2020)
A typical life cycle of farmed salmon begins in a hatchery facility. Here, the eggs are bred and fertilized. Already in this phase, a lot of effort is put into developing fish that are more resistant to diseases and parasites.The young fish will then continue to nursery facilities, where they stay for about 10 to 16 month for smoltification. That is the biological process in which the fish transform from fresh- to seawater. At this stage, the fish are called smolt and transferred to the sea cages where they grow to a harvest size of 4-5 kg. This last phase takes about 10 to 24 month depending on ambient conditions and smolt size. In open net cages the salmon is exposed to several risks like diseases, parasites, and environmental influences. To reduce the exposure time there is a trend to grow smolt larger to a size of up to 1kg, the so called post-smolt, before transferring them into the sea cages.(Moe et al. 2022)
The most common parasite on farmed salmon and hence one of the biggest problems in Norwegian aquaculture is the salmon louse. It is a small crustacean that attaches itself to the salmon and then feeds of the mucus, skin, and blood of the host fish. This effects the fish severely and makes it also more vulnerable towards other infections. In a worst case this leads to the death of the host fish. Besides some preventive measures, chemical or mechanical delousing is a common practice to treat infected farmed salmon.(Institute of Marine Research 2021)
A Norwegian fish farm normally includes several cages secured by a mooring system and a feed barge. The feed barge includes feed storage rooms and living areas for the crew. The most used cage types are open net cage systems. The principal of these floating flexible cages is still the same as for the first once introduced in the 1970s. It comprises of a flexible floating collar commonly made from high-density polyethylene and a synthetic fiber net. Advantages of these cage types are relatively low production costs, a high resistance towards rotting and bio-fouling as well as high resilience to wave forces. On the other hand, the cages experience problems with net deformation in high currents and in bad weather the walkways are insecure to access for the workers. (Chu et al. 2020)

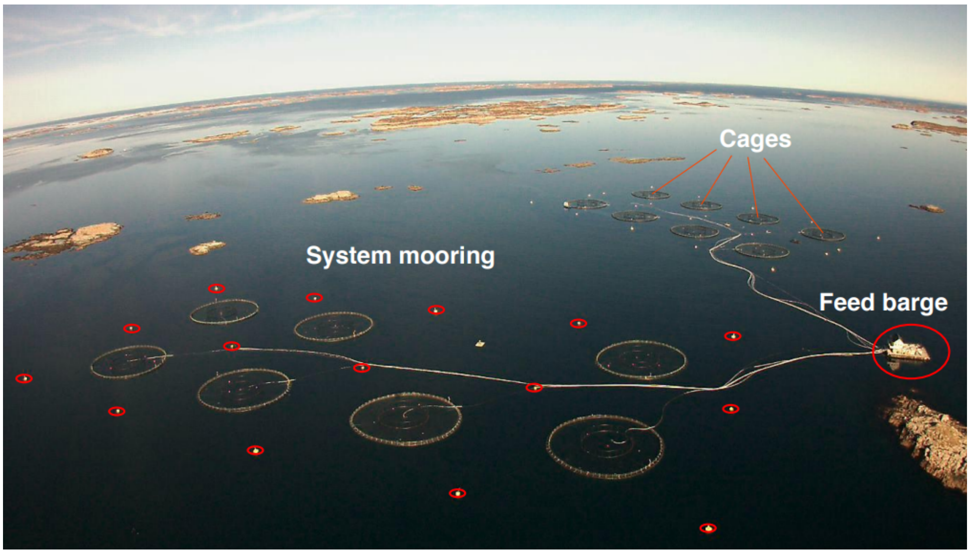


Figure 1: Typical fish farm in Norway with cages, mooring system, and feed barge (Lader 2020)

2.1.2 Importance of Aquaculture

Since the 1960s, the global fish consumption has increased steadily by 3,1% per year. This rate is significantly higher than that of other animal proteins and almost twice as high the the annual growing rate of the world population. In 2017, already 17% of the global animal protein intake was due to fish consumption. Additionally, to being protein rich, fish also comprises of long-chain omega-3 fatty acids, vitamins, and minerals, making it a valuable source for healthy food. It is hence no surprise that fishery products are among the most traded food commodities in the world. (FAO 2020)
This shows the already high importance of aquaculture which, as of 2018, accounted for 46% of the global fish production. However, with an ever growing world population the demand for food also increases steadily. Aquaculture is anticipated to continually grow and to fill the supply-demand gap for notorious food. Besides fish, also vegetable alternatives like edible seaweed can be farmed. (FAO 2020) Additionally, farmed fish is considered a relatively low-carbon-footprint food as the energy use per unit mass of protein production is less then that from most land-based animal productions. (He et al. 2018) Finally, the livelihood of millions of people worldwide depends on the aquaculture sector (FAO 2020).
As mentioned before, mostly high priced salmon is produced in Norwegian aquaculture. It is therefore unlikely to help combat hunger in an ever growing world population. However, it is still an important contributor to the worldwide production of healthy and nutritious food. (Federation of Norwegian Industries n.d.) The Norwegian aquaculture sector is especially focused on innovation and technology development. New solutions found in Norway could also be exported and help to improve the aquaculture industry globally. Furthermore, the export of fish products is especially important for Norway as over 800 companies are involved in this sector. The focus on new innovations and the exploitation of offshore areas for aquaculture are also likely to create many new jobs in the country. (Innovation Newsnetwork 2021)

2.1.3 Climate Change Effects on Norwegian Aquaculture

Climate change has significant effects on the marine environment. It leads to changes in abiotic conditions like the sea temperature, oxygen levels as well as salinity and acidity. Based on this, biotic conditions like primary production and food webs will change as well. These effects can also be observed in the Norwegian waters of the North Atlantic. (FAO 2020, Peck & Pinnegar 2018) As for the effects on Norwegian aquaculture, the rise of the sea temperature will most likely lead to increased growth, including harmful algae or jellyfish blooms. The increased plant growth causes further oxygen-depletion in the water, leading to oxygen stress in fish and other organisms. In a worst case, so called dead zones will occur. This happens also in Norwegian fjords. Ocean acidification is only a smaller problem in salmon farming as it has more severe effects on crustaceans. However, the acidity of the ocean rises at a rapid rate. The oceans absorb 25% of all CO_2 emissions and when the CO_2 desolves in the sea water, carbonic accids are formed. (Moe et al. 2022)

2.1.4 Future Developments and Emission Reduction

Aquaculture products have a relatively low energy use per unit mass protein production. Nevertheless, it is estimated that the aquaculture sector emitted 385 million tonnes of CO_2-equivalent in 2010. Here, the boundaries are set in a way that also includes feed production and supply in the emissions of aquaculture. The emissions per unit mass production for intensive productions of finfish are greatest among other things because of the feed . (He et al. 2018) Knowing about the effects CO_2 emissions can have on the oceans - direct in form of acidification or indirect due to temperature rises - it is mandatory to reduce these emissions.
Most CO_2 emission in aquaculture stem from to the feed production. This includes the production of the ingredients as well as the milling of the feed. The second most contributor to CO_2 emissions is transport. (McGrath et al. 2015, He et al. 2018) Here, technological developments and efficiency improvements can contribute significantly to reduce the use of fossil fuels and hence the production of CO_2 emissions. Furthermore, improving the efficiency is likely to reduce the production costs. Improvements are possible in the vessel design as well as in the propulsion system.(FAO 2020) Wind-assisted ship propulsion is for example one of the technologies that can be used to reduce the fuel consumption of a ship.
Norway has always been at the forefront of innovation and technological development in modern aquaculture (Norwegian Seafood Council 2020, Innovation Newsnetwork 2021). Furthermore, the Norwegian salmon is perceived as healthy, sustainable, and desirable product. It should continue to do so to keep revenues high. (Federation of Norwegian Industries n.d.) Customer awareness and an increased demand for transparency and sustainable life cycles throughout the value chain put additional pressure on the industry. Although, more prominent environmental issues concerning aquaculture are fish welfare, eutrophication, and feed sources, CO_2 emissions represent another large footprint and are coming more and more into focus. (Moe et al. 2022) The future development of Norwegian aquaculture sees more and more offshore fish farms to mitigate environmental issues and explore new production areas (Moe et al. 2022, Norwegian Seafood Council 2020, Innovation Newsnetwork 2021, Chu et al. 2020). On the other hand, this leads to longer distances for bringing the smolt to the farms and the grown-up fish back to the slaughtering facilities, as well as the regular supply of feed to the farms. This increase in transport demand makes it even more important to focus on efficiency and fuel reduction.

2.1.5 Vessel Types used in Norwegian Aquaculture

There is little information available about the vessels that are used in aquaculture along the Norwegian coast. Moe et al. (2022) name well-boats, processing, and feed vessel as the three main vessel types in aquaculture transport, but no further information in given about the ships parameters. Therefore an online search was conducted to compile a list of reference ships. A search for "fish farm support vessel" under Norwegian flag on HTTPS://MARITIME.IHS.COM/ led to a resulting list of 27 vessel. It is assumed that actually not all vessel used in aquaculture are reported to that category. Furthermore, in this data base "fish carrier" and "fish factory ships" are grouped into separate categories. Here it can not be distinguished if these ships are used in the aquaculture sector or in the wild catch fishing industry. During further online research, it was discovered that the Frøy Group has 65 vessel of their own fleet listed on their website (https://froygruppen.no/). Frøy says of itself: *"Frøy is Norway´s largest competence environment within aqua service. We are a total supplier of vessel services [...]"* (Frøy n.d.*a*). Based on the reference ships list, the following vessel types can be distinguished: well and treatment boats, cargo vessel, work and service boats as well as diving boats. These vessel types will be explained briefly in the following and an indication will be given if they are favourable for WASP installation or not. The decisive factor here will be the available deck area.

Well and Treatment Boats

Vessels of the type well boats or fish carrier are used to transport fish either to or from the fish farms (Moe et al. 2022). They have large tanks on board for live fish transport and incorporate systems and mechanisms to load and unload the fish via pipes (Frøy n.d.*j*). Treatment vessel are used to treat the fish against parasites and deceases, mainly for delousing of the salmon. Sometimes they are also called delousing vessel. More and more, well boats are used for treatment of the fish as well (Moe et al. 2022). On average a well boat has a length of about 75 m. They are characterised by a rather high volume (GT) probably due to the storage tanks for the live fish transport. A well boat has typically some equipment installed on deck, which reduces available deck area for WASP installation. Additionally, they often have smaller cranes installed on deck. A WASP system including a fixed superstructure might interfere with the operation of these cranes. The treatment boats are generally a bit smaller than the well boats in length and especially in gross tonnage, probably because they do not include the big storage tanks a well boat does. Typically, they are rather slender ships with a length of about 50 m. Characteristic for a treatment boat is the high amount of deck equipment incorporating the delousing system. Both vessel types seam therefore not favourable for the installation of WASP.

(a) Picture of the well boat Reisa showing cranes and equipment on deck (Frøy n.d.*e*)

(b) Picture of the treatment boat Frøy Merlin showing the high amount of deck equipment (Frøy n.d.*c*)

Figure 2: Pictures of Typical Well and Treatment Boats

Work and Service Boats

Work and Service boats are used for several tasks at a fish farm. Typical operations include inspection, maintenance and repair, as well as cleaning of the cages. Therefore Frøy subdivides the category of washing boats from the work boats. However, they are very similar to each other. All vessels in this category are rather short with common length around 20 m and hardly over 25 m. Characteristic is the comparably great width of the ships with 10 m to 15m leading to a wide and open working deck area behind the decks house in the front. These vessels are often built with a catamaran hull, but also mono hull constructions are common. Typical equipment on these ships comprises one or two working cranes, a strong winch and maybe some special equipment like an ROV. Although work and service boats have a relatively large free deck area, these vehicles are not suitable for the installation of WASP. The free deck space is essential for the work to be carried out and thus for the operation of the ship. (Frøy n.d.*i*)

Figure 3: Picture of the Frøy Multi, a typical work or service boat. The wide working deck and the deck equipment can be seen. (Frøy n.d.*d*)

Cargo Ships

Cargo ships are widely used in the aquaculture sector for the transport of raw materials for feed production (He et al. 2018) or downstream for the transport of fish products. However, the focus here is on vessels used directly in combination with the fish farms. These are cargo ships specialized in the fright of fish feed. (Moe et al. 2022) Typically, the fish feed in pellet form is stored in large cargo compartments within the ships which are equipped with self-unloading systems. The ships are classified as general cargo ships and with a size of up to 80 m length and a volume of around 3000 GT they are rather smaller cargo ships. Generally, these ships have relatively large available deck areas, beneficial for the installation of WASP systems. However, it should be considered that deck cranes or the cargo handling system may pose problems for the installation of these systems. Nevertheless, fish feed transport vessel seam to be the most favourable for the installation of WASP within the vessels used in aquaculture. (Frøy n.d.*h*)

Figure 4: Picture of the Rotsund, a typical cargo ship used for fish feed transport in aquaculture (Frøy n.d.*f*)

Diving Boats
Diving boats, according to Frøy, are designed for quick emergency response including diving support and ROV operation. They are mostly fast slender boats with a length of around 15 m. But also vessel types similar to the work boats are common. In both cases the diving boats seem not favourable for the installation of WASP as they are mostly too small. (Frøy n.d.*g*)

Figure 5: Picture of the Frøy Gard, a typical diving boat (Frøy n.d.*b*)

2.2 Wind-Assisted Ship Propulsion

The first sails can be dated back roughly to 3100 BC (Chou et al. 2021) and sails have been the main propulsive source for ships and to move cargo all around the world for centuries (Reche-Vilanova et al. 2021). From the middle of the 19th century, when steam ships became popular, their share in the global fleet grew rapidly. As of today most ships are propelled by internal combustion diesel engines. Although shipping is the most efficient way for transporting goods over long distances, the whole shipping sector still accounts for about 3% of the global antropogenic Co_2-emissions. (Rojon & Dieperink 2014) With increasing pressure to decarbonise and fulfill the climate goals set by the United Nation´s 2015 Paris Agreement and new IMO rules, the industry is in need for alternative propulsion methods. Hydrogen, methanol, and ammonia are some of the alternative fuel that are discussed. They will reduce direct emissions, but some have very high well-to-tank emissions and thus just move the emissions upstream. Besides often missing infrastructure, the lower energy densities of these fuels, leading to an increased requirement for energy storage capacity onboard, are another problem. Increasing the ship´s energy efficiency will not only directly reduce the fuel consumption and hence emissions, but might also be an enabler for those alternative fuels. One technology that can be used to increase the energy efficiency is wind-assisted ship propulsion and in literature emissions reduction potentials above 20% can be found. (Chou et al. 2021)
The origin of the sail systems used today often dates back several decades, however, they only became interesting and economical viable with increasing oil prices. Continuous research and development, as well as the availability of modern engineering tools, make these systems more efficient than the traditional sails. (Reche-Vilanova et al. 2021) There are many different systems available on the market and the definition of wind-assisted propulsion is as diverse as the manifestations of modern sailing. Reche-Vilanova et al. (2021) simply defines them as *"devices [that] can be retrofited to existing ships as a means of auxiliary propulsion power"*. The International Windship Association, IWSA, founded in 2014 with the purpose to *"encourage, advise and advocate for the use of wind propulsion technologies in the shipping industry"* (Fairtransport 2014) on the other hand distinguishes between four categories of wind ships (IWSA n.d.):

- Motor Vessels - The standard ship where no wind technology is installed

- Wind-Assisted Motor Vessels - Wind technologies (wing sails, rotor sail , etc.) are installed and used for fuel reduction purposes up to 30%. The main combustion engine system, however, remains unchanged and all schedules can be kept up using the combustion engines only.
- Hybrid Wind/Motor Vessels - Here a higher amount of wind technologies is installed and in favourable conditions savings up to 70% are possible. The ships have also a combustion engine system to keep up schedules in less favourable conditions. The hybrid version offers benefits from both sides (combustion engine = predictable, wind propulsion = fuel savings) and an average emission reduction of 50% is possible.
- Purely Wind Vessels - The ship is propelled to 100% by wind most of the times. For harbour manoeuvres a smaller auxiliary combustion engine propulsion system is included. This can also be used in periods without wind but will only provide a slow speed. This vessel type is highly dependent on the weather and hence subject to uncertainty. Keeping up the schedules might be problematic.

Another way to divide the WASP ships up is by the technology used. DNV for example distinguishes in standard DNVGL-ST-0511, wind-assisted propulsion systems, between rotor sails and wing rigs. Whereby the definition for a rotor sail is *"a rotating cylinder generating an aerodynamic lift force perpendicular to the apparent wind direction. This force is excited by the pressure difference on windward and leeward side of the rotor, when it rotates. This effect is called the Magnus effect."* (DNVGL (2019)). The second technology they consider is the wing rig defined as *"a 3-dimensional structure equipped with an aerodynamic foil, as opposed to a conventional single pane membrane sail."* (DNVGL (2019)).
In the context of this thesis a wind-assisted ship propulsion or WASP system is defined as a sail system to increase the energy efficiency of a vessel while reducing power demand and fuel consumption. Some WASP systems of interest in context with this study are presented below.

2.2.1 Sail Technologies

The "traditional" sail, that creates a lift and hence a thrust force in an parallel air inflow uses the still the same physical principals as centuries ago and that are also applicable for air plain wings. The aerodynamic forces created here are strongly dependent on the wind speed and the sail area. (Reche-Vilanova et al. 2021) It comes in many different shapes from soft sail systems to soft or rigid wing sails as well as ventilated foils (Hoffmeister & Hollenbach 2022). Not all types shall be described in detail here, but some promising technologies for wind-assisted propulsion of commercial cargo ships are mentioned briefly.
The first one is the Dyna Rigg. It was invented in the 1960s by Wilhelm Prölss with the intention to propel cargo ships. However, it was first implemented onboard the super yacht Maltese Falcon about 45 years later. The Dyna Rigg is a modern interpretation of a traditional square rigger with slightly curved beams. It forms hence a cambered soft sail. (Reche-Vilanova et al. 2021) The rig has free-standing rotating masts, which supports the efficiency of the system. And Dykstra Navel Architects have proposed an updated version of a cargo ship with Dyna Rigg. (Lu & Ringsberg 2020) Otherwise, information about commercial use of Dyna rigs is rather sparse and a drawback of the system is that the mast are non-retractable (Reche-Vilanova et al. 2021). Some studies find possible fuel savings of about 5% to maximum 15% to 35% (Chou et al. 2021).
Wing sails, originally invented for high-tech sailing yachts, become more and more popular in commercial shipping. Ideally, these wings provide high lift forces but minimum drag. High-lifting devices can help to improve the lift to drag ratio of a wing sail. (Reche-Vilanova et al. 2021) Chou et al. (2021) find in their review average fuel savings of 8% to 10% with maximum possible savings of 20%. Most of the wing sail systems are retractable, reducing air resistance while not in use (Reche-Vilanova et al. 2021) and improving cargo handling as well as passage of bridges (Hoffmeister & Hollenbach 2022). Ridgid wing sail systems are available from BAR Technologies in Portsmouth, UK and Yara Marine Technologies (WindWings) as well as AlfaWall Oceanbird (Oceanbird concept including also route optimisation). A commercially available example for a soft wing sail are AYRO OCeanwings 3.6.3 by VPLP Design. All of these systems are furthermore

highly automated to improve the operability of the sails. (Hoffmeister & Hollenbach 2022) The Turbosail, invented by Jaques Cousteau in the 1990s (Reche-Vilanova et al. 2021) is a technology today also known as ventilated foil or suction wing. In general, it is a rigid wing sail equipped with a fan to suck air from the boundery layers through many small holes. This will increase the lift and hence efficiency of the wing. These systems are available commercially from eConowind as a pair of two ventifoils mounted within a container. (Hoffmeister & Hollenbach 2022) This boxed system allows for easy refit of the system on existing ships. Thies & Ringsberg (2021) find a maximum lift coefficient of 5 for suction wings but a comparably high lift to drag ration of 3.5 which make it favourable for installations with large sail areas.

(a) Dyna Rig (Dykstra n.d.)

(b) Rigid Wing Sails (Oceanbird n.d.)

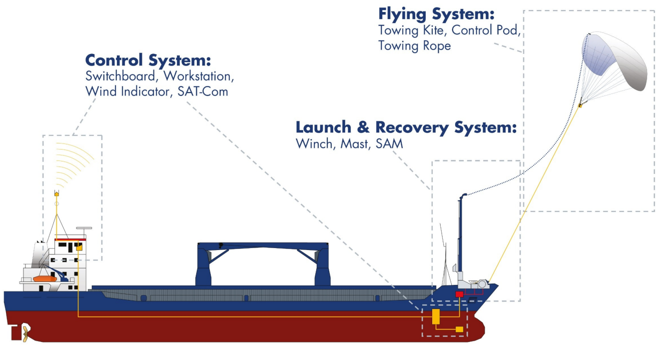
(c) Ventifoil (eConowind n.d.)

Figure 6: Illustration of three typical sail types and their applications

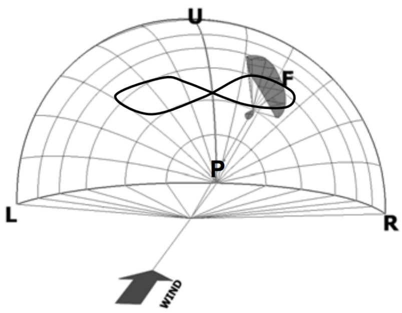
Kites

A kite can be seen as a wing surface attached to the ship via a towing line as is indicated by the schematic in Figure 7a. The towing line gives the radius of a quarter sphere in which the kite can be moved and positioned, the flight envelope. This envelope is within the surface layer of the atmosphere. This means the wind speed will increase with increasing altitude over the water surface along a logarithmic profile. The kite flying higher above the ship will therefore experience stronger winds than a WASP system directly mounted on deck. Additionally, when the kite is moved within the flight envelope it develops a certain speed which adds to the apparent wind speed experienced by the kite, thus increasing this apparent wind speed as well as the resulting towing force. A favourable track to manoeuvre the kite on might be an orbit close to the so-called power zone indicated by P in Figure 7b. (Naaijen & Koster 2007)

The edge of the flight envelope (LR) is always perpendicular to the apparent wind on board the ship. If a resultant force is still to be generated in the ship´s direction of travel, the usable range in the flight envelope will be gradually restricted as the wind comes more and more from the bow. With apparent wind angles of less than 60° from the bow, the kite cannot be used. If the wind direction turns aft, the efficiency of the kite increases, and between wind angles of 120° and 150° from the bow the greatest fuel savings can be achieved. (Naaijen & Koster 2007) Chou et al. (2021) find in their review on WASP technologies fuel saving potentials of a kite between 1-50% depending on various factors like ship, weather, and voyage parameters.



(a) Schematic of a SkySails Kite System installed on a Merchant Ship (Courtesy of the SkySails Group - www.skysails-marine.com) (SkySails n.d.)



(b) Schematic showing the Flight Envelope and a possible Track of the Kite (Naaijen & Koster 2007)

Figure 7: Illustrations of a Kite System and its Flight Envelope

There are two companies commercially involved with towing kites. The SkySails Group has already implemented some commercial projects between 2008 and 2012 and a spinn-off of the Airbus Group, Airseas, has recently entered the market. (Chou et al. 2021) Both companies advertise similar systems. As presented in Figure 7a, the kite is installed at the bow of the ship so there is no interference with the cargo space (SkySails 2021). Additionally, positioning the attachment point of the kite as far to the bow as possible minimizes the rudder angle needed to obtain yaw balance (Naaijen & Koster (2007)). Both systems are fully automated. When the kite is launched, first, a telescopic mast is raised to deploy the kite from its storage. Once the kite is fully unfurled, the towing rope is released until the kite reaches its designated altitude. Now the kite is controlled by an autopilot and maneuvered along a preferred path within the flight envelope, optimized for the current weather and travel parameters. (SkySails 2021)) Figure 7a illustrates the main components of the system (flying system, launch and recovery system, control system) and their location on board.

Particular benefits of a kite compared to other WASP systems named in literature (Chou et al. (2021), Naaijen & Koster (2007)) as well as by the two companies, SkySails and Airseas, are:

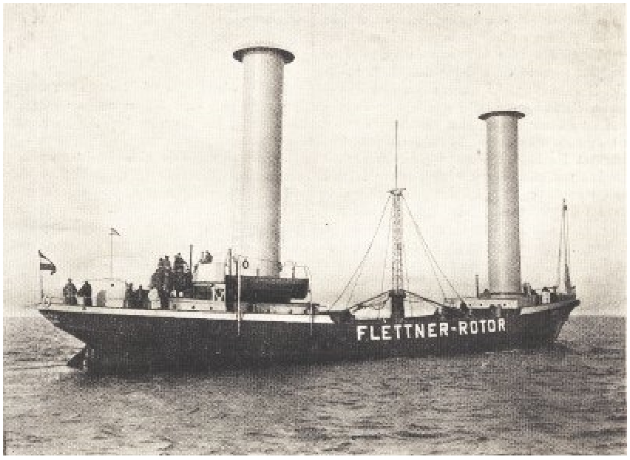
- The efficiency of the system due to the higher relative wind velocity created by the kites actively controlled movement and the exposure to stronger winds in higher altitudes.
- The small size of the system not compromising the cargo space. SkySails compare the size of their system on their website (SkySails n.d.) to the size of a telephone booth.
- When the kite is restored there are no bigger superstructures left on deck that might interfere with the passage of bridges, cargo handling or the operation of the ship.
- The system can easily be retrofitted within a few hours while the ship stays afloat.

Rotor Sails

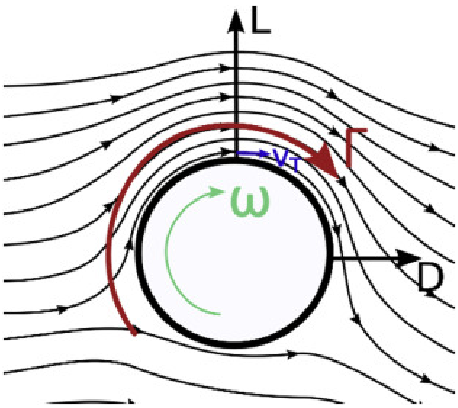
The rotor sails were invented in the 1920s by Anton Flettner (Reche-Vilanova et al. 2021) and a first ship, the Bukau, was equipped with two of the rotor sails as a demonstration project. The technology was then further studied by Thom in the 1930s. However, it got not established and no further progress was noted until the installation of four rotors on the general cargo ship E-Ship 1 in 2010. The number of installations of rotor sails has significantly increased in the most resent years since 2018. (Chou et al. 2021)

Rotor sails use a physical superposition principal, the so called Magnus effect, to create a driving force. Figure 8b shows a schematic of the principal. While a cylinder is rotating in a free-stream parallel flow, the flow created by the rotor adds to the incoming flow on the side where both flows move in the same direction. On the other side, the resultant flow is is equal to the difference of the parallel and circulatory flow. This velocity difference leads to an unequal pressure distribution and hence the manifestation of a lift force perpendicular to and a drag force in line with the parallel

inflow.(Reche-Vilanova et al. 2021) These forces can then further be translated in a desired thrust force in the ships sailing direction and an unwanted aerodynamic side force (see Section 8.1). (Tillig & Ringsberg 2020)
As the Magnus effect is based on a superposition principal, no lift force is generated if either the rotor is not rotating or there is no sufficient inflow (wind speed). If the rotor is not rotating, it, however, still creates an air resistance or drag force. Moreover, the lift coefficient and the resulting forces depend on the velocity ratio, the relation of the cylinder surface velocity to the wind speed, of the cylinder. This correlation allows for the rotor sails to be reefed by changing the rotor speed. (Reche-Vilanova et al. 2021)
Rotor sails work best in situations where the wind is coming from the side of the ship with angles between about 60° to 120° (Chou et al. 2021, Lu & Ringsberg 2020, Reche-Vilanova et al. 2021) On average, realistic fuel savings of up to 25% are found to be possible (Chou et al. 2021, Hoffmeister & Hollenbach 2022). Flettner rotors can achieve a maximum lift coefficient of up to 12. This is especially beneficial for smaller sail areas while a relative low lift to drag ratio of 3 can lead to problematic side forces and de-powering of the rotors for ships with larger sail areas. (Thies & Ringsberg 2021)



(a) The Bukau equipped with two Flettner Rotors in 1924 (Unknown author 1924)



(b) Schematic showing the Flow around a rotating Cylinder with indication of Lift and Drag forces (Tillig & Ringsberg 2020)

Figure 8: Picture of a Ship with Flettner Rotors and Illustration of the Magnus Effect

Hoffmeister & Hollenbach (2022) identify rotor sails to be the *"most popular and least-risk WAPS technology available for commercial ships today"*. The systems are available commercially for example from Norsepower, Anemoi Marine Technologies Ltd., or Eco Flettner. These modern systems are available in a tiltable version to allow for easier passage of bridges and the like, as well as mounted on rails to improve cargo handling onboard the ship. (Hoffmeister & Hollenbach 2022) The systems are suitable for new buildings as well as retrofit projects where they can be installed quite easily depending on the available deck area and steel structures. Once the system is installed, it is operated highly automated. (Norsepower n.d.*a*)
Other than most of the common WASP technologies, rotor sails are active-rotating devices and need powering. This power demand has to be considered when calculating the efficiency and possible power savings of such a system (Reche-Vilanova et al. 2021). Additionally, the rotor represents a large superstructure that can lead to difficulties in the operation of the ship, some of them can be mitigated by installing tiltable or movable systems (Hoffmeister & Hollenbach 2022). Nevertheless, rotor sails are found to be the most efficient WASP systems as they produce the highest savings while having the smallest sail area (Lu & Ringsberg 2020, Reche-Vilanova et al. 2021). Further points, that speak for the system are the comparably easy installation also in refit projects as well as the high commercial availability with several competing suppliers. Together with the comparably well developed rules and standards for rotor sails (DNVGL 2019) this indicates a certain maturity of the system. Several implementation projects as well as a high

2.2.2 General Remarks about Installation and Performance of WASP Systems

From the above list of sailing technologies, it can be concluded that some are still at an early stage (Rojon & Dieperink 2014), but the number of companies offering such systems is increasing, as is the diffusion of the systems in the global fleet(Chou et al. 2021). In general, more and more attention is being paid to wind propulsion, which can also be seen in the increasing amount of in research projects. In addition, key IMO regulations such as the EEDI and EEXI have recently been revised to better and more realistically reflect the energy efficiency gains from WASP systems. (Hoffmeister & Hollenbach 2022) In fact, WASP technologies can lead to an significant improvement in the EEDI. A supporting structure of rules and regulations is often identified as an important factor for further diffusion of WASP systems. other factors are monetary incentives or uncertain and increasing fuel prices (Karslen et al. 2019). WASP systems and the fuel savings they implement make a ship less dependent on fossil fuel supply and prices and symbolise hence an operational hedge against volatile fuel costs (Chou et al. 2021). Social responsibility and an awareness about the effects transport can have on the environment resemble a third beneficial pillar for the increased implementation of WASP systems (Mander 2017). Additional factors identified by van der Kolk et al. (2019) are an increasing perceived value of the goods if they are shipped with less emissions as well as an increased trust and strengthening of brands using sustainable supply chains.
High capital costs and uncertainty about the performance of the system are often named as reasons against the implementation of WASP (Chou et al. 2021). Interviews conducted by Rojon & Dieperink (2014) also show that financial resources, as well as scientific and practical knowledge, are perceived the most important factors. The use of parametric simulations and performance prediction programs offers the possibility to fill this knowledge gap in an easy and comprehensive way in theoretical terms. Many different factors can be checked in this way, but there is a lack of practical studies to verify the results obtained.(Chou et al. 2021) Karslen et al. (2019) also point out the importance of successful pilot projects for building up the trust in new technologies and supporting their diffusion. Experimentation within shielded niches as well as hybridisation of the new systems can help to overcome resentments towards wind-propulsion. In a symbiotic relationship between old and new technologies, the performance of the technologies can be tested. Further, the new technologies might benefit from the cooperation with established brands and their established image. (Mander 2017)

More practical considerations regard technical and operational factors. It is of significant importance to select the best fitting WASP technology for each individual ship. As can be seen from Section 2.2.1, the different technologies have variant requirements and specifications. The available deck area, as well as the size of superstructures and the amount of deck cargo, appear decisive with this regard. For a container ship for example, the containers stored on deck would highly disrupt the wind inflow to a deck mounted sail system. A kite system would be a better option here. The route of the ship and the trade pattern are further influencing factors and some operating areas are more beneficial for the for the use of WASP. (Chou et al. 2021, Hoffmeister & Hollenbach 2022) Additional forces due to the wind propulsion system have to be accommodated by the hull and the implementation of such a system in a new build project, where these forces can specifically be accounted for in the design is beneficial compared to a retrofit projects. Nevertheless, most of the systems are comparably easy to retrofit as well. (Hoffmeister & Hollenbach 2022) Aerodynamic side forces, which inevitably occur in connection with sails as well as all their resultants (e.g. heel, yaw, leeway) and their effects on the vessel, are of particular concern as regularly pointed out in the work by Tillig & Ringsberg (2019, 2020), Tillig et al. (2020) and Thies & Ringsberg (2021). These forces can further have influences on the operation and especially of the manoeuvrability of the ship. Other operational factors often concern the large superstructures of most sail systems as they obstruct the view from the navigational deck. They might interfere with the cargo handling, or restrict the operational area as bridges and the like can possibly not be passed. Therefore a hazard identification or risk assessment is highly recommended. (Hoffmeister & Hollenbach 2022) Further, there are several external factors that influence the performance of a WASP system and the success of its implementation. Chou et al. (2021) find in their research review that the performance of a sail system is directly dependent on the speed and direction of the wind and fuel savings will increase with the wind speed. On the other hand, high wind speeds are usually accompanied by higher waves, which increase the induced resistance of the ship. This should be taken into account when choosing a route. (Chou et al. 2021) Generally, it can be noted that with increased wind speed, the total power output of the WASP system increases, however, the relative savings due to the system might not be increased as the required power increases as well with additional induced resistances. There are also operational limits for all these systems that might be reached eventually and the sails must be reefed or de-powered for to ensure for the safety of the ship. Besides the general suitability of a sea area with better wind conditions, seasonal differences can also be noticed. Wind speeds in the northern hemisphere are often higher in winter than in summer. The direction of voyage, especially in relation to the direction of the wind, is another important factor. (Chou et al. 2021) The weather in the northern hemisphere is generally characterized by westerly winds. A route along the north-south axis is therefore likely to have frequent beam winds and good sailing conditions. An east-west route, on the other hand, is likely to have frequent tail or head winds that are less beneficial. (van der Kolk et al. 2019). Ship weather routing is often named in this context to optimize the route of a ship for better utilisation of the sails (Chou et al. 2021, van der Kolk et al. 2019) Finally, Chou et al. (2021) find that longer voyages are better suited for wind propulsion as wind speeds tend to be higher in open water leading to higher fuel savings.

2.3 Feasibility of WASP in Aquaculture

Of the vessels presented in Section 2.1.5, the cargo ships and well boats seem to be the most suitable ones for the installation because of their size and available deck area. Treatment or delousing boats, although comparable in size to the before mentioned ones, have no free deck area available due to the high amount of deck equipment needed for the treatment of the fish. Work and service boats are rather small. They have some deck area available. However, this area is needed as working deck. Kite systems by Skysails Yachts are also available in in four sizes between 20 m^2 and 160 m^2 (SkySails Yacht n.d.) and could be a feasible solution for these vessel types. However, as described in the Section, kite systems are quite limited in terms of wind angles and the start and landing process of the kite takes time. Therefore, vessels using a kite propulsion system are limited in their maneuverability and the systems seem to be better suited for longer distances and open seas. However, the work and service boats are more likely to be used on shorter distances and in near coastal waters. Here, an increased traffic volume can be assumed, moreover obstacles on the route (islands and the same) are present with relative frequency. This requires a high degree of maneuverability and mobility of the vessel, which does not tend to exist under kite propulsion. In coastal areas, electric transmission lines pose a further hazard, as kites flying at high altitudes can become entangled in them. As for the other sail systems, rotor sails and suction wings seem favourable, as they are found to have higher efficiencies in relation to their sail areas. Further, these systems apear to be easily retrofitted. Especially the eConowind ventifoil mounted in a container appears to have a retrofit benefit as long as enough free deck area is available and a sufficient mounting is available (Hoffmeister & Hollenbach 2022).
Concluding, the combination of cargo ships or well boats with either a rotor sail or suction wing seem to be the most feasible applications of WASP technologies on vessel used in aquaculture. How these systems actually perform in operation along the Norwegian coast will be estimated using a performance prediction program in a case study approach.

2.4 Literature Study on Performance Prediction Programs for WASP

Lu & Ringsberg (2020) consider rotor sails and wing sails as well as a Dyna rig in their paper on the ship energy performance of these technologies. The ship energy performance and hence the total fuel oil consumption or reduction in the fuel consumption is simulated using a model based on Tillig & Ringsberg (2019) as well as statistical weather data and specific voyage information. In their study, they find that all systems contribute to fuel savings between 5% and almost 10% and that the rotor sails produce the highest savings while having the smallest sail area. Additionally, a parametric study on the rotor sails shows the influence of details like the size, number, and position of the rotors and the type and size of the ship on the energy performance of the systems. They also remark that the energy needed to spin the rotor can have a negative effect on the fuel savings and that the ship speed has higher influences on the fuel consumption than the rotor sails. (Lu &

Ringsberg (2020))
The before mentioned model Tillig & Ringsberg (2019) was developed and refined over the years and a latest version is presented in Tillig et al. (2020). The model is called ShipCLEAN and that latest version also includes a transport economics tool. Generally can the model be divided into three parts:

- The static part for calculation of calm water resistance based on a minimum of input data. This allows to model generic ships and new concepts in an early design phase.
- The dynamic part calculating the required propulsion power with four degrees of freedom (surge, drift, yaw and heel) and under realistic operational conditions (see Tillig & Ringsberg (2019))
- The economic part for estimating cost, income and return rates

The model seems fairly good developed and the validation study presented shows good fit of the predictions. The report further also includes a study on size and number of rotor sails installed on a ship. Tillig et al. (2020) find maximal fuel savings of up to 85% with six rotor sails under ideal conditions. However, they also point out, that especially with higher amounts of WASP, automated reefing will reduce the contribution of the wind system to reduce undesired side effects like heeling, thus leading to an overall fuel saving potential of 12%. Due to the high and linear increasing installation costs of the rotor sails investigated, they find high payback times and a single rotor solution to be most viable. (Tillig et al. (2020))
A similar approach considering the four degrees of freedom is followed by van der Kolk et al. (2019) and they come to similar results. One of the biggest issues they see is the yaw moment introduced due to WASP. It has a destabilising effect on the course-keeping ability, which gets compromised leading to reefing to avoid loss of control. They see herein a big design challenge. Further do they mention that the effects on the main combustion engines must be considered and whether the use of WASP pushes them into an unfavourable operational point. Finally, an outlook on ongoing work is given, which includes mitigation of the yaw moment to increase the WASP power that can be used. (van der Kolk et al. (2019))
Reche-Vilanova et al. (2021) even propose a six degrees of freedom performance prediction program. Similar to Lu & Ringsberg (2020) they include wing sails, rotor sails and Dyna rig in there program. However, the plan to include more WASP options in the future. The aim is to provide an quick and easy tool to assess the performance of any cargo ship equipped with a sail system with a small number of input data on a generic basis to contribute to further knowledge about the performance of WASP.The results are validated with real sailing data and show reasonable agreement with these measurements. In the comparison of the systems, they find rotor sails to be most efficient when generated driving force per sail area is considered. (Reche-Vilanova et al. 2021)
These studies give good inside on the modelling of WASP technologies and their efficiencies. The use of statistical weather data and the simulation of realistic operational conditions are targeted. The presented literature will give valuable input for the development of a power prediction program for ships used in aquaculture along the Norwegian coast.

3 Introduction of the Case Study

The development and use of a performance prediction program to evaluate the use of WASP systems in Norwegian aquaculture shall be illustrated based on a case study. This case study was conducted in cooperation with Egil Ulvan Rederi AS (Ulvan). This family owned business was established in 1919 for transport of mainly fish and also other goods along the Norwegian coast. Ever since the company has grown and in the 1990s, they started long term contracts with companies within the aquaculture sector. They were always at the upfront of development and new technologies. So, in 1977 they were the first ones in Norway to install an unloading facility for fish feed on one of their ships. Before that, fish feed was transported in big bags. From then onward, it was unloaded as bulk, improving the work on the fish farms. Today, Ulvan has two main pillars, they continue to operate the coastal transport of goods within Norway, and on the other hand, they are specialized in the transport of fish feed. Here they build on long-term contracts with their customers. In 2014, they therefore invested in two new ships for Marine Harvest (now Mowi (Mowi n.d.*a*)). With a capacity of 3,000 tons, these ships were the largest of their kind at the time. They were equipped with LNG propulsion and advanced technology. This reflects the commitment and environmental awareness of both Ulvan and Mowi. The sister ships have the names "With Marine" and "With Harvest". (Egil Ulvan Rederi AS n.d.*a*)
To continue with the development of advanced technology and environmental friendly solutions, Ulvan plans to take the next step and implement WASP on the sister ships With Marine and With Harvest. The concept here is to extend the 69.9 m long ships in the mid ship section by 12 m. The extension will increase the cargo capacity of the ship but also the resistance and hence the propulsion power needed. To compensate for that, a Flettner rotor (24 m height and 4 m diameter) shall be installed on board the ships. In the end, the goal is to transport more fish feed using the same amount of fuel as before. The extension and the position of the rotor are illustrated in Figure 9. (Ulvan 2022)
By answering the question whether the increased propulsion power due to the extension can be compensated by the rotor sail, it is exemplary shown how the viability of WASP systems can be assessed based on a performance prediction program. Further, a performance prediction program tailored to this specific use case is developed. Methods and considerations presented here could also be transferred to develop such a program also for WASP applications in other niche areas.

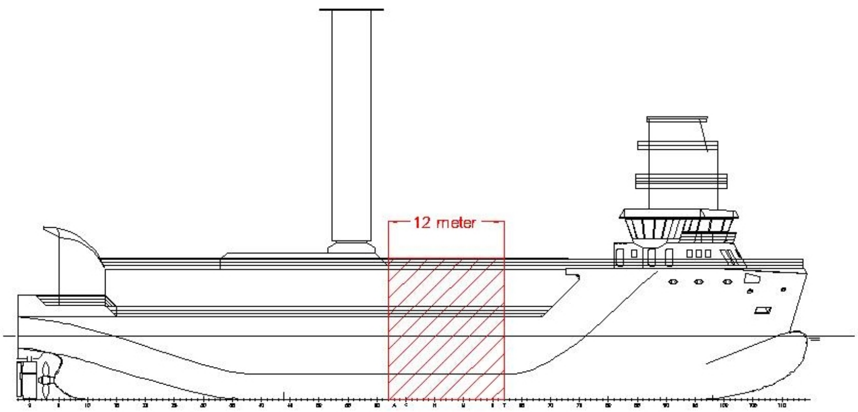


Figure 9: Illustration of the extended ship with the Flettner rotor installed. It can be seen that the extension will be in the mid ship section and the rotor is installed at about half of the ship length. (Based on the general arrangement plan provided by the operator (Ulvan n.d.))

3.1 Ship Extension - Estimating the New Parameters

Extending the original ship by 12 m means that most of the ship parameters that, are needed for the performance prediction, will change. In the following it shall be explained briefly how the new parameters for the extended ship can be estimated.

3.1.1 Wetted Surface Area and Volumetric Displacement

For calculating the additional wetted surface area and volumetric displacement the parameters as indicated in Figure 10a are needed. These are the breadth of the ship, B, which is not affected by the extension and remains unchanged, the draught, T, and the chine radius, r, which is considered to correspond exactly to a quarter circle.
The additional wetted surface area, ΔS can be calculated by multiplying the wetted perimeter in the mid ship section, U, by the length of the extension, 12 m.

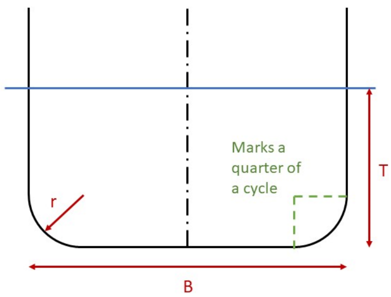
$$\Delta S = U \cdot 12\ m \tag{1}$$

$$U = 2T + B + (\pi - 4)r \tag{2}$$

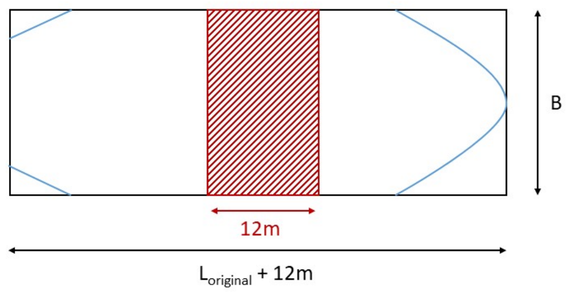
The additional volumetric Displacement, $\Delta Displ$, can be calculated by multiplying the area in the mid ship section, A, by the length of the extension, 12 m.

$$\Delta Displ = A \cdot 12\ m \tag{3}$$

$$A = B \cdot T - 2r^2 + \frac{\pi r^2}{2} \tag{4}$$



(a) Indication of important measures in the mid ship section



(b) Indication of important measures in the water plane area

Figure 10: Indication of Important Measures to estimate the Parameters of the Extended Ship

3.1.2 Ship Specific Coefficients

Ship specific coefficients, that will be needed in further calculations, are the block coefficient, c_B, the midship coefficient, c_M, the prismatic coefficient, c_P, and the waterplane coefficient, c_{WP}. The block coefficient, the ratio of the volumetric displacement to the volume of a block with length equal to L, width equal to B, and height equal to T, can be calculated easily once the additional volumetric displacement is known.

$$c_B = \frac{\nabla + \Delta Displ}{(L_{original} + 12\ m) \cdot B \cdot T} \tag{5}$$

The midship coefficient, the ratio of the mid ship area to a rectangle of B times T, is not affected by the extension and remains unchanged. The prismatic coefficient, the ratio of the volumetric displacement to a prism with a the midship area as cross-section area and length equal to L, can then easily be calculated by dividing the block coefficient by the midship coefficient.

$$c_M = unchanged \tag{6}$$

$$c_P = \frac{c_B}{c_M} \tag{7}$$

For calculating the waterplane coefficent, the ratio of the waterplane area to a rectangle of L times B, first the waterplane area, A_{WP} of the original ship has to be calculated using the original parameters. Then the new waterplane coefficient can be calculated by adding a rectangular area of B times the length of the extension, 12 m, to the original waterplane area and dividing this by the new L times B as is indicated in Figure 10b.

$$A_{WP} = c_{WP,original} \cdot L \cdot B \tag{8}$$

$$c_{WP} = \frac{A_{WP} + B \cdot 12\ m}{(L_{original} + 12\ m) \cdot B} \tag{9}$$

3.1.3 Ship Capacity (DWT)

To estimate the additional capacity of the ship, a closer look at the extension plans and the stability booklet provided by the operator Ulvan (n.d.) is taken. The extension is placed in the former cargo hold number 3. This cargo hold has a length of 13 frames and a combined capacity of starboard and port side holds of 871.2 m^3. The extension of 12 m equals 20 frames. The length of the cargo hold will hence be increased by additional 154%. Assuming the cross-sectional area of the cargo hold remains constant, the volume of the cargo hold can be scaled linearly by the same factor as the length. The additional cargo volume thus amounts to 1340.3 m^3. Compared to the total cargo volume of the original ship this equals an increase by 26.5%. The new cargo hold will be subdivided by five transverse walls and longitudinal one in the middle. Accounting for the additional portioning and equipment, the volume increase will be reduced by 2.5% points to 24%. Considering that the ship is loaded homogeneously with fish feed of similar density, it can be assumed that the capacity of the ship in DWT will also increase by 24%. This is a rough approximation to determine the additional capacity, but based on the given data, this is assumed to be sufficiently accurate.

3.1.4 Draught and Longitudinal Center of Buoyancy

Due to lack of better knowledge and data, it is assumed that the draught in the respective loading conditions remains unchanged. To the best of our knowledge and belief, this is the most sensible way to proceed in this case. However, it must be noted that as soon as further information about the draught behavior of the extended ship is known, the results obtained here must be re-evaluated and, if necessary, the calculations corrected.
The same applies to the location of the longitudinal center of buoyancy (LCB). For now it is assumed that the longitudinal center of buoyancy moves by the halve of the extension to $LCB{+}6\ m$. This, however, is a very simplified and rough assumption and should be considered with caution. Nevertheless, it was decided that this is the most sensible way to proceed within the scope of this thesis.

3.1.5 Required Propulsion Power

A common method to estimate the calm water resistance and hence the required propulsion power of a ship is the regression method developed by Holtrop (1984). For this thesis, a program based on Holtrop´s method implemented in python by Polić (2022a) and internally available at the Department of Marine Technology (IMT) at NTNU was used.

For the original ship, curves of the calm water resistance at five differed speeds and at three different draughts are available in a report of the numerical propulsion test provided by the ships operator (Ulvan n.d.). It is assumed that better estimations of the required power for the extended ship can be generated if the Holtrop regression is done for the original ship as well as for the extended ship in all points available from the numerical propulsion test. The results can then be compared to get the percentage power increase between the original and extended ship based on the Holtrop method. These percentage values can in a next step be used to scale the available curves from the original ship to the estimated curves for the extended ship. This gives in total three curves for the extended ship showing the required power from the main engines over the speed at three different draughts. The required power for other draughts has to be interpolated from these three curves.

3.2 Positioning of the Rotor

Most important when positioning the rotor is that the operation of the ship is not influenced or restricted by the rotor. Therefore, a brief introduction in the operation of the sister ships With Marine and With Harvest will be given. The ships are loaded with fish feed at a fish feed production facility. Then they sail to various fish farms and deliver the fish feed to the respective feeding barge. Therefore, the ships have a fish feed unloading system installed. Underneath the cargo holds, a conveyor belt transports the fish feed to the front of the ship. Within the decks house, a lift transports the feed further up to a level above the bridge deck. The external part of the system is installed there. This consists of a kind of crane arm and a nozzle. While the ship is sailing, this crane arm is mounted on the deckhouse behind the mast, perpendicular to the longitudinal axis of the ship. When the ship arrives at the feed barge, the crane arm is swung either to starboard or forward beyond the bow. The nozzle is then used to connect to the feed barge and unload the feed. Figure 11 shows the ship With Harvest unloading fish feed at a fish farm. The crane arm is swung to the starboard and clearly visible. Further, a provision crane can be seen on this picture. When placing the rotor it is necessary that both systems, the unloading system and the provision crane, can be operated without restrictions. These means especially, that the rotor is not placed within their moving radius, so that they can be swung freely over the deck.

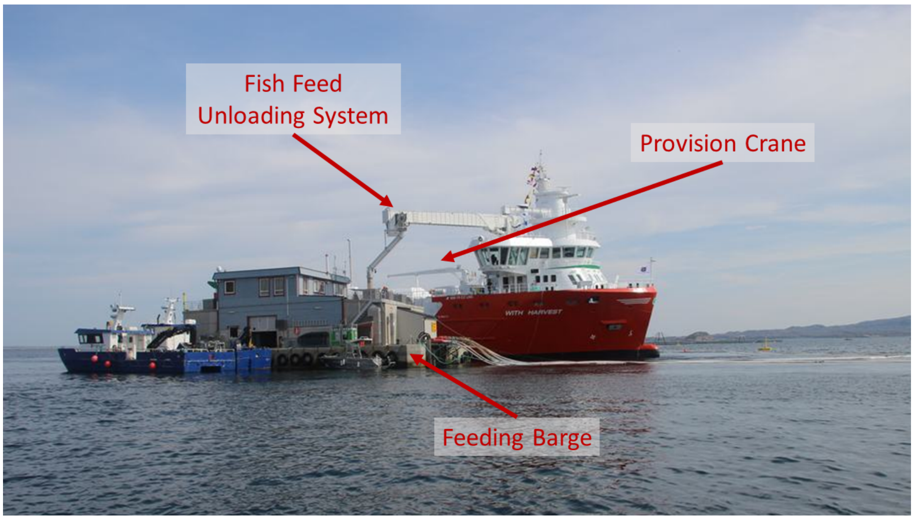


Figure 11: Illustration of the operation of With Harvest unloading fish feed to a feeding barge at a fish farm. The feeding barge, the fish feed unloading system as well as a provision crane on board With Harvest are pointed out. (Based on photo by Egil Ulvan Rederi AS (n.d.*b*))

In the general arrangement plan for the extended ship provided by the operator (Ulvan n.d.), the operation of the deck equipment was considered and the rotor is placed just outside the reach of the provision crane. However, this means that the rotor would be installed exactly above the gas tank, which is enclosed in a deck structure at this point. Possible restrictions and regulations should be checked here. In addition, it must be checked whether, despite the position, there is sufficient introduction of the forces into the hull. If necessary, the gas tank enclosure must be reinforced accordingly.

Another important fact to be considered for the positioning of the rotor is the yaw moment, an active deviation from the designated course due to the additional sail forces as opposite to leeway drift. This moment has to be balanced for the ship to stay on course. The rudder has a more favourable lift to drag ratio than the hull and is thus better suited to balance the yaw moment. A high rudder load is achieved by positioning the rotor towards the aft of the ship. However, a too high load on the rudder, leading to large rudder angles, should be avoided to keep manoeuvrability. In cases with too high rudder load, the rotor sail has to be de-powered.(Thies & Ringsberg 2021) If the rotor is not to be de-powered constantly, a position must be found in which the rudder has a sufficiently large influence on the yaw moment, but is not regularly overloaded.
Thies & Ringsberg (2021) evaluate in their paper the influence of the longitudinal sail position on the performance of a WASP system. They found that the most favourable position is slightly aft of midships, whereby they define midship as the half of the length between the perpendiculars, L_{PP}. They also conclude that optimally positioned sails achieve about 14% fuel savings to otherwise only 10%. L_{PP} is given with 78.79 m in the general arrangement plan for the extended ship provided by the operator (Ulvan n.d.). The position of the rotor is measured in this general arrangement plan with 33.3 m between the aft perpendicular and the axis of the rotor. This means the rotor is placed at 42.3% L_{PP} from the aft perpendicular. This is exactly where Thies & Ringsberg (2021) found the most favourable position of the rotor to be.

3.3 Method Description - Performance Prediction Program (PPP)

The aim of a performance prediction program is to predict the theoretical performance of a sail system. For this prediction, mathematical models are used to balance hydrodynamic hull forces and aerodynamic sail forces to calculate the performance of the sail system under certain ambient conditions. The mathematical model can be structured in two ways depending on the objective function. On the one hand, the objective function can be to maximize the vessel speed by using a sail. In this case it would rather be called a velocity prediction program (VPP). VPPs are commonly used in sailing yacht design. On the other hand, the objective function can be to minimize the fuel consumption by reducing the delivered power of the engines. This form of a PPP is for example used to predict the performance and possible power savings of a WASP system installed on a cargo ship.(Reche-Vilanova et al. 2021)
As mentioned, the PPP has to balance all hydrodynamic and aerodynamic forces in an equilibrium to find a feasible sailing condition. Traditional PPP only have one degree of freedom (1 DOF). That means they only balance the resistance including added resistance due to wind and waves, and the propulsive power. Here, the sail is simply seen as an additional propulsor comparable to a conventional propeller drive train. However, this will neglect the large side forces and resulting effects of the sails. A PPP with four degrees of freedom (4 DOF) is recommended to account for surge, drift, yaw, and heel of the ship. In this way, the performance prediction will become more accurate as realistic limits can be set for example for the heel, drift, and steering angles. (Thies & Ringsberg 2021)
In the present work, a performance prediction method was be developed especially tailored for the investigation of niche applications of WASP like the coastal transport. It shows how the calculations can be structured and how input parameters are selected. Moreover, the practical use of such a performance prediction to evaluate the potential and viability of a specific WASP application is illustrated.

4 Development of a Performance Prediction Program

To evaluate whether WASP is a viable solution for a specific ship on a given route, the performance of the WASP system under the given parameters is important to know. A performance prediction program (PPP) is used to estimate said performance, here based on historic weather data. Using historic weather data to calculate the performance of the WASP system is an easy way to get an estimate on the performance along a specific route. However, it is not sure the weather evolves in the future. A more advanced PPP might hence also address the fact of uncertainty about future weather development. In this thesis, though, the focus is rather on showing how a PPP can be developed and used in a decision process. Therefore, only historical weather data is used and no further predictions are made about the development of the weather.

Additional underlying assumptions have been made for the development of this PPP. Figure 12 illustrates these as well as the general principal of the code. It is assumed that for each route, the coordinates of the start point A as well as the time at which the ship starts sailing the route, are known. Based on this information, the historic weather data at this location and time can be found. The true wind speed (TWS) is directly known from the metocean data and the true wind angle (TWA) can be calculated from the global wind direction and the heading of the vessel. Based on TWS and TWA in point A ,the power savings due to the WASP system in accordance to that exact combination of TWS and TWA can be found. Further, it is assumed that the weather conditions and hence the power savings stay constant for the whole sailing leg until reaching the next point B. From the distance between the points A and B and the vessel speed, which is assumed to be constant throughout the route, the sailing time or duration of the leg can be calculated. This gives then the time at which the vessel reaches point B, or the start time in B. Now the weather data and power savings in point B can be derived analog to point A and will again apply until reaching the next point. In this way it will be continued until reaching the end point. Here only the coordinates are known and no further information is needed.

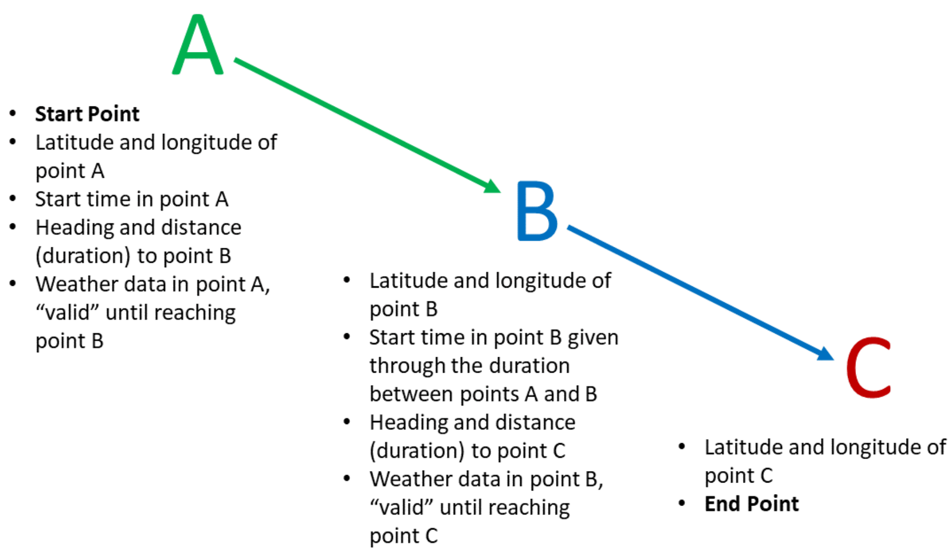


Figure 12: Simple illustration of the underlying assumptions of the performance prediction program

In the following the development of the PPP will be described in more detail. First Section 4.1 will focus on the information about the route itself as well as the weather data needed. The second Section deals with the performance estimation of the WASP system and finally in Section 4.3 it will be described how to simulate a route in several iterations over a longer period of time.

4.1 Route Information and Weather Data

This part deals with of the input data comprising a list of waypoints, the vessel speed and a start date. Further, the data frame will be prepared for use of the metocean downloader and metocean downloader itself will be described. Finally, the derived weather data has to be cleaned and TWA is calculated.

4.1.1 Waypoints

To simulate the exact performance of the WASP system along a specific route, detailed information about this route is necessary. It is given in form of a list of waypoints. Traditionally, a waypoint indicates a change of course along a route. Between two waypoints the ship will then sail in a straight line. In this way a route is divided into several legs. The list of waypoints needs to include the following information for each point:

- The coordinates of the waypoint in decimal degrees and with north latitudes and east longitudes as positive and south latitudes and west longitudes as minus values
- The heading or direction to the next waypoint in degrees
- The distance to the next waypoint in nautical miles

For the last waypoint, the end point, the heading and distance to the next waypoint will be zero as there is no next waypoint following the end point. In the further course of the simulation, the power savings are determined for all waypoints based on the environmental conditions. Power savings would also be found for the end point. Since this point is not followed by another leg, the energy savings (power savings times sailing time) would be zero. The total energy savings would therefore not change. However, the values found for the end point would affect the calculation of the average power savings (sum of all savings divided by the number of waypoints). For ease of use in the simulation, the endpoint is therefore removed from the list of waypoints. The number of legs is then equal to the number of waypoints.

4.1.2 Time Stamps

Further input to the PPP is including a start time at which the vessel is starting to sail the route in the start point as well as the vessel speed, which is assumed to be constant throughout the whole route. The start time is given as unix time stamp. The unix time stamp is a running count of total seconds since January 1st, 1970 (Coordinated Universal Time) (Dan´s Tools n.d.). With the distance between two waypoints given in the list of waypoints and the vessel speed in knots the sailing time between these two waypoints in hours can be calculated. Transforming the duration of the first leg into seconds and adding it to the start time will give the exact time at which the vessel will be in the second waypoint. Continuing in this way, the duration of a leg in seconds will be added to the unix time stamp of the start point of this leg to get the unix time stamp of the end point of this leg.

$$t_i = Start\ Time \qquad , i = 1 \tag{10}$$

$$t_i = t_{i-1} + \frac{d_{i-1,i}}{v} \cdot 3600 \qquad , i > 1 \tag{11}$$

With:

t_i	Unix time stamp at waypoint i
$d_{i,j}$	Distance from waypoint i to the next waypoint in nautical miles
v	Vessel speed in knots

4.1.3 Metocean Downloader

To access the metocean data needed, the metocean downloader is used. This is a lightweight Python library that helps access Copernicus Marine Data Services and is based on tutorials provided by Copernicus (Lagemann 2022). Copernicus is an earth observation program by the European Union. It provides several services, amongst others the Copernicus Marine Environment Monitoring Service (CMEMS) for the global ocean and the European regional seas. These marine monitoring services offer a variety of information about the marine ecosystem including metocean data. (Copernicus n.d.*a*) Metocean is a syllabic abbreviation of the words meteorology and oceanography. This means metocean data combines meteorological data (e.g., wind) and oceanographic data (e.g., waves). (Chakrabarti 2005) The products of the Copernicus marine environment monitoring service are available in the Copernicus Marine DataStore (CMDS) via an OPeNDAP connection (Open-source Project for a Network Data Access Protocol). To access the data an authentication via a Central Authentication Service (CAS) with username and password is required. (Copernicus n.d.*c*)
The metocean downloader has two working modes. The download function downloads subsets of the available data and stores this information locally. The download of the required data is based on the input of a geographical area (minimum latitude, maximum latitude, minimum longitude, maximum longitude) and an observation time interval (start time and end time). The downloaded data will be stored in a NetCDF file. The metocean downloader also includes a request function (exact time, latitude, longitude) for specific points in time and locations. The data requested via this function is returned as a dictionary that can be accessed by [< variable label >][< value/unit >]. For each request, the metocean downloader will first check whether the requested time and position are contained in the local files. If the requested information cannot be found in the local files, the OPeNDAP connection is used. (Lagemann 2022)

The Copernicus marine datastore provides a variety of data sets. By default, the metocean downloader is set to use the data set with the title Global Ocean Wind L4 Reprocessed 6 hourly Observations (doi: https://doi.org/10.48670/moi-00185) for assessing required meteorologic wind data. This data set is based on satellite observations and provides estimations of 6-hourly blended wind fields over the global oceans (00h:00; 06h:00; 12h:00; 18h:00 UTC). The temporal coverage is from 1992-01-01 to 2020-12-31 and the spatial resolution is 0.25° × 0.25°. (Copernicus n.d.*b*) The metocean downloader extracts the following information from the Global Ocean Wind L4 Reprocessed 6 hourly Observations data set:

- Wind direction in 10 m height, unit: degrees
- Wind speed in 10 m height, unit: m/s

For requests with times and positions laying between the mentioned values (6h time steps and spatial resolution 0.25°x0.25°) the corresponding wind data is interpolated by the metocean downloader. The data set only contains ocean wind data and although the resolution is relatively high, some areas very close to the shore line might not be covered by the dataset. In cases no wind values can be interpolated, the metocean downloader will return no value. (Lagemann 2022)

4.1.4 True Wind Speed and True Wind Angle

The metocean downloader gives the global wind speed and direction in each waypoint. For further calculations, however, the wind as experienced by the vessel (TWS and TWA) is needed. The true wind speed (TWS) is equal to the global wind speed as the vessel speed is not considered in the TWS. Therefore it can be directly taken from the metocean downloader output.
The true wind angle (TWA) gives the relative angle between the global wind direction and the ships direction and can hence not be taken directly from the metocean downloader output. Figure 13 illustrates the calculation rules for TWA depending on α, the difference between the global wind direction and the heading of the ship. If α is less than $-180°$, $360°$ have to be added to α to get TWA. Opposite, if α is greater than $180°$ it has to be subtracted from $360°$. In between TWA is equal to the absolute of α.

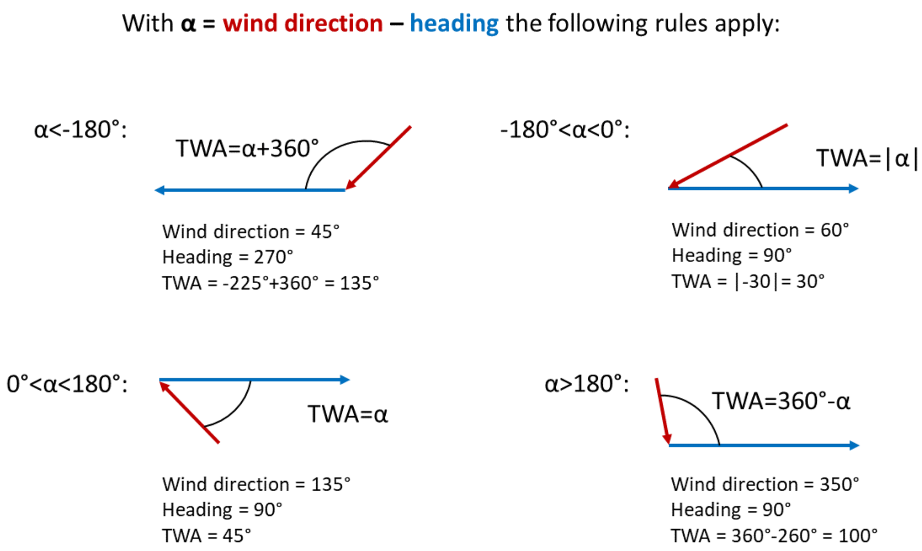


Figure 13: Rules for calculating TWA from the global wind direction and the heading of the ship

4.1.5 Assumptions about the Weather Data

There are some assumptions and simplifications made about the weather data in the PPP. These shall be pointed out and explained shortly. The first simplification is that the weather conditions are assumed to stay constant for a whole leg in a route. With longer legs this can lead to inaccuracies in the simulation as the weather might indeed change more often between the two navigational waypoints. Additional waypoints might be set along a leg without significant change of course to shorten the intervals between two waypoints and get weather data more often. Depending on the vessel speed, a waypoint might be set every 15 to 20 nautical miles so that there is new weather data taken at least about once an hour over the whole route.

The PPP is highly dependant on the weather data available for the metocean downloader. Based on the coverage and resolution of this data set, a problem might arise for coastal routes close to the shore line if no weather data is found for these coordinates. In case the metocean downloader gives no wind values for a waypoint, it is assumed that the same wind conditions will apply as have had in the waypoint before. This is a significant simplification and can impose some inaccuracy. Therefore it shall be handled with caution. Coming from further off the shore towards the coast, it can be assumed that the wind speed is most likely to be reduced due to increasing effects of the land. If then no weather data is found for the waypoint close to the shore while the point before was further off-shore the wind speed should not be considered the same in both points but be reduced in the point closer to the shore by a certain factor. However, if the route follows the shore line, it is assumed, that it has many waypoints in short distances due to navigation around obstacles. In this very dense mesh of waypoints it seems accurate enough to assume constant weather conditions between a waypoint with missing data and the point before. Additionally, moving parallel along the shore line the variation in the effects of the land on the wind conditions are less significant. For such a route it can be considered to not factor the wind speed in the waypoint with missing data. Especially, if two or more of these points follow in a row, which is a possibility for routes close to the shore line including a lat of manoeuvring, there is a risk to reduce the wind speed to much if it is factored down each time. Considering that the test case for the PPP is for vessels navigating along the Norwegian coast, no factoring is implemented yet.
If there is no weather data found for the start point of the route, there is no possibility to take the wind values from the point before. In this special case it is assumed, that there is no contribution from the WASP. This is reasonable as the WASP system might not be used right away for example while leaving a harbour. However, the next waypoint should be set close enough to ensure an accurate simulation.

4.2 Determining the Performance of the WASP

The performance of the WASP system is mainly dependant on there variables, the vessel speed, TWS and TWA. The vessel speed is considered constant throughout the route. This leaves a two dimensional performance matrix of TWS and TWA. As of now the performance matrix is not calculated in the PPP but needed as an external input. The calculation and the program used are described below. In an updated version of the PPP the calculation of the performance matrix should be included in the PPP directly. This would reduce the amount of calculation steps in different programs and the transfer of input data, hence the risk for mistakes and faults in the performance prediction.

4.2.1 Calculating the Performance Matrix

For the calculation of the performance matrix the model according to Lindstad et al. (Unpublished) is used. This model is designed to calculate the possible power savings of a Flettner rotor. As the power savings are equal to the difference between the power needed with and without the WASP system, Lindstad et al. (Unpublished) use the following equation to calculate the power savings:

$$P_{saved} = P_{noWASP} - (T_{prop}u/\eta_p + P_{req,WASP}/\eta_e)$$

Lindstad et al. (Unpublished) define the variables in this equation as follows:

P_{saved}	Saved Power due to the use of WASP
P_{noWASP}	Power required for the same ship speed without WASP
T_{prop}	Thrust required from the propeller (includes contribution from rotor and additional drag from hull)
u	Surge speed
η_p	Propeller efficiency assumed to be constant at 0.7
$P_{req,WASP}$	Required power by the rotor
η_e	Electrical losses between generator and rotor assumed to be constant at 0.8

The required power without WASP is calculated following known ship theory and hydrodynamic principals and rules. For the calculation of the savings, the contribution from the WASP system needs to known. Therefore, first, the true wind speed and true wind angle as observed by a fixed object have to be transferred into apparent wind speed and apparent wind angle as observed by a ship taking into account the vessel speed and the occurring deviations in the true wind values. The apparent wind values can then be used to calculate the according thrust and side force generated by the rotor sail. The lift and drag coefficients need for these calculations are taken from Tillig & Ringsberg (2020). Moreover, it has to be noted that friction between the moving are and the sea surface lead to the formation of a typical boundary layer, meaning the wind speed increase with the altitude about the surface. Furthermore, the wind angle is also slightly deflected. This wind shear effect is considered by a power-law coefficient. This boundary layer approach leads to the fact that the rotor experiences different wind conditions over its height. In the presented method a strip method and quasi-steady approach is followed. Thereby, the rotor is divided in several strips. For each strip the respective aerodynamic forces based on the applicable wind conditions is calculated. The total thrust and side force is found summing over all stripes.(Lindstad et al. Unpublished)

The mentioned aerodynamic side forces are compensated by a leeway of the ship. The vessel deviates downwind from the center line by a certain drift angle. While the surge speed remains in ship longitudinal direction, the ship speed towards the next waypoint deviates from it by the drift angle. Because the hull moves slightly angled through the water, there are also hydrodynamic lift and drag forces, which are taken into account in the method. The same applies to wind-induced drag. What the method, however, not accounts for is the yaw moment due to heeling of the ship, which would normally lead to a de-powering of the rotor if the ruder cannot balance the yaw

moment sufficiently enough. As the hull moves slightly angled through the water, there are also hydrodynamic lift and drag forces, which are taken into account in the method. The same applies to wind-induced drag.(Lindstad et al. Unpublished)
The method as described in Lindstad et al. (Unpublished), however, does not consider the yaw moment due to heeling of the ship and a possible de-powering of the rotors if the yaw moment can not be balanced by the rudder. Also interactions between the rotor and superstructures like the decks house are neglected. Doing so might give incorrect results for wind angles close to headwind and tailwind.

In the present case the method the presented method is used to generate a fitting performance matrix as input to the PPP. Therefore, a program written by Dražen Polić was used that implements the above mentioned method in Matlab (Polić 2022*b*).

4.2.2 Getting the Savings for each Waypoint

The performance matrix should give the performance of the WASP depending on TWS in increments of 1 m/s and TWA in increments of 5°. For each waypoint the TWS is then rounded to an integer while the TWA is rounded to the nearest five. This allows, in a next step, to read out the power savings due to the WASP system for each waypoint in accordance with the current wind conditions. Rounding TWS and TWA is yet again imposing inaccuracy in the PPP. However, these inaccuracies are considered negligible for a good enough estimation of the power savings.
Once the power savings on each leg are known the energy savings can be calculated by multiplying these power savings with the duration of the leg. In a next step the specific fuel consumption (SFC), given in mass-unit fuel per energy consumption of the engine, is used to calculate the fuel savings for each leg. Additionally, with a conversion factor in mass-unit CO_2 per mass-unit fuel specific for each fuel type the reduction in CO_2 emissions due to the WASP system can be calculated.

$$ES_{i,i+1} = PS_i \cdot \frac{d_{i,i+1}}{v} \tag{12}$$

$$FS_{i,i+1} = ES_{i,i+1} \cdot SFC_i \tag{13}$$

$$CO_2 savings_{i,i+1} = FS_{i,i+1} \cdot c_{CO_2} \tag{14}$$

With:

PS_i	Power savings in waypoint i
$ES_{i,i+1}$	Energy savings on the leg between waypoint i and the next waypoint
$FS_{i,i+1}$	Fuel savings on the leg between waypoint i and the next waypoint
$d_{i,i+1}$	Distance from waypoint i to the next waypoint
v	Vessel speed
SFC_i	Specific fuel consumption in waypoint i
c_{CO_2}	Conversion factor from mass-unit fuel to mass-unit CO_2

4.3 Iterative Simulation over a longer Time Periode

So far, a performance prediction method for a route along several waypoints as illustrated by the block diagram in Figure 14 has been established. The figure shows the input parameters needed on the left hand side. With the distance between two waypoints, the vessel speed, and the start date, the time and date for each waypoint can be calculated. This information together with the coordinates of the waypoints is used as input for the metocean downloader. The output of the downloader gives the global wind speed and direction. The global wind speed is set as TWS while TWA has to be calculated from the global wind direction and the heading of the ship. With TWS and TWA the respective power savings can be read from the performance matrix. Additionally, energy, fuel, and CO_2 emission savings can be calculated for each waypoint as described in Section 4.2.2.

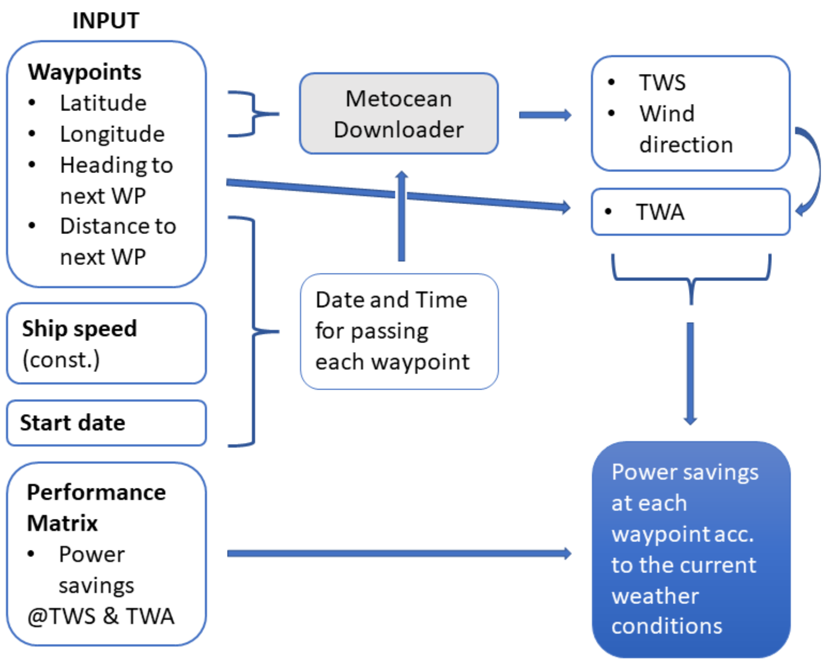


Figure 14: Block Diagram of the Performance Prediction Program

The described method should provide sufficient results for simulating the route. However, simulating the route only once, gives a very biased result as the performance of the WASP system is only estimated for one particular set of weather conditions. To get a better understanding of the performance of the WASP system and to obtain results that reflect more realistic conditions, the same route should be simulated in several iterations over a longer period of time, for example a year. Then, the average savings to be expected on this route throughout the year can be presented as a more realistic estimation of the performance of the WASP system on this route.
For this modified version of the simulation, the same principal performance prediction method as illustrated in Figure 14 can be used. The same set of waypoints is then run several times with different start times to obtain an iterative simulation over a longer period. To get the right start times for each iteration, a dummy waypoint is put between each iteration.

4.3.1 Dummy Waypoint

The dummy waypoint shall fill the time gab between the total sailing time of the route and the time interval between two iterations of the simulation. In principal, the first simulation of the set of waypoints is run. Then, the dummy waypoint is added and its start time is calculated according to Equation 11. After that, the set of waypoints is added again to be simulated a second time. The start time for this set is then again calculated according to Equation 11. With the correct duration for the dummy waypoint, the start time for the second set of waypoints is exactly within the intended simulation interval. In this way it will be continued for all iterations of the simulation. The duration for the dummy waypoint can then be calculated as follows:

$$duration_{DWP} = m \cdot 24 - \sum \frac{d_{i,i+1}}{v} \quad (15)$$

With:

m	Time interval between two iterations in days
$d_{i,j}$	Distance from waypoint i to the next waypoint in nautical miles
v	Vessel speed in knots

To ensure that the dummy waypoint does not influence the result of the simulation, it is removed from the data frame again after the weather data has been determined. To make it clearer to identify the dummy waypoint, it is advisable to give it coordinates outside the route. Then all points with these coordinates can simply be deleted.

4.3.2 Average Performance of the WASP

The performance matrix used here gives additional to the actual power savings also the percentage of saved power compared to the baseline power needed to propel the vessel to the same speed without the use of WASP. As per definition in Section 4.1.1 the number of waypoints and legs is equal as the end point is dropped from the waypoint list. Thus, summing up all percentage savings over the simulation period and dividing that by the number of legs (equal to the number of waypoints, nwp) and the number of iterations, gives the average achievable power savings on one leg, $\%Savings_{i,average}$.
Analogous to that the average TWS and TWA can be calculated. This is, however, a very inaccurate representation of the wind conditions, especially the wind direction, over the observation period of the simulation. Nevertheless, it will give a first indication whether the wind conditions have been rather favourable or unfavourable for the WASP system. Additionally, a windroseplot will be created showing the frequency of different TWS and TWA in more detail.
The actual power savings can be treated in the same way as the percentage savings. Summing them all up and dividing by the number of legs and iterations gives the average achievable power savings on one leg, $PS_{i,average}$. The energy savings in each leg have been calculated for each waypoint according to Equation 12. Here, it is more interesting to know the average total savings on the route than the achievable savings per leg. Therefore the sum of all savings is only divided by the number of iterations giving the total power savings achieved on average on this route, $ES_{total,average}$. Similarly, the total savings in fuel and CO_2 emissions achieved on average on this route can be calculated based on the fuel savings (Equation 13) and CO_2 savings (Equation 14) in each waypoint.

$$\%Savings_{i,average} = \frac{\sum \%Savings_i}{nwp \cdot n} \quad (16)$$

$$PS_{i,average} = \frac{\sum PS_i}{nwp \cdot n} \quad (17)$$

$$ES_{total,average} = \frac{\sum ES_{i,i+1}}{n} \quad (18)$$

With:

$\%Savings_i$	Percentage power savings in waypoint i
PS_i	Power savings in waypoint i
$ES_{i,i+1}$	Energy savings on the leg between waypoint i and the next waypoint
nwp	Number of waypoints equal to number of legs (see Section 4.1.1)
n	Number of iterations

5 Input Data

5.1 Loading Cases

The operator of the ships, Egil Ulvan Rederi AS, has provided a stability booklet of the ships. Four different loading conditions are presented in there:

- Loaded, departure: All cargo holds are completely filled and all tanks and consumables are filled up as well.
- Loaded, arrival: All cargo holds are completely filled, fuel and consumables, however have been used.
- Ballast, departure: All cargo holds are empty but all tanks and consumables are filled up.
- Ballast, arrival: All cargo holds are empty and the fuel and all consumables have been used.

Figure 15 presents these loading cases and the respective displacement, deadweight, and draught of the ship. From the regression presented in this figure it can be seen that there is a linear relationship between the draught and the displacement for the four loading conditions.

Loading Case	Displ [t]	Dead-weight [t]	Mean Draught [m]
Loaded, dep.	5333,3	3387,3	6,900
Loaded, arr.	5181,0	3235,0	6,722
Ballast, dep.	3961,6	2015,6	5,512
Ballast, arr.	3809,3	1863,3	5,332

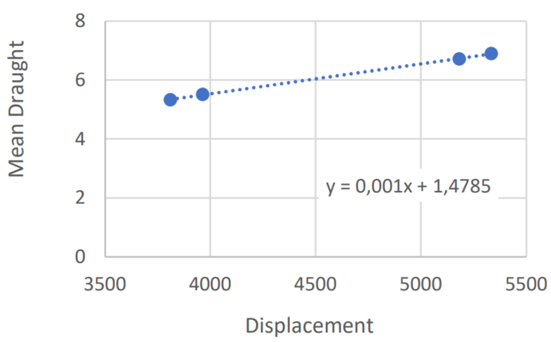


Figure 15: Summery of the four loading cases presented in the stability booklet provided by the operator of the ships (Ulvan n.d.). The regression on the right shows a linear relation between the displacement and the draught.

For the loading cases in the present case study, some assumptions and simplifications have to be made. In real operation, the loading conditions of the ships might be more variant. However, simplifying this is considered to still lead to good enough estimations of possible power savings. It is assumed that the ships are operated on roundtrip routes from and to a fish feed production facility, where they will be fully loaded with fish feed when they leave the facility (Loaded, departure) and they will arrive back completely empty (Ballast, arrival). In between, the ships will sail along the coast delivering fish feed to fish farms until all cargo holds are empty. Then they will return to the fish feed factory. In this turning point the ships will change into ballast mode. However, half of the fuel and consumables have already been used. The displacement in the turning point, $\nabla_{turning\ point}$, can be estimated as:

$$\nabla_{turning\ point} = \nabla_{Ballast,departure} - \frac{\nabla_{Ballast,departure} - \nabla_{Ballast,arrival}}{2} \tag{19}$$

The corresponding draught can be calculated using the regression presented in Figure 15 and is equal to 5.36 m. For the loaded leg, fish feed factory to the turning point, the departure draught is then 6.9 m and the arrival draught is 5.36 m. The average draught in loaded condition is 6.13 m and shall be used for further calculations. For the return leg in ballast mode the departure draught is 5.36 m and the arrival draught is 5.33 m. In the following the average ballast draught of 5.35 m shall be used.

5.1.1 Vessel Speed

It is assumed that the ships will sail at a constant speed with an main engine load of 75% MCR. This value is also used in the EEDI calculations (IMO 2018) and most engines have the optimal operational point with the lowest specific fuel consumption around 75% to 80% MCR. The corresponding speed can be read from the propulsion curves. These curves give the required power over the speed of the ship. As described in Section 3.1.5, the propulsion curves of the original ship have been scaled using Holtrop´s method. The resistance of the ship and hence the required power changes not only with the speed but also with the draught of the ship and for the extended ship three curves are given for the draughts of 5.2 m, 6.0 m, and 6.6m.
For the case study ship,s 75% MCR equal a power out put of 1770 kW. With the given propulsion curves, the respective speed at the given draughts can be calculated. The respective speed corresponding to this power value for different draughts can then be calculated using the regression presented in Figure 16. For this case study two loading cases have been defined. In loaded conditions the draught is 6.13 m which corresponds to a peed of 12.5 knots at 75% and in ballast mode the draught is 5.35 m leading to a speed of 13.1 knots at the same engine power. For better comparability it is assumed that the ships will maintain the same constant speed when WASP is used. The main engine power will than be reduced and the relative savings compared to the baseline values without WASP will be calculated.

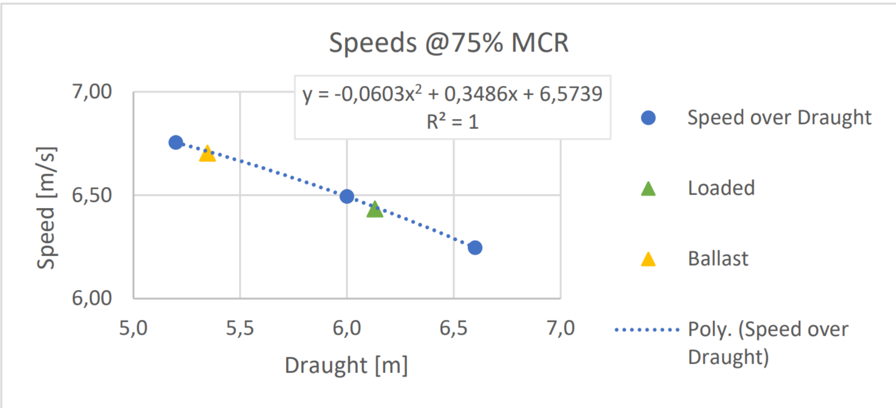


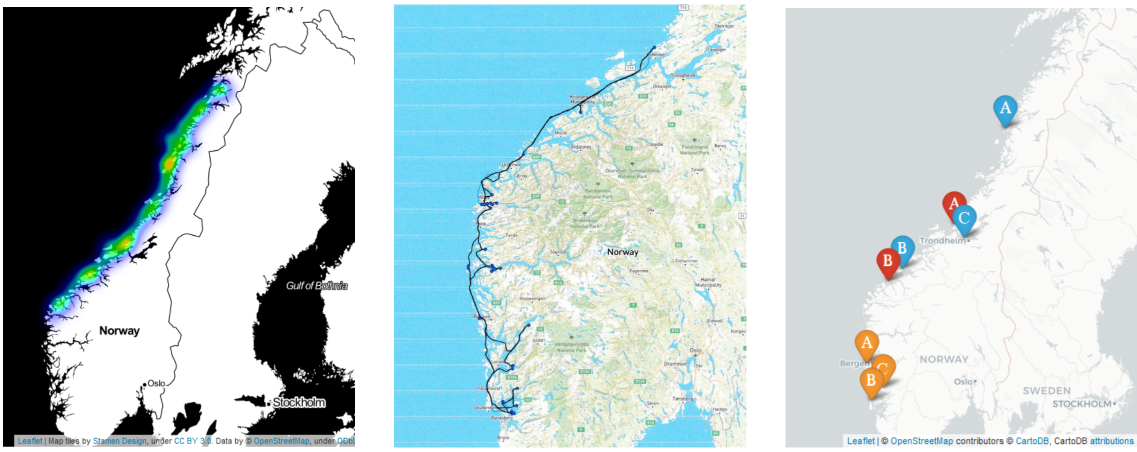
Figure 16: Regression of the speed at 75% MCR over the draught of the ship

5.1.2 Specific Fuel Consumption

In this case study, a constant specific fuel consumption, SFC, is used in all operational points due to a lack of better information. In reality, however, the operational point of the main engines will change due to varying contribution of the WASP system based on the wind conditions. With varying operational points also the specific fuel consumption of the engine will change. For most engines, however, these differences are not very large as long as the rating of the machine is not reduced too much. Assuming more moderate power savings it is considered to get accurate enough results using a constant SFC. If higher savings are occurring regularly, it should however be considered to use a varying SFC. Additionally, the case study ships are equipped with a controllable pitch propeller and a shaft generator. Both these systems can help to adjust the propulsion system to the WASP use case and improve the main engines operational point. A controllable pitch propeller enables to change the propeller parameters, while the shaft generator can - to a certain extend - increase the load on the main engines.
A constant SCF of 182 g-fuel/kWh is used. (Ulvan n.d., Kongsberg Maritime 2022) It could be considered to add a safety factor of for example 5% to that to get more conservative results. However, in the present case the same SFC is used in all points and also to calculated the baseline fuel consumption. Increasing the SFC will hence not influence the percentage savings possible. It should still be noted that the actual values might deviate from the realistic fuel consumption, the relative values however should be fairly accurate.

5.2 Route Generation

For the route generation, it is important to know the operational area of the ships With Marine and WIth Harvest. This is approached in a tripartite way. First, AIS data is used. The Automatic Identification Systems (AIS) were developed in the 1990s to improve the safety at sea by improved identification of vessels and hence avoidance of collisions. Since the early 2000s, AIS is mandatory for most vessels. The AIS transponder sends in regular intervals of some seconds to a few minutes automatically messages to shore stations or satellites. These messages include, amongst other information, the position of the ship and can be used to plot a heatmap. (Kim & Smestad 2021) The heatmap presented in Figure 17a is based on AIS data collected over the year 2020. It shows that the ships operated roughly between Ålesund in the south and Bodø in the north along the Norwegian coast. At about the height of Trondheim and Mo i Rana, an increased agglomeration of data points can be identified based on the light yellow coloration.
Secondly, the operator of the ships, Egil Ulvan Rederi AS, provided additional data including typical tour reports. These show approximately a similar northern boundary of the operating area. However, according to this information, the ships are deployed on southern routes that reach approximately into the region of Haugesund, as is illustrated in Figure 17b. What is also striking is that the routes presented in this record always seem to start and end in the same port. It is located near Trondheim. (Ulvan n.d.)
Finally, both ships have been investigated on MarineTRaffic (https://www.marinetraffic.com). With a subscription plan, this website also offers information about the ports of call of the ships for the years 2015 to 2022. These ports are marked in Figure 17c. Red are the ones that have been called by both ships (A - Valsneset, B - Ålesund), orange the ones only called by With Harvest (A - Ågotnes, B - Haugesund, C - Utåker), and blue the ones only called by With Marine (A - Herøy , B - Aukra, C - Rørvik). The most called port for both ships with over 400 calls per ship is Velsneset. (MarineTraffic n.d.*b*,n) This matches what was found about the start and end point of the routs in the data provided by the operator. Further research showed that Mowi, the long term customer of Ulvan for whom the both ships have been build (see Section 3) owns a fish feed production facility in Valsneset (Mowi n.d.*b*).



(a) Heatmap based on AIS data of the ships from 2020

(b) Mapping of a typical route for the ships provided by the operator (Ulvan n.d.)

(c) Ports of call, red for both ships, blue for With Marine, and orange for With Harvest

Figure 17: Indication of the operational area of the ships based on AIS data, information given by the operator, and the ports of call listed on MarineTraffic (MarineTraffic n.d.*b*,n)

All three approaches to the operating area show similar results. The AIS data and the data provided by the operator agree, especially for the northern extent. For the southern extent, there is a match between the data provided and the information found on MarineTraffic. In all three data sets, it appears that Valsneset is the main port of call for the vessels. This can be confirmed by the fact that a fish feed factory is located there.

Based on the data presented, Valsneset is defined as the starting and end point of each roundtrip route. From here, a northern and a southern route will be investigated. For the sake of simplicity, the southernmost and the northernmost port of call are defined as the turning points of the routes. This means that the northern route runs between Valsneset and Herøy and the southern route between Valsneset and Haugesund. For the way from the fish feed production facility to the turning point of the routes it is assumed that the ships take a route close to the shore and inwards of all islands if possible. That mimics the real operation of the ship as it will be delivering feed to the fish farms located in the fjords and sheltered areas along the coast. For the way from the turning point back Valsneset, it will be assumed that the ships take an alternative route more off-shore to better facilitate the WASP system as it is more likely to have stronger winds further off the shore. Additionally, the off-shore route is likely to be shorter. Furthermore, it is determined that the ships are in the loading condition "loaded" on the first part of the route up to the turning point. On the way back, ballast mode is to be assumed. However, this means that the outward and return routes have to be considered separately. The resulting four routes, which are to be examined for this case study, are shown in the figure. Additionally, the dummy waypoint is marked which was selected with latitude 64° longitude 9° clearly out of the range of all routes. This makes it easy to deleted the point again later on, but it is still close enough to the routes that no that no unnecessarily large section of the wind data must be downloaded.

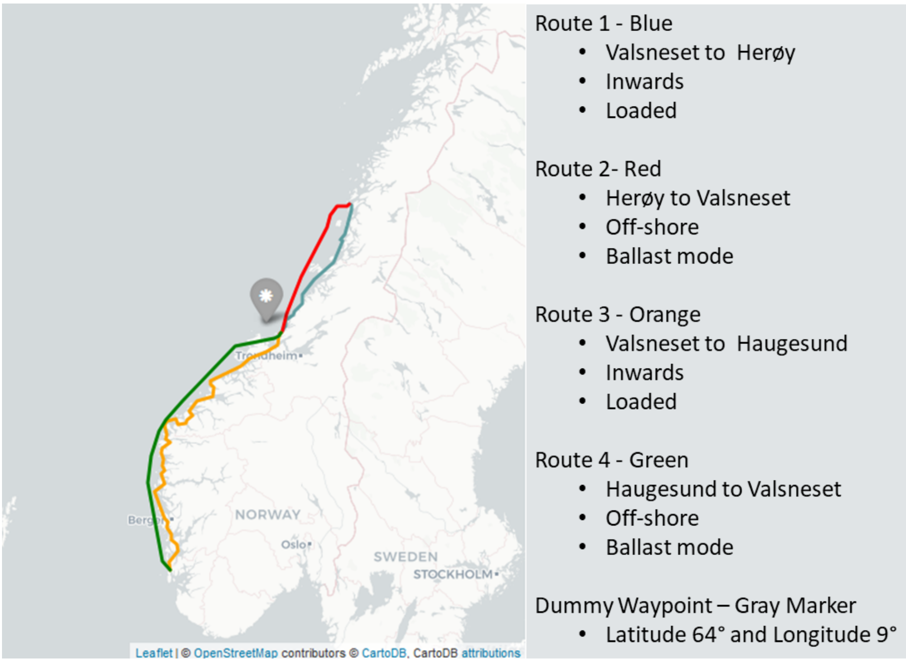


Figure 18: The four routes that will be simulated for the present case study

The routes have been generated using OpenSeaMap (https://www.openseamap.org). It has been checked that the routes are feasible. This means the ships will not cross land or other obstacles. Further, it was checked that all bridges that are passed have a high enough clearance. The vertical distance from the base of the ship to the rotor base is 15.3 m. With a minimal draught of 5.3 m in ballast arrival conditions, this leads to a free board of 10 m. (Ulvan n.d.) The additional height of the rotor is 24 m plus 2.5 m for the rotor base (Norsepower n.d.*b*). In total, the ship including the rotor has a height of 36.5 m. Within the scope of this study, it is assumed for simplicity that the rotor cannot be tilted. A minimum clearance height of 40 m for all bridges or the like is therefore defined as a feasibility criterion including a safety measure of 3.5 m. For Route 1 that means that Stokkøybrua (30m) and Brønnøysund bru (30m) cannot be passed, for Route 3 only the bridge between Sandøyna and Mjømna (30m) cannot be passed.
It is to be noted that both, the Copernicus data set (see Subsection 4.1.3) and OpenSeaMap, use WGS84 as coordinate reference system. (Copernicus n.d.*b*, OpenStreetMap n.d.*b*,n)

5.2.1 Northern Route

The northern route comprises of Route 1 and Route 2. Route 1 runs from Valsneset to Herøy with 47 waypoints including the endpoint. The total sailing distance of this inward roue is 163.35 nm and the ship sails in loaded conditions at 12.5 knots. The total sailing time for this leg is hence 13.1 h. Based on the information given by the operator of the ships on typical routes and operation, it can be assumed that a ship will service 20 fish farms on this route. A visit at a fish farm unloading feed will on average take 1 h. Adding this to the pure sailing time for the leg leads to a total duration of 33.1 h.
For the way back on Route 2, 26 waypoints were set including start and endpoint. Most of these waypoints are not navigationally necessary but were added subsequently to divide the route into shorter legs, each no longer than 15 nm. Thus, new wind data is requested more frequently and the simulation reflects a more accurate picture of the actual conditions. The maximum distance of 15 nautical miles has been chosen based on the spatial resolution of the used weather data set of $0.25° \times 0.25°$. Since one degree is equal to 60 minutes and one minute is equal to one nautical mile, 0.25° is exactly 15 nautical miles, at least when distances are considered in latitude. The longitudinal distance is somewhat shorter. The total sailing distance on this off-shore route is with 156.18 nm about 5% shorter than the inward route. On this route, the ship sails in ballast mode with 13.1 knots leading to a sailing time of 11.9 h.
To account for uncertainty, a safety factor of 5% is added to these computed times adding up to a total round-trip time, Route 1 plus Route 2, of 47.2h. In the information given by the operator, a round-trip time of 48h is given for a similar route (Ulvan n.d.). This indicates that the made assumptions are fairly accurate. The utilisation of the ships based on data collected by MarineTraffic in the last 12 month (MarineTraffic n.d.*b*,n) shows that the ships spend only 55% of the time underway, the rest of the time is spent waiting, idle, or in port. Accounting for this utilisation rate, the time per trip including port and waiting times increases to 86 h. In one year a ship will thus be able to sail the northern route about 100 times.

5.2.2 Southern Route

The south route consists of Route 3 for the way out and Route 4 for the way back between Valsneset and Haugesund. Route 3 is with 71 waypoints and a total sailing distance of 390.39 nm the longest route. The ship will again be sailing in ballast mode with a speed of 12.5 knots leading to a total sailing time of 31.2 h. It is assumed that 25 fish farms are visited on this route, with each visit taking about 1 h (Ulvan n.d.). The duration of Route 1 including the unloading times at the fish farms is then 56.2 h.
Route 4 has with only 32 waypoint less then half the amount of waypoints. Comparable to Route 2, most of the waypoints are set to divide the route in shorter legs rather than for navigationally reasons. The total sailing distance on the off-shore Route 2 is with 340.55 nm about 15% shorter than the inwards Route 3. The total sailing time at ballast speed 13.1 knots, is 26 h.
Analog to the northern route a safety of 5% is added to the total round-trip time, leading to 86.3 h. This matches exactly the average time calculated for a similar route based on the data provided by the operator (Ulvan n.d.). With the same utilization rate of 55% underway time, the total duration of a round-trip on this southern route including all additional waiting and port times is 157h. A ship can sail this route hence about 55 times a year.

5.2.3 Route Option Inwards on the Return Legs

As described above, the ships will always take the inward route on the outbound leg while delivering the fish feed. It is assumed that taking an off-shore route is unfavourable here as the fish farms are mostly located in the sheltered near shore areas. Going back and forth between an off-shore route and inwards located fish farms is expected to increase the sailing distance to an unpractical level. For the return leg however, it is assumed that the ships will sail on an off-shore route, as this is the shorter distance. However, going completely inwards would be a feasible alternative. In Section 2.2.2, it was pointed out that higher wind speeds are expected on more outwards routes but that these are also accompanied by higher waves, which can be disadvantageous. Therefore, an inward route option shall be tested for both the return legs following the same path way as the respective outbound route would just in opposite direction. The number of legs and total distance, however, will be the same. Further, the relevant input parameters are changed from loaded condition to ballast condition.

5.3 Observation Period and Simulation Intervals

For the present case study it was decided to simulate the performance of the rotor over an observation period of four years. This should account sufficiently for changing weather data and uncertainty of the wind conditions while keeping the simulation time reasonably short. As historic weather data is used to predict the future performance of the system, it is assumed that the most resent data available will give the best results. The data set used includes data up to December 31st 2020 (Copernicus n.d.*b*). Hence the observation period is set from January 1st 2017 to December 31st 2020. The first start time will then be January 1st 2017 12 O´clock.
One way to set the intervals between to simulations would be to use the realistic estimates from Section 5.2. However, here it was decided to take the same standardized intervals for each route for better comparison between the single route options. Further, a small sensitivity study is carried out to show the influence of the number iterations and the time interval between the iterations on the results. Therefore, the simulation for each route option will be run four times with start intervals of 28 days (one start every month), 14 days (one start every two weeks), 7 days (one start each week), and 3.5 days (two starts each week) and respectively 52, 104, 208, and 416 iterations over the four year period.

5.4 Performance Matrix

For the calculation of the performance matrix using the program by Polić (2022*b*) the following main input parameters are used:

- Ship main parameters, length in the water line, breadth of the ship, draught, and the block coefficient. Besides the breadth, which is constant over all loading cases, the respective values for the cases "loaded" and "ballast" have been computed.
- The ship speed and the mean power derivatives, showing the relation between power input and vessel speed. The power derivatives or propulsion curves are dependent on the draught of the ship and have been interpolated following the same principal as presented in Section 5.1.1.
- Information about the rotor including the number of rotors installed (here one), the rotor height (24 m) and rotor diameter (4 m). The height of the rotor base is based on supplier information estimated to be 2.5 m. The installed power per rotor as well as the maximum RPM and thrust of the rotor are also set according to the information of the rotor manufacturer and the deck height at the position of the rotor is measured from the general arrangement plan provided by the operator of the ships Norsepower, Ulvan.
- For the calculation of the aerodynamic forces following the strip theory the stripes are selected with in increments of 0.5 m.

The performance matrix gives, as described in Section 4, the power savings due to the rotor in dependency of TWS and TWA. Here, it was decided to calculate the performance of the rotor for wind speeds from 0 m/s to 30 m/s in increments of 1 m/s and for wind angles between 0° and 180° in increments of 5°. As the arrangement of the rotor is symmetrical to the longitudinal axis of the ship it is sufficient enough to use only the wind angles up to 180°.

6 Results

The results of all routes, northern, southern route as well as the inwards route options, are presented in Appendix A and only the main findings shall be pointed out here. For each route, the results for all four different simulation intervals (28 days, 14 days, 7 days, and 3.5 days) are presented in form of a rose plot as shown in Figure 19. The sectors of the plot represent the TWA. The experienced TWA is grouped in nine bins. The coloured sectors within one bin represent the experienced TWS. The radial scale in the upper left sector gives the accumulated probabilities of the respective combinations of TWS and TWA. For example, looking at the bin at 90°, it can be seen that over the whole observation period of four years about 7.8% of the time TWA was 90° with TWS up to 7.6 m/s. 10.8% of the time the wind speed was up to 11.4 m/s and 3% of the time the wind speeds were between 7.6 m/s and 11.4 m/s both with the same TWA.

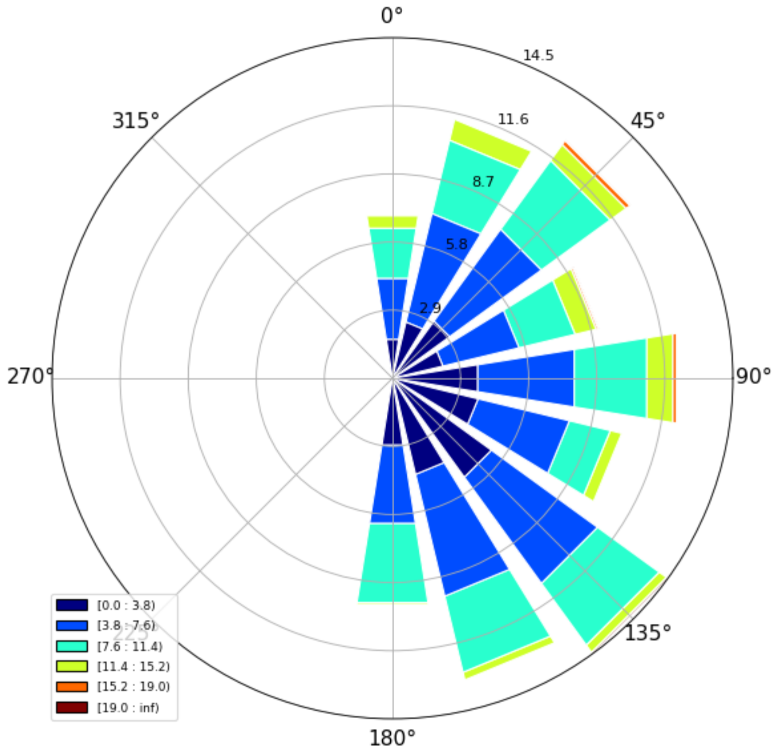


Figure 19: Example of a roseplot as used for the presentation of the results. Here for the experianced TWS and TWA on Route 1 with a simulation intervall of 28 days.

Additionally to the roseplots, the average TWS as well as average power savings per leg and average energy savings per trip are given for each rout option. The average savings are given as percentages of the baseline values. The baseline power, the power required to propel the vessel to the same speeds investigated without the use of WASP, is calculated as reference value during the computation of the performance matrix and can be taken from there. For the loaded case, the program gives a value slightly below the previously determined reference value at 75% MCR (1770 kW) of 1761,6 kW. The value in ballast mode is slightly higher with 1788,9 kW. The according baseline energy consumption can be calculated by multiplying the applicable (depending on the loading case) baseline power with the duration of a route.

$$E_{baseline} = P_{baseline} \cdot \sum_{i=1}^{i=nwp} \frac{d_{i,i+1}}{v} \tag{20}$$

With:

$d_{i,i+1}$	Distance from way point i to the next way point
v	Vessel speed
nwp	Number of waypoints equal to number of legs (see Subsection 4.1.1)

It is to be noted that in the present case a constant SFC was used in all conditions hence the percentage fuel savings are equal to the percentage energy savings. The percentage emission savings are also equal to the percentage fuel savings as a constant conversion factor is used. Nevertheless it shall be pointed out that the main engines on board the case study ships use LNG as a fuel. The conversion factor for this fuel is 2.75 kg-CO_2 per kg-LNG according to the EEDI calculation guidelines (IMO 2018). This means that each kilogram of saved fuel equals almost 3 kg of saved CO_2 emissions.

6.1 Main Findings

For better interpretation of the presented results, the theoretic performance of the rotor as presented in Figure 20 has to be taken into consideration. The Polar diagram gives the possible power savings over the wind angle for for different speeds as calculated in the performance matrix. It can be seen that the maximum savings can be achieved with TWA around 100° to 120°. With TWA over 140° almost no savings are possible anymore. In the region with angles smaller than 100°, the power savings are increasing steadily with increasing TWA.

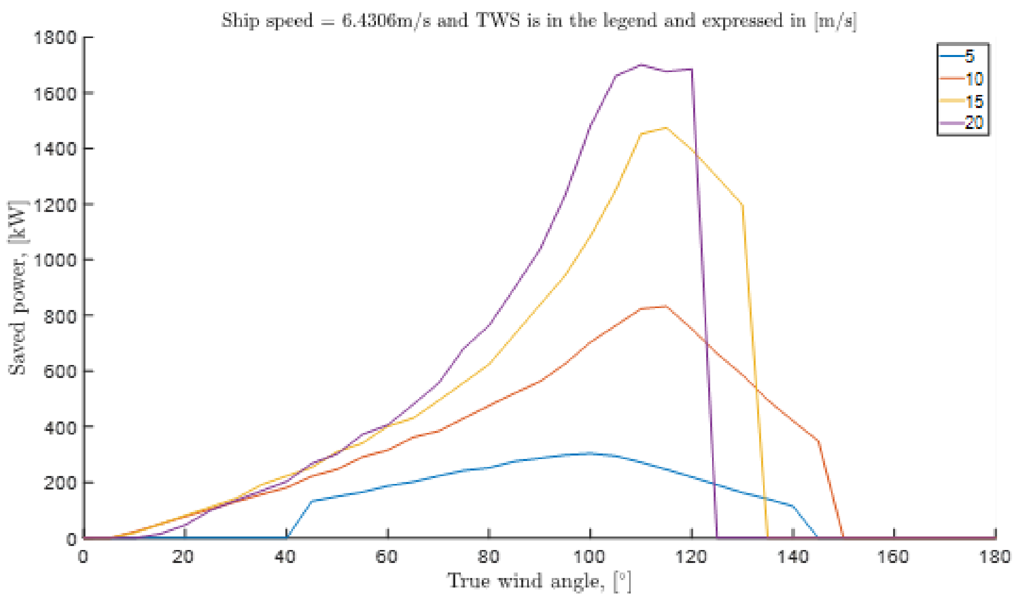


Figure 20: Polar diagram visualising the possible power savings in dependency of TWS and TWA for the loaded case. The shape of the diagram for ballast mode is similar.

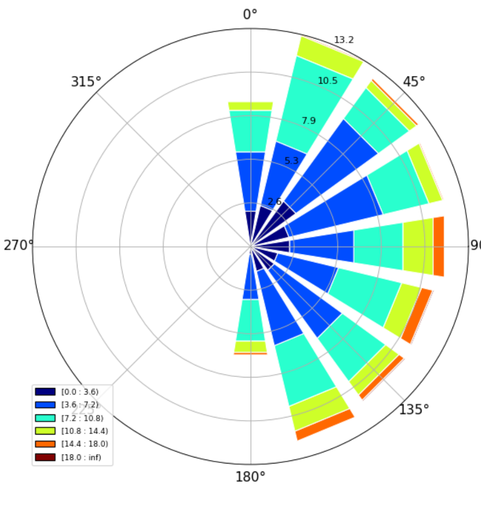
6.1.1 Main Wind Conditions

The main sailing direction on Routes 1 and 3 is from southwest to northeast. On Routes 2 and 4 it is opposite. Further, on Routes 1 and 3 it can be observed that TWA tend to be more beam to tail winds with a high occurrence of 135°. On the other routes, more beam to head on winds are experienced and a main TWA is 45°. As the direction of the routes is roughly opposite, a difference of 90° in the most occurring TWA indicates that on all routes the same mean global wind direction is experienced. This is further an indication that the achieved results are coherent and valid. On

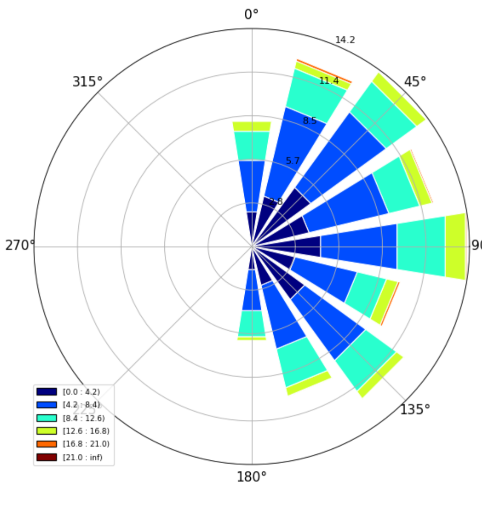
the northern route the average wind speed is slightly higher on the off-shore route (6.17 m/s) than on the inwards routes (5.97 m/s and 5.94 m/s). The wind speed on the southern route is generally higher with around 6.8 m/s. However, there is not such a clear distinction between off-shore and inwards routes.
With Figure 20 in mind, it can be assumed that the rotor performance better on the routes going from southwest to northeast as more reaching winds are experienced which is where the rotor performance best. This is basically true for Routes 1 and 4 having higher savings than route 2. The highest savings, however, are achieved on Route 3. Further, better performance is found on Route 1 compared to Route 4 whereas on Route 4, being the off-shore route, a higher average wind speed was found. It becomes clear that there are various influencing factors and the performance can not be estimated from the main wind conditions alone.

6.1.2 Dependency on the Simulation Interval

The dependency on the length of the simulation interval can especially be seen looking at the results for Route 2. For better illustration, the respective plots for simulation intervals of 28 days and 3.5 days are shown below in Figure 21. In the plot for the longer interval, no dominant wind direction can be distinguished and it is noticeable that quite high wind speeds are reached. In the second plot the share of extreme high TWS is less prominent, but the prevailing wind angles become more pronounced. It can be concluded that a simulation with a higher number of iterations in shorter intervals tends to provide, as expected, a more precise and realistic representation of the actual wind conditions. The average wind speed varies only slightly between the results of the simulations for one route. Furthermore, no clear pattern (e.g. constant increase of the average wind speed with shorter intervals) is recognizable. In addition, it is not clear from the results at which interval length the results become independent of these, or which interval provides the best and most realistic results. Further parametric studies or at best a measurement of real sailing results would be necessary here.



(a) Rose plot for Route 2, Interval = 28 days



(b) Rose plot for Route 2, Interval = 3.5 days

Figure 21: The difference between these two plots for Route 2 shows the dependency on the simulation interval

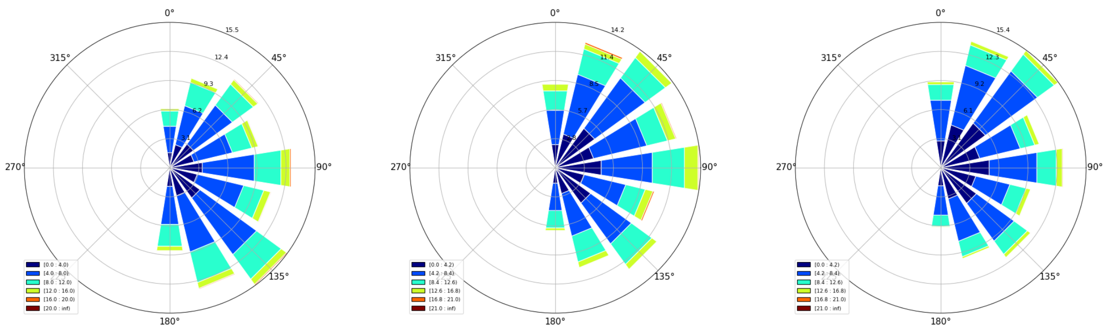
6.1.3 Power Savings vs. Energy Savings

For all simulations, it can be observed that the percentage power savings are higher then the respective percentage energy savings. The power savings presented here give the average possible energy savings on a leg in the route. If these average power saving is multiplied by the total sailing time of a route, the resulting percentage energy savings are equal to the percentage power savings. The energy savings presented here, however, are calculated in a different manner. For each point in a route the individual power savings are calculated and multiplied by the duration of the next leg. The sum of all these savings gives then the total energy savings on this route. The variation of the actual power savings in each point to the average power savings as well as the duration of each leg influence this result and the actual percentage energy savings on the route are lower than assuming average power saving over the whole distance. Within the scope of this study, no further statement can be made about the extent to which the individual power saving values and the length of the legs influence the energy savings achieved. This would require a further parametric study in which, for example, the length of the legs would be varied.

6.1.4 Northern Route

On the northern route three route options have been considered:

- Route 1: Outbound route in loaded condition, inwards, main sailing direction: northeast
- Route 2: Return leg in ballast mode, off-shore, main sailing direction: southwest
- Route 2 - Inwards Option: Return leg in ballast mode, inwards, main sailing direction: southwest



(a) Route 1
Average TWS = 5.95 m/s
Average Power Saving = 6.69%
Average Energy Saving = 6.51%

(b) Route 2
Average TWS = 6.69 m/s
Average Power Saving = 5.60%
Average Energy Saving = 5.43%

(c) Route 2 - Inwards Option
Average TWS = 5.97 m/s
Average Power Saving = 4.52%
Average Energy Saving = 4.36%

Figure 22: Results for the northern route options each with a simulation interval of 3.5 days

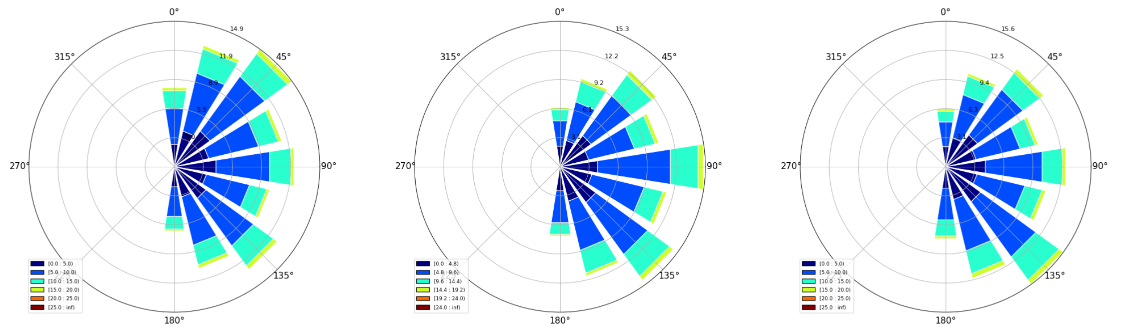
The results for the three options with a simulation interval of 3.5 days are presented in Figure 22 and shall be discussed briefly. The highest savings can be achieved on Route 1 with average energy savings per trip of 6.51%. The wind angles on this route are favourable with TWA varying mostly between 90° and 135°. The average wind speed is the lowest of the three options. However, the good wind angles out-way this fact, leading to the high savings. Additionally, from Figure 20 it is known that the maximum savings at higher TWS are also higher, however, the savings curves for medium TWS covers a higher range of TWA.
In comparison of the rose plots for Route 1 and Route 2 it can be seen that the TWA shifted and more head to beam winds are experienced. Although the TWS is the highest on this route with 6.69 m/s, the comparably bad wind directions lead to energy savings of only 5.43%, over one percentage point lower than on Route 1. This shows that higher wind speeds on an off-shore route are not an guaranty for higher savings.
The alternative route option for Route 2 follows the same waypoints than Route 1 in opposite direction. Since the same weather conditions prevailed on both routes over the observation period, the plots are comparable and appear mirrored on the 90° axis. Smaller deviations and variations result from the fact that the waypoints were approached in reverse order and therefore at slightly

different times. The different lengths of the legs also play a role here. so, compared to Roue 1, this route option favours less optimal TWA. The TWS is similar to Route 1 but lower than on the off-shore Route 2. The combination of both these facts lead to the least savings achieved on this route. As this route option is also longer than Route 2 (see Section 5.2) it is not recommended to take the inwards route on the return leg.

6.1.5 Southern Route

On the southern route, three route options have been considered:

- Route 3: Outbound route in loaded condition, inwards, main sailing direction: southwest
- Route 4: Return leg in ballast mode, off-shore, main sailing direction: northeast
- Route 4 - Inwards Option: Return leg in ballast mode, inwards, main sailing direction: northeast



(a) Route 3
Average TWS = 6.82 m/s
Average Power Saving = 7.42%
Average Energy Saving = 7.21%

(b) Route 4
Average TWS = 6.91 m/s
Average Power Saving = 6.45%
Average Energy Saving = 6.15%

(c) Route 4 - Inwards Option
Average TWS = 6.79 m/s
Average Power Saving = 5.79%
Average Energy Saving = 5.57%

Figure 23: Results for the southern route options each with a simulation interval of 3.5 days

Similar to the northern route, the results for the three southern options with a simulation interval of 3.5 days are presented in Figure 23. The most savings of all options are achieved on Route 3. Comparable to Route 1, this route has not the highest average TWS of the southern route options but it is still almost 1 m/s higher than for Route 1. The TWA on this route seem less favourable than on Route 1. A TWA of 45° has a high occurrence, with wind speeds mainly between 5 m/s and 15 m/s there is still a decent amount of savings expected. More favorable TWA between 60° and 135° also occur relatively often. On the other hand, the occurrence of very low TWA under 20° or very high TWA above 135° is comparably low. In this regions, only few or no savings are achieved according to Figure 20. The rose plot presented here speaks for a constantly high saving level over all TWA together with the relatively high wind speed this leads to the significant high savings potential.
Route 4 shows, yet again, slightly more dominant reaching winds as the sailing direction is also more favourable towards the main wind direction. However, the effect is not as dominant on the southern route compared to the northern route. The northern route also leads in a more or less straight line up the coast of Norway, while the southern route circumvents the "Horn of Norway" at Leikanger and follows a more north-south direction along the west coast of Norway. The prevailing wind angles are hence less pronounced. Being the off-shore option on the southern route, Route 4 has the highest wind speeds but the achieved savings are lower than for Route 3. The distribution of TWA for Route 3 and Route 1 is quite similar. The average wind speed on Route 3 is almost 1 m/s higher, but the distribution of high and low TWS over TWA seems more favourable for Route 1 leading to the higher percentage savings on this roue.

For the the relation between the inwards option of Route 4 and Route 3, the same applies as mentioned for the relation between the inwards option of Route 2 and Route 1. The wind speed is slightly lower than on the off-shore route and the angles look good. However, angles above 135° occur fairly often where the rotor produces no power savings and for the other angles wind comes slightly more from the font compared to Route 1. With 5.57% the energy savings are the lowest on the southern route. Similar to the inwards option for Route 2 this is the longer option of the return leg and not recommended.

6.2 Fuel Savings

first the annual fuel savings are calculated. Based on these findings the question is answered whether the rotor can compensate for the ship extension.

6.2.1 Annual Fuel Savings

Based on the findings presented in Section 6.1 the options Route 1 and 2 are chosen for the northern route and Routes 3 and 4 for the southern route. The inwards option for the return leg is never chosen. From Section 5.2 it is known that the northern route can be sailed 100 times a year. The annual fuel savings on this route can further be calculated as follows:

$$Annual\ Savings_{North} = (Savings_{Route1} + Savings_{Route2}) \cdot 100 \tag{21}$$

With the saving values from the simulation with 3.5 days interval this leads to annual fuel savings of 48.4 t synonymous to savings of 133 t Co_2. Without WASP 807.1 t fuel are used for 100 trips a year. This leads to total annual fuel savings of 5.99% on this combined northern route.
The savings for the southern route can be calculated similarly. As this route is longer it will only be sailed 55 times a year. In total 68.34 t fuel and 187.9 t CO_2 can be saved annually. With a fuel consumption of 1016.2 t per year the annual fuel savings on the combined southern route are 6.7%.

6.2.2 Will the rotor compensate for the ship extension?

As mentioned in Section 3 the basic project idea by Ulvan is to extend the ships to increase the transport volume. The ship extension will lead to an increased resistance and hence fuel consumption. The installation of the rotor shall compensate for that and hence allow to transport more fish feed while keeping the annual fuel consumption constant at the level of the original ship. To answer this question, first the original fuel consumption has to be computed. So far, it was assumed the the engines are used at a constant loading of 75% MCR. For better comparability the same will be assumed for the original ship. With the same loading cases and draughts and the original propulsion curves provided by the operator (Ulvan n.d.) the reference speeds are determined to be 13 knots in the loaded condition and 13.4 knots in ballast mode. The same routes and condition as defined in Section 18 apply and the required power is set to 1770 kW. The original annual fuel consumption, $fuel\ consum._{original}$, can then be calculated as follows:

$$fuel\ consum._{original} = (fuel\ consum._{outbound} + fuel\ consum._{inbound}) \cdot trips\ per\ year \tag{22}$$

With:

$$fuel\ consum._{outbound} = \frac{distance_{outbound}}{speed_{outbound}} \cdot 1770\ kW \cdot 182\ \frac{g - fuel}{kWh} \tag{23}$$

For the north route, the annual fuel consumption of the original ship amounts then for 780.2 t. The original ship hence used 3.33% less fuel a year on this route then the extended ship will use.

The annual savings due to the rotor sail on this route were found o be 5.99%. The rotor can compensate the ship extension on the northern route.
The annual fuel consumption of the original ship in the southern route sums up to 982.3 t. The original ship uses equally 3.33% less fuel a year on this rout than the extended ship will use. The annual savings on this route are slightly higher and with 6.7% twice as high as the percentage difference in fuel consumption. The rotor sail will hence compensate the ships extension also on the southern route.

6.3 Validation of the Results

The results as presented here seem plausible and coherent. Nevertheless, they should be validated by another source. The best way for validation of the method and the results would be measurements of actual sailing performance. So far, no comparable ship operating a long the Norwegian coast is, so this validation method is not available at the moment. Alternatively, there are some free online tools available that could be used for validation of the results.
One such tool is the Flettner SAvings Calculator by Lloyd´s Register. The tool is based on in-service performance data aquired from the Maersk Pelican as well as other published material for generic merchant ships.(Lloyd's Register n.d.) The tool offers a selection of four ship types, tankers, bulk carriers, ro-ro, and passenger vessel, that can further be specified by a variety of optional input parameters. However, these input parameters are limited by minimum and maximum allowable values. While trying to customize a ship in this tool to match the case study ship it was found that their values were often out of the allowable range. For example, the tool requires a minimum installed propulsion power of 4000 kW while the case study vessels have only 2300 kW installed. (Lloyd's Register n.d., Ulvan n.d.) This online tool is hence also no feasible option for validation of the results.
The rotor manufacturer Norsepower also offers an online evaluation tool on its website. This tool offers no selction of specific ship parameters. Only the rotor size, vessel speed, and time at sea are select able. Further, it is only possible to simulate the savings on predefined routes. (Norsepower n.d.*c*) The closest route option found to the presented case was a route from the Netherlands to Norway, Oslo. The average annual fuel savings simulated by this tool are at 205.8 t. This is significantly higher to the savings found here. However, the route comprises more open sea passages than are considered in the case study. Further, no information is given about the vessel they consider in the calculations. This tool is as well not found suitable for validation of the method and results of this thesis.
A last option for validation would be to calculate the EEDI of the new ship. The rotor sail would be considered in this calculation as energy efficiency measure and would improve the rating. (IMO 2018) The percentage improvement in the rating due to the WASP system could then be taken as indication for the fuel savings to be expected. However, the EEDI calculations are very time consuming and it was found that within the time and the scope of this thesis it was not feasible to calculate the EEDI for means of verification of the results.
Summing up, no feasible way of verification of the methods and results in this thesis was found. As such a validation is found to be of high importance, further work on the topic should include the search for a suitable verification method.

7 Evaluation and Discussion

Some points have already been pointed out and explained in the course of the text. However, attention should be paid here to a few important points that call for a more detailed discussion.

7.1 Method

The here presented performance prediction method is not jet a fully integrated program. As already pointed out in Section 4.2 the process as of now requires many manual steps and the performance matrix has to be calculated externally. This multi-step calculation process is accompanied by the risk of errors occurring and certain values not being transferred correctly. In a next version of the method, the performance calculation should be integrated into the program. For this, however, the calculation method for the performance matrix would first have to be transferred from Matlab to Python so that it is compatible with the main program. In the scope of the present work, the focus was not on the performance calculation itself but rather on illustrating how such a performance calculation can be used to make specific statements about a use case. The performance calculation itself and the also relatively complex route generation will be discussed separately below.
Another drawback of the method developed here is, that as of now, only rotor sails and their performance can be evaluated. For other systems, the lift and drag and hence the performance of the system are calculated differently. This would have to be implemented in a modular performance prediction method. Systems that could be interesting to implement in the next version of the method could for example be suction wings.
On the positive side, it has been possible to develop a method that seems reliable and accurate. For a more detailed evaluation, a more detailed validation of the results, which was not possible within the scope of this work, would be necessary (see: Section 6). The method uses comparatively few ship-specific input data and can therefore be easily applied. The relatively complex calculation of the input data in the present case only resulted from the extension of the ship and the associated change of the parameters. Without this extension, the required data could have been read directly from the documents provided by the shipowner.
The method uses historical weather data from the ship´s area of operation. This is especially an advantage for niche applications and coastal shipping, such as the aquaculture sector. Other performance prediction programs sometimes use only the statistical global wind values, which is a sufficient approach for ships operating worldwide. However, for a more specific, smaller operational area, such as the Norwegian coast, the same values cannot be adopted one-to-one. Here, the local weather conditions are much more specific and the coast itself has a large influence on the wind values.
Overall, the performance prediction method developed here still has great potential for improvement, especially with regard to the integration and automation of work steps. This can increase usability and avoid errors due to unclean data transfers. Nevertheless, it has been successfully demonstrated how such a performance prediction method can be developed and tailored to specific application areas and how such a method can be used to make qualitative statements about the viability of a WASP application.

7.2 Performance Calculation

The method used in the present case for calculation of the performance matrix (Polić 2022*b*) is still in a development state. The version used already produces decent output, however, some important aspects are not covered yet. Most strikingly, the yaw moment is excluded under the assumption that it can be compensated by the rudder at any time. However, in reality, if the yaw moment cannot be sufficiently compensated by counter steering, the rotor will be de-powered, resulting in lower savings in these cases. The work presented in the literature review also indicates that it is important to consider the yaw moment and to use a method with at least four degrees of freedom. It is planned to improve this in a next, improved version of the method.
Furthermore, as shown in Figure 24, it can be stated that under special conditions savings of over 100% can be achieved. The reason for this is a lack of limiting the savings as a constraint in the

calculation method used. These extremely high savings do not occur very often and only at high wind speeds above 15 m/s. The values exceed the 100% mark only slightly by a few percentage points. An improved version of the calculation method, which includes an additional constraint to limit the savings, has already been developed. However, this was not available in time to be used in this paper. Therefore, the potential savings as presented here have been used in this paper and had to be considered to be sufficiently accurate. Nevertheless, this should be taken into account when evaluating the results found.
If the two improvements mentioned here are implemented in the method, it is expected that the shape of the polar diagram as shown in 20 and 24 will change significantly. It is assumed that the maximum will shift and be at a TWA of about 90°. Also, the maximum value will be lower and below the 100% mark. The slope of the curve on either side of the maximum will steadily decrease. The shape of the curve is expected to be approximately symmetrical with a flattened slope. The shift in the maximum mentioned here and the changed savings curve will also have a significant impact on the results of the case study and simulation presented. However, it is difficult to predict exactly how the savings achieved will change, as many factors are involved. It is assumed that the observed significant advantage of diagonal tailwinds will disappear and routes with more crosswinds will be favoured. It is also assumed that the overall savings will be somewhat less, as rotor performance is limited by the yaw moment and the additional constraint. However, it is not easy to predict how much the annual savings will be reduced, as there are complex relationships to consider. It is also not possible to make a clear statement on the question of whether the rotor is still able to compensate for the additional energy demand caused by the ship extensions if the calculation method is optimized. However, since the savings calculated here were about twice as high as the increase in energy demand, there is some room for interpretation and it can be optimistically assumed that the savings could still be sufficient even with an improved calculation method.

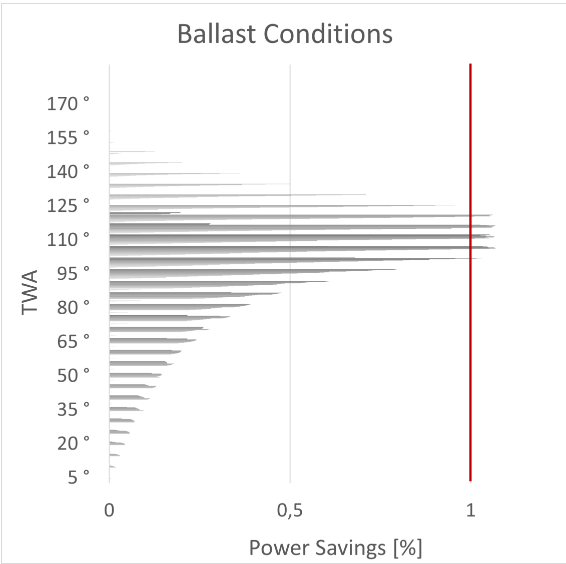


Figure 24: Polar diagram for the ballast case showing the possible power savings in percentage of the total power

7.3 Route Generation and Weather Data

The route generation as it was carried out in the present case study was quite time-consuming since each waypoint of each route was set manually. Here it should be considered how the process of route generation can be improved, if necessary also automated. On the other hand, a ship operator wishing to use the presented method to assess the potential of WASP for his ship may already have the required route information and waypoints at hand.
With regard to the weather and the wind data, the assumption was made that these remain constant over the period of a leg (see: Section 3). This is a simplified assumption that was considered

sufficiently accurate. In addition, this simplification means that the performance calculations can be carried out in an uncomplicated manner and the computing time is kept relatively short. However, the influence of the leg length on the savings achieved should be further investigated. In addition, the spatial resolution of the weather data used must be considered. The data set used here has a resolution of 0.25° x 0.25°. With a maximum route length of 15 nautical miles, it is assumed that the weather data are queried with sufficient frequency and that every change in the weather is taken into account when a subdivision line is crossed.

8 Further Considerations about the Viability of WASP in Norwegian Aquaculture

The performance of the rotor sail on a specific route has been set as the main decisive factor for the viability of WASP. However, there are some other important factors to consider. These comprise risk and safety as well as more detailed economic considerations. Both shall be presented briefly and in a qualitative way.

8.1 Risk and Safety Consideration

New and innovative technologies often lack comprehensive standards, rules, and regulations. these will further evolve with the development and diffusion of the technologies as more and more references and example cases will be available. Especially, in the earlier phases of a new developing technology, it is hence of high importance to consider possible risk and safety issues thoroughly on an individual basis. Within the scope of this thesis and due to a lack of time and detailed information, there was no quantitative risk assessment carried out as part of the case study. Nevertheless, some important considerations about risk and safety of WASP systems in Norwegian aquaculture shall be presented here to give a more comprehensive few on the viability of WASP in this sector. Furthermore, the focus in this section is mainly on rotor sails.

The DNV standard for wind-assisted propulsion systems (DNVGL 2019) gives in Appendix A physical principles and safety considerations some valuable input about operational effects due to aerodynamic forces and general operational obstructions. The operational effects mentioned here concern mainly the aerodynamic side forces. These lead to a resulting heeling moment, as well as leeway and possibly yaw of the vessel. These forces have a significant influence on the manoeuvrability of the ship and should be investigated carefully. (DNVGL 2019) Van der Kolk et al. (2019) see the yaw moment as having the most severe destabilizing effect on the course-keeping ability of the vessel. The yaw moment can be balanced by the rudder to a certain extent. However, to keep sufficient manoeuvrability, the maximum rudder angle should be restricted and the sails have to be de-powered eventually. The yaw moment is thus a key design concern when selecting the size and number of rotors installed. (van der Kolk et al. 2019) For a vessel with more than one rotor sail along the longitudinal axis, there is the option to reverse the rotation of the aft sail to create a steering force through the thrust difference between the sails. Thus balancing the yaw moment and reducing the rudder load and steering angle. Nevertheless, this is only an option for ships with large sail areas and multiple rotor sails. (Thies & Ringsberg 2021) Further, a reduced heeling moment might also have a reducing effect on the yaw moment (Tillig & Ringsberg 2020) To counterbalance the heeling moment adaptive ballasting systems can be used. The third resultant of the aerodynamic side forces, the leeway, has to be compensated with a certain weather helm and is to be considered in the navigation of the ship. (DNVGL 2019)
Another fact that is mentioned in the DNV standard is the interaction of sail forces and vessel motions, especially rolling motions. These can be dampened or amplified with a modified amplitude or frequency due to the aerodynamic forces. These forces as well as their effect on the ship's motions vary with the wind speed. For rotor sails, it shall also be noted, that the rotating mass of the rotor induces a gyroscopic force that can further influence the ship's motions in similar ways. (DNVGL 2019) While dampening of the motions might be a beneficial effect, amplification or a change of amplitude or frequency might lead to risky situations. Large roll angles, high roll speeds, or certain resonance conditions can be examples of such hazardous situations.

General operational obstructions listed in the DNV standard (DNVGL 2019) include an obstructed view from the navigational deck, and influences on cargo handling and bridge clearance due to the tall over deck structures of the WASP system. An obstructed view from the navigation deck can have severe consequences for the navigation of the ship. This shall be taken into consideration when deciding about the kind of WASP used and the placement of the system. Further, relevant regulations about the line of sight and the like have to be obliged and exceptions might be inquired if necessary.
As for cargo handling, often cargo is loaded and unloaded using cranes. A rotor sail has to be

placed in a position clear of the operational area of onboard cranes. Otherwise, there will be the risk of collision between the crane and the rotor which can lead to severe damage to both systems. For the case study ships that was already checked in Subsection 3.2. A similar risk also exists when using external land-based cranes, for example when loading the ship. Especially when many different places on deck need to be reached by the crane and frequent movement of the crane is necessary, there is a risk of the crane colliding with the rotor sail and damaging it. However, for the case study vessels, this risk is considered to be moderate. They have a central loading point just behind the deckhouse. From there, a conveyor belt runs along the top of the holds on each side of the ship and distributes the cargo to the respective compartments. This means that the loading crane only has to approach this central loading point once, after which the crane and ship remain in constant positions for the duration of the loading process.
In Subsection 5.2 it became clear that the sailing height of bridges was a problem in the route generation process. Although in the case study case only three bridges had not had a high enough clearance, that might still become a severe problem. The Norwegian coast comprises many fjords and islands providing the sheltered sea areas needed for fish farming but also bridges connecting islands to the mainland. Some of which have a clearance not high enough for a ship with a rotor sail. For pure route generation between two points, as was presented in the case study, these bridges can simply be circumnavigated. Taking also into account the location of the fish farms along such a route, the circumnavigation of a bridge might mean that a fish farm located in the fjord or sound behind might not be reached or might only be reached by taking a significantly longer route. Inexperienced navigation or laps of the crew could lead to a collision of the rotor sail with a bridge or other obstacle reaching over the designated pass way of the ship. Severe damage to the ship and the rotor can be the result. Especially in ports, cranes, or the like can also represent such an obstacle with the associated risk. A more thorough analysis of the operation of the ship and the location of the serviced fish farms as well as ports of call is hence necessary.

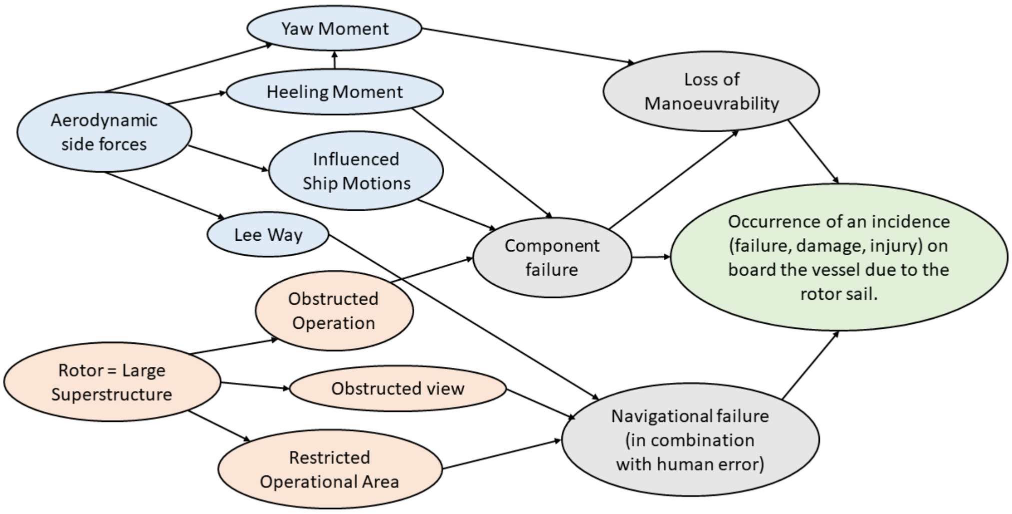


Figure 25: Schematic representation of the potential risks that could lead to an incident (damage, failure, injury) for a Norwegian aquaculture vessel with one rotor sail installed

So far, only operational risk has been contemplated. Another, part to be regarded is technical risk involving equipment failure. Increased vessel motions and permanent heel can induce malfunctioning or failure of vessel equipment and structures (DNVGL 2019). Special attention should be paid to the structures that absorb the rotor forces and transfer them to the hull. In addition to the lift and drag forces, as well as the gyroscopic force, the rotor represents an enormous lever arm, through which huge load peaks in the base can occur during heeling or rolling. Vibrations and critical resonance are other factors that ways in here and can lead to damage to the ship as well as the rotor.
In storms or other conditions when the rotor will not be used it has to be secured in a fixed position. If the fixation system breaks that can lead to uncontrollable motions of the rotor and the ship. Especially in more severe weather conditions, this puts the vessel in a potentially hazardous

situation. The same applies to a failure of the control system, leading to overspeed or overload and potential damage to the rotor. A failure of the control system will further have influences on the vessel itself. Too high heeling and yaw moments due to a failed de-powering of the rotor can in a worst-case scenario lead to the loss of manoeuvrability. Besides storms, ice is another severe weather condition that is likely to happen especially along the coast of Northern Norway. It shall hence also be included in a thorough risk assessment. Other points of interest comprise amongst others fire, static electricity, and human error (DNVGL 2019).

8.2 Situational and Economical Considerations

Analysing the contextual situation will help to understand possible benefits and risks or costs for the implementation of WASP technologies in the Norwegian aquaculture sector. This is be done using a SWOT analysis and followed by a classical cost-benefit approach. Further considerations are given about environmental and/or social cost-benefit analyses.

8.2.1 SWOT-Analysis

A SWOT (strengths, weaknesses, opportunities, threats) analysis can be used to evaluate the situational context for implementing a new technology. The analysis presented here will be used specifically to contextualize the use of WASP in the Norwegian aquaculture sector.AS can be seen from Figure 26 the SWOT analysis includes more generic external opportunities that are valid for most decarbonisation technologies as well as internal strengths and weaknesses specific to WASP technologies.
The opportunities include an uncertain development of fuel prices and carbon taxes. With increased prices, saving fuel becomes more and more important not only from an environmental perspective but also an economic one. This will also be supported by ever tightening rules and regulations. Compliance with these rules from an early stage one might lead to an extended use phase of the vessel if this means that a necessary new acquisition to replace the vessel can be postponed. Further, an increasing green shift in society can be observed. As mentioned in Subsection 2.1.4 the social pressure towards more environmental friendliness, transparency, and sustainable supply chains including the transport of materials and goods is also recognized in the aquaculture sector. Although other factors might be more present with regards to fish farming, CO_2 emissions are getting more and more in the focus as well. (Moe et al. 2022) Being at the forefront of innovation and decarbonisation on the other hand might improve a company's image and lead to a competitive benefit.(van der Kolk et al. 2019) A common threat and main barrier for energy efficiency technologies is due to split incentives. While the owner of the ship is paying for the implementation of these technologies it is the operator or charterer that benefits the most due to reduced fuel costs. The incentive for the owner to invest in these technologies is however limited as are his benefits. (Karslen et al. 2019) Further, the investment in WASP technologies can be considered with high economical risks. The development of fuel prices and carbon taxes, which is likely to benefit energy efficiency measures is still subject to high uncertainty as is the further development of the fairly immature technologies. These are all factors that put risk on the investment as payback periods and break-even points are hard to predict. The immaturity of most systems further leads to the fact that there is less trust in these systems due to the lack of knowledge and example cases. Further, an intensified risk assessment and hence an increased work effort might be necessary as there is still a lack of standards and rules to follow.
The great strength of WASP systems is that they use the wind as a main power source. The wind is an abounded source hence no dependencies on land-based fuelling infrastructures or fuel supply arise. This seems to be a clear benefit compared to other fuel options like hydrogen or ammonia. As is the fact, that wind power does not need an energy carrier and storage. it can be directly translated into an active propulsion force. Furthermore, the wind is freely available and only minimal operational costs occur (for example power needed to propel a rotor sail or maintenance). On the other hand, the wind is an uninfluenceable natural force and it is hard to predict the weather conditions and hence the actual performance of such a system. As a hybrid WASP ship, the vessel can rely on its ICE main engines and will keep up its schedule. However, lower utilisation of the system will lead to reduced fuel savings and a lower payback rate. Another weakness of WASP

systems is that most systems involve large superstructures. These can obstruct the view from the navigational deck as well as the operation of the ship, additionally, the operational area might be restricted and problems with port infrastructure (cranes) are possible to occur. The last and probably most severe weakness of wind propulsion is the aerodynamic side forces and the thereby induced moments as has been discussed in more detail in Section 8.1.

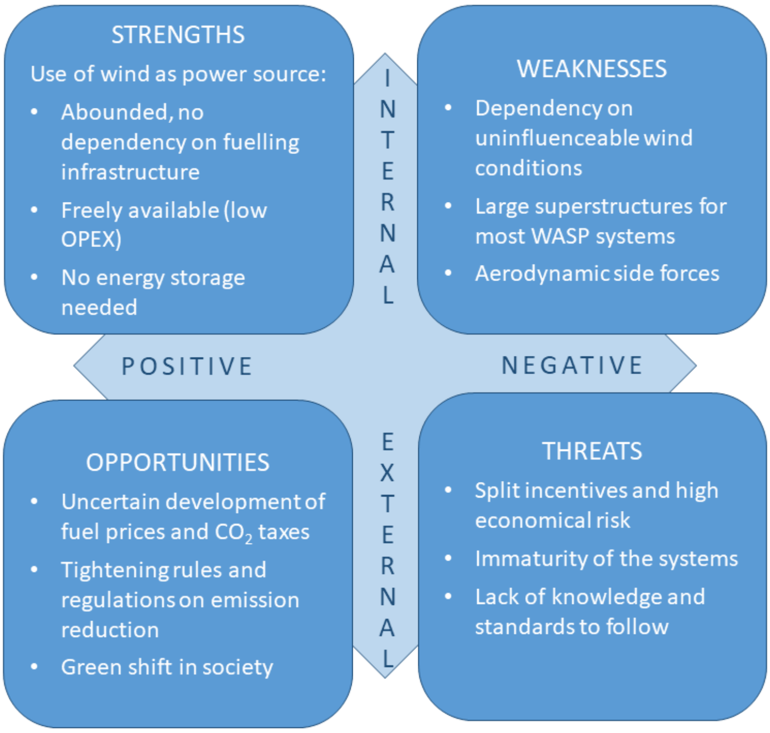


Figure 26: A SWOT analysis showing external opportunities and threats generic to most decarbonisation technologies in shipping and internal strength and weaknesses specific to WASP

8.2.2 Cost-Benefit Analysis

A cost-benefit analysis (CBA) is a common tool to assess the economic viability of a project. From a strictly commercial perspective, the costs or accumulated investments for the purchase and installation of a WASP system are set against the savings achieved due to the WASP system. Van der Kolk et al. (2019) then find a savings function describing the difference in the operational costs of the vessel with and without WASP to be dependent on fuel cost, maintenance, revenue, insurance, administration, and payroll. They find changes in revenue to be negligible and no changes in insurance and administration costs, as well as the payroll as no specially trained crew is needed to operate the system. However, they quote the annual maintenance costs to be 2% of the investment costs. (van der Kolk et al. 2019) With the average fuel savings per trip known from the performance prediction as well as the utilisation of the ships presented in Section 5.2 the annual fuel savings can be calculated. Multiplying this with the applicable fuel price will give the monetary savings per year due to fuel savings. Furthermore, in the present case study case it is known that the transport volume is increased by 24% by the extension of the ship. Therefore a revenue increase of 24% can be assumed while the additional costs for the extensions add to the cost side of the function. The investment is a one-time cost while the savings are time-dependent and increase over the long term. The break-even point is found when the savings level out the investment. The time up to this point is the payback period. The prices for fuel, fish feed, and other factors of this function are subject to change over time. To account for this a discount rate is used to present the value of the investment today with respect to future changes as net present value. In the present case, detailed information about the investment costs and expected revenue are missing. Nevertheless, the following functions can be established for the cost-benefit calculation:

$$Savings(t) = \nabla fuel\ costs(t) + \nabla revenue(t) - \nabla maintenance\ costs(t) \tag{24}$$

$$\nabla fuel\ costs(t) = annual\ fuel\ savings \cdot fuel\ price \tag{25}$$

$$\nabla revenue(t) = \nabla transport\ volume \cdot fish\ feed\ price \tag{26}$$

$$Annual\ maintenance\ costs = 2\%\ Investment\ costs \tag{27}$$

For finding the payback period the following equation has to be fulfilled:

$$Savings(t) - Investment = 0 \tag{28}$$

From Section 3 it is known that the transport volume is increased by 1340.3 m^3 while the performance prediction gives annual fuel savings for each route option (see Section section 6).

In addition to purely economic CBA, the question of social or even environmental CBA, which considers broader factors, is increasingly being raised in connection with projects that have an impact on the environment. Such a social CBA is for example mentioned in Rojon & Dieperink (2014). A first step in this direction is the monetary quantification of CO_2 emissions in the form of a carbon price. In Norway, such a carbon tax has already been implemented in 1991 and can be included in the CBA (Sumner et al. 2011). Alternatively, the European Commission published a GUIDE TO COST-BENEFIT ANALYSIS OF INVESTMENT PROJECTS in which a calculation of carbon prices is proposed. Further, they state: *"Any CBA should integrate the economic cost of climate change resulting from positive or negative variations of GHG emissions."* Sartori et al. (2014). This seems especially important for projects in the transport sector and although these guidelines are developed for public investments and policy making, this is still an idea that should be transferred to the private sector as well. Karine Nyborg, in her book THE ETHICS AND POLITICS OF ENVIRONMENTAL COST-BENEFIT ANALYSIS, even goes a step further and says: *"Putting a price tag on the environment is controversial."* (Nyborg 2012). The question remains as to how best to incorporate these additional environmental and social factors into an analysis of the profitability of a technology. Whether it is possible to put a price tag on them, or whether a broader factual background is needed than that covered by a cost-benefit analysis.
These questions cannot be answered within the scope of this thesis. However, practically applied to the given case, this means that the emission savings can be considered relatively easily via a carbon price in the CBA. Other benefits resulting from the implementation of WASP, such as the extended usability of the ship due to compliance with stricter environmental regulations, or an improved image, are more difficult to quantify.

9 Conclusion and Recommendation for Further Work

The aim of this thesis was to present how a comprehensive approach can be used to access the potential and viability of wind-assisted ship propulsion in Norwegian aquaculture. The main focus thereby was on the development of a performance prediction method tailored to this niche as main decision criterion. A case study was used to illustrate the application of the method and additional considerations about the safety of the system as well as the contextual situation and economic viability were presented.

The initial background study presented a good knowledge base of important facts about aquaculture as well as wind propulsion. It can be taken away that most vessels used in the aquaculture industry are too small or have no free deck area for the installation available. However, for the bigger vessel types, the cargo ships and well boats, rotor sails, and suction wings are promising options.

The following case study was conducted in cooperation with Egil Ulvan Rederi AS (Ulvan). The idea is to extend two of their existing vessels to increase the transport volume of fish feed. The extension will also increase the resistance and hence the propulsion power needed. To compensate for that, a Flettner rotor shall be installed on board the ships. To answer the question whether the increased propulsion power due to the extension can be compensated by the rotor sail, a performance prediction method was developed and it was exemplarily shown how this can be used to evaluate the viability of such an installation. It was found that the original ship uses 3.33% less fuel than the extended one will use. The average savings due to the use of WASP were found to be around 6%. It was hence shown that the rotor can compensate for the extension. However, these savings shall be met with caution. Missing constraints in the performance prediction are expected to have led to an over-prediction of the potential savings. Nevertheless, since the savings calculated here were about twice as high as the increase in energy demand, there is some room for interpretation and it can be optimistically assumed that the savings could still be sufficient even with an improved calculation method.

With regard to the safety of the system, some essential points have been discussed. The aerodynamic side forces as well as the large superstructures of most WASP systems can lead to hazardous situations. As most systems are fully automated the handling of the system is not concerned an issue in a well-functioning system. However, as most WASP technologies are still in a development state applicable rules and standards are comparable spares. An individual and detailed risk assessment is hence recommended. This lack of knowledge and split incentives are the most prominent barriers for new decarbonisation technologies at the moment. Nevertheless, the contextual environment for the implementation of such systems is considered favourable. The specific strength of WASP systems lies in the use of the wind as a power source. On the other hand does the dependency on the volatile wind also resemble a potential threat. No final conclusion can be given about the economic viability of the system as not all input factors were available. Additionally, quantifying environmental and social factors resulting from the use of WASP are hard to quantify. Considering the promising power savings as well as the favourable environment, it can be concluded that the use of WASP in Norwegian aquaculture seems to have some promising potential. For clarification and validation of the findings in this thesis further research on the topic is recommended. Especially since it is assumed that the potential fuel savings are over-predicted by the method used here. An improved calculation method might lead to the conclusion that WASP is not a viable solution in Norwegian aquaculture as the savings are not high enough. Further topics of interest to investigate would be whether ship weather routing can improve the performance of a WASP system or the hybridisation of WASP and alternative fuels.

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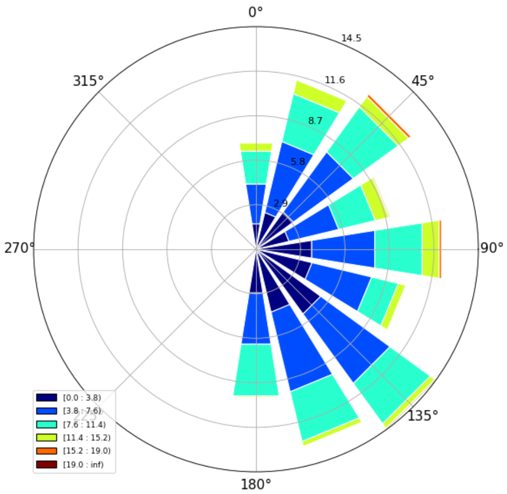
Appendix

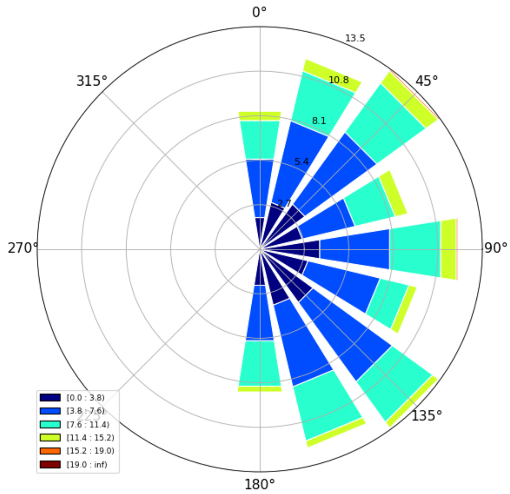
A Simulation Results

A.1 Northern Route

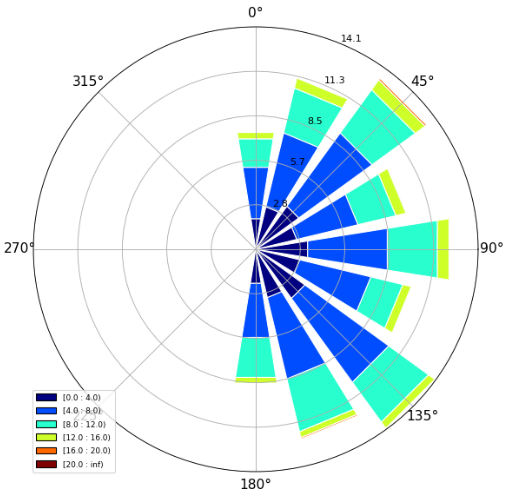
Route 1



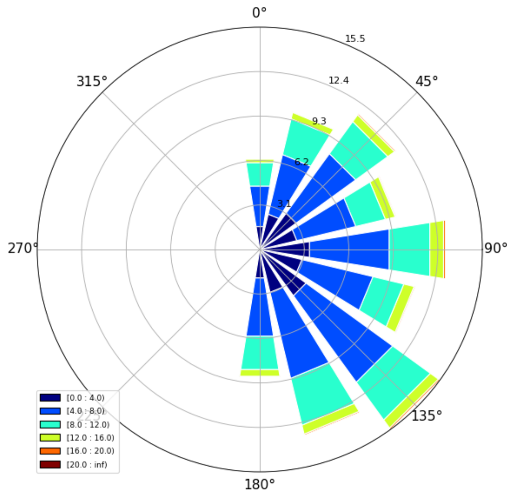
(a) Interval = 28 days
Average TWS = 5.96 m/s
Average Power Saving = 6.29%
Average Energy Saving = 5.99%



(b) Interval = 14 days
Average TWS = 5.98 m/s
Average Power Saving = 6.23%
Average Energy Saving = 5.90%



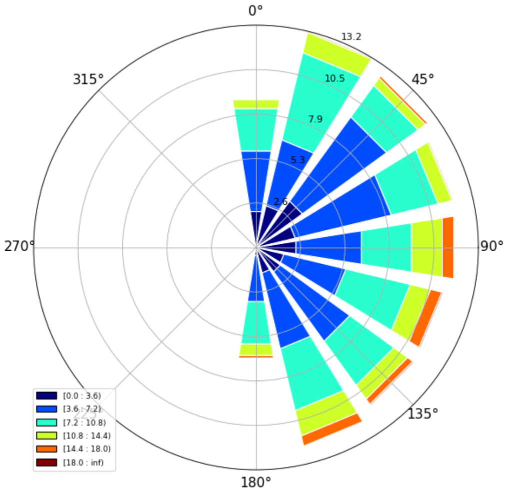
(c) Interval = 7 days
Average TWS = 5.99 m/s
Average Power Saving = 6.53%
Average Energy Saving = 6.31%



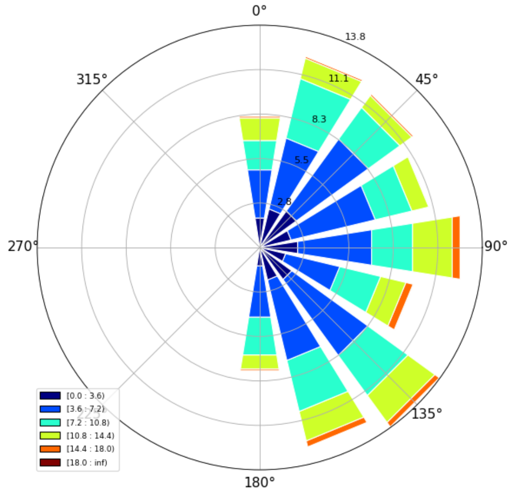
(d) Interval = 3.5 days
Average TWS = 5.95 m/s
Average Power Saving = 6.69%
Average Energy Saving = 6.51%

Figure 27: Roseplots of TWS and TWA and average savings achievable on Route 1 for the four different simulation intervals

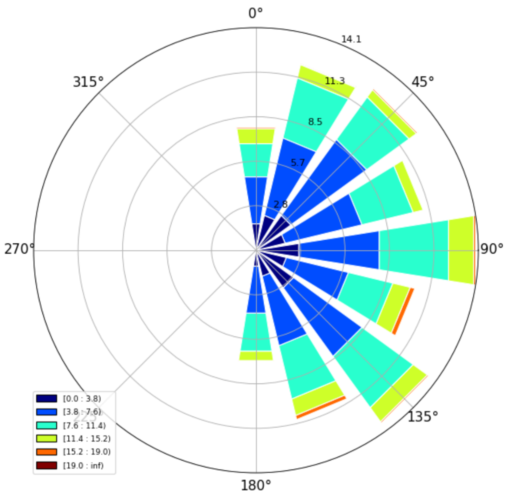
Route 2



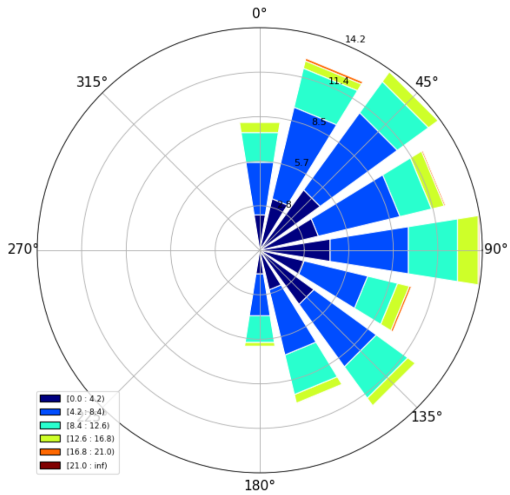
(a) Interval = 28 days
Average TWS = 6.77 m/s
Average Power Saving = 5.54%
Average Energy Saving = 5.33%



(b) Interval = 14 days
Average TWS = 6.84 m/s
Average Power Saving = 5.87%
Average Energy Saving = 5.60%



(c) Interval = 7 days
Average TWS = 6.77 m/s
Average Power Saving = 5.90%
Average Energy Saving = 5.75%

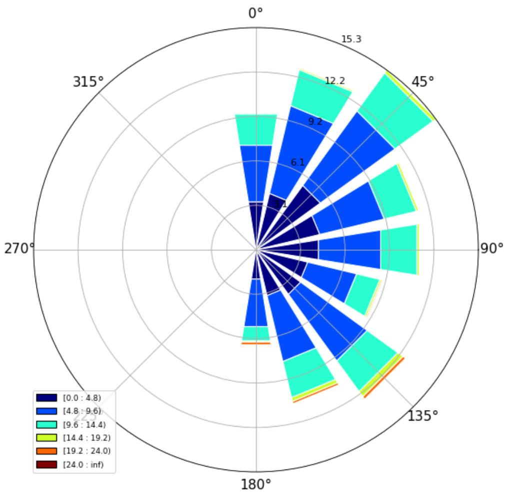


(d) Interval = 3.5 days
Average TWS = 6.69 m/s
Average Power Saving = 5.60%
Average Energy Saving = 5.43%

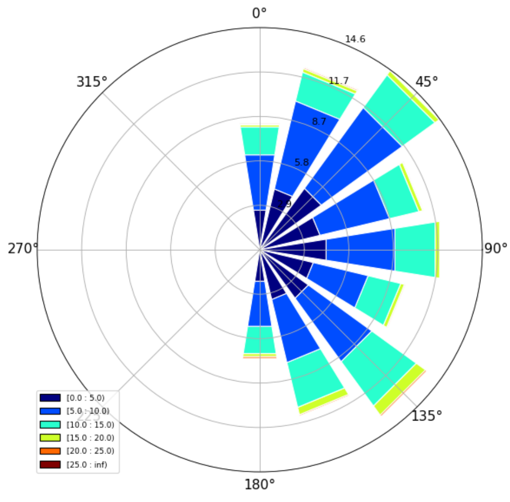
Figure 28: Roseplots of TWS and TWA and average savings achievable on Route 2 for the four different simulation intervals

A.2 Southern Route

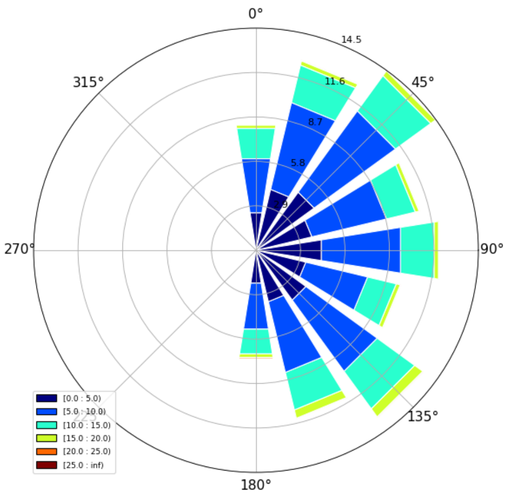
Route 3



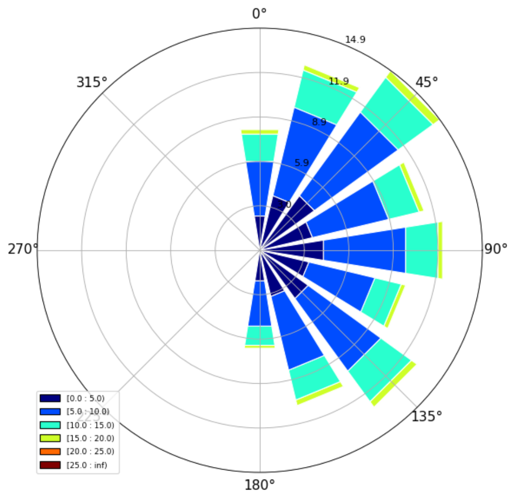
(a) Interval = 28 days
Average TWS = 6.79 m/s
Average Power Saving = 7.10%
Average Energy Saving = 6.94%



(b) Interval = 14 days
Average TWS = 6.97 m/s
Average Power Saving = 7.44%
Average Energy Saving = 7.12%



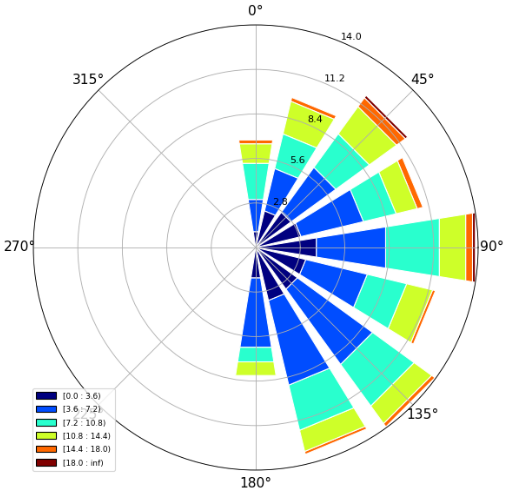
(c) Interval = 7 days
Average TWS = 6.88 m/s
Average Power Saving = 7.28%
Average Energy Saving = 7.06%



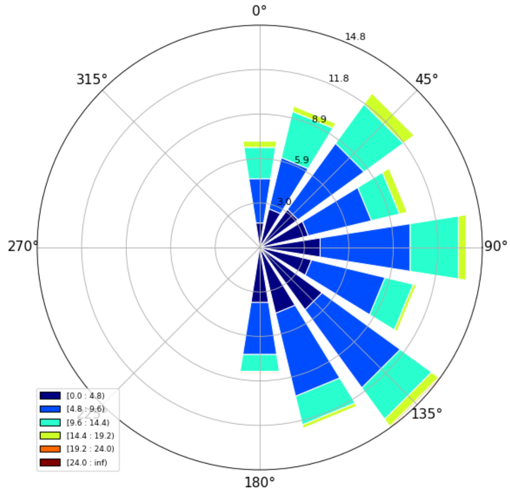
(d) Interval = 3.5 days
Average TWS = 6.82 m/s
Average Power Saving = 7.42%
Average Energy Saving = 7.21%

Figure 29: Roseplots of TWS and TWA and average savings achievable on Route 3 for the four different simulation intervals

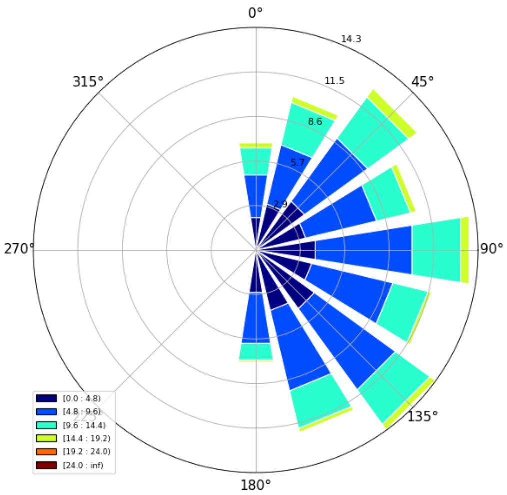
Route 4



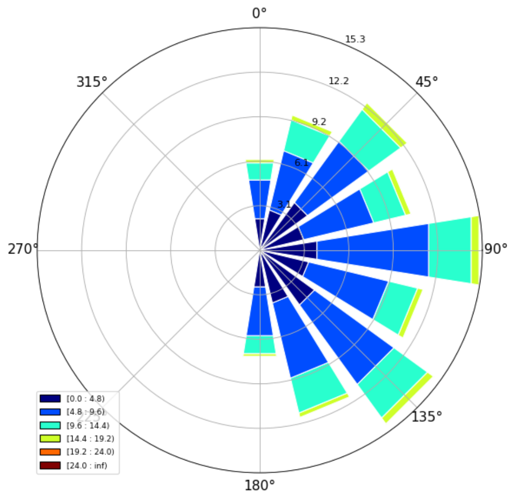
(a) Interval = 28 days
Average TWS = 6.63 m/s
Average Power Saving = 5.97%
Average Energy Saving = 5.63%



(b) Interval = 14 days
Average TWS = 6.92 m/s
Average Power Saving = 6.07%
Average Energy Saving = 5.69%



(c) Interval = 7 days
Average TWS = 6.92 m/s
Average Power Saving = 6.28%
Average Energy Saving = 5.98%

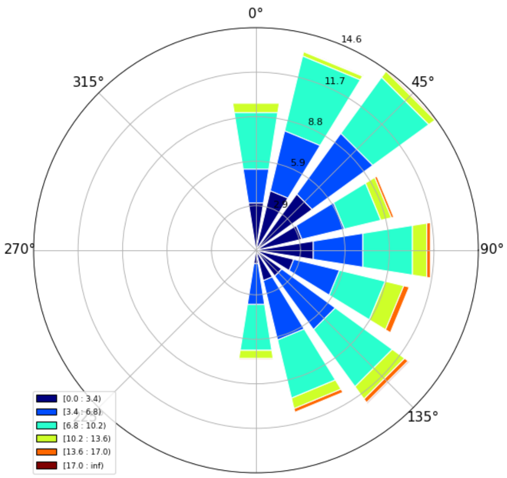


(d) Interval = 3.5 days
Average TWS = 6.91 m/s
Average Power Saving = 6.45%
Average Energy Saving = 6.15%

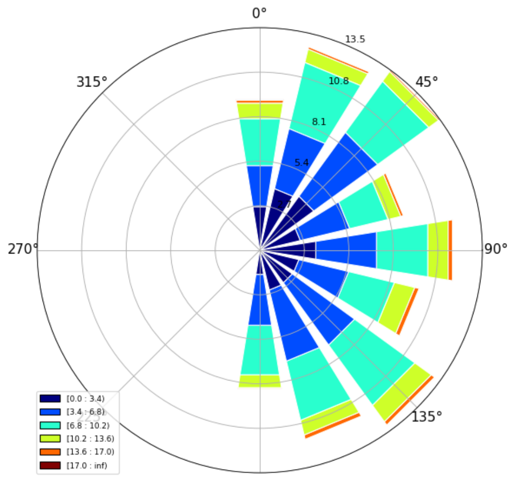
Figure 30: Roseplots of TWS and TWA and average savings achievable on Route 4 for the four different simulation intervals

A.3 Route Option Inwards on the Return Legs

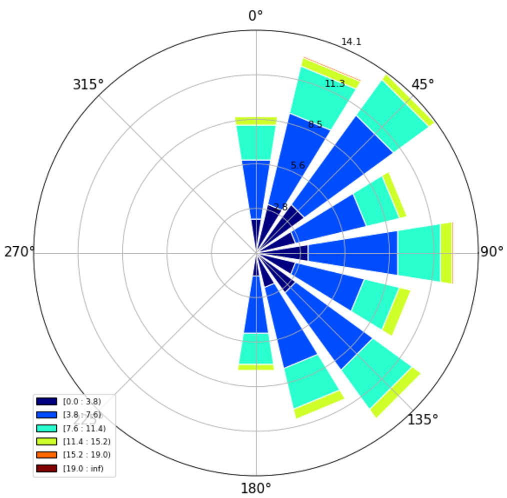
Route 2 - Option Inwards



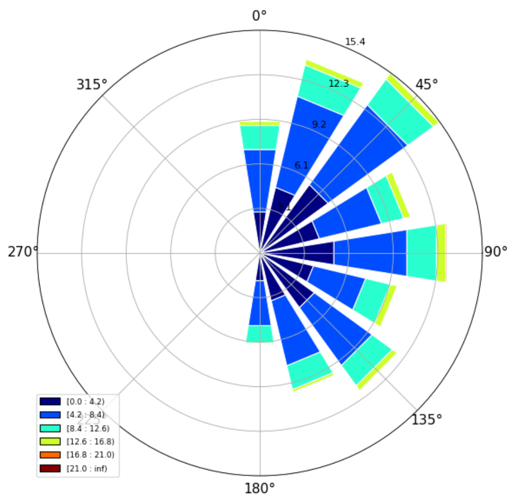
(a) Interval = 28 days
Average TWS = 5.85 m/s
Average Power Saving = 4.53%
Average Energy Saving = 4.36%



(b) Interval = 14 days
Average TWS = 5.97 m/s
Average Power Saving = 4,73%
Average Energy Saving = 4.60%



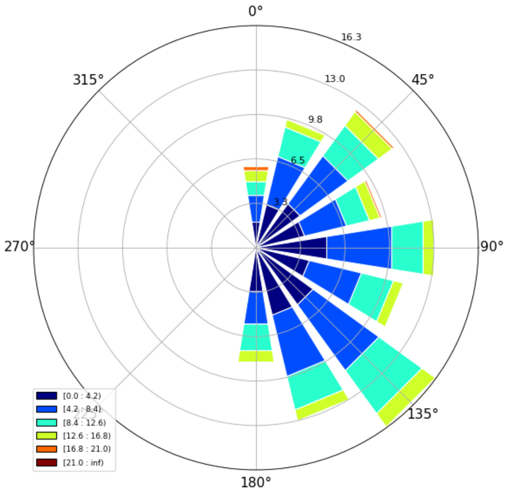
(c) Interval = 7 days
Average TWS = 5.96 m/s
Average Power Saving = 4.65%
Average Energy Saving = 4.53%



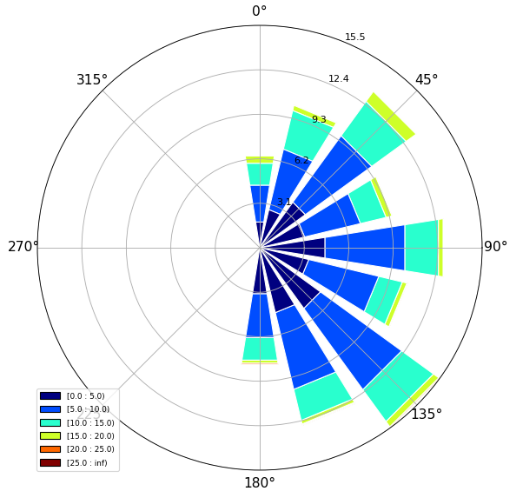
(d) Interval = 3.5 days
Average TWS = 5.97 m/s
Average Power Saving = 4.52%
Average Energy Saving = 4.36%

Figure 31: Roseplots of TWS and TWA and average savings achievable on Route 2 - Option Inwards for the four different simulation intervals

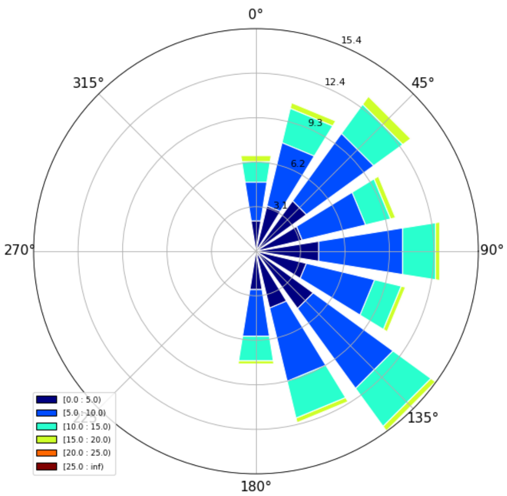
Route 4 - Option Inwards



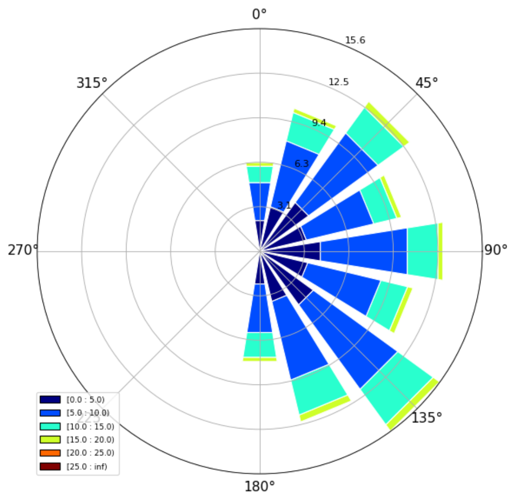
(a) Interval = 28 days
Average TWS = 6.62 m/s
Average Power Saving = 5.66%
Average Energy Saving = 5.22%



(b) Interval = 14 days
Average TWS = 6.87 m/s
Average Power Saving = 5.76%
Average Energy Saving = 5.53%



(c) Interval = 7 days
Average TWS = 6.81 m/s
Average Power Saving = 5.68%
Average Energy Saving = 5.44%



(d) Interval = 3.5 days
Average TWS = 6.79 m/s
Average Power Saving = 5.79%
Average Energy Saving = 5.57%

Figure 32: Roseplots of TWS and TWA and average savings achievable on Route 4 - Option Inwards for the four different simulation intervals

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