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Trabajo de Fin de Máster

Logistics and Port Call Optimization of Wind Powered Ships

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Madrid
August 1, 2023

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Logistics and port call optimization of Wind Powered Ships

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LOGÍSTICA Y OPTIMIZACIÓN DE ESCALAS EN PUERTO DE BUQUES PROPULSADOS EÓLICAMENTE

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RESUMEN DEL PROYECTO

1. **Introducción**

   El comercio internacional es actualmente responsable de alrededor del 20% de las emisiones totales de CO_2, lo que supone la mayor parte de las emisiones mundiales de Gases de Efecto Invernadero (GEI). La industria marítima representa actualmente el 90% de este comercio mundial en volumen y el 70% en valor, lo que también se traduce en aproximadamente el 2.5% de las emisiones mundiales de CO_2 [1]. Estas cifras sin duda seguirán aumentando si no se toman las medidas correspondientes, por lo que la Organización Marítima Internacional (OMI) está estudiando diferentes estrategias para reducir las emisiones de GEI del sector, con el objetivo principal de reducir las emisiones anuales totales de GEI en al menos un 50% en 2050 en comparación con los niveles de 2008 [2].

   Teniendo en cuenta esta necesidad de reducir las emisiones globales en la industria marítima, en los últimos años se han propuesto algunos enfoques y tecnologías diferentes. Una tecnología que está emergiendo y ganando atención en el sector es la propulsión eólica, que se define como el uso de un dispositivo que genera empuje a partir de la fuerza del viento. Con ello se pretende que los sistemas de propulsión sean más sostenibles al reducir la fuerza total que tiene que hacer el motor, lo que se consigue gracias a que se proporciona una potencia auxiliar. Esto se traduce directamente en una reducción del consumo total de combustible y de las emisiones totales [3].

   Este proyecto analizará cómo pueden implantarse estas tecnologías en grandes buques comerciales y cómo pueden contribuir a la descarbonización del sector, así como el posible ahorro que puede lograrse al optimizar estas tecnologías. Además, este proyecto analizará cómo estas tecnologías pueden combinarse con algunas otras medidas, concretamente con la optimización de las escalas en puerto, cuyo objetivo es ajustar la velocidad del buque para que llegue al puerto en un momento en el que esté disponible, con el fin de evitar el consumo de combustible y las emisiones liberadas mientras se espera a que el puerto esté disponible.

2. **Metodología y desarrollo del proyecto**

   El modelo desarrollado en este proyecto tiene como objetivo simular el posible ahorro que puede obtenerse combinando sistemas de propulsión asistida por viento (WASP) con motores comerciales. El enfoque tomado al desarrollar este modelo es una simulación que toma suposiciones sobre los parámetros de las tecnologías y los buques utilizados, así como las condiciones de viento, basado en artículos y bases de

datos, y calcula la producción neta de energía que estas tecnologías pueden generar, así como el ahorro de combustible asociado.

En este proyecto se estudiarán tres casos, cada uno de ellos simulando un buque navegando entre diferentes puertos y utilizando diferentes tecnologías de viento. Gracias a la variedad de estos casos, se podrán analizar diversas condiciones climáticas y de navegación. Una breve descripción de estos tres casos pueden verse en la Tabla 1.

Caso	**Origen**	**Destino**	**Tipo de barco**	**Tecnología WASP**
1	Rotterdam	Trondheim	Petrolero (KVLCC2)	5 Rotores Flettner
2	Amberes	Nueva York	Buque	4 DynaRigs
3	Hong Kong	Algeciras	Portacontenedores (Kriso Container Ship)	8 Velas rígidas

Table 1: Definición de los casos de estudio

En cada uno de estos casos se analizarán tres escenarios. El primero modela un Caso Base en el que el buque seleccionado realizará un único servicio de ida entre los puertos seleccionados a una velocidad constante. El segundo escenario (escenario WASP) modela el mismo servicio de ida que el modelado en el Caso Base, usando el mismo buque pero con la ayuda de la tecnología WASP seleccionada. La velocidad también se mantendrá constante a lo largo de la ruta, y será la misma que la utilizada en el Caso Base. Finalmente, el tercer escenario implementará la optimización de escalas en puerto, también llamada Just-In-Time (JIT, "Justo A Tiempo") sobre el escenario WASP. Simulará por lo tanto el mismo servicio que en los casos anteriores, pero se ajustará la velocidad en el último 10% de la ruta para llegar a la hora especificada por el puerto.

La principal característica de este modelo es que se utilizará un rango de velocidades que varían en 0.1 nudos entre límites establecidos, los cuales dependen de las velocidades mínimas y máximas especificadas por el buque). Se analizarán todas estas velocidades y se llevarán a cabo dos processos de optimización, uno que minimice costes y otro que minimice emisiones. Las rutas seleccionadas también se dividirán en pequeñas secciones ("way-points"), y cada una de ellas tendrá sus propias condiciones de viento.

El primer paso que realiza este modelo es inicializar todas las especificaciones de los buques y las tecnologías seleccionadas, así como definir las rutas y las condiciones de viento en cada uno de ellas. Cabe destacar que se incluirá una penalización que represente el peso de la tecnología WASP instalada, la cuál se ha incluido como un aumento de la fuerza total que el motor necesita realizar para poder navegar.

Una vez inicializada toda la información, para cada una de las secciones y cada de las velocidades, el modelo calculará el empuje total que la tecnología puede generar con las condiciones de viento dadas. Con esto se podrá obtener la fuerza total que el motor necesita generar, lo que luego se traducirá en consumo de combustible y emisiones liberadas en cada una de las secciones. Cuando se hayan realizado todos estos cálculos para todas las secciones, se calcularán los resultados totales para toda la ruta, y finalmente se implementará el JIT en el último 10% de la ruta. Al implementar esto y teniendo en cuenta la disponibilidad del puerto, el buque ajustará la velocidad para llegar a un tiempo en el que el puerto esté disponible, para así poder evitar el consumo adicional de combustible y emisiones mientras espera. El último paso será calcular los costes totales de toda la ruta.

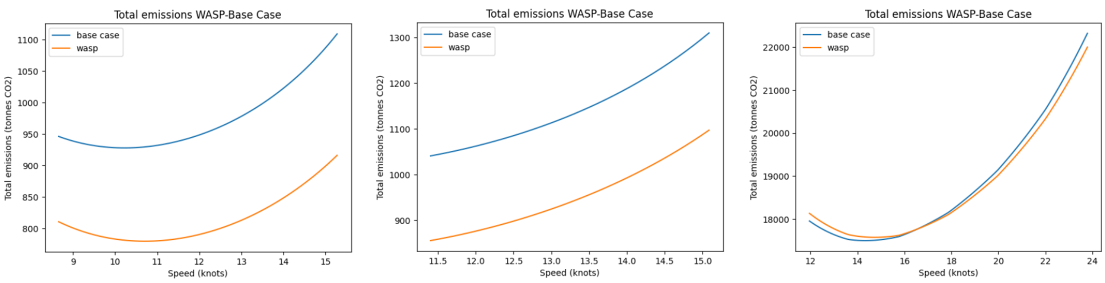
Todos estos cálculos se realizarán para todas las velocidades definidas, y por último se obtendrán las dos velocidades óptimas, una que minimiza emisiones y otra que minimiza costes.

3. **Resultados**

Se obtendrán los siguientes resultados para los escenarios presentados anteriormente. Cabe mencionar que no se presentarán resultados totales del Caso Base, y sólo se analizarán las diferencias entre este escenario y el escenario WASP.

- Resultados totales WASP
- Diferencias entre el escenario WASP y el Caso Base
- Resultados totales JIT
- Diferencias entre el escenario JIT y el WASP

Las emisiones liberadas totales en los escenarios WASP (en naranja) y Caso Base (en azul) pueden verse en la Figura 1. Estas emisiones no incluyen las liberadas mientras el buque espera en puerto a que este esté disponible, ya que estas emisiones serán iguales en ambos escenarios y aquí sólo se pretenden analizar las diferencias entre los escenarios.



(a) Caso 1 **(b)** Caso 2 **(c)** Caso 3

Figure 1: Emisiones totales en el escenario WASP y el Caso Base (toneladas CO_2)

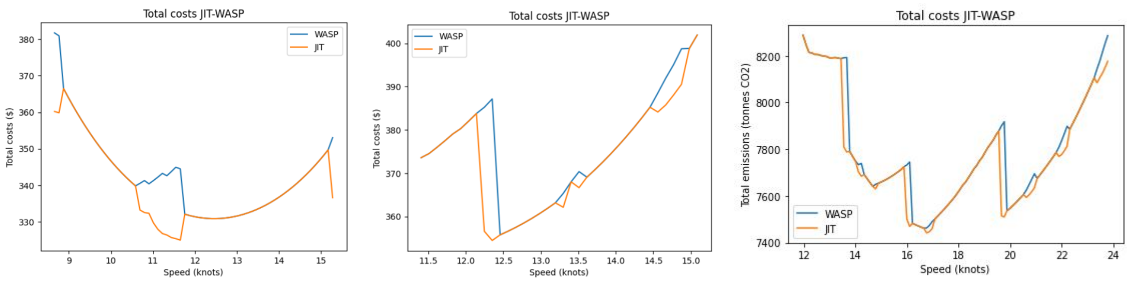
Es destacable cómo las emisiones liberadas en el escenario WASP son notablemente más bajas que las liberadas en el Caso Base en los dos primeros casos, mientras que el tercer caso presenta una situación diferente. Hay que recalcar que se está penalizando al sistema por el peso añadido de la tecnología y que este caso tiene implementadas 8 velas rígidas de 200 toneladas cada una. Este notable peso adicional, añadido a las malas condiciones de viento que presenta esta ruta, ya que navega por el Mar Mediterráneo y el Canal de suez, lleva a un resultado no favorable al implementar esta tecnología. La fuerza total generada por la tecnología no es suficiente para que este sistema sea beneficioso, ya que la propia tecnología está introduciendo en el sistema una resistencia adicional que provoca que el motor tenga que realizar aún más fuerza para vencer esta resistencia total.

Por otro lado, en la Tabla 2 se encuentran los porcentajes de uso de las tecnologías WASP para las velocidades más bajas y las más altas. Es de esperar que el porcentaje de uso de las tecnologías disminuya para velocidades más altas, ya que para estas velocidades, la resistencia total que el buque tendrá que superar para poder navegar aumentará, mientras que la fuerza generada por la tecnología no crecerá a un ritmo tan rápido, ya que las condiciones de viento se mantienen iguales en todas las simulaciones. Los resultados obtenidos para el tercer caso otra vez vuelven a indicar que este caso no es beneficioso por la combinación de malas condiciones de viento y la pesada tecnología.

		Velocidad [nudos]	WASP
Caso 1	Velocidad mínima	9	41.53%
	Velocidad máxima	16	25.6%
Caso 2	Velocidad mínima	11	35.29%
	Velocidad máxima	15	22.47%
Caso 3	Velocidad mínima	12	-3.37%
	Velocidad máxima	24	1.87%

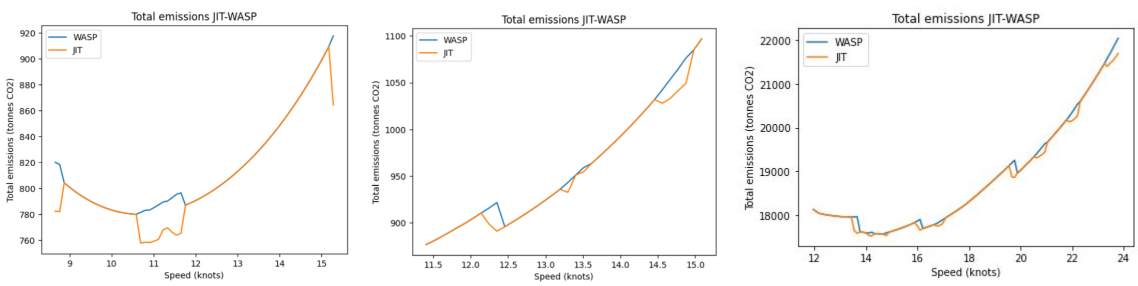
Table 2: Porcentajes de uso de las tecnologías WASP en cada uno de los casos

Respecto a la implementación del JIT, la Figura 2 muestra los costes totales tanto en el escenario WASP como en el JIT, mientras que la Figura 3 muestra las emisiones totales. Aquellas velocidades para las cuales los resultados son iguales en ambos escenarios son velocidades para las que el JIT no es factible, ya sea porque el puerto ya está disponible cuando el barco llega y por lo tanto no hace falta implementarlo, o porque la modificación de la velocidad que propone el JIT no es factible teniendo en cuenta las especificaciones de los motores. En todas las figuras puede apreciarse cómo tanto los costes como las emisiones disminuyen siempre que el JIT se puede implementar.



(a) Caso 1 **(b)** Caso 2 **(c)** Caso 3

Figure 2: Costes totales en los escenarios WASP y JIT (k$)



(a) Caso 1 **(b)** Caso 2 **(c)** Caso 3

Figure 3: Emisiones totales en los escenarios WASP y JIT (toneladas de CO_2)

Por otro lado, también se ha analizado cómo la dirección del viento afecta al rendimiento de las tecnologías. Para ello se han simulado las rutas inversas de los dos primeros casos, lo cuál muestra cómo la ruta inversa de Trondheim - Rotterdam presenta un peor rendimiento de la tecnología, con un porcentaje de uso que varía entre -12.48% y -5.36%, mientras que la ruta inversa Nueva York - Amberes presenta condiciones de viento mucho más favorables, con un porcentaje de uso que oscila entre 70.73% y 51.9%.

La ruta inversa del tercer caso no se ha simulado dado lo poco favorables que son las condiciones de viento en este caso, pero sí que se han simulado el buque con la tecnología WASP en las otras dos rutas, para analizar su funcionamiento en condiciones de viento más favorables. El portacontenedores con velas rígidas navegando entre Amberes y Nueva York presenta un porcentaje de uso de entre 9.11% y 4.03%, mientras que este mismo barco con esta tecnología navegando entre Rotterdam y Trondheim consigue obtener un porcentaje de uso que varía entre el 32.78% y el 18.33%, lo que demuestra que la tecnología puede ser beneficiosa cuando está trabajando en las condiciones de viento adecuadas.

Por último se ha calculado un sencillo caso de negocio en el que se calcula la diferencia entre el Valor Actual Neto del escenario WASP y el del Caso Base, con el fin de analizar la rentabilidad de los tres casos. Tal y como era de esperar, los dos primeros casos presentan resultados positivos en esta diferencia de VAN entre un escenario con la tecnología instalada y otro sin la tecnología, lo cuál sigue confirmando que estas inversiones parecen rentables. Por otro lado, la diferencia del VAN entre estos dos escenarios en el tercer caso es negativa, lo que también era de esperar dado que los resultados mostrados previamente no muestran este caso como uno prometedor.

4. **Conclusiones**

Gracias al modelo desarrollado en este proyecto, los posibles ahorros de costes y emisiones que se pueden obtener al instalar tecnologías WASP en buques comerciales pueden evaluarse. A pesar de que se han realizado varias simplificaciones mecánicas durante el desarrollo de este modelo, se ha podido comprobar que instalar la tecnología WASP apropiada en el buque apropiado y trabajando en las condiciones de viento apropiadas es crucial para obtener los máximos ahorros.

Los resultados obtenidos demuestran que los ahorros en costes y emisiones pueden alcanzar hasta un 17%, mientras que el porcentaje de uso de las tecnologías puede llegar hasta un 35% cuando trabajan bajo las condiciones de viento adecuadas.

Este proyecto también ha analizado cómo otras medidas como la optimización de escalas en puerto también puede conducir a ahorros destacables sin necesidad de costes adicionales, ya que esta metodología puede ser implementada simplemente mejorando la cooperación y comunicación entre los buques y los puertos.

5. **Referencias**

[1] European Commission. Reducing emissions from the shipping sector. URL: `https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en`

[2] Martina Reche-Vilanova. Performance Prediction Program for Wind-Assisted Cargo Ships. 2020

[3] World Trade Organization. Trade and Climate Change - Information brief n^o 4. 2021

LOGISTICS AND PORT CALL OPTIMIZATION OF WIND POWERED SHIPS

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ABSTRACT

1. **Introduction**

International trade is currently responsible for around 20% of total CO_2 emissions, which accounts for most of the global Greenhouse Gases (GHG) emissions. The maritime industry itself currently accounts for 90% of this global trade by volume and 70% by value, which also translates in approximately 2.5% of the world's total CO_2 emissions [1]. These numbers will undoubtedly continue to rise if no action is taken, and the International Maritime Organization (IMO) is consequently looking into different strategies in which GHG emissions from this industry can be reduced, with their main target set at reducing total annual GHG emissions by at least 50% by 2050 compared to 2008 levels [2].

Considering this need for reducing global emissions in the maritime industry, some different approaches and technologies have been proposed during the last few years. One technology that is emerging and gaining attention within the sector is wind propulsion, which is defined as using a device that generates forward thrust from the power of the wind. This aims to make propulsion systems more sustainable by reducing the total force that the engine needs to make, which is achieved thanks to providing an auxiliary power. This directly translates into a reduction in the total fuel consumption and the total emissions [3].

This project will analyze how these technologies can be implemented in large commercial vessels and how they can support in the decarbonization of the industry, as well as the potential savings that can be achieved by optimizing these technologies. Moreover, this project will analyze how these technologies can be combined with some other measures, specifically Port Call Optimization, which aims at adjusting the speed of the vessel so that it will arrive at the port at a time when it is available, in order to avoid fuel consumption and emissions released while waiting for the port to be available.

2. **Methodology and development of the project**

The model developed in this project aims at simulating the potential savings that can be obtained from combining Wind Assisted Propulsion Systems (WASP) with commercial engines. The approach taken when developing this project is a non-route-based simulation that makes assumptions about parameters of the modeled technologies, vessels and weather conditions based on literature and databases, and calculates the net energy output of these technologies and the associated fuel savings.

Three case studies will be studied in this project, each of them sailing with a different vessel between different ports and using different WASP technologies. Thanks to these varied case studies, diverse weather and sailing conditions will be considered. A brief definition of each of them can be seen in Table 3.

Case study	**Origin**	**Destination**	**Type of vessel**	**WASP technology**
1	Rotterdam	Trondheim	Tanker (KVLCC2)	5 Flettner rotors
2	Antwerp	New York City	Bulk carrier	4 DynaRigs
3	Hong Kong	Algeciras	Container (Kriso Container Ship)	8 Rigid sails

Table 3: Overview of the case studies

Moreover, three scenarios will be analyzed in each of the case studies. The first one will model a Base Case in which the selected vessel will perform a one-way service between the selected ports at a constant speed. The second scenario, the WASP scenario, will model the same selected vessel performing the same one-way service as the one modeled in the Base Case but with the help of a selected WASP technology. The speed will also be maintained constant along the route and it will be the same one as the one used in the Base Case. Finally, the third scenario will implement the Port Call Optimization, also called Just-In-Time (JIT), over the WASP scenario, meaning that it will model the same one-way service as the one modeled in the previous scenarios but will adjust the speed on the last 10% of the route in order to arrive at the time specified by the port.

The main consideration in this model is that a range of speeds varying by 0.1 knots between set bounds (which will depend on the minimum and maximum sailing speeds specified by the vessels) will be analyzed, and two optimization processes will be carried out. One of these optimization processes will find the optimal sailing speed that minimizes costs, while the other one will minimize emissions. Moreover, the routes simulated in the case studies will be divided into smaller sections (way-points), each one of them having their own wind conditions.

First step in this model will be initializing all specifications of the selected vessels and the selected WASP technologies, as well as defining the routes and the wind conditions in each of them. It is noteworthy that a penalization accounting for the additional weight of the WASP technology will be included by increasing the total resistance that the engine needs to overcome in order to sail through the water.

Once all the information has been initialized, for each of the way-points and for each of the speeds, the model will execute the corresponding wind calculations in order to obtain the total thrust that the WASP technology can generate given the wind conditions. With this, the total force that the engine of the vessel needs to make in order to sail will be calculated, which will then be translated in total fuel consumption and emissions released in each of the way-points. Once all the way-points have been computed, total results for the whole route will be calculated, and JIT will finally be implemented in the last 10% of the route. With this and whenever the port availability allows it, the speed of the vessel will be adjusted so that it will arrive at a time where the port is available and will therefore avoid extra fuel consumption and emissions released while idling (while waiting for the port to be available). Last step will be calculating total costs for the whole trip.

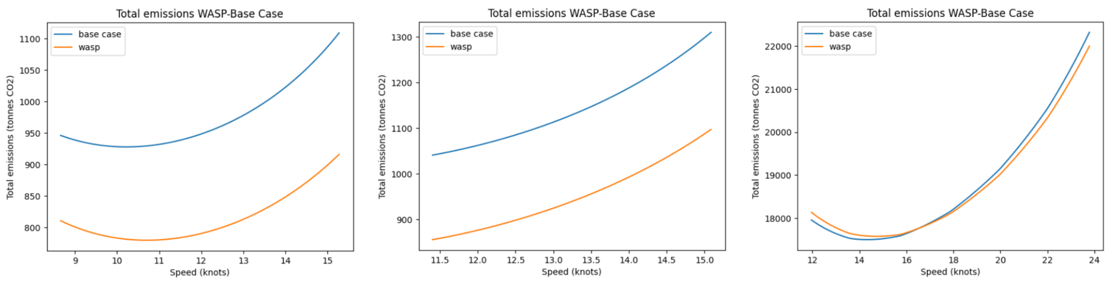
All these calculations will be performed for each of the speeds in the range, and the optimal speed both when minimizing costs and when minimizing emissions will be found within these speeds.

3. **Results**

The following results will be obtained with respect to the scenarios presented above. It is worth mentioning that total results of the Base Case will not be presented, and they will only be shown as the difference obtained between this scenario and the WASP scenario.

- Total results WASP
- Comparison between WASP and Base Case
- Total results JIT
- Comparison between JIT and WASP

Figure 4 shows total emissions released in both the WASP scenario (in orange) and in the Base Case scenario (in blue) for each of the case studies. It must be kept in mind that these calculations do not include emissions while idling, since these emissions are equal in both scenarios and only the differences between them are relevant here.



(a) Case study 1 **(b)** Case study 2 **(c)** Case study 3

Figure 4: Total emissions in the WASP and the Base Case scenarios (tonnes CO_2)

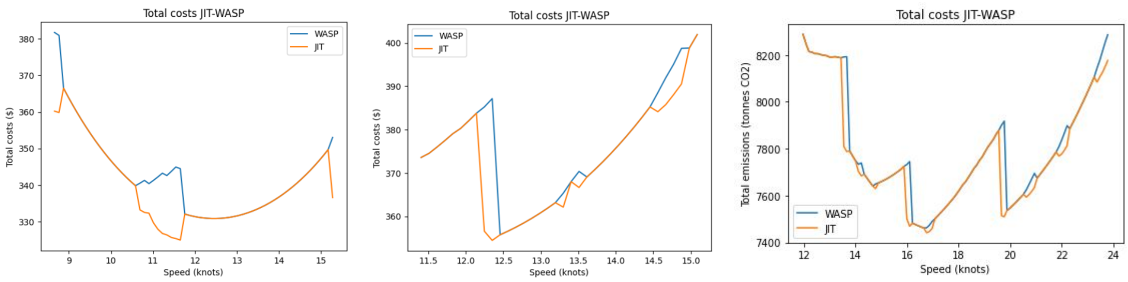
It is eye-catching how the first two case studies release remarkable lower emissions when implementing the WASP technology, while the third case study presents a more complex situation. It must be kept in mind that a penalization due to the weight of the WASP technology is included in the model, and that 8 rigid sails are being installed in this case study, each one of them with a total weight of 200 tonnes. This remarkable additional weight, added to the poor wind conditions presented in this route, as it sails through the Mediterranean Sea and the Suez Canal, translates into this system not being profitable. The total thrust that can be obtained from the rigid sails is not enough to make the WASP system beneficial, as the WASP itself is bringing in an additional resistance that ends up in this case study needing more force from the engine in order to overcome this additional resistance.

On the other hand, utilization of the WASP technologies for the lowest and highest speeds can be seen in Table 4 in the form of WASP %. It is expected that the percentage of WASP utilization decreases for higher speeds, as the total resistance that the vessel will need to overcome in order to sail through the water will also increase with speeds, while the total thrust obtained from the WASP technology will not increase at such a faster pace, as the wind conditions are kept the same ones in all simulations. Results obtained for the third case study also show what has been previously presented about the third case not being beneficial due to the poor wind conditions and the heavy technology installed.

		Speed [knots]	WASP
Case Study 1	Minimum speed	9	41.53%
	Maximum speed	16	25.6%
Case Study 2	Minimum speed	11	35.29%
	Maximum speed	15	22.47%
Case Study 3	Minimum speed	12	-3.37%
	Maximum speed	24	1.87%

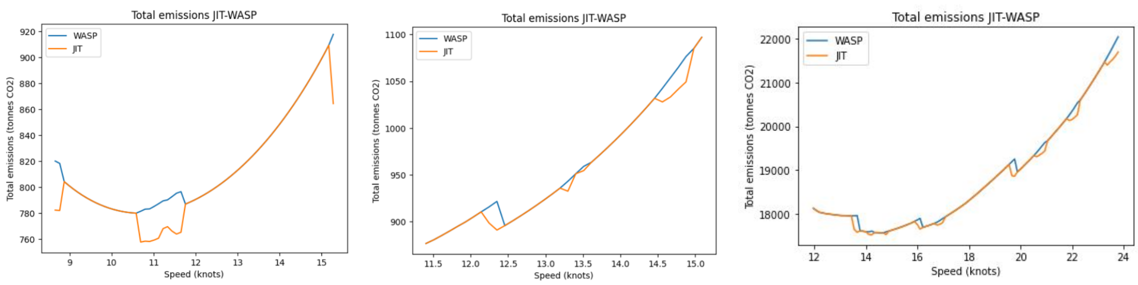
Table 4: Total WASP percentages and speeds in each of the case studies

With respect to implementing JIT, Figure 5 shows total costs in both the WASP and the JIT scenarios, while Figure 6 shows total emissions. Those speeds for which results are equal in both scenarios are speeds where JIT is not feasible, either because the port is already available when the vessel arrives and there is therefore no point in implementing JIT, or because the speed adjustment proposed by the JIT is not feasible considering the specifications of the engines. It can be appreciated here how both costs and emissions will decrease with respect to the WASP scenario whenever JIT is implemented, showing how this methodology will always lead to savings.



(a) Case study 1 **(b)** Case study 2 **(c)** Case study 3

Figure 5: Total costs in the JIT and the WASP scenarios (k$)



(a) Case study 1 **(b)** Case study 2 **(c)** Case study 3

Figure 6: Total emissions in the JIT and the WASP scenarios (tonnes CO_2)

Moreover, the effect of the direction of the wind and how it affects the performance of the WASP technologies has been studied. The reverse route of the first two case studies have been simulated, showing how the reverse route of Trondheim - Rotterdam presents a worse performance of the WASP technology with the WASP % ranging from -12.48% to -5.36%, while the reverse route of New York - Antwerp presents much more favorable conditions, with the WASP % ranging from 70.73% to 51.9%.

The reverse route of the third case study has not been simulated given the unfavorable wind conditions, but the selected WASP technology and the selected vessel have been simulated in the other two routes. The container ship with rigid sails sailing from Antwerp - New York presents a WASP % ranging from 9.11% to 4.03%, while the same vessel with this technology sailing from Rotterdam - Trondheim presents a WASP % ranging from 32.78% to 18.33%, showing how the technology can be beneficial when working under the appropriate wind conditions.

Finally, a simple business case calculating the Net Present Value difference between the WASP scenario and the Base Case has been carried out, in order to show economical feasibility of the three case studies. As expected, the first two case studies show positive results in the NPV difference between the WASP scenario and the Base Case, showing how these investments seem profitable. On the other hand, the NPV difference between these two scenarios for the third case study is negative, which also aligns with the non-promising results already obtained in this case study.

4. Conclusions

The model developed in this research project is able to assess the potential savings that the WASP technologies can achieve, both in terms of costs and of emissions. Several mechanical simplifications have been made during the development of this project, but even with these simplifications, it has been proven that appropriate WASP technologies mounted on the appropriate vessel and working under the appropriate wind conditions are crucial in obtaining the optimal deployment.

Results obtained from this model have shown that costs and emissions savings can reach up to 17%, while WASP utilization can reach up to 35% when working under the right wind conditions.

This project has also shown how other measures such as Port Call Optimization can also lead to remarkable savings with no additional costs needed, as only improvements on cooperation and communication within ports and vessels are needed for implementing this methodology.

5. References

[1] European Commission. Reducing emissions from the shipping sector. URL: `https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en`

[2] Martina Reche-Vilanova. Performance Prediction Program for Wind-Assisted Cargo Ships. 2020

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Thank you.

María Tornos

Contents

List of Figures

List of Tables

List of Symbols

TWS	True Wind Speed	m/s
TWA	True Wind Angle	degrees
Vs	Vessel speed	m/s
AWS	Apparent Wind Speed	m/s
AWA	Apparent Wind Angle	degrees
L_A	Lift	Newtons
D_A	Drag	Newtons
C_L	Lift coefficient	-
C_D	Drag coefficient	-
ρ	Density	kg/m^3
R_A	Aerodynamic force	Newtons
F_A	Driving force - Thrust	Newtons
S_A	Side force	Newtons
MCR	Maximum Continuous Rating	kW
$SFOC$	Specific Fuel Oil Consumption	g/kW h
η	Propeller efficiency	-
EC	Emissions coefficient	g CO_2/g fuel
W	Weight	kg
R_C	Resistance of calm water	Newtons
FP	Force of the propeller	Newtons
R_add	Resistance of additional weight	Newtons
P	Power of engine (auxiliary/main)	kW
FC	Fuel consumption	tonnes fuel
E	Emissions	tonnesCO_2
$Idle$	Idle time	hours
F_p	Fuel price	$/tonne fuel
P	CIF value of the cargo	$/tonne cargo
R	Cargo owner's cost of capital	-
h	Inventory holding cost	$
$OPEX$	Operational costs	$
C_p	Carbon price	$/tonne CO_2
NPV	Net Present Value	$
PP	Payback Period	
CF	Cash Flow	$
$IInv$	Initial Investment	$
Inc	Income	$
s_r	Spot rate	$/tonne cargo
t	Time	hours

Index

w	WASP
b	Base Case
j	JIT
m	Main engine
aux	Auxiliary engine
ll'	Waypoints
s	Sailing
i	Idling
T	Total
F	Fuel
P	Price
$*$	Optimal solution

1 Introduction

1.1 Background

International trade is currently responsible for around 20-30% of total carbon dioxide (CO_2) emissions, which on their side account for most of the global Greenhouse Gases (GHG) emissions. This percentage is certainly associated with the increasing quantities that are imported and exported all around the world, which have been constantly growing in the last decades. There are a few exceptions to this growth, such as the 2008 financial crisis and the COVID pandemic in 2020, but they will indeed keep growing in the following years. Special contributors to these emissions are the energy and transportation sectors, which account for more than 75% of the total emissions embedded in international trade [1].

Out of these total quantities, the maritime industry is responsible for approximately 90% of global trade by volume and 70% by value, and even though it is currently the most cost- and fuel-efficient mode of transport, it is also responsible for around 3% of total anthropogenic CO_2 [2]. At the European level, maritime transport represents between 3 and 4% of the EU's total CO_2 emissions, which translates into approximately 144 million tonnes of CO_2 in 2019. These numbers have been on the rise and will continue to rise if no drastic action is taken, and the International Maritime Organization (IMO) is consequently looking into different strategies in which greenhouse gas (GHG) emissions from the maritime industry can be reduced, with their main target set at reducing total annual GHG emissions by at least 50% by 2050 compared to 2008 levels [3].

Taking into account this need for reducing global emissions and especially the environmental impact of the maritime industry, some different approaches and technologies have been proposed during the last few years. One technology that is emerging and gaining attention within the sector is wind propulsion, which aims to make propulsion systems more sustainable. It can be essentially defined as using a device that generates forward thrust from the power of the wind. This allows for reducing the total force that the engine needs to make by providing an auxiliary power while maintaining the same speed, and it therefore directly translates into a reduction in the total fuel consumption and the total emissions [4]. This becomes especially relevant in present times with the price volatility of fossil fuels and the focus on switching to green energies.

There certainly are several drawbacks associated with these technologies, such as their linked high investment costs, the current uncertainty on attainable fuel consumption reduction, and the reliability of the weather conditions, which are the main contributors to their slow expansion. However, they indeed seem a promising solution for accomplishing the targets set by the IMO, and there is at the moment a big focus on researching how these technologies can be implemented most optimally. A recent study shows that the potential emissions reduction that can be achieved by implementing Wind Assisted Shipping Propulsion (WASP) technologies reaches up to 20% [5]. The combination of these technologies with other proposals such as alternative fuels or speed reduction measures could lead to an even more significant emissions reduction, which is also one of the main focuses of current research.

1.2 Mission

As presented above, there is indeed a serious urgency on implementing measures that will help cut down GHG emissions, and, bearing in mind the global impact of the maritime industry, it is also essential that this sector is kept in mind when analyzing these measures. The total savings that could be obtained with wind propulsion technologies seem encouraging towards reaching the IMO GHG targets, but there is unfortunately a substantial lack of expertise in this field and in how they can perform. This knowledge and further investigation are essential for understanding how economically, technically, and environmentally feasible they are.

Consequently, the main goal of this master thesis project is to analyze how these technologies can be implemented in large commercial vessels and how they can be combined with regular engines so that their performance under different weather conditions can be optimized. To achieve this, a model that will assess the economic and environmental behavior of three different WASP technologies will be developed. This model will consider different sailing speeds and, taking into consideration the thrust provided by the wind propulsion system, will find the optimal sailing speeds that can minimize emissions and costs. These optimization tests will be carried out separately, so there will be a chosen speed for minimal emissions and a different one for minimal costs. Moreover, the combination of WASP technologies with speed reduction measures will be investigated by implementing a methodology called Port Call Optimization, which involves adjusting the speed of the vessel so that it will arrive at the port at a time when it is available, to avoid fuel consumption and emissions released while idling (waiting for the port to be available).

As will be presented throughout this research project, three different case studies considering different vessels and different WASP technologies will be analyzed. The considered vessels are a tanker, a container ship, and a bulk carrier, while the technologies studied are Flettner rotors, rigid sails, and DynaRigs, and these are analyzed while sailing under different wind conditions. The reasons for why each of the vessels and each of the technologies will be analyzed in each case study will be further explained in Section 4, but these decisions are mainly taken due to physical constraints and limitations in the ports analyzed, as well as terminal options in each of the ports selected. The wind conditions will be obtained from real data wind averaged over the last 23 years for the chosen routes.

1.3 Goals

Thus, the goals that need to be accomplished when carrying out this analysis are the following:

- Investigate the current regulations set by the IMO regarding limits of emissions and fuel consumption, as well as the vessel's efficiency requirements.
- Research the currently available WASP technologies and present an overview of the advantages and disadvantages of the most widely studied in current research.
- Develop an analytical model able to find the optimal speed of the dual combination of the selected WASP technology with the engine.

- Weigh the performance of the selected WASP technologies against different wind conditions.
- Study how WASP technologies can be combined with additional abatement measures such as Port Call Optimization and analyze the extra savings that can be obtained from this combination.

2 Theoretical Background

2.1 Regulatory context, IMO and MBMs

Worldwide maritime trade has increased quite remarkably during the last decades, currently accounting for around 90% of the global trade by volume [2]. Maritime trade numbers fell in May 2020 compared to May 2019 due to COVID, but they quickly recovered from this dip and returned to the expected numbers, as shown in figure 2.1, which shows the international maritime trade in cargo tonne-miles during the last 20 years [6]. These numbers are expected to triple by 2050 [7].

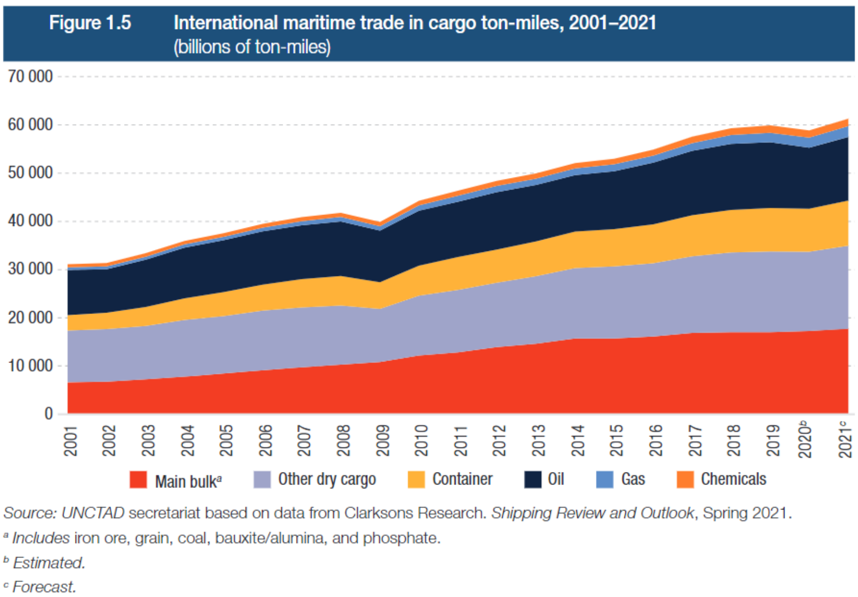


Figure 2.1: International maritime trade in cargo ton-miles, 2001–2021 (billions of ton-miles).

However, these high volumes mean that the shipping industry also accounts for big quantities of emissions, currently representing 2.9% of the total GHG emissions [7]. Taking into account this expected increase in the global maritime trade, these emissions associated with the industry are also expected to increase, and therefore measures that will limit and reduce these emissions have been proposed and introduced during the last few years.

The IMO first introduced Market-Based Measures (MBMs) as effective measures to decarbonize the shipping industry in 2010 [8]. An Expert Group was selected to evaluate eleven MBM proposals, some of them targeting the "in-sector" emissions - aiming to reduce emissions that occur within the maritime sector - and some others targeting the "out-of-sector" emissions - via the collection of funds that will be later used for reducing emissions in other sectors [9].

In 2011, the IMO adopted mandatory energy efficiency regulations for ships, defining the Energy Efficiency Design Index (EEDI) for new ships and the Energy Efficiency Management Plan (SEEMP) for all ships [10]. The EEDI determines the minimum level of efficiency that a vessel must meet, and it was further developed by the introduction of the Energy Efficiency Exiting Ship Index (EEXI) and the Annual Operational Carbon Intensity Indicator (CII) in 2020. The IMO also adopted in 2016 a mandatory Data Collection System (DCS) for ships over 5000 gt to collect and report their fuel oil consumption data. This collection system first started on January 1st, 2019 [11].

The IMO adopted an initial GHG strategy in 2018 to target the reduction of GHG emissions from shipping, where the main goal is cutting the annual GHG emissions from international shipping by at least half by 2050, compared to 2018 levels. The purpose is totally cutting out GHG emissions from shipping as soon as possible and within this century. This Strategy also considers a reduction in the carbon intensity of international shipping by at least 40% by 2030 and aims for 70% by 2050 compared to levels in 2008, as an average across international shipping. This Initial Strategy has been revised at the Marine Environment Protection Committee (MEPC 79) at the end of 2022 and is expected to be adopted at the MEPC 80 in July 2023 [11].

MBMs have been included in the Initial IMO Strategy as candidates for medium-term measures, meaning that they are to be finalized and agreed to between 2023 and 2030. It must be clarified that even though they are considered medium-term measures, they can all have short-term or long-term impacts [12]. There are several of the MBMs that have been proposed to the IMO either in 2010 or during the last few years that are worth mentioning, such as a bunker levy/carbon levy and Emissions Trading Systems (ETS) [9].

- Bunker levy: this measure entails imposing a tax depending on the fuel consumption of the vessels [13]. Several key elements need to be taken into account if a levy were to be imposed, such as which ships would be subject to the levy, if the levy would be modified depending on the type of fuel being used, who would be collecting the levy, etc [9].
  The most controversial aspect here is defining the price of the levy. This should be defined by trying to maximize the level of compliance with the IMO GHG reduction target, but it has been proven that it is indeed challenging finding a solution that will avoid the split incentive problem between the ship owner and the charterer - where the owner is not obtaining an adequate return on the investment that has been made in the energy efficiency measure [14] -, as well as preventing the shift to other modes of transport - which could ultimately lead to higher emissions [9].

- ETS: this measure works by the "cap and trade" principle, where there is a cap on the total GHG emissions that a ship can emit that is set a priori, and making it illegal for vessels to operate over this cap [13]. Within this cap, which will be adjusted and lessened yearly, companies buy or receive emissions allowances based on the tonnes of reported CO_2 emissions, which they can trade with one another as needed [15]. The EU ETS are already in place covering several sectors and gases such as CO_2 from electricity and heat generation or perfluorocarbons (PFCs) from the production of aluminum, and they were proposed by the European Commission (EC) to include GHG emissions from the maritime sector in 2021, as a way to reach the emissions reduction target set by the IMO [8].
  The tonnes of CO_2 emitted are reported by the EU Monitoring, Reporting, and Verification (EU MRV) system [8]. As both this reporting system and the ETS (not yet including shipping) are already well-defined from the legal perspective, it looks like there is compatibility with the existing regulations and legal framework.

However, the main challenge with the installation of this measure is that, unless it is also defined on a global level, it is not clear how the reduction target for 2050 will be met. In the same way, as with the bunker levy, it could also lead to shifts to other modes of transport [9]. Further research and studies need to be carried out to assess this measure, but it is expected that the maritime sector will be included in the EU ETS from 2024, which will be revised in Q1 2023 [16].

Another operational measure that has been highly discussed throughout the literature is speed reduction. Reducing the speed will imply lower fuel consumption levels, and therefore lower emissions emitted, as these are proportional to the liters of fuel consumed by the vessel. This option ideally presents a "win-win" solution, as it will lead to reduced fuel costs and emissions, and it can be achieved in two levels.

The first level is a technological one, where ships are built with a reduced horsepower capacity so that they are not able to sail at a speed faster than the prescribed one. The second level is a logistics-based one, where an already existing ship can be forced to sail slower than its design speed, which is referred to as "slow steaming". "Slow steaming" is indeed one of the short-term solutions that is currently implemented in the maritime industry, and it is one of the solutions that have the highest potential to reduce emissions. It however requires several technical and legal considerations in order to be implemented, as well as attention to the split incentives problem [14]. This will be further discussed in section 2.4.

2.2 Wind Assisted Propulsion Systems

A number of technologies and alternative fuels have also been developed as abatement measures that will aim to comply with existing regulations and accelerate the reduction of emissions and the maritime industry's decarbonization process. Currently, the most considered abatement measure is the adoption of alternative fuels such as hydrogen, liquified natural gas, biofuel, or ammonia. There are however certain concerns with these solutions, as it has been shown that there is a high risk of transferring emissions upstream, given their pollutant production methods and raw materials. Investments needed for their storage and implementation also pose a disadvantage when considering these measures [17].

Consequently, it looks like relying simply on alternative fuels will be optimal neither economically nor environmentally efficient, and therefore, WASP technologies have emerged as promising solutions, as they increase the efficiency of the vessel by exploiting the power of the wind to replace a portion of the engine's power. Empirical evidence from multiple studies has shown that WASP technology's CO_2 emissions reduction potential can reach up to 20% for retrofit installations. Fully wind-powered ships (newly built) are expected to save up to 90%, in which both the hull and the entire ship will be efficiently designed to withstand WASP forces [17]. Notwithstanding several drawbacks such as poor reliability of the weather conditions and the requirement for a trained crew, these technologies offer promising opportunities for further optimization through ongoing research and experimentation.

An overview of the most promising available WASP technologies will be further presented below [17] [18] [19].

- **Flettner rotors.** Flettner rotors are rotating cylinders that generate forward thrust from the Magnus effect. This effect describes the generation of thrust force resulting from the air pressure difference on opposite sides of a spinning body. The

rotors are mounted on the deck and operated by low-powered motors.
This system can be adjusted by simply modifying the rotating speed of the rotor to match the direction of the wind. Consequently, one of its main advantages is its ease of operation, and therefore no need for extensive specialized training, as well as the ease of retrofit and retractability.
On the other hand, these rotors pose several disadvantages that can limit their adoption. Firstly, they require power for their operation, which reduces their overall efficiency. Secondly, they generate significant side forces that can impact the vessel's stability under adverse weather conditions. The stability of the vessel can also be compromised by the vibrations generated by the rotors, although proper placement and design of the rotors can help mitigate these side effects. A RoLo (Roll-on/Lift-off) cargo ship powered with four Flettner rotors can be seen in Figure 2.2.

Figure 2.2: Flettner rotor.
[20]

- **Rigid sails.** Rigid sails are foils that work as traditional sails that can be adjusted to produce aerodynamic forces. Thrust is generated by the pressure difference between the two sides of the sail, and the shape of the sail remains constant regardless of wind conditions. As a passive system, rigid sails do not require additional power for operation. Current research is focused on optimizing the aerodynamic profile and designing sails capable of providing optimal power outputs in low wind conditions.
  One of its main advantages is its high lift-draft ratio at close-to-the-wind conditions (steering the boat as close as possible to the direction in which the wind is coming from) [21]. Additionally, rigid sails are relatively simple to operate, requiring minimal adjustments, and the majority of them can be easily folded for retraction. However, they are large and heavy equipment, which results in high installation and maintenance costs. Furthermore, stiff and non-retractable sails may pose safety risks in strong wind conditions, as the wind surface cannot be reduced. A vessel powered with two rigid sails can be seen in Figure 2.3.

Figure 2.3: Rigid sails.
[22]

- **Soft sails.** Soft sails are traditional sails with modern features, which rely on the pressure difference between their two sides to generate thrust. It is a passive system and offers a range of technological choices, including horizontally or vertically durable panels and 360º rotational masts that allow for optimal sail surface depending on the wind conditions. The DynaRig is the most widely used type of soft sail today, and they are easy to operate, as they simply work with an on/off button that rotates the mast.
These sails also present a high lift-draft ratio and are lightweight, but they are also large systems with high installation costs and are difficult to retrofit. Their lack of full retractability makes them less efficient when moving up-wind, and they are difficult to retrofit. A vessel powered with four DynaRig sails can be seen in Figure 2.4.

Figure 2.4: Soft sails.
[23]

- **Turbosails.** Turbosails are oval-shaped sails oriented to the wind that creates a low-pressure area behind them that generates forward thrust. They use a boundary layer suction system that creates a high lift coefficient, and this suction is created by a fan powered by an electric motor [24].
As mentioned, the main advantage of this system is the high lift-draft ratio that it can generate, as well as the ease of retrofitting and retractability. However, they are active systems that require external power to operate, and there is currently not enough research carried out on them to analyze their efficiency. A vessel powered with two turbo sails can be seen in Figure 2.5.

Figure 2.5: Turbosails.
[24]

- **Kites.** Kites are shaped like traditional sails, and they provide thrust with the lift generated by high-altitude winds. They are attached to the bow by a cable that generates tensile power, which is later directly used by the ship. At present, there exist two distinct categories of kites, static and dynamic. Static kites are classified as passive systems that generate drag and are only efficient in downwind conditions (wind coming from behind). Conversely, dynamic kites follow an eight-shaped movement that enhances the wind speed directed towards the kite, subsequently increasing the force generated [25].
  Their main advantage is undoubtedly the minimum required deck space and their easy retractability. They are on the other hand difficult to operate and difficult to control, which makes them dangerous devices in extreme weather conditions. A vessel powered with a kite can be seen in Figure 2.6.

Figure 2.6: Kites.
[26]

2.3 Physics of sailing

For centuries, humans have utilized the power of the wind to navigate through water, a practice known as sailing. Sailing has played a significant role in the development, survival, exploration, trade, and entertainment of various civilizations throughout history. In fact, its origins can be traced back to prehistoric times. Despite its ancient roots, the underlying physics of sailing is rather intricate.

Sailing can be defined as the skill of traveling through the space between two flow fields while maintaining a balance of forces in both domains. Although this thesis is not focused on the mechanics nor the fluid behavior of vessels, it is one of the core pillars within the calculations of the final model. Through this chapter and with the help of Martina Reche Vilanova's thesis, "Performance Prediction Program for Wind-Assisted Cargo Ships" the basics of the physics of sailing are explained in a very simple way, as well as some important concepts which are a must for a good understanding of the final results [4].

2.3.1 Wind Velocity Triangle

Principally, to propel the ship forward, the force generated by the sails must overcome the resistance to motion. According to Isaac Newton's first law of motion, inertia is the resistance experienced by an object when attempting to alter its state of motion. In sailing vessels, this resistance depends on the properties of both the water and the airflow fields. Consequently, sailing entails a complex interplay between the resistance offered by the hull and rig, the propulsive power of the sails, and the stability of the entire system.

The driving force behind the sails is generated by the apparent wind, which can be defined as the airflow perceived by an observer in motion. It represents the relative velocity of the wind with respect to the observer and is determined by the vector sum of the headwind velocity and the true wind velocity. In simpler terms, it is the combination of the wind's actual speed and direction modified by the vessel's own velocity.

When sailing, as the ship accelerates, the magnitude of the apparent wind increases, and its direction shifts forward. This apparent wind is what sailors feel on board and what the sails encounter as incoming airflow. Conversely, if the ship reduces its speed, the apparent wind tends to align with the true wind. In contrast, the true wind remains unchanged regardless of the vessel's speed, as it is an external environmental factor.

Summarizing, the relationship between the True Wind Speed (TWS) and True Wind Angle (TWA), the ship sailing speed (V_S), and the Apparent Wind Speed (AWS) and Apparent Wind Angle (AWA) generates the wind velocity triangle. The shape of this triangle and the AWS depends on the ship's heading. In navigation, the heading of a vessel or aircraft is the compass direction in which the craft's bow or nose is pointed. Note that the heading may not necessarily be the direction that the vehicle travels, which is known as its course or track [27]. When sailing pure downwind (TWA = 180º), the total AWS is the TWS minus V_s. On the other hand, when sailing in beam-reach (TWA = 90º), it is the hypotenuse of both vectors. AWS and AWA can be calculated with the following equations:

$$AWS = \sqrt{{V_s}^2 + TWS^2 + 2 \cdot V_s \cdot TWS \cdot \cos(TWA)} \tag{2.1}$$

$$AWA = \arccos\left(\frac{TWS \cdot \cos(TWA) + V_s}{AWS}\right) \tag{2.2}$$

This can be seen in the figure below, followed by the formulas used to compute the apparent wind parameters.

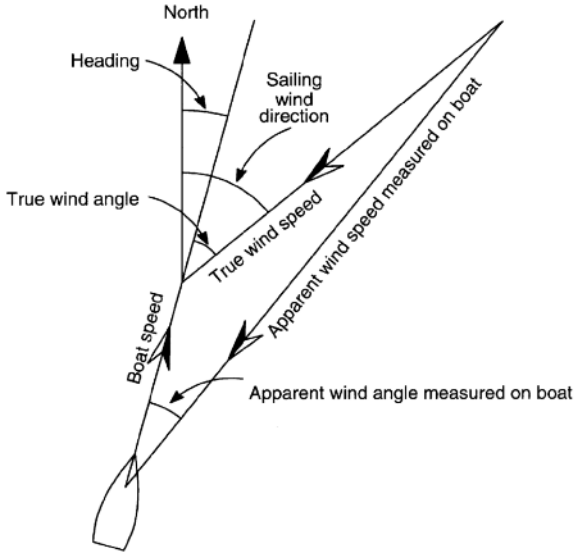


Figure 2.7: Wind Velocity Triangle
[4]

2.3.2 Basic Steady State Condition

"A steady state condition is meant such as the value, rate, periodicity, or amplitude of a specific situation exhibits only negligible change over an arbitrarily long period of time" [28].

During stationary sailing, there is a balance of hull (hydrodynamic) and sail forces (aerodynamic). When experiencing an AWS, the sail generates a total aerodynamic force thanks to the pressure difference between its leeward, downwind, and windward sides. This force is composed of a perpendicular component to the incoming flow, the Lift (L_A), and the Drag (D_A), the parallel component. The total aerodynamic force (R_A) a sail can create is calculated as shown below:

$$L_A = \frac{1}{2} \cdot \rho_{air} \cdot V^2 \cdot A \cdot C_L \tag{2.3}$$

$$D_A = \frac{1}{2} \cdot \rho_{air} \cdot V^2 \cdot A \cdot C_D \tag{2.4}$$

$$R_A = \sqrt{{L_A}^2 + {D_A}^2} \tag{2.5}$$

The resulting aerodynamic force (R_A) on a sail depends on its alignment with the apparent wind. When the AWA is aligned with the entry point of the sail (small angle of attack), lift (L_A) becomes the dominant component of the total aerodynamic force (R_A). However, when sailing downwind, drag (D_A) becomes the primary component. High lift-to-drag ratios and high lift coefficients are the main characteristics of high performance.

The total aerodynamic force (R_A) is counteracted by hydrodynamic forces (R_h) in the water. A sailing craft is thus only efficient at reducing the AWA and sailing upwind if it has a high-performance aerodynamic system combined with a high-performance hydrodynamic system. These forces can be decomposed into a driving force (F_A), which propels the boat forward and overcomes hydrodynamic resistance generated by the hull, and a side force (S_A), which acts perpendicular to the boat's motion and creates a heeling moment, tilting the craft sideways. To maintain the desired course and prevent drifting or capsizing, a submerged "sail" called the keel is necessary to produce an equal and opposite side force, providing a reaction known as the righting moment. To have a stationary sailing condition both flow forces must be balanced as numerically defined below.

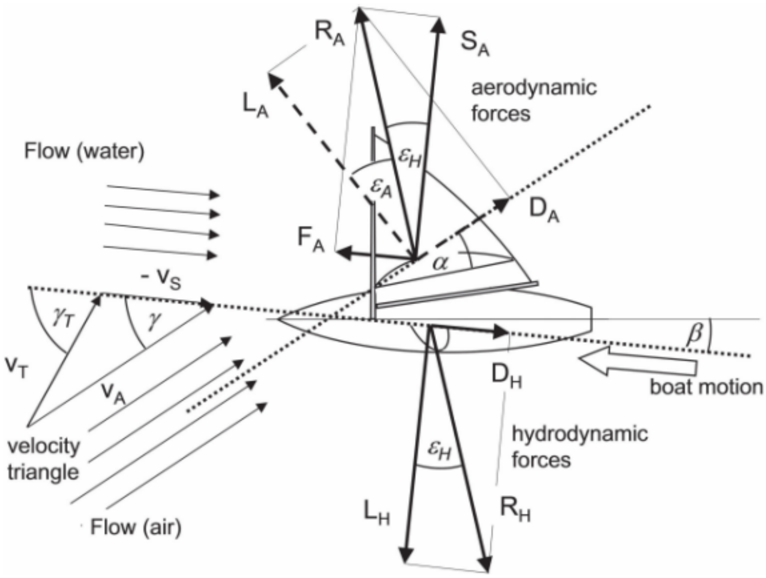


Figure 2.8: Basic Steady State Condition
[4]

$$\vec{F_A} = \vec{L_A} \cdot \sin(AWA) - \vec{D_A} \cdot \cos(AWA) \tag{2.6}$$

$$\vec{S_A} = \vec{L_A} \cdot \sin(AWA) + \vec{D_A} \cdot \cos(AWA) \tag{2.7}$$

2.4 Port Call Optimization and Berth Allocation problem

To reach the IMO's goal of reducing total emissions of GHG by at least 50% compared to 2008 levels by 2050 [11], the industry needs to come up with both technological advancements and optimization of the current processes. This reduction in emissions needs to be implemented without a major increase in costs, as shipping companies and ports are businesses that act according to profitability. Increased costs or transit times may result in a less competitive industry, and consequently, customers may choose to look for other means of transporting their cargo. This chapter aims at briefly discussing Just-In-Time (JIT), which focuses on streamlining port call processes so that idle time while waiting for port services is minimized by vessels steaming slower and arriving accordingly to availability at the port.

Sea-borne container shipping plays a major and important role in the world transportation system and the global supply chain. A terminal, as a point in the transportation network, acts as an interchange of the different modes involved in the overall transportation process; therefore, efficiency and productivity improvements in terminal operations are crucial in reducing the overall trip duration and costs [29].

With up to 1,200 ports throughout the world receiving anything up to 55,000 different types of ships, the International Taskforce kept its focus and faith in three credos: simplification, unification, and standardization [30]. The **port call process** is based on a high-level business process of port calls, which is based on IMO regulations, BIMCO (The Baltic and International Maritime Council) contracts, and requirements of port authorities and other stakeholders, making it a port and trade agnostic process. A complete definition of the port call process has been mapped out from a physical, technical, legal, and data exchange perspective as can be seen in Figure 2.9. This has been after four years of research and cooperation between industry partners to a point where the next step will involve agreeing on a standard data format for information exchange [31].

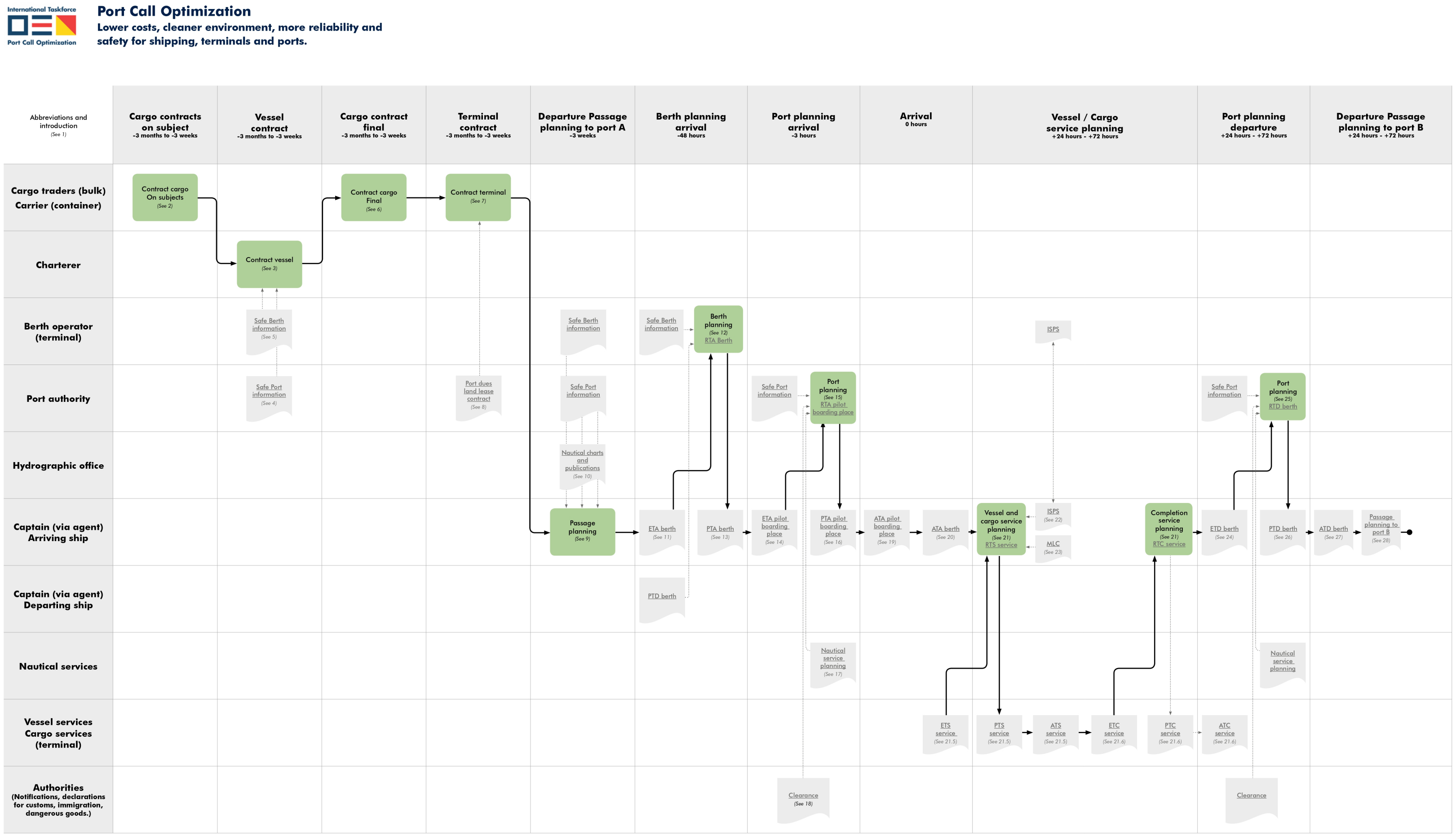


Figure 2.9: Port Call Procedure and Berth Allocation [31]

The ultimate objective is to improve vessel turnaround time at ports everywhere, which can potentially reduce GHG emissions in and around coastal areas, reduce bunkers and also improve efficiencies on the landside leg of the chain for cargo and passengers. It is composed of an initial contractual phase and a later operational one, and port call data sets such as nautical data (data provided by Hydrographic Offices in navigational charts where masters are obliged to navigate berth to berth by using official Nautical Charts and Nautical Publications to fulfill SOLAS (Safety of Life at Sea) carriage requirements); administrative data (data submitted by ships or other non-authority parties to authorities in notifications and declarations); and operational data (data submitted to non-authority parties as part of planning or execution of certain operations).

The SOLAS Convention in its successive forms is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The first version was adopted in 1914, in response to the Titanic disaster. The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment, and operation of ships, compatible with their safety. Flag States are responsible for ensuring that ships under their flag comply with its requirements, and several certificates are prescribed in the Convention as proof that this has been done. Control provisions also allow Contracting Governments to inspect ships of other Contracting States if there are clear grounds for believing that the ship and its equipment do not substantially comply with the requirements of the Convention - this procedure is known as port State control. The current SOLAS Convention includes Articles setting out general obligations, amendment procedures, and so on, followed by an Annex divided into 14 Chapters [32].

Vessels arrive over time at marine terminals, and terminal operators seek to assign them to berths to be served and depart as soon as possible. Terminal operators seek two objectives: (a) maximizing berth productivity by minimizing the total service time and delayed departures for all vessels and (b) minimizing the total emissions and fuel consumption for all vessels while in transit to their next port of call, both resulting in keeping customer satisfaction at a desired level [33]. This dilemma is called the berth-allocation problem and constitutes an NP-complete programming problem, a class of computational problems that are extremely hard to solve in terms of computing time. Computing optimal solutions gets very demanding even for powerful computers as the number of factors that have been considered increase [34].

For each vessel, the Ocean Carrier usually requests a time stamp of departure so it can meet its scheduled arrival at the next port of call. This stamp is determined based on the vessels' average operating speed and the distance between two ports. Depending on the time of departure, the vessel might need to increase or decrease its speed, thus changing the originally estimated fuel consumption and emissions production [33].

To reach the IMO's goals, the reduction in emissions needs to be implemented without a major increase in costs, as shipping companies and ports are businesses that act according to profitability. **JIT** shipping focuses on streamlining port call processes so that idle time while waiting for the availability of nautical services is minimized by vessels steaming slower and arriving according to availability at the port. Some individual vessels may see increased consumption as a result of having to speed up to meet the required arrival time, but avoiding unnecessary idle time will decrease the emissions of harmful particles from bunker fuel in port areas, by sailing slower when near the port and spending less time at anchorage and maneuvering. While anchorage, the main engine of the vessel is idle, however, auxiliary engines will be kept running to facilitate essential services on the ship. Hence, the excessive fuel consumption used to arrive early serves as a form of inventory holding cost [34].

Estimates from Marine Traffic [34] indicate that vessels spend between 5-10% annually at anchorage. While JIT shipping aims to reduce this time, some repairs and maintenance require the ship to be at anchorage and hence cannot be eliminated.

There are three broad classification schemes for berth scheduling:

- Discrete vs. Continuous berthing space. The discrete problem considers the quay as a finite set of berths, while in the continuous problem, vessels can berth anywhere along the quay.
- Static vs. Dynamic vessels arrival. In the static arrival problem, all the vessels to be served are already at the port, while in the dynamic problem not all the vessels to be scheduled for berthing have arrived at the time scheduling begins.
- Static vs. Dynamic vessel handling time. In the static handling time problem, the vessel handling time is known, whereas in the dynamic one, it is an unknown variable.

The approach implemented in this paper is the static vessel handling time, finite set of berths (discrete), and dynamic vessel arrival. The reason for choosing this approach is that it has been assumed that vessels will arrive at a specific time depending on the port availability and there will be no berth allocation since this is out of the scope of the project. Additionally, the handling time of the vessel will not be used in this project, as only costs while sailing will be considered.

Similar models explored in the past could be Imai et al (1997) [35] that concluded that in order to achieve high port productivity, an optimal set of ship-to-berth assignments should be found without employing the First-Come-First-Served (FCFS) allocation strategy originally considered when structuring the berth allocation problem. Park and Kim (2002) [36] had one objective consisting of the costs related to delay time and the ones relative to berthing at an undesirable berth. While these two issues are evaluated as a single objective in a combined manner, they are contradictory. The A. Imai et al. (2007) [37] model serves ships within respective time windows of services as long as possible and considers the total service time dependent on the berth allocation. They assume that each berth will handle one ship at a time in a continuous performance without interruption proving Park and Kim's conclusion of likely yielding non-inferior solutions to the problem of the minimization of the weighted delay time of departure and the minimization of the total service time. The referred weight would address a cost penalty based on ship size class and the ship's expected handling time is applied to the delay time.

3 Market analysis and current state of WASP technologies

WASP technologies seem to be a promising solution for accelerating the shipping industry's decarbonization efforts. The status quo of the WASP technological growth within the maritime transport sector reveals that despite the existing limited number of WASP installations, there is a promising trend of diffusion of the technology within the industry [17].

The earliest known sailing ship can be dated back to 3100 BC, when Egyptians utilized the north wind to travel south on the Nile. In the following centuries, maritime transportation relied heavily on the mercy of wind, before a major transition occurred in the 19th century, when steamships greatly enhanced the flexibility and reliability of transporting cargo and passengers. The world tonnage shares of steamships increased from 15.8% in 1855 to 97.1% in 1910, making sailing ships practically irrelevant [38]. The pursuit of efficiency has side-lined wind power for nearly two centuries, until recently, when decarbonizing goals moved it to the top of many company agendas.

3.1 Alternative market

Notwithstanding the appealing character and the broad variety of available WASP technologies, the diffusion of these technologies within the maritime transport sector is still limited. Simply put, the main benefits of using wind power on ships are the same as for the general wind power industry, namely, low carbon emissions and reduced exposure to the price volatility of fossil fuels. The high capital costs required for this investment and the uncertainty of its implications in terms of fuel consumption reduction represent some of the factors that slow the technology's diffusion. The present chapter explores the status of WASP uptakes and its underlying commercial fundamentals in more detail.

The maritime industry has, over the years, explored different abatement measures including changes in hull design, power, and propulsion system, alternative fuels, alternative energy resources, and operations [5]. Currently, the most discussed abatement measure is the development and adoption of alternative fuels such as hydrogen, methanol, ammonia, liquified natural gas, and biofuels. The alternative fuels promise to significantly lower tank-to-propeller ship emissions. Some fuels could results in high well-to-tank emissions comparable to conventional heavy fuel oil and marine gas oil depending on the production method source of feedstock. In other words, there is a high risk of emissions being transferred upstream. As a result, recent studies have not yet arrived at a conclusion about alternative fuels' impact on total life cycle emissions and impacts. Moreover, the capital requirement and cross-sector collaboration required for alternative fuel are enormous. An assessment of selected alternative fuels and technologies for 8 different parameters can be found in Figure 3.1 [39].

	GENERAL	1. PRICE	2. INFRAESTRUCUTRE	3. REGULATIONS	4. SCALABILITY	5. ENVIRONMENTAL IMPACT	6. TECHNOLOGY	7. CAPEX	8. OPEX
REFERENCE FUELS - HFO AND MGO	HFO has a maximum sulphur limit of 3.5 per cent. MGO contains 0.1 per cent. HFO representing 6 per cent of the fuel mix once the sulphur cap takes effect.	HFO: Below crude oil MGO: above crude oil	A well-developed worldwide infraestrucure.	Emission control areas (ECAs) for SOX were introduced. Also, NOX-restricted areas.	Will not be known until the industry starts consuming compliant fuel.	Oil-based ship fuel has a greater environmental impact than the alternative fuels discussed in this guidance paper	Scrubber and exhaust gas recirculation (EGR) systems.	150 to 100 USD per kilo-watt (40,000 kilowatt and larger engines).	An exhaust gas cleaning system requires energy to remove the SOX.OPEX is 0.7 per cent of the total fuel cost.
LNG	The main component is methane (CH4). Practically sulphur-free with low CO2 emissions. Twice the volume compared to HFO and 3 or 4 time to fuel oil.	Lower than crude oil and HFO. Reached the most competitive feedstock price level historically among all alternative fuels.	While still limited, bunkering infrastructure is improving quite rapidly.	National. Need to be evaluated on a case-by-case basis.	No principal limitations to production capacities that could limit the availability.	Cleanest fossil fuel available but with methane release (slip) than can cancel out the positive effect achieved. None of these cause any tank-to-propeller carbon dioxide emissions (TTP emissions).	Available for decades.	CAPEX decreasing but higher than the associated to HFO.	Comparable with oil-fuelled systems without scrubber. A number of ports offer discounts to LNG-fuelled ships.
LPG	Any mixture of propane and butane in liquid form. Lower density than oil. Two main sources: byproduct of oil and gas production or as a byproduct of oil refinery. Also, possible to produce from renewable sources.	More expensive than LNG but cheaper than low-sulphur oil.	Easy to develop bunkering infrastructure at existing storage locations by simply adding distribution installations.	Not included in the IMO IGF Code. Main safety concern is related to the density vapours leak, detectors and special ventilation systems should be used.	Production has been increasing by 2 per cent annually. Expected the demand to be safely covered until 2030.	CO2 emissions 16 % lower than HFO. The global warming potential is 3 to 4 times higher than that of CO2 (LPG slip).	Three main options for using LPG as ship fuel, only a single two-stroke diesel engine model is commercially available.	Roughly half that of an LNG system. No need for special materials.	Comparable to those of oil-fuelled vessels without a scrubber system.
METHANOL	Simplest alcohol with the lowest carbon content and highest hydrogen content. Relies on a cheap, widely available resource, but the GHG emissions are twice as high as from natural gas. Tanks have a size 2.5 larger.	More expensive than distillate marine fuels.	Distribution to ships can be accomplished either by truck or by bunker vessel.	Main applicable guideline is the IGF Code. Chapter for methanol is currently under development.	Production safely cover the demand until 2030.	Combustion reduces 10 % CO2 emissions (tank-to-propeller [TTP] value) compared to oil. Complete life cycle (well-to-tank [WTT] and TTP) total CO2 emissions are equivalent oil-based fuels.	Two options: similar to LPG, only a single two-stroke diesel engine is available.	1/3 that associated with LNG systems. No need for special materials.	Comparable with oil-fuelled vessels without scrubber technology.
BIOFUELS	Most promising are hydro-treated vegetable oil (HVO), fatty acid methyl ester (FAME) and liquefied biogas (LBG).	More expensive than their fossil counterparts	Lack of global infrastructure and bunkering facilities. HVO can be distributed using the ex-isting distribution systems, FAME can't. LBG can use LNG infrastructure, which is expanding.	ISO 8217:2017, a commercial quality standard for marine fuels. EN590, EU standard to civer FAME % . The International Council on Combustion Engines (CIMAC) provides guidelines. EU Renewable Energy Directive as well as ISO 13065, specifies principles, criteria and indicators for the bioenergy supply chain. The Global Bioenergy Partnership (GBEP) defines sustainability indicators.	Currently very limited.	Does not directly reduce carbon emissions. CO2 emitted is considered as part of the natural CO2 cycle. HVO has higher reduction potential than FAME. Only LBG can satisfy the IMO's Tier III NOX requirements without using additional NOX abatement technology.	HVO can directly be used in existing installations. FAME not LBG can in essence be used as a fuel by LNG-powered ships.	No additional costs when switching to HVO, FAME less than 5%. LBG would be the same as for LNG.	Additional costs for biofuels may result from monitoring, operational practice, and staff training.
HYDROGEN	Produced from various energy sources such as electrolysis of renewables or from reforming natural gas. It can be stored as cryogenic liquid, compressed gas or chemcally bound	- The cost of H2 production varies greatly depending on the price of electricity (in the case of electrolysis) or natural gas. They might also depend on where it is produced	Most of it is produced from natural gas using industrial, land-based infrastructure. Production from electrolysis is well-known and commercially available, suitable for local production, which would eliminate the need for distribution infrastructure	IGF Code does not cover hydrogen storage. Rules for the use of hydrogen in fuel cells are under development.	As hydrogen can be produced from water using electrolysis, there are no principal limitations to production capacity	Hydrogen used in fuel cells as energy converters does not produce any CO2 emissions and could eliminate NOX, SOX and particulate matter (PM) emissions from ships	Hydrogen-fuelled internal combustion engines for marine applications are said to be less efficient than diesel engines.	Similar to LNG-fuelled engines. Storage tanks more expensive than LNG tanks because of thermical requirements	OPEX comparable to oil-fuelled systems. Distribution costs are marginal when produced using electrolysis, and expected crew training requirements could be comparable to those of LNG/CNG
WIND-ASSISTED PROPULSION	Inexhaustible power source.	Most of them require a secondary source of energy to be operated. Availability of wind must be considered when calculating costs	No infrastructure required, but specialized knowledge might be. Restrictions for passing under bridges. Some types may difficult loading and unloading	Exclusive dependence on wind would not be feasible due to strict schedules - a propulsion engines is required to compensate for inadequate conditions	Quantity and quality of this energy source is not constant		Most available ones: Flettner rotor, DynaRig, rigid sailn and kites	Installation costs vary between technologies	Training costs and maintenance costs
BATERIES	Easy to optimize in terms of performance, safety and fuel efficiency. Limited by the size of the required battery or cost	Battery prices are decreasing rapidly, driven by demand (mainly in the automotive and consumer electronics industries)	Batteries do not face serious infrastructure requirements; they only require an adequate charging grid (they may often require additional resources)	-	Mainly drive by automotive and consumer electronic industries	They produce zero emissions while operating but their manufacture is energy-intensive	Leaders of the market: Iron phosphate (LFP) and Nickel Cobalt Manganese (NCM). Lithium-ion battery systems can provide an advanced level of safety	Lifetime mainly depends on the duty cycle for which they are used, relative to their size, and system integration costs can sum up to equal the cost of the full battery itself	OPEX is driven by electricity prices. OPEX of an electric ship can be lower than that of its conventionally-powered equivalent
FUEL CELLS	Convert the chemical energy stored in the fuel directly into electrical and thermal energy by electrochemical oxidation	Mass production (expected beyond 2022) should allow production costs to reach a competitive level	Depends on the availability of maintenance and repair components and services.	The requirements for fuel cell installations currently under development at the IMO might be integrated into the IGF Code in 2028 at the earliest.	Currently available in small numbers from several manufacturers, it will be mostly dependent on availability of suitable fuels in larger amounts, as materials availability is not critical.	Eliminate emissions of NOX, SOX and particulate matter (PM) nearly to zero. Achievable 30% CO2 emissions reduction when using hydrocarbon-based fuels.	In the maritime industry, there are currently only small fuel cell applications in operation with an electrical power output of up to 100 kilowatts.	Still too expensive for the car market, but attractive for ship applications.	Will be competitive when durability is improved (reaching durability of combustion engines) and primary fuel prices are competitive with MGO. Maintenance costs are low

Figure 3.1: Alternative fuels and technologies. (Own Figure)

Ammonia is assumed to be the primary alternative fuel adopted, as it has cost and storage advantages over methanol. The Global Maritime Forum estimated that an investment of USD 1.4 trillion $ into this new fuel over 20 years is needed for the land-based infrastructure of the supply chain and ship retrofits in order to meet the current IMO 2050 goal. In view of this discussion, relying solely on alternative fuels may not produce the most optimal results in terms of emissions reduction and economic efficiency. In the study performed by Bauman et al. [5] they reviewed 22 technological and operational practices and concluded that relying on a single technology is not sufficient for meeting the IMO target, whereas the combination of measures could secure better emission reduction results (i.e. up to a 75% reduction). Another finding of the study is the potential emission decline achieved by the adoption of WASP technologies, whose CO2 reduction potential falls above 20%. This finding is in line with existing literature, which identifies WASP technologies as a strong option to increase the energy efficiency profile of the maritime transport industry. Table 3.1 shows a review of the potential benefits of WASP technologies [5].

Key Strengths and Advantages of the WASP Technology
10-40% improvement in the EEOI (along with improved block coefficient).
1-50% CO2 emission reduction (ranked third alternative fuels and energy)
2-60% fuel savings; particularly suitable for high sea shipping
No infrastructure required; proven technology from long-term development
High cost-effectiveness (negative marginal abatement cost)

Table 3.1: Review of potential benefits of WASP technologies.

3.2 Uptakes of the WASP technology

Although the adoption of WASP technologies remains relatively low compared to the overall number of vessels in the global commercial shipping fleet, there is a noticeable and consistent increase in its diffusion. Various trends can be observed in the maritime transport industry, indicating the industry's experimentation with this technology. These trends include the adoption of larger ship sizes, a greater diversity of ship types, an increase in the number of ship owners utilizing the technology, and the size of installations.

Initially, the majority of WASP installations were carried out on small general cargo ships with a dead-weight tonnage (DWT) of up to 10,000. These installations were predominantly undertaken by ship owners from northern European countries who exhibited familiarity with and enthusiasm for the success of the domestic wind power industry. Over time, the adoption of WASP technology has expanded to include larger vessels such as tankers and bulk carriers. Furthermore, ship owners from Greece, Japan, and China, who are among the top global tonnage owners, have also entered the space and embraced the technology. [40]

Despite the limited overall adoption, the growing diffusion of WASP technologies signifies a growing recognition and interest within the maritime transport industry. This trend suggests a shift towards exploring and implementing sustainable and environmentally friendly propulsion systems in an effort to reduce GHG emissions and mitigate the impact of shipping on the environment.

3.3 Economic impact

Shipping is an energy-intensive industry and fuel costs account for a large share of a vessel's OPEX and total costs. Therefore, ship owners/operators are generally informed and concerned about fuel consumption. Improved fuel efficiency not only increases the expected profitability of the asset but also provides an operational hedge against volatile fuel costs. Given the volatility of bunker prices within the maritime transport sector as seen in Figure 3.2, marine fuel has been traded in the range between USD 250 and USD 1250 per tonne for 2020 to 2023 in two major bunker ports such as Rotterdam and Singapore.

Figure 3.2: Heavy fuel oil price from June 2020 to June 2023 [41]

3.4 On board and commercial factors

In cases where a route is optimized for the WASP technology to achieve a lower fuel consumption, the trip duration may vary when trying to maximize the most favorable wind, resulting in a sub-optimal economic result [42]. The optimal route will probably not be in a straight line but more in a zig-zag that plays with the angle at the wind is incoming the WASP.

The ship's crew is responsible for the navigation of the ship and the deployment of the machinery, they may experience a large workload and need additional training to operate and maintain WASP technology effectively. At least two passages on the open sea under suitable wind conditions are required to make a new captain understand how to operate the new vessel and what to do in critical situations [43]. Additionally, the change of the crew takes place regularly and therefore the level of operational efficiency could be difficult to maintain [44]. As the ship master oversees the navigation of the ship, a fully automated system may not allow the flexibility of a competent ship master with good sailing skills to achieve an optimal result.

In 2021, two tiltable Norsepower rotor sails certified by DNV were retrofitted on board SC Connector, a Sea-Cargo Ro-Ro vessel operating in the North Sea [43]. Captain Artur Sylwestrzak assures that although he had been captain of SC Connector before the rotor sails were installed, he was surprised at how much its behavior had changed. The rotor sails improved the ship's sea-keeping behavior as the center of gravity rose by one and a half meters and, with sufficient wind, the ship could maintain its speed without needing help from the propeller. Either way, the main engine needs to be kept running to create enough flow to the rudder, otherwise the control over the steering may be lost. Within the interview in DNV [43], further technicalities regarding the operational limits for the rotor sails on the vessel and how they affect the operation of the ship are discussed.

It is beneficial at times to change a ship's speed and course to catch favorable winds to maximize fuel savings, which demands good decision-making from the shipmaster. Captain Sylwestrzak claims they no longer sail the shortest route since they have to adapt to the current condition of the weather forecast. Extending the route compensates by gaining extra speed from the rotor sails, so the rotor sails are a key aspect for their timing. Plus, the SC Connector operates on a fixed schedule, and the captain needs to be able to rely on the additional portion of the propulsion energy coming from the wind in case they need to alter their routes.

3.5 Market survey on Wind Propulsion Technologies

There is a whole variety of stakeholders within the current market for a deployment like this. It has been decided to circulate a survey within respective social platforms and communication channels, with the aim of reaching anyone who is part of the shipping and/or logistics sector and may have an interest in wind propulsion's potential to decarbonize shipping. The main objective is to sketch the priorities and main considerations of all involved stakeholders in the end-to-end supply chain of a hypothetical deployment of a Wind Propelled Fleet.

The survey is composed of 5 questions:

1. To provide an overview, please select the area that you feel most closely related to.
2. How would you describe your level of knowledge when discussing WASP systems in the shipping industry? Grade from 1-5 being 1 the least.
3. How skeptical are you towards the idea of having a WASP fleet in the near future? Grade from 1-5 being 1 the least.
4. What are your main concerns regarding the implementation of WASP technologies on a vessel and on the logistics/operations of commercial shipping?
5. Which of the concerns above do you believe to be most influential globally?

Firstly, the survey clusters the stakeholders into 11 related areas: *"scholar or researchers"*, *"logistics and transport onshore"*, *"worker on a vessel (captain, crew member, engineer. . .)"*, *"manufacturer or WASP development related"*, *"cargo owner"*, *"shipowner"*, *"operator"*, *"regulator"*, *"surveyor"*, *"port authority"*, *"financial or banker"*, *"shipyard"* and *"designer/project manager"*, plus giving the option of choosing *"other"*. It next evaluates the level of knowledge when discussing WASP systems in the shipping industry and how skeptical they may be towards the idea of having a WASP fleet in the near future. Finally, in a more open approach, it gives the opportunity of highlighting the main concerns regarding the implementation of WASP technologies on a vessel on the logistics/operation side of commercial shipping. The most influential concerns globally are addressed by stakeholders checking how many boxes they feel are significant.

3.6 Relevant conclusions on the survey

In light of the survey being broadcasted to a niche population, not as many answers as expected were obtained. With a total of 53 answers to the survey conclusions can be drawn from the respondents but how representative these may be, is something that should be further studied.

From the 11 possible clusters, all respondents fell into only 8 categories, as shown in Figure 3.3, where the distribution is displayed in the form of percentages. Highlighting that the TOP 3 related areas in respective order are, *"Scholar or Researcher", "Ship Owner", and "Operator"* and *"Worker on a vessel (Captain, crew member, engineer...)"* tied up in third place.

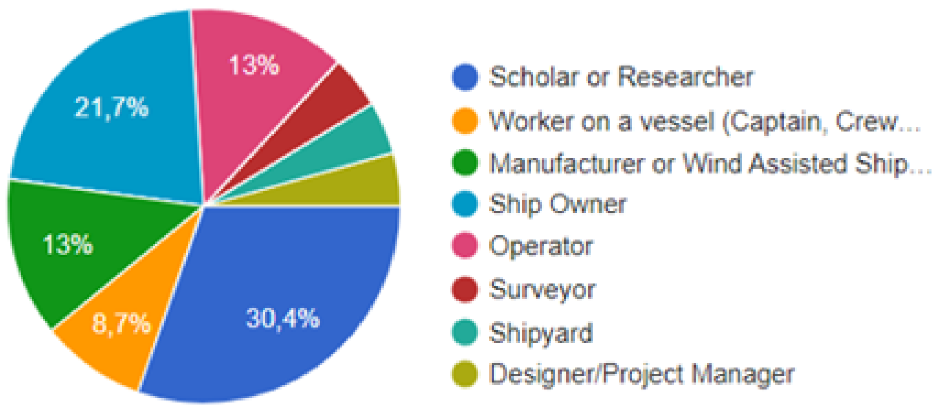


Figure 3.3: Distribution of Survey respondents

Conjointly, out of all respondents, 17.4% possessed a high knowledge of WASP, being the mean response to question 2 a 3.391 out of 5. This is a right-sided distribution. Although this survey may not constitute a quantitative assessment as it was originally intended, it has resulted in a qualitative source of information with a spectrum of profiles. The distribution is seen in Figure 3.4.

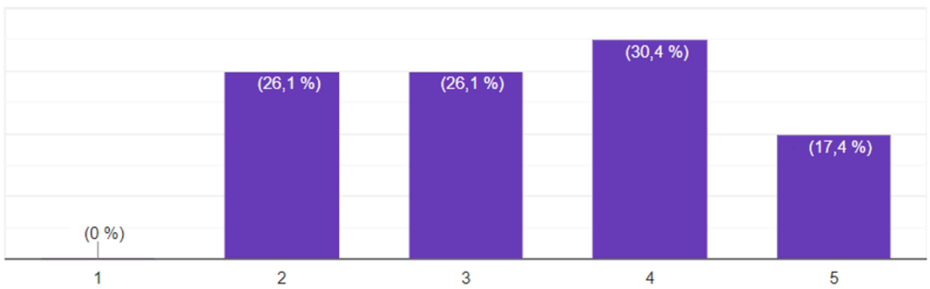


Figure 3.4: Distribution of answers concerning the level of knowledge of stakeholders being 1 the lowest.

Moving forward, respondents' opinions on a WASP fleet were distributed across a range of perspectives as seen in Figure 3.5. Approximately 39.1% of the respondents expressed significant skepticism (answered 1 and 2), while 17.4% remained indifferent, and 43.4% displayed a high level of acceptance towards the technology (answered 4 and 5). These findings align with the existing hypothesis that the WASP market is still in its early stages, despite being recognized as a pivotal technology for the present and future maritime industry. To fully leverage its potential, the market requires extensive exploration to enhance the technology and effective utilization of existing resources.

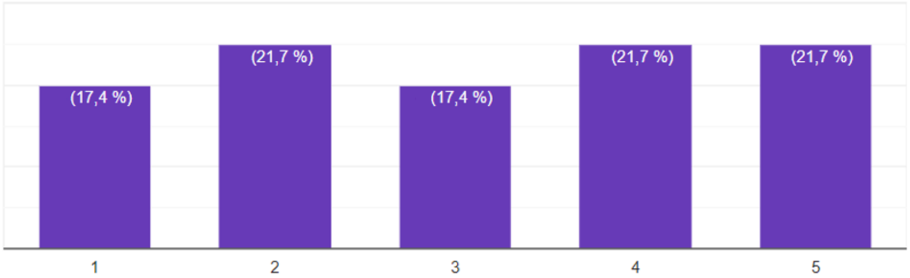


Figure 3.5: Distribution of answers concerning the level of skepticism towards a WASP fleet in the near future of stakeholders being 1 the lowest.

The public and the industry can be dubious about uncertainty, which may terminate in disinterest. On one hand, the shipping industry is profit-based, ergo, there is a clear and expected overall concern that outdid the rest, *"Initial investment for retrofitting of vessels"*. On the other hand, the following most concerning arguments are proven not to be that relevant, which emphasizes the misconception of the implementation of WASP technologies on a commercial vessel. Some of these are: *"Unloading-loading operations"* or *"Training/maintenance or any crew related costs"*. The former has extensively been proven not to be an issue in numerous ports since most WASP technologies are retractable in case they happen to become a constraint. Cranes would need to be careful with sail masts and other added obstacles. Ports would need to be trained. The latter has been discussed in the previous subsection with the DNV interview, concluding that given a motivated environment, crew members show eagerness on understanding the physics of the technology and are willing to use it. The rest of the concerns are displayed in Figure 3.6

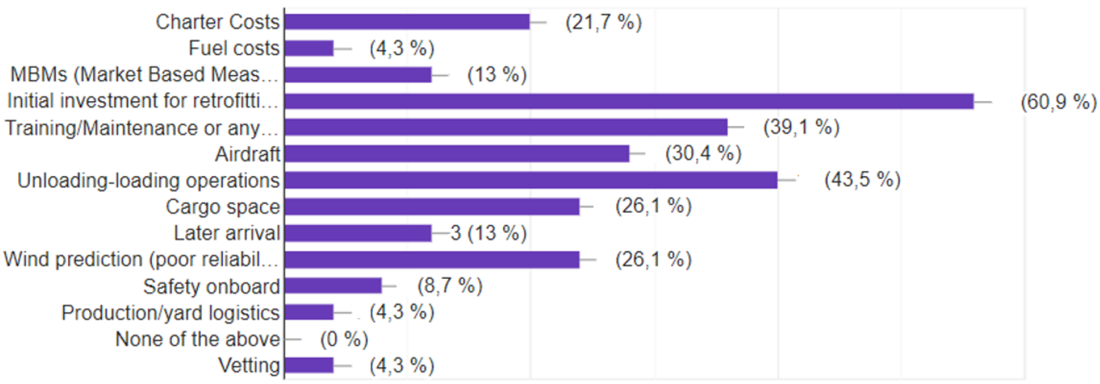


Figure 3.6: Distribution of answers concerning the level of skepticism towards a WASP fleet in the near future of stakeholders being 1 the lowest.

To finalize with the survey's insights, most respondents show increasing concern for uncertainty regarding weather prediction and routing, fluctuating fuel prices, and the return of initial capital. Although out of scope for this thesis, numerous weather routing programs are currently being developed and taken to the market. Then, fluctuating fuel prices should not be a bottleneck because most transport-related technologies still depend on fuel and if WASP is developed to excellence, no fuel will further be needed, thus, no need to worry about it.

Finally, while the initial investment may be significant, it is important to consider the long-term impact of the technology in terms of reduced emissions and fuel consumption. The implementation of technologies that seek to reduce emissions and fuel consumption aligns with established global and regional sustainability goals. These objectives, such as the reduction of GHG emissions and the transition to a low-carbon economy, are essential to address climate change and promote environmental protection.

They can also generate value and competitive advantages for companies. As awareness of sustainability grows, consumers and regulators are increasingly interested in supporting and partnering with organizations committed to reducing their environmental footprint. This can translate into business opportunities and increased possibilities for collaboration with other companies and stakeholders.

3.7 Definition of KPIs

Taking into consideration all that has been presented above, the definition of the relevant KPIs was rather straightforward, and the final selected ones are the following:

- Time: total time needed to sail the selected distance. This KPI will not be optimized but will be used to represent the willingness of certain customers to pay for arriving earlier over slow steaming. To analyze this behavior, an extra cost will be penalized for the extra inventory holding time and extra operating time.
- Cost: costs associated with the total operation of the vessel, from origin to destination. A full explanation of the specific costs that are considered will be presented in the following sections when the whole model is discussed, but it is worth mentioning that the main costs considered are fuel and emissions costs, OPEX, and inventory holding costs. These will be minimized to find an economically optimal sailing speed.
- Fuel consumption: the implementation of WASP technologies will certainly lead to a fuel consumption reduction, as the wind propulsion system will be providing some of the forward thrust. The ratio between the fuel consumption when using the WASP technology and the fuel consumption without the technology will be calculated and presented as one of the main results.
- CO_2 as a representation of GHG emissions: directly connected to fuel consumption, GHG emissions will also be reduced with the implementation of WASP technologies. These will be minimized when finding the environmentally optimal sailing speed, and it is important to mention that the emissions considered in this research project are the "tank to wake" (TTW) emissions, that is, only the emissions released when the fuel is already in the tank, so upstream emissions are not considered [45]. These are the ones currently considered by the IMO, and that is the reason why they were chosen in this analysis.

4 Model Formulation

Unsurprisingly, WASP technology developers claim substantial fuel savings when promoting their products. As observed also during the GST 2020 International Wind Propulsion for Shipping Forum in Copenhagen in March 2020 [46], ship owners who have adopted WASP technologies clearly pointed out the importance of legitimate economic benefits for their investment. In other words, emission reduction alone is not sufficient to justify investment in WASP due to the CAPEX and operational risk involved. An economic case must be made, so the potential financial upside compensates the costs and risks.

In this chapter, a discussion about the economic and environmental advantages of the usage of WASP technologies is provided, considering the costs linked to their installations and the new emission restrictions. Relevant results have been obtained for different routes, speed ranges, and WASP technologies while investigating the best arrangement to minimize both the emissions and the installation cost payback period. A computer-based study will be presented, as well as the deriving economic evaluations and considerations. A discussion on how this model will be developed will also be presented.

The first aim of the simulations conducted is to model the wind power contribution towards ship propulsion. Among the studies in the literature, three approaches are observed:

1. The first approach is a non-route-based simulation that makes assumptions about parameters of modeled technologies, ships, and weather conditions based on literature and databases, calculates the net energy output of the technologies in a simulation model and translates the net energy output to fuel savings. This will be the approach taken in the computer-based study carried out in this project.
2. The second approach is a route-based simulation, which in addition to the first approach reconstructs specific routes from the ship's Automatic Identification System (AIS) data and takes into account wind conditions along the voyage of each route. AIS is a VHF-based navigation and anti-collision tool making it possible to exchange information between ships on their position, and identification such as IMO number and voyage details [47]. This approach will not be considered in this research project.
3. The third approach does not rely on simulation but also requires measured fuel consumption data from ships sailing with WASP technologies. The amount of fuel saving is found by switching the technology on and off in identical sea and wind conditions and comparing the amount of fuel consumption [17]. This approach will also not be included in this project.

The methodology using parametric simulations has several advantages, however, the scarcity of verifiable studies done on actual sailing ships is concerning. Without actual data, it is difficult to verify if the simulations have been sufficiently comprehensive and if the results have accounted for all important variables.

Similarly to the above, the analysis in this report involves three steps. First, an optimization model that determines the optimal speed for the laden service based on fuel prices and total minimal costs is developed. Berth availability is added as a binary constraint in a way that the port services will either be available at the time of arrival or not, forcing the vessel to wait in anchorage. The model further considers the implementation of WASP to reduce fuel consumption and aid ship movement. This will be held into comparison with a base case that has no additional wind propulsion and therefore does not benefit from the extra aid obtained from it. Data is gathered from various sources, including the WorldScale (WS) database [48], Drewry report on tanker freight rates [49], and the UNCTADStats database [50].

In reference to the mentioned base case without WASP, time is also a constraint. The simulation can't afford to have different arrival times since that would constitute a different optimization problem. With the relaxation of the arrival time parameter, the ship will eventually carry out fewer services annually and as a result, will transport less cargo concluding in a different initial question: "Should the line invest in more services (number of vessels performing a round route) or into higher sailing speed to comply with the initial demand for the base case?". Hence, once the base case has established an arrival time, it is fixed for the other two scenarios, which will be presented below.

Note that what is fixed is the berthing time, as well as the departure, but not the sailing time. With this, speed can be modified and optimized considering that vessels can arrive beforehand and wait anchored adding idle time to the traveled time. Here a port call optimization function to regulate the speed within the last 10% of the route before arriving at the port is implemented, and with this, reduce emissions or hazardous near port outcomes, optimizing the fuel function and maintaining an appropriate schedule.

Summarizing, the initial analysis is divided into three basic scenarios: Base, WASP, and JIT. These scenarios include:

- Base: the base case is the selected vessel performing a one-way service between the selected ports at a constant speed and without further modifications.
- WASP: the WASP case is the same selected vessel, performing the same one-way service between the same selected ports as the Base case but with the help of a selected WASP technology. The speed will be maintained constant along the route, but the WASP technology helps with the thrust of the vessel and reduces fuel consumption as well as the overall emissions.
- JIT: the JIT case is the same selected vessel, performing the same one-way service between the same selected ports with the same selected WASP technology as the WASP case but with a speed optimization when arriving at port depending on the Terminal Usage. It is important to mention that only adjustments to the speed of the vessel will be made in order to maximize savings, but no route optimization will be performed. The wind conditions that are taken as input in this analysis correspond to the straight line between the two ports analyze and speed will be optimized for this route only. Route optimization would probably lead to significantly increasing the savings from the WASP technologies, but it is left to future research.

4.1 Case Studies

A total of three case studies will be presented and analyzed in this research project, each of them sailing between different ports, with different vessels, and with different WASP technologies. Thanks to these varied case studies, diverse weather and sailing conditions will be considered and the advantages and disadvantages of each one will be analyzed. The selection of the case studies has been made taking into account considerations on the wind conditions in different locations of the world, as well as specific regulations and conditions in the ports. A more detailed explanation of each of the case studies and why they were chosen will be presented in the following section, but a brief definition of each of them can be seen in Table 4.1. Further details on why each vessel and each WASP technology are being used in each case study will be provided both in this section and in the following one, but these decisions have been mainly made due to physical limitations in the routes and the type of cargo handled in each route and in each port.

Case study	**Origin**	**Destination**	**Type of vessel**	**WASP technology**
1	Rotterdam	Trondheim	Tanker (KVLCC2)	Flettner rotors
2	Antwerp	New York City	Bulk carrier	DynaRigs
3	Hong Kong	Algeciras	Container (Kriso Container Ship)	Rigid sails

Table 4.1: Overview of the case studies

4.1.1 Definition of Routes and Vessels

Specifications on each of the selected routes and the chosen vessels will be presented in this section. Each of these routes will be divided into smaller sections (referred to as way-points), each one having its own wind conditions, in order to make calculations more realistic.

Trade patterns are also identified to have a significant impact on the fuel-savings potential of WASP technologies, as wind and ocean currents in different geographic locations affect the performance of a ship. It is important to match the right technology to the right trade pattern. The study carried out in [51] show that for dry bulk carrier ranging from 0 – 35,000 DWT, there is a match between areas of higher wind speed and areas where ships consume more fuel (North Pacific, North Atlantic, Indian Ocean), which is a positive sign for the type of ships to consider WASP technologies. Moreover, the study carried out in [52] found that fuel savings in the western coast of Europe, the South China Sea, the Indian Ocean, and the Arabian Sea are the largest, while they are smaller in the Mediterranean Sea and off the west coast of Africa.

Plus, highlight that the routes of the ships are open paths as the ships do not return to port, but this causes no loss of generality as the path and tour problems are reducible to one another (or one could assume that the ship after visiting the port will return to finish the services, but yet again cargo holds would have to be considered since the trade is not equal both ways).

According to the 4th IMO GHG study, three sectors remain the dominant source of GHG emissions: containers, bulkers, and oil tankers, in that order [53]. Container ships are first in the inventory of international shipping GHG emissions, mainly because of their higher service speed, followed by bulk carriers and oil tankers. These three types of vessels will therefore be the chosen ones in the case studies.

As mentioned above, the three WASP technologies that will be studied here are Flettner rotors, rigid sails, and DynaRigs, as these are currently the most widely tested and used ones. The reasons for which technology to implement in each case study were done according mainly to height requirements, both in bridges entering the port of New York and the Suez Canal.

1. **Rotterdam (Netherlands) - Trondheim (Norway).** The port of Rotterdam is located in the province of South Holland and it currently is the largest port in Europe and the world's largest one outside of East Asia. It handled 467.4 million tonnes of cargo in 2022, mainly attracting the transport and logistics sectors, and chemical, refining, and energy industries, even though all types of cargo are transshipped at this port [54]. Moreover, the port of Rotterdam authorities currently have a high focus on fighting climate change and they aim to be leaders in the global energy transition [55].

   On the other hand, the port of Trondheim is located in the Trøndelag municipality, approximately 500km north of Oslo. It is a key transportation port connecting all of Norway, Sweden, and Europe. The main cargo that is exported from this port is fish, metals, or chemicals, while also has tanker facilities with five berths operated by different oil companies. There are annually 1,300,00 tonnes of cargo handled on average in this port [56].

   Several studies have shown that the North-Western European seas have very favorable wind conditions for installing wind platforms, as they have the highest average wind speeds in Europe [57]. This route was hence chosen to analyze the potential high fuel savings that could be obtained from the WASP technology, as can be seen in Figure 4.1.

   Regarding the type of vessel selected for this case study, both of these ports are important hubs for the trade of crude oil in Europe, and Rotterdam specifically is one of the largest energy ports in the world. Consequently, the selected vessel for this route is an oil tanker, specifically the KVLCC2. The reason why Flettner rotors were installed in this vessel is that the port of Rotterdam has participated in several projects installing these rotors in large vessels, as will be shown in Section 4.1.2.

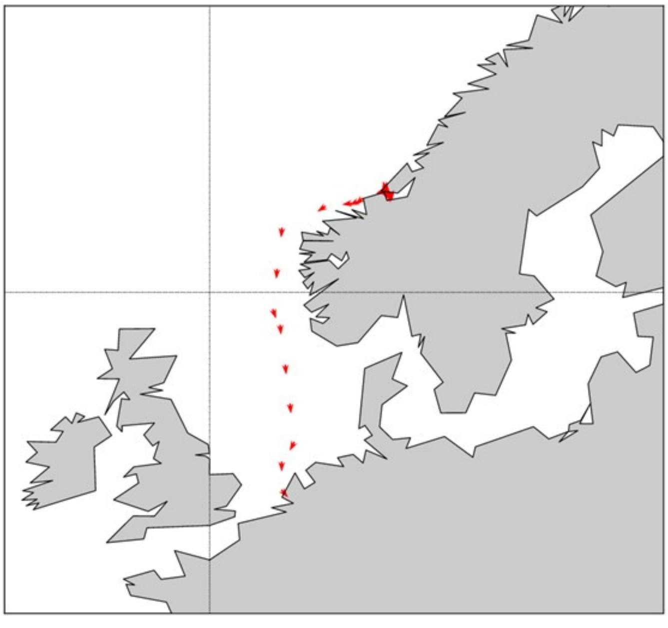


Figure 4.1: Sailing Route generated Trondheim - Rotterdam

2. **Antwerp (Belgium) - New York City (United States of America).** The port of Antwerp is located in the city of Antwerp, and it is the second largest port in Europe, only outsized by the port of Rotterdam. It annually handles around 290

million tonnes of international maritime cargo of all types, the main one being break bulk cargo. This port also has a big focus on the transition towards green energies, especially on the hydrogen transition, and they are working towards becoming Europe's biggest import hub for green hydrogen [58].

On the other hand, the port of New York is the largest port on the East Coast and the third biggest one in the US. It has six terminals where all types of cargo are traded and all types of vessels are accommodated. It is worth mentioning that there are several bridges when entering the port of New York and, as will be further explained in Section 4.1.2, these limitations will be used as the decision factor for finally installing DynaRigs in this case study, as the other two remaining technologies might not comply with these height regulations.

Given the ports selected for this case study and the type of cargo handled in them, the selected vessel for this route is a bulk carrier. This service can be traveled in either of the two directions and the vessel will always be in laden conditions, therefore the service Antwerp-NYC has been initially chosen arbitrarily, as shown in Figure 4.2.

It must be kept in mind that wind conditions in the North Atlantic are very favorable, and therefore big savings are expected to be obtained in this case study. It is interesting analyzing how both the service Antwerp-NYC and the service NYC-Antwerp will differ in terms of savings, as winds in the North Atlantic Ocean rotate clockwise and might probably lead to bigger savings in the service NYC-Antwerp. Both services will be analyzed to compare the results obtained.

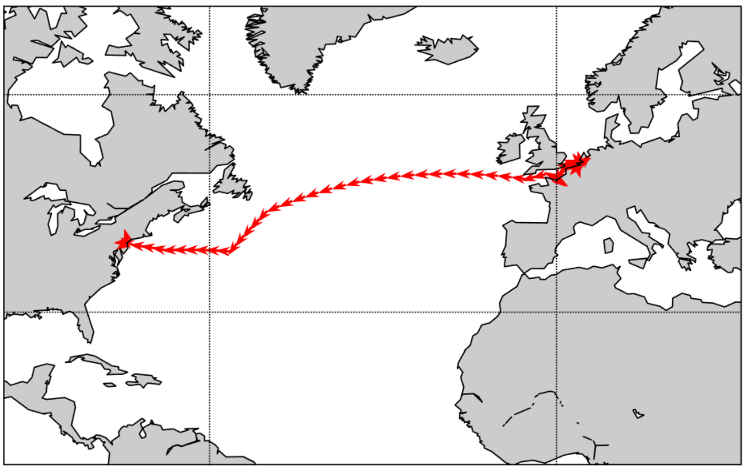


Figure 4.2: Sailing Route generated Antwerp - New York City

3. **Hong Kong (China) - Algeciras (Spain).** The port of Algeciras is located in the province of Cádiz, in the south of Spain. It is the largest port in Spain and the 7th busiest container port in Europe. The main types of cargo handled in this port are general cargo, liquid bulk, and solid bulk [59].

   The port of Hong Kong is located in the South China Sea, and is one of the busiest ports in the world, both in passenger and cargo handling. The main type of cargo handled in this port is manufactured containerized goods, as it handled nearly 17 million TEUs of containers in 2022 [60].

   It is worth mentioning that this route is transited by the Triple-E Maersk family, which is composed of very large container ships with a capacity bigger than 18000

TEUs. These vessels are too wide to sail through the Panama Canal but can transit through the Suez Canal, making them suitable for this route [61].

Even though this route is not particularly windy, as it travels through the Mediterranean Sea, the Indian Ocean, and the South China Sea, as can be seen in Figure 4.3, it is one of the most transited commercial routes in the world, which is the reason why it has also been chosen as a case study, even though the fuel reduction savings in this route will not be as higher as the ones obtained in the other two cases.

Finally, the type of vessel chosen for this case study is a Kriso Container Ship, slightly slower than the Triple-E Maersk containers. It is worth mentioning that this route sails through the Suez Canal, but this vessel complies will all size limitations in this section of the route, as will be described in Section 4.1.2.

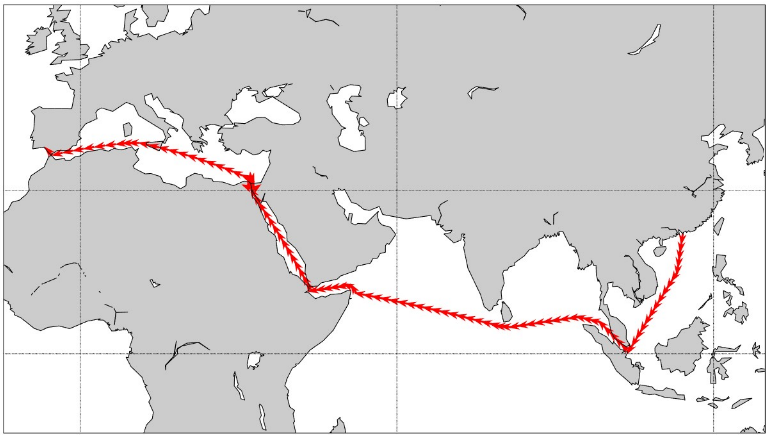


Figure 4.3: Sailing Route generated Algeciras - Hong Kong

As an overview of all the above and since the routes will be analyzed for the implementation of WASP technologies, Figure 4.4 shows a comparison between the absolute force of the wind considered to be blowing in the respective routes. Given the different lengths of the routes they bare different amounts of way-points, hence, Algeciras-Hong Kong, for example, has more data points than Trondheim-Rotterdam, but they have all been normalized for its representation with the accumulative percentage. As seen, Route 1 could seem to be the most feasible for WASP technologies but note that these values are in absolute figures and they come with a TWA which indicates the direction the wind is blowing.

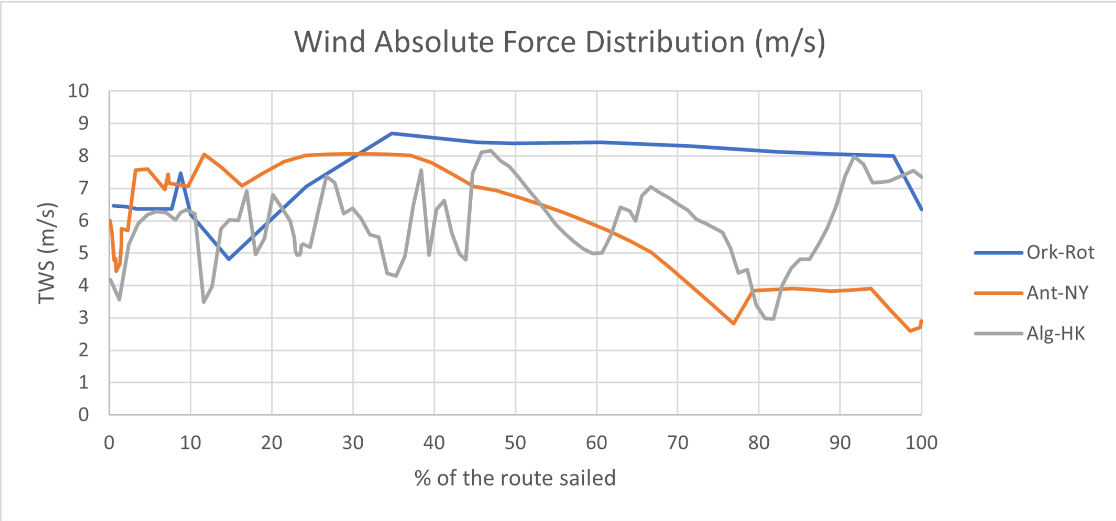


Figure 4.4: Wind Absolute Force Distribution [m/s] - (own figure)

4.1.2 Relevant Bottlenecks

The routes were chosen to comprehend different wind scenarios, lengths, and a variety of options that enlightened the reader in as many possibilities as permitted. In the pursuit of searching for various combinations, some bottlenecks were encountered. Also, some concerns of the relevant stakeholders are addressed in the following section.

Bridges entering New York

The selected terminal in the port of New York is terminal AmRod, a bulk and breakbulk cargo terminal [62]. In order to enter this terminal, vessels must sail under two bridges, the Bayonne Bridge and the Verrazzano Narrows Bridge. The Bayonne bridge is 66 meters high but can be raised in order to allow bigger vessels to go through it [63]. On the other hand, the Verrazzano Narrows bridge is 70 meters high and does not raise, constraining the air drought of the vessels performing this service route. This needs to be considered when selecting both the vessel and the WASP technology defined.

The vessel defined for this case study is a bulk carrier with 23.5 meters in height and a laden draught of 11 meters, therefore having a total of 12.5 meters over the waterline. This would allow for a DynaRig with a maximum height of 57.5 meters, which seems reasonable with typical DynaRig measurements. These sails have higher surfaces than the rigid sails but are more square-shaped, which allows for having higher heights than the rigid sails. Due to this, DynaRigs were chosen for this route over the rigid sails and the Flettner Rotors.

Suez Canal Transit

The Suez Canal connects the Mediterranean Sea and the Red Sea and extends for a total length of 192 kilometers. The Mediterranean entrance is situated at Port Said and the Red Sea entrance is at Suez Port. The route from Algeciras to Hong Kong sails through this canal. There is no restriction on the length of a vessel, max air draught is 68 meters, max beam is 70.1 meters and max draught is 17.07 meters. [64]

On an overview, the KCS modeled for this route has a length of 230m, a depth of 19m, a beam of 32.2m, and a draft of 10.8m [65] that generally carries 3600 TEUs. Assuming that there are 6 rows of containers displayed on the lashing bridge it would result in 23 meters over the waterline, which would allow the installation of a rigid sail of up to 47 meters which, as discussed with external manufacturers, falls within reasonable bounds, as these are typically around 30 meters high. It is worth mentioning that the height at which the rigid sail would be placed has to be above the container line so the wind is not obstructed.

Finally, an example of this is the Meltem project [66]. Meltem is a 185m container ship equipped with 8 rigid wings, which reduces the carbon footprint by 80% on a transatlantic journey at a speed of 11 knots developed by a company based at Atlanpole (France) company, Zéphyr & Borée. Their ship can be seen below in Figure 4.5

Figure 4.5: Meltem 1800 TEU Container Ship
[66]

Tanker Terminals

In one of the meetings, it was highlighted that some Tanker Terminals worldwide did not accept Flettner Rotors. This was due to the fact that they do not want to withhold liability if they result damaged due to operations in port. Cargoes carried on tanker ships are flammable in nature, as most of them release some types of gases which may form a combustible mixture composed of hydrocarbons. [67].

Contrary to the beliefs, Norsepower Oy Ltd., together with project partners Maersk Tankers, Energy Technologies Institute (ETI), and Shell International Trading and Shipping Company Ltd., successfully tested two Norsepower Rotor Sails onboard the Maersk Tankers product tanker, Maersk Pelican in August 2018 [68]. The Rotor Sails were installed in the Tanker Terminal of Rotterdam, Netherlands, and the aggregated total fuel saved from 1st September 2018 to 1st September 2019 was 8.2%. This is equivalent to approximately 1,400 tonnes of CO_2. Independent experts from Lloyd's Register's Ship Performance Group have analyzed and validated the performance data as well as confirmed the easy maneuverability, clearing all constraints any Tanker Terminal could try to impose.

Specifically in Rotterdam, there is also data on the SC Connector, a vessel from the shipping company Sea-Cargo converted into a modern sailing ship deployed on a scheduled service with other RoRo and breakbulk vessels between Western Norway, Denmark, the Netherlands, Sweden, and Poland [69]. Built in 1997, it was fitted with 35m high rotor sails in 2020, which can save 25% in CO_2 emissions and fuel consumption under favorable weather conditions.

Regulatory Constraints

General regulatory frameworks for the reduction of GHGs are discussed in the previous section "Theoretical Background - Regulatory context, IMO and MBMs". These include some measures to achieve IMO's reduction targets but WASP technology is analyzed. There is a reason for this.

The decarbonization of the shipping industry is the defining issue of the coming decade. One of the current leading decarbonizing technologies, direct wind propulsion, is receiving only very limited consideration in this critical debate over the future of shipping. MEPC 72 adopted resolution MEPC.304(72) [21] on Initial IMO Strategy on reduction of GHG emissions from ships and this is designated as the first milestone set out in the Roadmap for developing a comprehensive IMO Strategy on reduction of GHG emissions from ships approved at MEPC 70. It identifies that a revised Strategy is to be implemented in 2023. There are a number of regulatory and non-regulatory barriers that can be addressed to remove unnecessary restrictions on the uptake of this innovative and highly beneficial technology grouping.

As noted, these wind technology solutions are increasingly available today, with a growing number of demonstrator ships already in commercial operation, sea trialing, or in the late R&D stage. Wind propulsion can be deployed either as wind assist for primarily motor vessels or as a primary propulsor for newly built ships outfitted with auxiliary engines. It is important to demonstrate different types of wind propulsion to simulate technical and commercial competitiveness to ensure the market can access the best options and regulatory directives.

Support for designers, shipowners, and yards from classification societies has been growing but nothing has been legally established as a constraining standard. At the end of 2019, two sets of wind-assisted guidelines were published by leading classifications societies as a starter. Along with the development of wind propulsion systems, there has also been steady progress in the development of new testing procedures and performance criteria, energy management systems, and weather routing software development, and further work is underway including new digital/satellite-enabled wind data routing systems, etc [21]. Again, as well as the technologies, these regulations are in a development phase, hence, there is no issue to take into account when simulating the routes in this paper.

Visibility Restriction due to WASP

Marine transportation has always carried a slight danger of collision. This risk is now considerably greater because of the rise in bigger, faster vessels, despite advancements in navigating technology. This is why seagoing vessels must adhere to tight guidelines for visibility from the navigation bridge starting on or after the keel is laid on 1 July 1998.

SOLAS requirements of minimum visibility:

- The view of the sea surface from the conning position is not to be obscured by more than 2L or 500m, whichever is less, forward of the bow to 10° on either side for all conditions of draft, trim, and deck cargo under which the particular vessel is expected to operate.
- The horizontal field of vision from the main steering position spans an arc from directly ahead to at least 60° on each side of the vessel.

- From the conning position, the horizontal field of view must cover an arc of not less than 225°, or from directly in front of the ship to not less than 22.5° aft the beam on either side.
- The horizontal field of vision from each bridge wing must cover at least 225 degrees, or at least 45 degrees from the opposite bow to the right ahead and 180 degrees from the right ahead to the right astern on the same side of the ship. The bridge wing must be able to see the side of the vessel. [70]

All new vessels shall be provided with a Loading and Stability Manual containing Visibility Tables showing blind sectors as a function of draught and trim. The Visibility Plan shall be prepared as a part of As Build Drawings. It should contain the classification drawing Navigational Bridge Visibility and the Visibility Tables.

In the diagram below, it can be seen the visibility restrictions encountered from the Bridge. Currently, there are numerous tools to overcome these constraints such as the usage of AI or IoT sensors developed by numerous manufacturers in the industry that can detect unknown objects ahead.

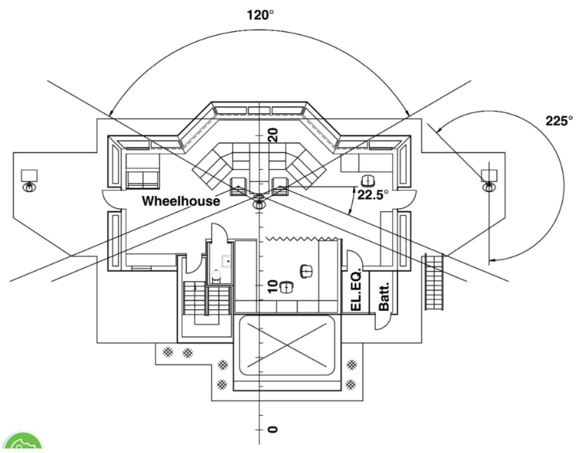


Figure 4.6: SOLAS Visibility Constraints from the Bridge.
[70]

Either way, WASP technologies (especially DynaRigs, which can occupy such a big space) can result in a complication when analyzing the visibility from the bridge and should be kept in mind when designing their deployment. In the simulations of this thesis, the chosen vessels all have the bridge situated in the fore deck, hence they do not see themselves affected by this condition.

4.2 Model Diagram

A diagram of the model that has been developed in this project can be found in Figure 4.7. Inputs are shown in blue, while outputs are shown in green. On the other hand, square-shaped blocks represent actions and diamond-shaped blocks represent decisions. As can be seen and as will be presented below, there are several actions that are taken for each of the way-points in the route, and most of the actions are carried out in a loop for each of the considered speeds. A full explanation of each of the steps involved in this model will be presented in the following sections.

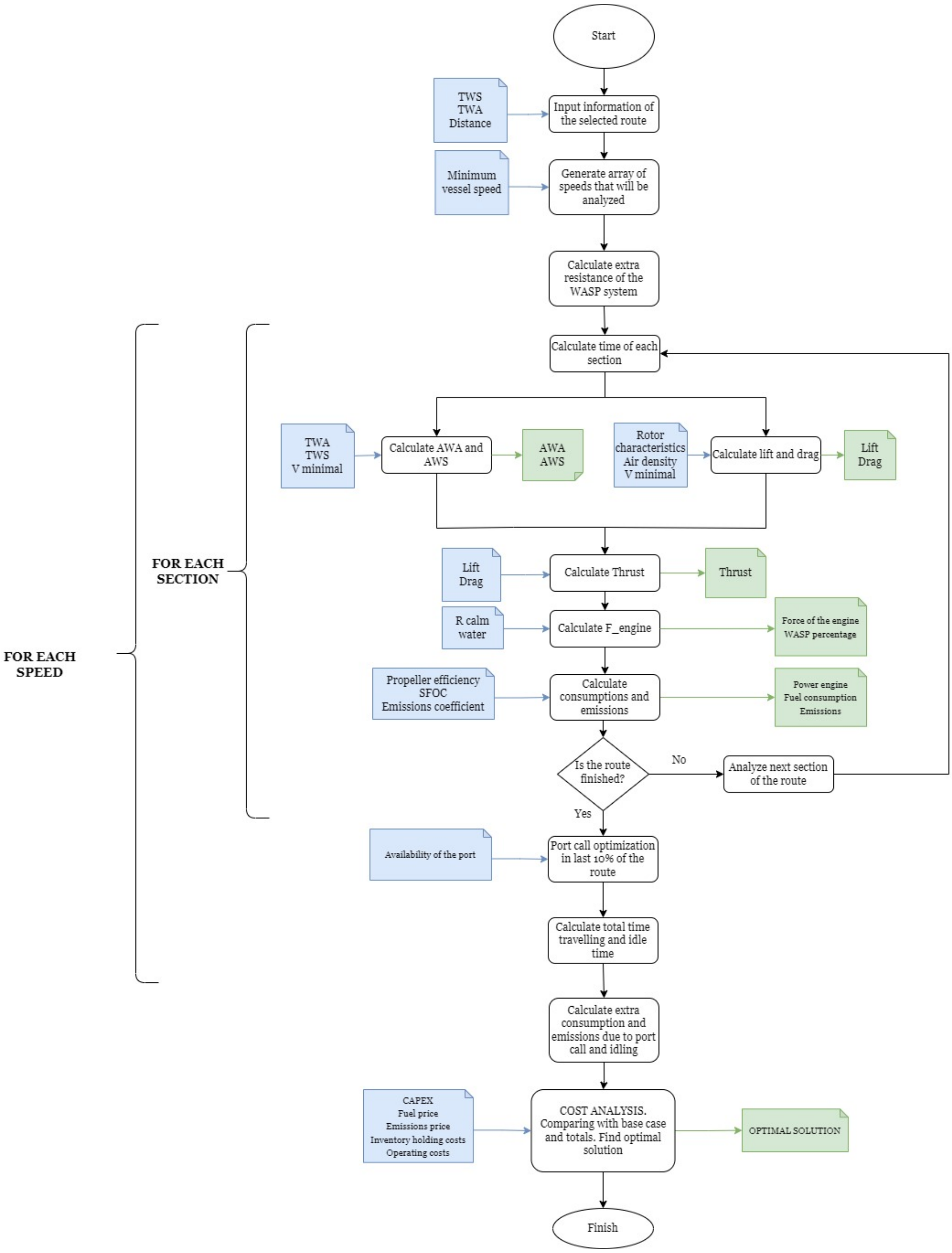


Figure 4.7: Model diagram. (Own Figure)

4.3 Methodology

The main consideration that needs to be mentioned before explaining each of the sections in more detail is that a range of speeds varying by 0.1 knots between set bounds (these will depend on the specifications of each of the vessels) will be analyzed, and two optimization processes will be carried out. One of these optimizations will find the optimal sailing speed for minimizing costs, while the other one will minimize emissions. These two speeds will indeed be different, which leads to the main dilemma of this analysis, as it is certainly very hard to obtain a win-win solution that will be optimal both in economic and environmental terms.

This situation is due to the need of reducing time when optimizing costs, since considering all relevant factors, those that are closely linked to the time factor are some of the highest costs. It is therefore essential to find the right balance between higher speed, which consumes more fuel but reduces operational costs, and lower speed, which reduces consumption. In general, the result tends to favor the higher speed in terms of costs, whereas, in the emission reduction scenario, it focuses exclusively on this aspect and tends to favor the lower speed, which is where emissions are lower, as explained above within the relation of speed vs consumption and emissions.

Thus, all the calculations that will be further presented will be carried out for each of the speeds in the range, and they will be carried out for the three different scenarios mentioned above (base case, WASP, and JIT). For each speed, total fuel consumption and emissions will be calculated for each individual way-point and these will be finally added up once all the way-points have been considered. Once the whole route's fuel consumption and emissions have been calculated, the economic and environmental optimization will start.

4.3.1 Input Variables

The main input variables in this analysis are the technical specifications of the engines of the proposed vessels and of the WASP technologies. The specifications of the engines can be seen in Table 4.2, while the corresponding specifications of the selected WASP technologies can be seen in Table 4.3. All the parameters of both the vessels and the WASP technologies have been obtained from personal communication with experts.

Vessel	η	$SFOC_m$ **[g/kWh]**	$SFOC_{aux}$ **[g/kWh]**	**EC** [gCO_2/ **gfuel]**	**MCR [MW]**	V_{min} **[knots]**	V_{max} **[knots]**
KVLCC2	0.68	165	217.5	3.11	32.97	9	16
Bulk carrier	0.65	165	217.5	3.11	8.5	11	15
KCS	0.69	165	217.5	3.11	92	12	24

Table 4.2: Specifications of the selected vessels

With respect to the Specific Fuel Oil Consumption, the value shown in the table above for the main engines is the ideal one. However, this value will change with the total power output, and these calculations will be further explained in the following sections. The SFOC of the auxiliary engines is assumed to be constant.

WASP	C_L	C_D	**Area** [m^2]	**Weight [tonnes each]**	**Number**	**CAPEX [M$ each]**
Flettner rotors	7	4	175 (35x5)	160	5	1
Rigid sails	2	0.1	250	200	8	1.5
DynaRigs	1.5	0.2	1000	40	4	2.5

Table 4.3: Specifications of the selected WASP technologies

The lift and drag coefficients have been briefly presented in Section 2.3. Given the limited time and resources available for this project, these are set as the optimal values for each of the corresponding WASP technologies, even though a more thorough analysis should be carried out on how these coefficients change depending on the weather conditions.

Moreover, all the routes will be divided into way-points, and each one of them will have their own wind conditions, so as to obtain more accurate calculations. Each of these way-points will therefore have its own TWS array (in m/s), TWA array (in degrees), and distance (in NM). This data has been obtained from the ERA5 database with real wind conditions from 2000, and it, therefore, shows averaged wind values over 23 years [48]. Thanks to using this database, the wind data that is being implemented in the model is already annualized and can be used as averaged conditions.

With respect to the port availability, real data from the Piraeus Port, located 7 km far from Athens, is used. This data has also been obtained from communication with relevant stakeholders. Data from the port usage over 30 days has been obtained and has been used as the base for simulating port availability over a longer time span.

The final input of the model is the resistance of the water, which will be explained in more detail in the following section.

4.3.2 Resistance of water

The resistance of the water has been briefly presented in Section 2.3, and is defined as the total force that the vessel needs to provide in order to sail through the water. This resistance will change depending on the vessel that is being modeled, as it depends on the hull shape, and therefore it needs to be included in the model for each of the considered vessels. It will also change depending on the sailing speed, as the vessel will have a different interaction with the water depending on the speed at which it is sailing.

It is worth mentioning that the resistance of the water will undoubtedly depend on the water conditions (e.g. waves, currents, etc.). However, due to the limited time for this project and for the sake of simplification, calm water conditions have been considered in this analysis for all three routes, as solutions will be relevant enough with this simplification and the main objective of this project is not to carry out a detailed mechanical analysis but a logistic one.

Consequently, there will be three resistance curves depending on the sailing speed, one for each of the vessels modeled. These can be seen in the following figures.

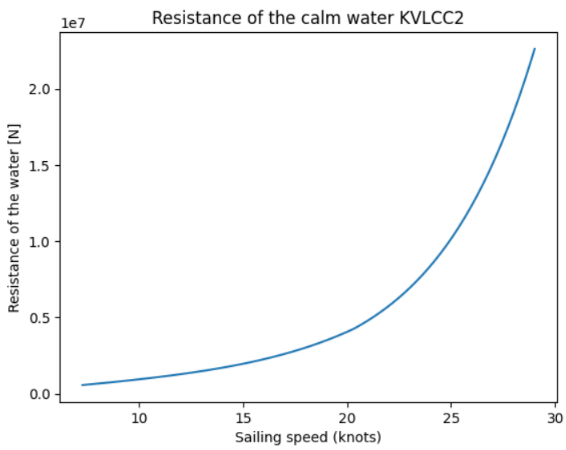


Figure 4.8: Resistance of the calm water of the KVLCC2 (Own Figure)

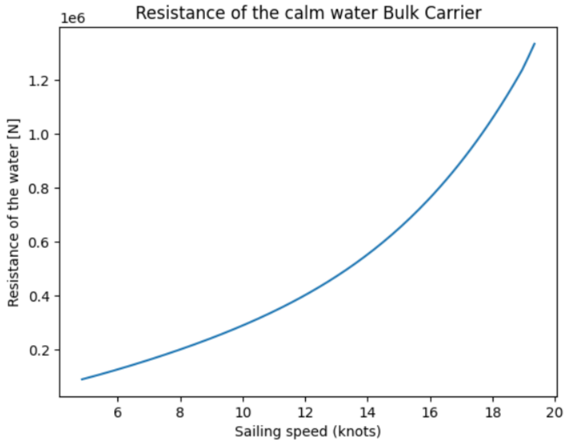


Figure 4.9: Resistance of the calm water of the Bulk Carrier (Own Figure)

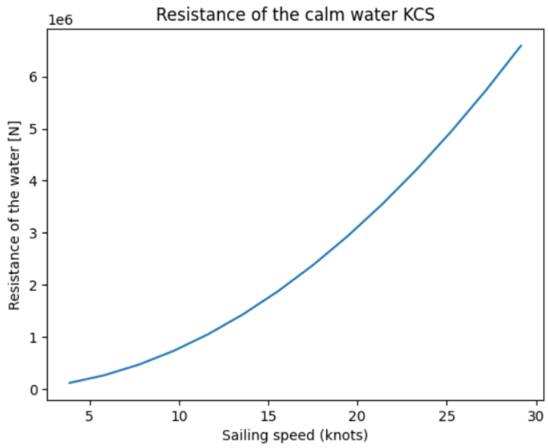


Figure 4.10: Resistance of the calm water of the KCS (Own Figure)

It can be easily derived from what has already been mentioned that, in order to sail through the water at a specific speed, the engine will need to make a total force that equals the resistance of the water for that given speed. However, when WASP technologies come into play, they will be providing an extra force (Thrust) that will help reduce the force that the propeller needs to give, as shown in the following equations [4]. On the other hand, the WASP technology will also be providing additional resistance due to its weight, which also needs to be accounted for. A full explanation of how the thrust and the additional resistance due to the weight will be shown in the following two sections, but their effect on the total force of the propeller is shown below.

Without WASP:

$$FP_b = R_c \tag{4.1}$$

With WASP:

$$FP_w = Rc + R_{add} - F_A \tag{4.2}$$

Where:

- $FP_{b/w}$ is the force of the propeller in the base case/in the scenario with WASP.
- Rc is the resistance of the calm water.

- R_add is the additional resistance due to the WASP technology.
- F_A is the thrust.

4.3.3 Added Weight due to WASP technologies

As has just been mentioned, adding additional weight to a commercial vessel can have a significant impact on its speed and performance. The speed of a vessel is influenced by a number of factors, such as the power of its engines, hull design, water conditions, and overall load. Alternatively, the added weight will reduce the ship's payload (if displacement stays constant), but this feature is analyzed in 4.4.1 since it will affect the operational outcome, therefore directly influencing the costs rather than the performance of the vessel, which is the focus of this subsection.

The main impact will be increased drag. The ship will need more energy to move through the water due to the greater mass it must displace and overcome hydrodynamic resistance. This can result in a decrease in the vessel's speed. A significant increase in weight can lead to a perceptible decrease in speed and require adjustments in operations and fuel consumption.

The addition of weight can also affect the ship's stability and maneuverability. Increased weight may alter the balance of the vessel, which may require adjustments in load distribution or trim to maintain proper stability. In addition, increased weight may require higher fuel consumption to maintain the desired speed, which in turn may affect the efficiency and operating cost of the vessel.

It is important to note that the exact impact on speed will depend on the specific characteristics of the ship, such as its design, propulsion, and carrying capacity. To calculate how additional weight reduces a vessel's speed, the following formulas can be used:

1. Forward resistance formula: is the force that the vessel must overcome to maintain a constant speed. This comes from the inputs explained above, *"resistance_water"*.
2. Formula for additional forward resistance due to weight: can be calculated using the formula:

$$R_{add} = (W_{add} \cdot g) \cdot k \tag{4.3}$$

   Where:

   - R_{add} is the additional resistance. This is the additional resistance due to the WASP technology mentioned in 4.2.
   - W_{add} is the additional mass.
   - g is the gravity acceleration (9.8 m/s^2 approx.).
   - k is a factor that represents the influence of the additional weight. It depends on the design and characteristics of the studied vessel. Generally, k is considered to be between 0.01 and 0.02
3. Calculation of speed reduction using the ratio of additional to total resistance [71]:

$$\triangle V = (R_{add}/R_{total}) \cdot V_{org} \tag{4.4}$$

   Where:

   - $\triangle V$ is the reduction of speed.

- R_{total} is the *"resistance_water"* (including additional weight). ($R_{TOTAL} = R_{add} + R_C$)
- V_{org} original speed.

The final speed that will be used for calculations will be the original speed minus this additional speed, as the added weight of the WASP technology will slow the vessel down.

4.3.4 Wind Calculations

Once the input to the model and the total resistance has been presented, the next step is carrying out the wind calculations. It is worth mentioning that this is the point where calculations for each individual way-point start, as the calculations that will be explained here have to be carried out for each way-point, and they will finally lead to calculating total fuel consumption and emissions in each section. Additionally, these calculations will also be carried out for each of the speeds, so there will be two loops in the model, one that analyzes all the way-points and another one that analyzes all the sailing speeds. The next steps will be followed for each way-point in order to get these results.

1. First step is calculating the time needed to sail through each of the way-points, which will be later used for calculating fuel consumption. It can be simply calculated by dividing the distance of each way-point by the sailing speed. It will be expressed in hours, so the corresponding change of units will be carried out before starting calculations.
$$t = d_{ll'} \cdot V_s \tag{4.5}$$
Where:
   - $d_{ll'}$ is the distance between way-points in meters.
   - V_s is the speed of the vessel in m/s.
2. Apparent Wind Speed and Angle: as explained in Section 2.3, the apparent wind is the one that the sailor feels on board, and the one that the sail encounters as an incoming airflow. It will therefore be the one that will generate the forward thrust, and it can be calculated with equations 2.2 and 2.1.
3. Lift and Drag: again, these are the components of the total aerodynamic force, and they were presented in Section 2.3, with equations 2.3 and 2.4.
4. Next, the total aerodynamic force can also be decomposed into the driving force (thrust) and the side force generated by the WASP technology. The driving force (thrust), calculated as shown in equation 2.6, is the one pointing into the vessel motion, and due to simplification, it will be the only one that will be accounted for, as it represents the forward extra force provided by the WASP system. The generated side force, calculated as in 2.7, is perpendicular to the vessel motion, and again, this will be neglected due to simplification, as only the forces in the x direction will be considered. For more accurate results a full simulation of at least 4 degrees of freedom would need to be done. However, the aim of this report is not to develop a full performance prediction program but to focus on the logistics.
5. Finally, the total force that the engine needs to provide can be calculated, taking as input the resistance of the water, the additional resistance due to the WASP's weight, and the thrust generated by the WASP and as shown in equation 4.2. It must be noted that the thrust calculated above is only the thrust provided by one WASP

element, so if more than one WASP element is being implemented, the total thrust provided by the system will be the multiplication of the number of elements by the total thrust provided by one element. Furthermore, the simulation is neglecting any aerodynamic interaction effects between several WASPs that may cause a reduction in thrust generation.

Additionally, it must be kept in mind that the rotor is an active system, meaning that it requires a small power input when they are working. It has been assumed that rotors need approximately 10% of the total power that they are generating as an input. Therefore, the total thrust that the Flettner rotors will finally be able to provide is 90% of the total thrust that they are generating. On the other hand, both rigid sails and DynaRigs are passive systems, meaning that they do not require any additional power to work.

It is important to mention that there are some way-points in which the input of TWS and TWA are not favorable for the WASP technology and the thrust ends up having a negative value. One important assumption that has been taken at this point is that, whenever this is the case, the thrust has been set to 0, simulating that the WASP technology is disconnected in the case of the rotors or closed in the case of the sails. This has been done so as to optimize the WASP system to its maximum and not use it when it will not be beneficial given the wind conditions. A limitation to this assumption is the DynaRigs. They can't be fully retracted, even though they are put down, hence the vessel will still experiment some drag from the standing mast.

Once the force needed by the engine has been calculated, the total percentage of force that the WASP is providing in each section can be calculated, representing how much the total force of the engine can be reduced by implementing WASP technologies, which is calculated with the following equation:

$$\%\, WASP = \left(1 - \frac{FP}{R_C}\right) * 100 \tag{4.6}$$

It is worth mentioning that the lengths of the way-points are not always constant, since some way-points are 150 km long while others are only 30 km long. The total WASP percentage along the whole route must account for these differences, and hence the individual WASP percentage in each way-point will be then multiplied by the percentage of the route that it is associated to.

4.3.5 Main Engines

The next step is calculating both fuel consumption and emissions released by the main engine. In order to get this consumption, first the power of the main engine needs to be calculated. It must be kept in mind that these calculations are also carried out for each of the individual way-points, and the total fuel consumption and emissions throughout the route will be calculated in the end as the sum of all the consumption and emissions once all the way-points have been considered. The following calculations need to be carried out in this step:

1. First step is, as mentioned, calculating how the total force that the engine needs to provide (FP) translates into the total power consumption of the engine in kW, which is shown in the following equations, with the corresponding change of units

and where η represents the main engine's efficiency.

$$P_{main} = \frac{FP \cdot V_s}{\eta \cdot 1000} \tag{4.7}$$

2. Next step is calculating the fuel consumption. In order to get these results, the final SFOC first needs to be calculated. As was mentioned in Section 4.3.1, the SFOC will vary as the power output of the engine changes, and this change needs to be accounted for. The engines that are being considered in this project are 2-stroke engines, and the variation in the total SFOC will depend on the deviation between the brake power of the engine and the MCR.

   As recommended by MANEnergy Solutions, marine engines cannot operate lower than 10% of installed MCR and are advised to it higher than 20%. Under 10% of MCR, the lubrication and cooling systems may not perform correctly which can cause engine damage. [72]

   Both the deviation in power output and in the SFOC can be calculated with the following equations [73]:

$$\%MCR = \frac{P_{main}}{Total\ MCR} \cdot 100 \tag{4.8}$$

$$SFOC\ deviation(\%) = 0.0028 \cdot MCR^2 - 0.41 \cdot MCR + 15 \tag{4.9}$$

   Finally, the total extra SFOC that must be added due to a change in the power output is calculated as follows [73]:

$$Extra\ SFOC = \frac{SFOC\ deviation(\%) \cdot SFOC\ ideal}{100} \tag{4.10}$$

   With this, to obtain the current SFOC:

$$SFOC_{main} = Extra\ SFOC + SFOC\ ideal \tag{4.11}$$

3. The fuel consumption of the main engine in each way-point can be simply calculated as follows, with the corresponding change of units and in tonnes of fuel:

$$FC_{main.s} = \frac{SFOC_{main} \cdot FP \cdot t_{ll'}}{10^6} \tag{4.12}$$

4. Finally, emissions released in each way-point can be easily calculated as follows, where $E_{main.s}$ are the emissions released by the main engine while sailing in tonnes of CO_2 and EC is the emissions coefficient:

$$E_{main.s} = FC_{main.s} \cdot EC \tag{4.13}$$

4.3.6 Auxiliary Engines

Auxiliary engines will be working while sailing, they supply power to additional equipment in the vessel, such as lighting, pumps, cranes, etc. On the other hand, whenever a vessel arrives at the port and it cannot be attended because there are no berths available, it will have to wait outside of the port, which is referred to as idling, and will only keep its auxiliary engines on, turning the main ones off. Therefore, these fuel consumption and emissions must also be accounted for.

With respect to their power output, several studies have proven that power of the auxiliary engines while sailing is approximately 27.8% of the total MCR of the main engine [74]. On the other hand, their power has been proven to be approximately 7% of the total MCR while idling [75]. These numbers have been corroborated with certain simulations within a Maersk database. Fuel consumption and emissions of the auxiliary engines will be explained with the availability of the port in the following section.

Additionally, the SFOC of the auxiliary engines has been assumed to remain constant regardless, contrary to one of the main engines. This is mainly due to their power requirements. These do not change with sea state or speed as the main engine, but it only depends on the loads which are expected to be rather constant. On the other hand, the emissions coefficient of the auxiliary engines has been assumed as the same one used for the main engine. Fuel consumption and emissions can thus be calculated as follows:

$$P_{aux.s} = 0.278 \cdot MCR \tag{4.14}$$

$$P_{aux.i} = 0.07 \cdot MCR \tag{4.15}$$

$$FC_{aux.s} = SFOC_{aux} \cdot P_{aux.s} \cdot t_{ll'} \tag{4.16}$$

$$E_{aux.s} = FC_{aux.s} \cdot EC \tag{4.17}$$

Where:

- $P_{aux.s}$ is power of the auxiliary engine while sailing in kW
- $P_{aux.i}$ is the power of the auxiliary engine while idling in kW
- MCR is the maximum container rating in kW
- $FC_{aux.s}$ is the fuel consumption of the auxiliary engine while sailing in tonnes
- $SFOC_{aux}$ is the specific fuel oil consumption in gr/kW * hour
- $t_{ll'}$ is the time it takes to sail between way-points in hours.
- $E_{aux.s}$ is the emissions released by the auxiliary engine while sailing in tonnes of CO_2
- EC is the emission coefficient in tonnes of CO_2 / tonnes of fuel

It is important to note that this is the point where calculations for each individual way-point finish, once they have been carried out for all of them. At this point, all the values for each of the way-points will be summed up and the final fuel consumption and emissions for the whole route will be obtained. This also applies to the total time of the whole route, as it will be the sum of all the individual times taken to sail through each of the way-points.

With regards to more technical aspects, it must be mentioned that all the consumption and emissions in each of the individual way-points and for each of the considered speeds will be saved in a matrix, where each row is a speed and each column is a way-point. When JIT is implemented and as will be further explained, the speed in the final part of the route will be modified, and therefore both the consumption and emissions will have to be changed. Saving results in a matrix will simplify future calculations when these changes need to be made.

4.3.7 Port Availability

Once the whole route has been analyzed, the availability at the port when the vessel arrives and the possible idle time and extra consumption and emissions are calculated. The terminal usage data has been obtained from the port of Piraeus, and it has been assumed that if the terminal availability is over 0.38 it will not be possible to berth. In a container terminal and in most ports the resources are available 24/7, it now depends on the workload. It is assumed that the service for the vessel is continuous until it departs, meaning that the loading and unloading operations will not stop until the vessel leaves the port.

In the first two scenarios (base case and WASP) the vessel will not be adjusting the speed according to the port availability and it thus might have to wait to be served if the port is not available at the arrival time. If this is not the case and the port is available, then the vessel will simply finish the route and berth, without having any extra fuel consumption or emissions released. However, if berthing is not available, there will be an idling time that will have to be included in the whole journey, which will imply extra fuel consumption, extra emissions, and extra costs due to longer times.

The total idle time will then be simply calculated as the remaining hours until the next time slot in which the port is available. The extra fuel consumption and extra emissions released while idling can be simply calculated with the following equations.

$$FC_{aux.i} = SFOC_{aux} \cdot P_{aux.i} \cdot Idle \tag{4.18}$$

$$E_{aux.i} = F_{aux.i} \cdot EC \tag{4.19}$$

Where:

- $FC_{aux.i}$ is the fuel consumption of the auxiliary engine while idling in tonnes.
- $SFOC_{aux}$ is the specific fuel consumption in gr/kW * hour
- $P_{aux.i}$ is the power of the auxiliary engine while idling in kW
- $E_{aux.i}$ are the emissions released by the auxiliary engines while idling in tonnes of CO_2.
- EC is the emissions coefficient in tonnes of CO_2

On the other hand, in the JIT scenario, the vessel will be sharing its arrival information with the port well in advance and the port will be giving them an estimated time of arrival where the port will be available. The vessel will try to adjust the speed so as to reach the port at exactly one of these available time slots and therefore save waiting time when reaching the port. The idle time will therefore ideally be zero. Further description of how the JIT methodology is implemented will be presented in the following section.

4.3.8 JIT optimization

For each of the considered speeds, the moment when the vessel sends the estimated time of arrival (ETA) to the port will be calculated, assuming this is the point of the journey where the vessel may vary its speed according to the answer received from the berth availability plan. Berth scheduling is out of the scope of this project.

These ETAs of vessels are sent by shipping companies 24 hours in advance of the vessel's arrival, once they enter the very high frequency (VHF) radio range. The berth scheduling then determines the optimal berthing start time of vessels, and therefore the speed optimization performed by the shipping companies is restricted by the time windows provided by the berthing plan. This is a constrained cooperation mode very commonly discussed in papers to achieve the JIT arrival, particularly for container terminals and shipping companies that have not adopted remote real-time data exchange.

Consequently, the first step in carrying out the JIT analysis is finding the point at which the vessel starts sharing information with the terminal and can start adjusting the speed. As mentioned, this will be set to 24 hours before arrival, and the total distance remaining to the port will also be calculated.

At this point, the availability of the port needs to again be taken into consideration. If the idle time calculated in the first two scenarios is zero (the port is available and the vessel will not have to wait), there will be no need of carrying out any speed adjustments, as there is no room for further optimizing the travel with JIT. However, if the port is not available at the estimated time of arrival, the port will be sent back to the vessel with the previous and next available time slots at which the vessel can arrive. The vessel will have to either increase the speed to arrive at the previously available time slot or decrease it to arrive at the next available one. In order to do this, all the wind calculations and fuel consumption calculations will need to be carried out again for the remaining part of the route for both of these two scenarios (referred to as quick and slow scenarios).

In order to do this, the first step is calculating how much time there would be left to complete the route in both of these scenarios and to what value the speed needs to be changed to reach these two new arrival times. From now on and until the optimal solution is found in the costs section, **calculations will need to be carried out for two scenarios for each speed within the range of considered speeds**. There will thus be twice the number of scenarios: one where the vessel has accelerated the speed and will arrive earlier (quick scenario), the other one where the vessel will decrease the speed and will arrive later (slow scenario). For both of these two scenarios, calculations of wind forces, main engine, auxiliary engine consumption, and emissions will be redone in the same way as they were done in the WASP scenario.

An important remark that needs to be made at this point is that there are several of these scenarios that are not feasible due to two main reasons.

- There are numerous cases, especially in the longer routes, where the quick scenario is not feasible, as the vessel would have had to adjust the speed much earlier in order to reach the previously available time slot (the previous time slot has already happened).
- Additionally, speed bounds need to be set to the new speeds generated in the quick and slow scenarios. There are several cases in which either the speed in the slow scenario is smaller than the minimum speed at which the vessel can sail, and several others in which the speed in the quick scenario is much higher than the maximum.

Both of these extreme cases have been classified as unfeasible and resolved by ignoring the JIT analysis and finalizing the route without adjusting the speed. When carrying out the comparison between the WASP and the JIT cases, these cases will be ignored. Highlight, these are assumptions of this specific model simulation, not a general constraint.

4.3.9 Base Case

There will be a total of three different base cases, each of them being compared to each of the case studies with WASP. These base cases will consider exactly the same initial conditions as the WASP case to which it is being compared, meaning that it will be using the same selected vessel performing the same one-way service between the selected ports and sailing at the same constant speed. The same range of speeds will be considered in these scenarios so as to maintain exactly the same conditions. It needs to be kept in mind that these speeds are the ones obtained after taking into account the added weight of the WASP technology, and even though the base case will not be using WASP, the final speed will be set equal to this same value so as to keep the same conditions, same total sailing time and same arrival time as in the corresponding WASP case.

In this scenario, the engine will need to provide the total force that the vessel needs to sail through the water, so the force needed will directly be equal to the total resistance of the water, as shown in equation 4.1. Further calculations of fuel consumption and emissions released will be carried out in the same way as in the WASP scenarios (shown in Section 4.3.5 and 4.3.6, always keeping in mind that the brake power of the engine is proportional to the resistance of the water for the specific sailing speed.

These results will later be used to compare costs with the WASP case and to find optimal speeds that will minimize the extra costs derived from implementing WASP technologies.

4.4 Cost Analysis

In an increasingly competitive business environment, cost analysis has become an essential tool for ensuring the profitability and sustainability of organizations. This analysis focuses on examining in detail the various economic components associated with a company's operations, from the acquisition of technologies from their manufacturers to the delivery of the final product or service to the customer. By understanding the relationship between costs and outcomes, organizations can identify areas for improvement and design effective strategies to reduce unnecessary or inefficient spending.

The intrinsic problem of the charter (cost) versus the ship owner (profit) is within the value of sailing, fulfilling more round trips per year, or counterbalancing by a more significant increase in the overall operating costs for the ship including a bunker levy [76]. Devanney (2011) [77] proved that regardless of the ship's charter type, the owner's and time charterer's speed optimization problems are mathematically equivalent. For a rudimentary chartering scenario, the speed that maximized the profit per day for a shipowner in the spot market is the same as the speed that minimized the average daily costs for a time charterer or a bareboat charterer. A simple speed optimization problem ignores port time, port costs, and port fuel consumption, and assumes the same speed and the same "at sea consumption" [9].

The appropriate sailing speed must be decided in all scenarios. The chartering context assumed is that of a time charter. Time charters constitute the majority of contracts in maritime transportation. They involve the rental of the ship for a specified period. The decision maker in all these cases is assumed to be the charterer. This is the effective owner of the vessel during the duration of the charter (in shipping parlance this is known as the 'disponent owner'). Consequently, the default assumption is that the charterer of the ship is also the cargo owner. This would be the case whenever an oil company, chemical company, bulk cargo company, or other industrial company charters the ship on time charter for a specified duration, so as to carry its own cargo. [78]

The fundamental parameters that weigh the most in a ship owner's or charterer's speed decision at the operational level are (a) the fuel price, (b) the state of the market (freight rate), (c) the inventory cost of the cargo and (d) the dependency of fuel consumption on the payload.

When a charterer enters into a time charter, they are faced with a trade-off between completing the trip as quickly as possible to reduce the charter paid to the ship owner or going slower to reduce fuel costs, which the charterer pays for. Fuel is assumed to be purchased at a known price of F_P ($/tonne), while port-related costs are excluded from the default scenario. In general, different speeds can be chosen for different routes, as long as they are within the speed window. Both bounds (upper and lower speed) are dictated by the maximum power and technology of the engine and by the ship's payload when sailing. Slower speeds can be achieved by "derating" the engine, which involves reconfiguring it to achieve a lower power output, such as by dropping one or more cylinders [78].

4.4.1 Input parameters and assumptions

The ability to model the decision-making process of the shipping line relies heavily on the crucial assumption that the line does not hold a monopoly or oligopoly position in the specific route's market [79]. It should be noted that in certain market segments where a shipping line commands a dominant position and holds a significant share of the traffic, it may utilize this advantage to set rates or control capacity on the route. However, given the current global focus on anti-trust policies and the fact that ports are served by multiple lines, it is believed that such scenarios are infrequent and that the assumption remains valid.

The main implication of this assumption is that the rates used in the model are considered to be exogenous inputs. This means that they are determined by the overall supply and demand in the market and are not within the control of the operator.

The second assumption is that the cargo demand between any two ports is fixed and known on a per-call basis. This demand is assumed to be independent of both the service period or frequency and the number of ships deployed by the line on the route, which is consistent with the assumptions made in the relevant literature. However, like freight rates, cargo demand may not be symmetric and can vary based on the direction of travel.

A third assumption in the model is that there is no unfulfilled demand for cargo to be transported by the shipping line. In other words, the optimization problem is considered an incapacitated one, where there is always available capacity on the ship to carry all cargo. This assumption is consistent with the scenarios used to test the model. Historical data shows that overcapacity in container shipping has occurred, particularly after the 2008 economic crisis. For example, FMC (2012) [80] reports that in the year 2010, the average capacity utilization for the US to Europe trade lane was 88% eastbound and 87% westbound. Similarly, for the US to Asia trade lane, the utilization rates were 85% eastbound and 57% westbound, and for Asia to Europe trade lane, the utilization rates were 92% westbound and 59% eastbound.

In the first half of 2020, the volume of U.S. maritime container imports, which refers to the transportation of U.S. goods imports by foreign maritime vessels, decreased by 7.0 percent compared to the same period in 2019 [81]. However, in the second half of 2020, containerized imports increased by 9.5 percent by volume compared to the same period in 2019, and year-over-year, they grew by 16.4 percent in the fourth quarter. This increase in demand allowed shipping lines to lower costs and mitigate the downward pressure on freight rates caused by overcapacity. Nevertheless, in mid-2020, there was a surge in economic activity and consumer demand, leading to a recovery in merchandise trade and capacity shortages in the maritime freight sector. Shipping companies struggled to restore capacity to previous levels, and U.S. imports from Asia in December 2020 were near 30% higher than in December 2019 due to a surge in online purchases. By the fourth quarter, container shipping firms were operating at almost full capacity [81].

Despite the slow fluctuation of cargo capacity percentages towards pre-pandemic rates and the current oversupply of vessels, the eagerness to implement slow steaming is slowing down the recovery due to fewer services being performed. However, given the current state of the industry, it is rare for a carrier without a dominant market position to encounter capacity problems.

Finally, these figures lead to the fourth assumption that the installation of any of the WASP technologies will not result in a penalty cost due to a sufficient loss of deck space, as the current vessels have the available capacity to accommodate the cargo demand.

Fuel consumption and Freight rates

The price of bunker fuel is influenced by several factors ranging from production and distribution costs to global market conditions. The main factors affecting bunker fuel prices in the maritime industry are:

- The price of crude oil, which is the main component used in production and whose global supply and demand, as well as geopolitical events can cause significant fluctuations in its price; refining costs.
- Taxes and regulations, as some countries apply special taxes, tariffs, or additional levies to finance the promotion of sustainable practices.
- Logistics and distribution.
- Finally, demand and supply are affected by global economic activity, international trade, and transport volume.

In all cases, the charterer would like to minimize the total cost of the trip. If the service is being time chartered, the charterer pays for the fuel. Fuel is assumed to be purchased at a known price of P_{FUEL} (USD/Tonne). The default scenario ignores port-related costs to be borne by the charterer. In-port fuel costs are assumed proportional to overall total port residence time, but as a constant proportional to total cargo moved, they can be ignored.

Fuel consumption is non-linearly related to speed, meaning that slower speeds emit much less than faster speeds. Fuel prices and freight rates are the two main determinants of ship speed. Reliable fuel price information is generally available, while freight rate data can be more complex and diverse, with accuracy, consistency, and quality vary depending on the shipping market. Freight rate is an exogenous variable mainly determined by market conditions. It can be high in boom periods or low in depressed market periods [78].

Fuel prices for the simulations are provided by OilMonster [82] and vary depending on the port and route, as can be seen in Table 4.4. They need to be constantly updated, but the final values obtained on the 3rd of June of 2023 to print the last results are the following:

	MGO [$US/Tonne]	Date
Rotterdam	668	29-may
Trondheim	859	29-may
Antwerp	636	03-jun
New York	551	03-jun
Hong Kong	679	03-jun
Algeciras	550	03-jun

Table 4.4: MGO Fuel Prices

Inventory costs of the cargo

The third component (being the first two fuel prices and transport freight) of the cost that the charterer bears are the inventory costs of the cargo. This cost is irrespective of whether or not the charterer is the cargo owner. The per unit volume and per unit time cargo inventory cost accrues from the time cargo is on the ship until it is delivered which corresponds to the in-transit inventory cost and will always be non-negative. In the model, it corresponds to the whole sailing time + idling time (if any). [78]

Inventory costs can be important if the timely delivery of the cargo is significant. The liner business involves trades of higher valued goods than bulk trades. The unit value of the top 20 containerized imports at the Los Angeles and Long Beach Ports in 2004 varied from about 14,000$/tonne for furniture and bedding to 95,000$/tonnes for optic, photographic and medical measures [83]. Delaying time on the latter category of cargo by one week because of reduced speed would cost some $91 per tonne. For an 80,000-tonne payload, this would amount to some 7.25$ million. This may or may not be greater than the economic benefit of a reduced speed due to fuel savings.

Mathematically, the per day in-transit inventory cost of a tonne of cargo can be seen in Equation 4.20, where P is the CIF value of the cargo and R is the cargo owner's cost of capital. This represents the revenue that is lost due to delayed delivery of one tonne of the cargo by one day. The CIF value represents cost, insurance, and freight price, and it is the price of goods delivered at the frontier of their importing country. It changes daily and is depending on the load transported as well as the spot rate at the port [78]. This quantity finally needs to be multiplied by the total cargo being transported in the vessel, the payload [84] [85].

$$h = \frac{P \cdot R}{365} \cdot Payload \tag{4.20}$$

The main assumption that has been taken at this point is related to the payload of the vessel, as it has been estimated that the payload of a vessel is approximately 95% of its DWT. The weight of the WASP technology installed must also be accounted for in this calculation.

Scenario	Vessel	Cargo	DWT [tonnes]	CIF cargo [$/tonne]
1	Tanker	Crude oil	250,000	927.5
2	Bulk Carrier	Coal, iron ore, etc	50,000	112.65
3	Containership	Industrial products	53,000	20,000

Table 4.5: Cargo costs.
[86] [87] [83]

Operating Costs

These costs include all expenses necessary to maintain and efficiently operate a vessel over a given period. They are generally divided into several categories, which may vary by company or ship type, but some of the common categories include:

- Crew: includes wages, benefits, and other crew-related expenses, such as food and accommodation.
- Maintenance and repairs: covers the costs of regular maintenance of the vessel, including painting, cleaning, inspections, spare parts, and repairs necessary to keep the vessel in optimal operating condition.
- Insurance: includes the costs of insurance required to protect the vessel, crew, and cargo in case of accidents, damage, or legal liabilities.
- Port fees: includes costs associated with port fees, mooring fees, pilots, port services, and other fees related to the use of port facilities.
- Supplies: covers the costs of provisioning the ship, such as food, water, cleaning products, and other items necessary for daily operations.
- Safety and regulatory compliance: includes costs associated with compliance with maritime and safety regulations, such as crew training, safety equipment, inspections, and certifications.

With the operational costs defined in the OpCost review from Moore Stephens [88] on December 2017 and the Drewry trends for inflation stalks vessel operating costs [49], the operational related costs are calculated. Operational costs are highly influenced by the market state and economic sphere, hence the annual % change has been plotted to forecast the 2023 costs with a moving average trend-line starting in period 2.

The operational costs accounted for in Figure 4.11 are those listed above. Fuel consumption is not included due to the high fluctuation of fuel prices and it is treated as an independent cost. OPEX costs can be seen in Table 4.6.

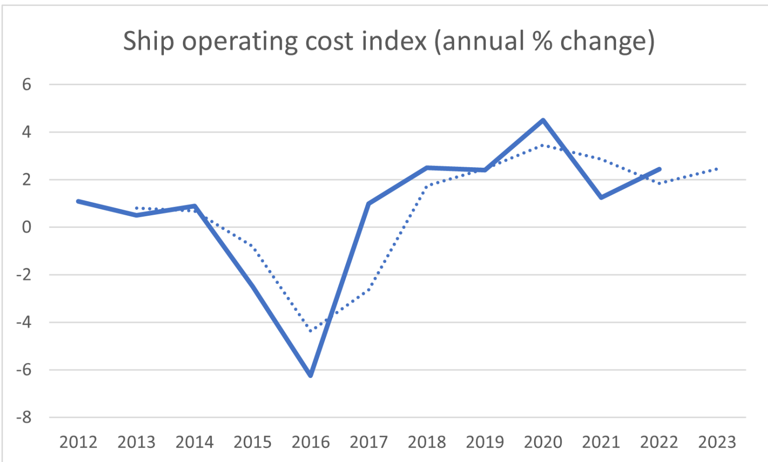


Figure 4.11: Ship operating cost index (own figure) [17]

Type of vessel	OPEX (daily rate - USD)		
	2017	2023 (forecast)	% increase
Tanker VLCC	9,95	11,580.99	16.39%
Bulk Carrier (Handymax (150m - 200m)	5,663	6,591.27	16.39%
Container: Feedermax (100 - 1,000 TEU)	4,372	5,088.65	16.39%

Table 4.6: OPEX daily forecasted rate for 2023 depending on the vessel type.

International maritime trade flows, which declined in 2020 by 3.8, bounced back in 2021 with 3.2 % growth, to a total of 11.0 billion tons – only slightly below pre-pandemic levels. The recovery was supported by an easing in the pandemic, with corresponding overall improving economic conditions and increased consumer spending. However, the revival in maritime trade was still constrained, not just by recurring COVID-19 disruptions but also by unprecedented port congestion and a global logistics logjam. Compounded by shortages of equipment and labor, these constraints also resulted in higher freight rates and less reliable services [89].

In 2022, the fragile recovery lost steam. There were fresh disruptions from the war in Ukraine, which contributed to global increases in inflation and the cost of living. At the same time, there were new waves of COVID-19 that further disrupted supply chains, particularly in China which had a zero-COVID policy. The world now faces the prospect of recession and stagflation. For 2022, UNCTAD [89] expects maritime trade growth to slow to 1.4%, or lower should the headwinds intensify. The war in Ukraine has also caused shifts in trade patterns and partners, generally extending the distances that goods have to travel – as registered in an increase in total 'ton-miles'.

CAPEX costs

CAPEX (Capital Expenditure) in the maritime sector refers to capital expenditures made to acquire, build or improve long-lived assets related to the maritime industry. Examples of CAPEX in the maritime sector include:

- Construction or acquisition of new vessels;
- Improvements to port infrastructure such as building additional berths, installing more efficient cranes and loading equipment, or improving land connectivity and logistics infrastructure
- Upgrading equipment and technology to improve operational efficiency and reduce costs in areas such as loading and unloading, navigation, monitoring and fleet management and,
- Complying with environmental regulations and adapting vessels to lower emission standards, such as installing exhaust gas cleaning systems or using cleaner fuels.

Estimated CAPEX (as of initial investment) is obtained from communication with external stakeholders, and they are shown below:

Scenario	Vessel	WASP technology	CAPEX [$/each]	Num needed
1	Tanker	Flettner rotor	1 M	5
2	Bulk carrier	DynaRig	1.5 M	8
3	Container	Rigid sails	2.5 M	4

Table 4.7: CAPEX costs of each of the WASP technologies.

These values are crucial when calculating the Net Present Value (NPV) in chapter 8, but they will not be considered in the one-way simulations, as they only have to be borne when installing the WASP technology.

Emissions Costs

The economic valuation of carbon is essential for various purposes: designing environmental policies like optimal taxes and evaluating the economic efficiency of projects. Furthermore, the disutility cost can be used in cost-benefit analysis and therefore in risk assessment.

"Carbon price" means the cost per unit of carbon dioxide equivalent emissions avoided or reduced. Carbon dioxide equivalent (CO_{2-eq}) provides a standard of measurement against which the impacts of releasing (or avoiding the release of) different greenhouse gases can be evaluated. According to IPPC (2007) [90] every GHG has a Global Warming Potential (GWP), a measurement of the impact that gas has on *"radiating force"*. The radiating force is the additional heat/energy which is retained in the Earth's ecosystem through the addition of this gas to the atmosphere. Global Warming potentials (GWPs) for the GHG regulated under the Kyoto Protocol under a 100-year time frame are as follows:

- Carbon dioxide has a GWP of 1
- Methane has a GWP of 35
- Nitrous oxide has a GWP of 310
- Sulphur Hexafluoride has a GWP of 23.90 [91]

The greatest difficulty in carbon valuation is that environmental goods have no price since they are not marketable. According to the literature, the most important ways to price carbon emissions are through:

- Social Cost of Carbon (SCC) or Damage Cost.
- Marginal Abatement Cost of Carbon (MAC) or Avoidance Cost, and
- Market Price (e.g. by using EU Emissions Trading Scheme (ETS) future price). In that sense, a market is created where units that permit the right to emit are traded, and therefore by definition this creates a market price that can be used in a cost-effectiveness analysis.

In this report, the third option is used. The advantage of using a market price is that it is very *"real"*. It is based on particular sectors and on a number of countries and although this does not cover the whole economy is it very representative.

In July 2021, as part of the "Fit for 55" package and the "European Green Deal," the European Commission (EC) proposed including shipping in the EU ETS. Compliance with this regulation would require purchasing emissions allowances for all CO_2 emissions on trips within the European Economic Area (EEA), 50% of CO_2 emissions for incoming trips to the EEA, 50% of CO2 emissions for outgoing trips from the EEA, and all at-berth CO_2 emissions at EEA ports. [76]

Following the IMO GHG study guidelines, [92] there is a linear relationship between fuel burned and CO_2 produced, with the proportionality constant being known. Overall, in each of the scenarios all emissions of CO_2 have been converted to CO_{2-eq}, and this total is eventually multiplied by the current carbon price corresponding to 93.38 USD/tonne of CO_{2-eq} emitted. This adds to the total cost as a penalization.

If ships are made to go slower, shippers may be induced to prefer land-based modes, mostly road. Even in long-haul scenarios such as the Far East to Europe trade, some cargoes may be tempted to use the rail alternative (via the Trans-Siberian Railway) if the speed of vessels is low enough. It is also noted that in the period 2010 to 2017, 9% to 18% of the Chilean cherry exports to China were carried by airplane [93], meaning that a potential reduction of ship speed may further shift some of these exports to aviation and/or make them less competitive vis-à-vis other cherry producers. This may also increase overall GHG emissions.

4.4.2 Cost Scenarios

The costs considered are fuel costs, inventory holding costs, operating costs, and emissions costs. Training costs have been neglected since they are very small compared to the other costs. The variables used will be the following: fuel price in USD/tonne (for the fuel costs), carbon price in USD/tonne (for the cost of emissions), cost of capital (for the inventory costs), CIF (value of the cargo, for the inventory costs) and operating costs. Four variants of the cost analysis are examined as follows:

1. Total Costs with WASP (no JIT). In this analysis, the following costs are included: fuel price, emissions costs, inventory costs, and operating costs. The following equations will be used to calculate them:

$$C_F = F_p \cdot FC \tag{4.21}$$

$$C_E = C_p \cdot E \tag{4.22}$$

$$Inv = h \cdot t_T \tag{4.23}$$

$$OpC = OPEX \cdot t_T \tag{4.24}$$

$$C_T = C_F + C_E + Inv + OpC \tag{4.25}$$

Where:

- C_F is the cost of the total fuel used in the journey in USD.
- F_p is the fuel price in USD per tonne of fuel.
- FC is the fuel consumption of both the main and auxiliary engines in tonnes of fuel.
- C_E is the cost of the total emissions released in the journey in USD.
- C_p is the carbon price in USD per tonne of CO_2.
- E is the emissions released by both the main and auxiliary engines in tonnes of CO_2.
- h is the inventory holding costs in USD per hour.
- t_T is the total time of the journey, both sailing and idling, in hours.
- Inv is the total inventory costs in the journey in USD.
- OPEX is the operational costs in USD per day.
- OpC is the total operating costs in the journey in USD.
- C_T are the total costs per journey in USD.

2. Compare WASP with the base case. Cost capital, CIF, inventory costs, and operational costs are negligible in this scenario, as they depend on the duration of the journey and the arrival time and these are kept constant in both scenarios.

   For each of the speeds analyzed per route, the differences in fuel consumption and costs are compared with and without WASP. This optimization is taken through two perspectives: (a) optimizing towards minimum emissions and (b) optimizing towards minimum total costs. The savings in total costs and emissions with the help of WASP technologies are also analyzed. These savings have been calculated as the difference between the base case and the WASP case.

3. Total Cost with WASP + JIT. The first step in this analysis will be, for each of the possible speeds, to find the optimum between the quick and slow variants. In order to do this, all costs are calculated for both the slow and the quick scenarios. The option (between quick/slow) that minimizes either costs or emissions will be chosen from the previous scenarios. The former is for the economic analysis and the latter for the environmental analysis.

4. Compare JIT with WASP. The implementation of JIT does not vary the ETA but it does change the total sailing time. This final costs scenario evaluates the influence on the total costs when implementing the JIT scheme and the deletion of the idling time.

5 Results

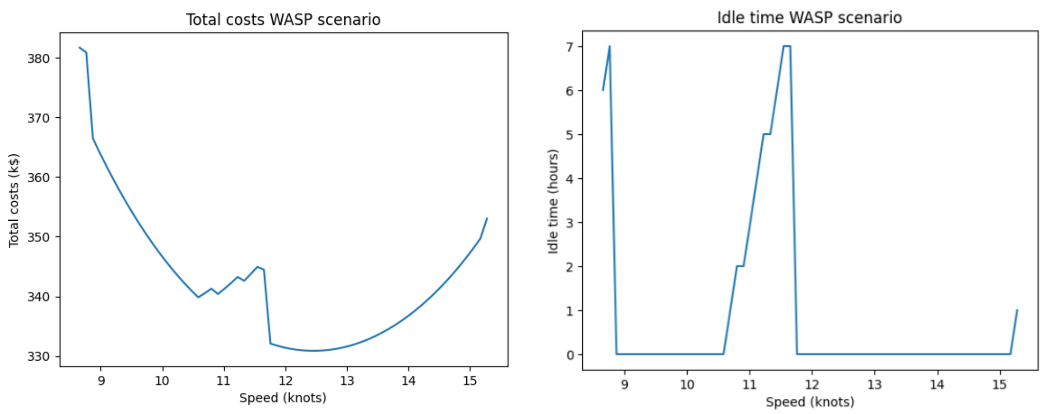
In this section, all the results obtained for the cost scenarios presented in 4.4.2 will be shown and analyzed. For all case studies and for all scenarios within each of the case studies, total results will be presented, followed by economic and environmental optimization.

5.1 Route 1: Rotterdam - Trondheim

5.1.1 Total results WASP

Total costs for the route between Rotterdam and Trondheim using the KVLCC2 (tanker) and five Flettner rotors can be seen in Figure 5.1a. The big change when analyzing speeds between 10.5 and 12 knots is simply due to a big change in the idle time, which can be seen in Figure 5.1b. As has been already explained, idling increases fuel consumption, emissions released and total time of the journey, so it was therefore expected that costs would increase when the idle time was higher.

As presented in Equation 4.25, total costs depend on fuel consumption, emissions released, inventory holding costs, and operating costs. Fuel consumption and emissions increase with speed, while inventory holding and operating costs decrease with speed due to the reduced traveling time. It can be observed from the shape of this graph that fuel and emissions costs have a higher impact on the end of the route, where an increase in the curve can be observed.



(a) Total costs ($) **(b)** Idle time (hours)

Figure 5.1: Total costs and idle time in the WASP scenario (route 1)

Total emissions can be seen in Figure 5.2, as well as their relation with changes in speed. It can be seen that the effect of the idle time is not as remarkable here as in the case of the costs, but this is simply due to the fact that the extra emissions released while idling are almost negligible compared to the additional costs that need to be bared due to this extra idling time, which is the reason why the impact is more striking on the total costs.

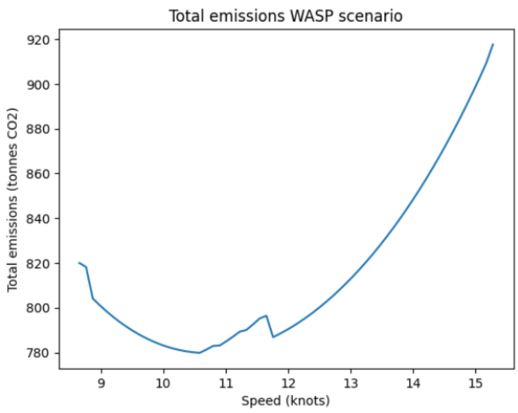


Figure 5.2: Total emissions in the WASP scenario (route 1)

It is noteworthy that, even though emissions are minimized when sailing at lower speeds, total costs are not minimum for the minimum speed due to the longer journey and therefore extra inventory and operational costs. This represents the difference between the optimal solution in the economical scenario and the environmental one, which is collected in the following table with all relevant results for both optimal solutions. It can be seen that the economic optimal speed is not obtained either for the maximum speed, as fuel and emissions costs will also increase with these higher speeds.

	Optimal speed [knots]	**Total costs [$]**	**Total emissions [tonnes CO_2]**	**Total WASP [%]**
Minimizing costs	12.40	330,857.76	797,893.22	31.96
Minimizing emissions	10.59	339,825.09	779.85	36.3

Table 5.1: Economical and environmental optimal results in the WASP scenario (route 1)

With respect to the WASP utilization in this case study, the WASP percentage varies from 41.53% in the case of the lowest speed considered to 25.6% in the case of the fastest speed. Additionally, the total thrust that the Flettner rotors are providing varies from 283kN for the lowest speeds to 355kN for the fastest speeds. It is expected that the percentage of WASP utilization decreases when speed increases even if the total thrust that it is able to provide is higher, as the resistance of the water for these higher speeds will also be much higher, as can be seen in Figure 5.3. This high percentage of WASP utilization was expected, as this route presents very favorable wind conditions.

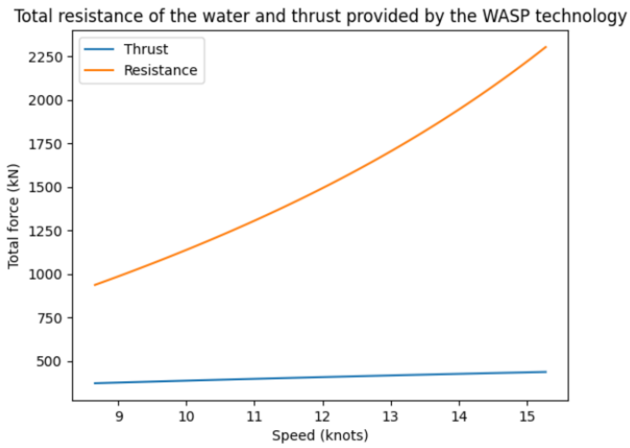


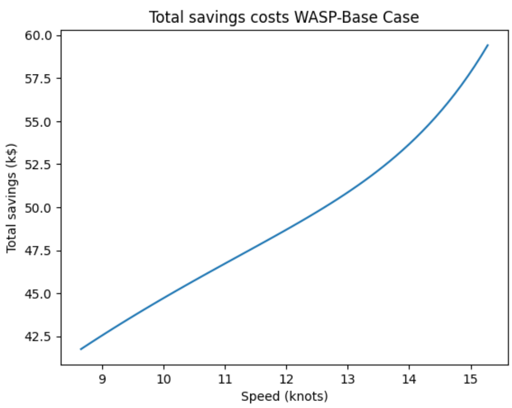
Figure 5.3: Resistance of the water vs total thrust provided by the WASP technology (route 1)

Finally and just as an additional remark, the total time spent in sailing this route ranges from 98.41 hours (4.1 days) with the lowest speed to 55.77 hours (2.32 days) with the highest speed.

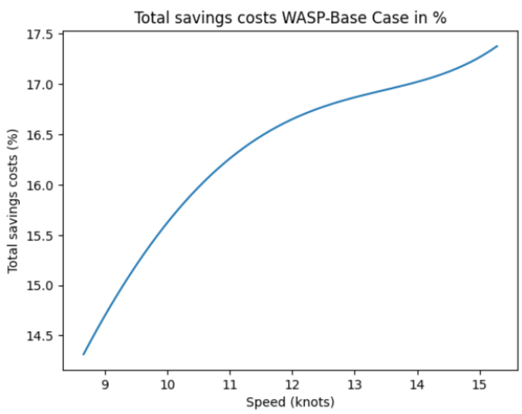
5.1.2 Comparing WASP with Base Case

Total savings in costs between these two scenarios can be seen in Figure 5.4a as total values and in Figure 5.4b as a percentage. This analysis has been calculated as savings when implementing the WASP technology. It must be mentioned that the savings shown here do not consider the installation costs of the WASP technology, as they only consider additional costs while operating.

As has already been mentioned, the only costs that are considered in this analysis are both fuel consumption and emissions costs, since the remaining ones will be equal in both the WASP case and the Base Case (due to sailing at the same constant speed in both). Taking into consideration the thrust that the WASP technology is able to provide and how this increases with speed, it is expected that savings will be higher when speeds increase, as the Flettner rotors will be giving more thrust and therefore leading to more savings. Moreover, it can be seen that savings in costs reach up to almost 17.5% with respect to the Base Case.



(a) Total savings costs ($)

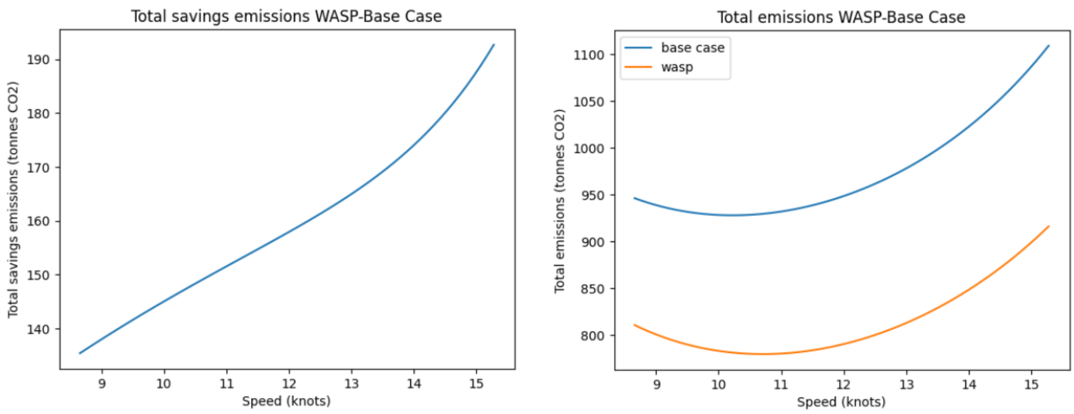


(b) Total savings costs (%)

Figure 5.4: Total costs savings between the Base Case and WASP (route 1)

Moreover, total savings in emissions can be seen in Figure 5.5a. Emissions released are directly proportional to fuel consumption, as was shown in Section 4.3.5, and it, therefore, was also expected that both the total cost savings and the total emissions savings graphs would have the same shape, as can be clearly seen. This is the same reason why the emissions savings in percentage have the same values as the total cost savings in percentage.

Additionally, the total emissions released in both scenarios can be seen in Figure 5.5b, where it can also be proven that, as expected, emissions are reduced when the WASP technology is implemented. It must be noted that emissions shown here do not include emissions released while idling since these emissions are equal in both scenarios and only the differences between them are relevant here. This is the reason why the graphs here are smooth and do not show the big peaks due to idle times.



(a) Total savings emissions (tonnes CO_2) **(b)** Total emissions (tonnes CO_2)

Figure 5.5: Emissions savings in WASP-Base Case and total emissions in each case (route 1)

Finally, economical and environmental optimal results can be seen in Table 5.2. Bearing in mind how this model has been calculated and given that there will be no difference in the additional costs associated with longer sailing times between both scenarios, it is not surprising that both optimal solutions are obtained for the minimum speed, as the costs function is proportional to the emissions one.

	Optimal speed [knots]	**Total savings costs [$]**	**Total savings emissions [tonnes CO_2]**	**Total savings costs/emissions [%]**
Minimizing costs	15.28	59,409.84	192.67	17.38
Minimizing emissions	15.28	59,409.84	192.67	17.38

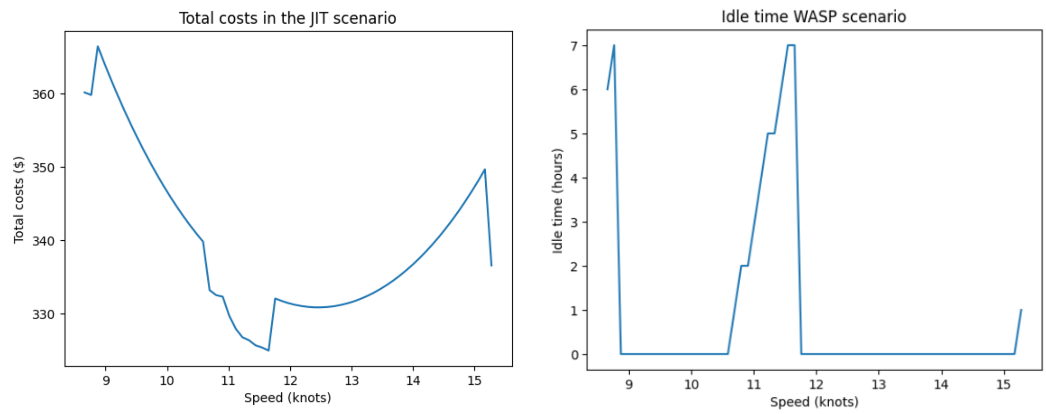
Table 5.2: Economical and environmental optimal results in the WASP-Base Case analysis (route 1)

5.1.3 Total results JIT

It is important to mention that the first step in this analysis is, for each of the possible speeds, finding the optimum between the quick and slow scenarios. There will be two approaches here depending on which analysis is being executed, as the economical one will choose the option that minimizes cost and the environmental one will choose the option that minimizes emissions. There will therefore be some speed options that choose the slow option when doing the economical analysis, while the environmental analysis chooses the quick option.

It is also worth mentioning that JIT could be implemented in all the scenarios in this case study, meaning that all the solutions proposed in either the slow or the quick options are feasible. As will be shown later, this is not the case in the other two case studies.

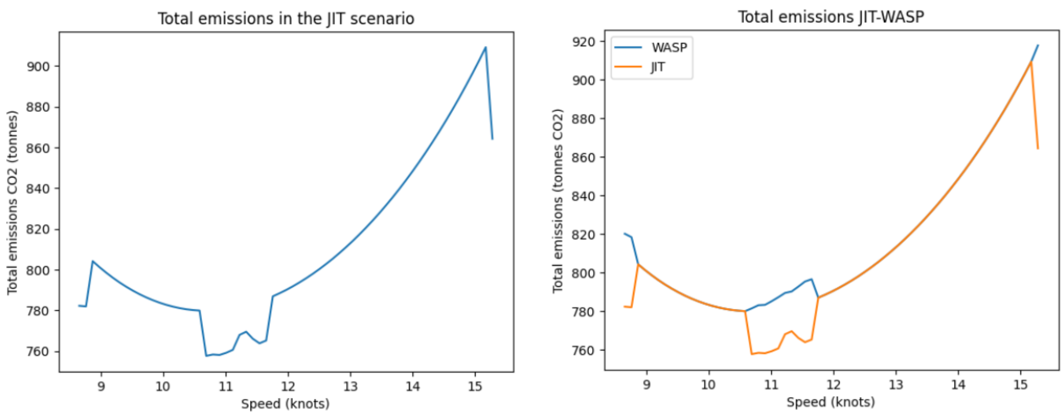
Therefore, total costs in the JIT scenario for the chosen option between quick and slow (according to costs) can be seen in Figure 5.6a. It has a similar shape to total costs in the WASP scenario, due to the similar interaction between the different costs and increase in the fuel costs when sailing at higher speeds. It can also be seen that the sudden changes in the graph correspond to the same speed as in the WASP scenario (speeds with high idle time, as shown in Figure 5.6b), but in this case, costs are lower than in the previous scenario, showing how implementing JIT leads to costs savings.



(a) Total costs ($) **(b)** Idle time (hours)

Figure 5.6: Total costs and idle time in the JIT scenario (route 1)

In the same way, as with total costs, total emissions have the same shape in this scenario as in the WASP scenario, as emissions increase with speed. These options are the chosen ones according to minimizing emissions. Total emissions in this scenario can be seen in Figure 5.7a, while these emissions compared to the ones in the WASP scenario can be seen in Figure 5.7b. Again, sudden changes in emissions are due to big speed adjustments, and it can be seen in Figure 5.7b that here emissions are lower than in the WASP scenario, showing that implementing JIT also leads to emissions savings.



(a) Total emissions JIT (tonnes CO_2) **(b)** Total emissions JIT and WASP

Figure 5.7: Total emissions in the JIT and the WASP scenarios (route 1)

Economical and environmental results can be seen in Table 5.3. Following what has been previously explained, the economical optimal solution is found within the slow/quick options chosen when minimizing costs, while the environmental optimal solution is found within the slow/quick options chosen when minimizing emissions. The pattern in these optimal solutions is the same as in the WASP scenario, as the economical optimization chooses a higher speed and the environmental optimization chooses a slow speed.

	Opt speed [knots]	**Idle time [hours]**	**Slow/quick during JIT**	**Total costs [$]**	**Total emissions [tonnes CO_2]**
Minimizing costs	11.65	7	Quick	324,958.41	765,144.77
Minimizing emissions	10.69	1	Slow	164,498.24	757.59

Table 5.3: Economical and environmental optimal results in the JIT scenario (route 1)

5.1.4 Comparing JIT with WASP

Calculations here have been carried out as savings from implementing JIT, so total results show savings JIT – WASP. Savings have been calculated as a percentage and again, all scenarios are feasible. Only the chosen scenario between quick and slow in the previous section has been compared to the WASP scenario.

Savings in total costs can be seen in Figure 5.8, where it can be seen that they reach up to 5.5% approximately. As will be shown when analyzing the remaining two case studies, this case study presents the lowest achievable cost savings when implementing JIT, even though they are all very similar. Further conclusions should however not be obtained from this analysis, as this is highly dependent on the port availability and different and better results could be obtained with different inputs of port availability. It must however be kept in mind that this is a percentage of a quite big number, and these savings are only for one one-way trip but would definitely be higher when more trips are performed. These savings should also be included on top of the savings obtained when simply implementing the WASP technology. Moreover, these savings will be obtained with no associated additional costs, as implementing JIT only requires communication and organization between the port and the vessel. Cases with 0% of savings are either a case where idle time is already 0 in the WASP scenario, thus cases where the port call cannot be implemented.

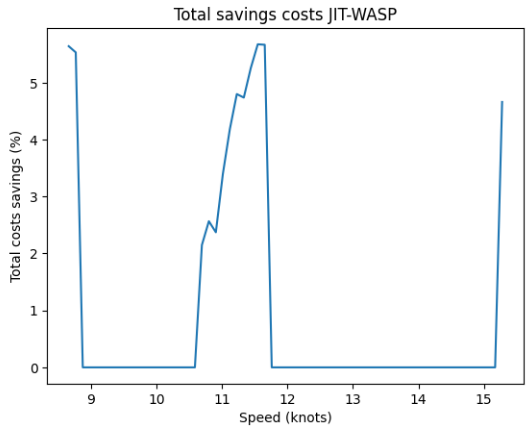


Figure 5.8: Total costs savings between the JIT and WASP scenarios (route 1)

On the other hand, savings in emissions can be seen in Figure 5.9. As will also be shown when analyzing the remaining two case studies, these are the highest savings in emissions obtained in the three case studies. Again, this is also highly dependent on the port availability, as it might happen that the given port availability forces the vessel to always choose the slow option, which is environmentally better than the quick one. This will be further discussed in the following section.

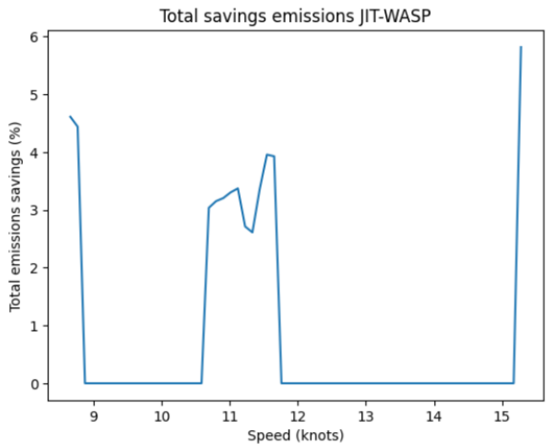


Figure 5.9: Total emissions savings between the JIT and WASP scenarios (route 1)

Finally, economical and environmental optimal results can be seen in Table 5.4. Looking at the previous graphs, it was expected that optimal solutions would be different in both analyses. Again, it must be kept in mind that this analysis will probably change depending on the availability of the port and optimal results will not be the same. It is noteworthy that these savings will go on top of the savings that were initially obtained by only implementing the WASP technology, as it is comparing the JIT scenario with the WASP one.

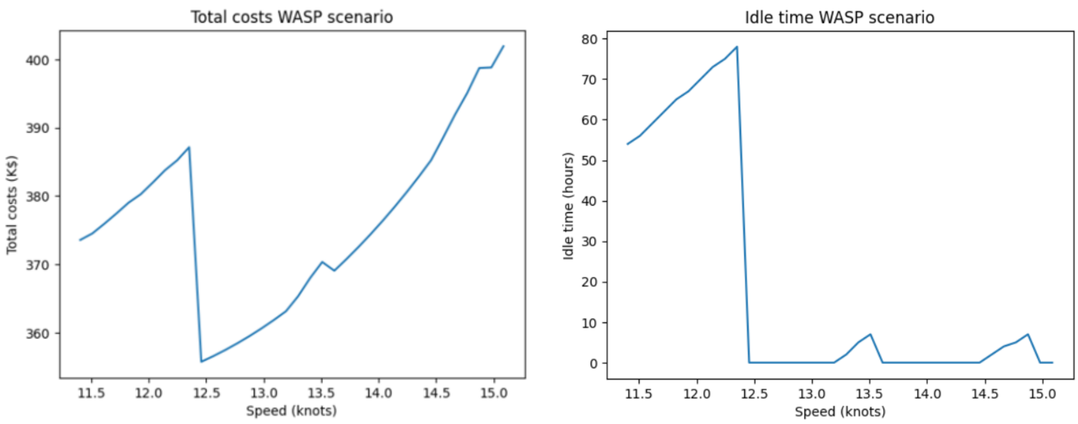
	Opt speed [knots]	Idle time [hours]	Slow/quick during JIT	Total costs [%]	Total emissions [%]
Minimizing costs	11.55	7	Quick	5.67	3.93
Minimizing emissions	15.28	1	Slow	4.66	5.82

Table 5.4: Economical and environmental optimal results in the JIT-WASP analysis (route 1)

5.2 Route 2: Antwerp - New York

5.2.1 Total results WASP

Total costs in the case study between Antwerp and New York City using a bulk carrier and 4 DynaRigs can be seen in Figure 5.10a. In the same way, as in the first case study, the big change in speeds below 12 knots is also due to a big change in the idle time, as can be seen in Figure 5.10b. The increase of the fuel and emissions costs for higher speeds is more remarkable here than in the previous case study, showing how they have a much bigger impact than the inventory and operating costs.



(a) Total costs ($)   **(b)** Idle time (hours)

Figure 5.10: Total costs and idle time in the WASP scenario (route 2)

On the other hand, total emissions in this scenario can be seen in Figure 5.11. As in the previous case study, it can be seen that emissions increase with the speed, due to the increased fuel consumption. Again, the effect of the idle time is not that remarkable in the case of emissions, as the additional emissions released while idling are not very big compared to the ones released over the journey.

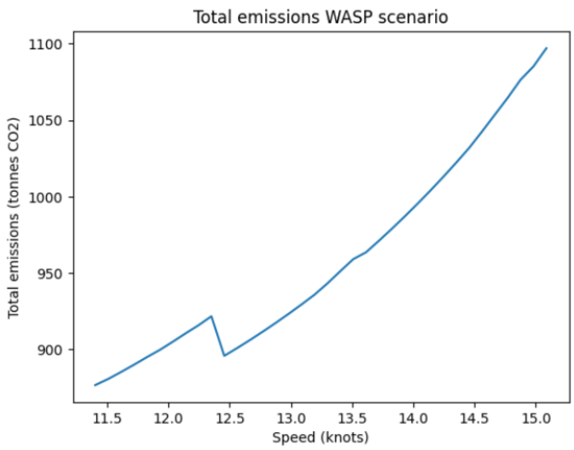


Figure 5.11: Total emissions in the WASP scenario (route 2)

Economical and environmental optimal results can be seen in Table 5.5 and again, different results are obtained for each of them. As expected, the optimal solution when minimizing emissions corresponds to the lowest speed, as this will correspond to the lowest fuel consumption.

	Optimal speed [knots]	**Total costs [$]**	**Total emissions [tonnes CO_2]**	**Total WASP [%]**
Minimizing costs	12.46	355,753.43	895.89	31.08
Minimizing emissions	11.4	373,582.05	876.78	35.29

Table 5.5: Economical and environmental optimal results in the WASP scenario (route 2)

With respect to the WASP utilization in this case study, the WASP percentage varies from 35.29% when using the lowest speed to 22.47% when using the fastest one. These high results were expected taking into account the good wind conditions on this route. Additionally, the total thrust that the DynaRigs are providing varies from 174 kN for the lowest speed to 197 kN for the case of the fastest speed. In the same case as in the first case study, this increase in the thrust but decrease in the WASP percentage is simply due to the fact that the resistance of the water increases much faster than the total thrust, as can be seen in Figure 5.12.

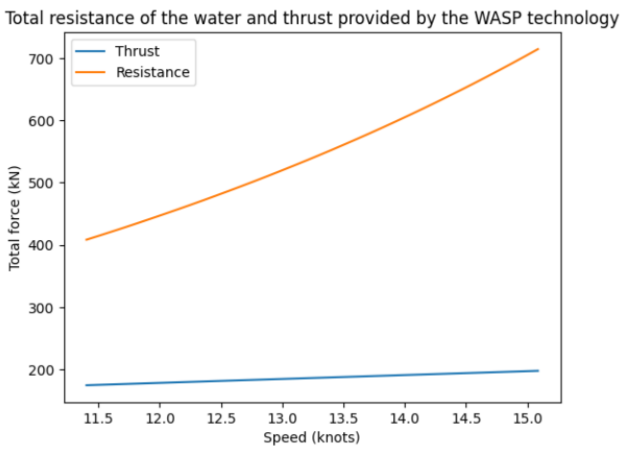


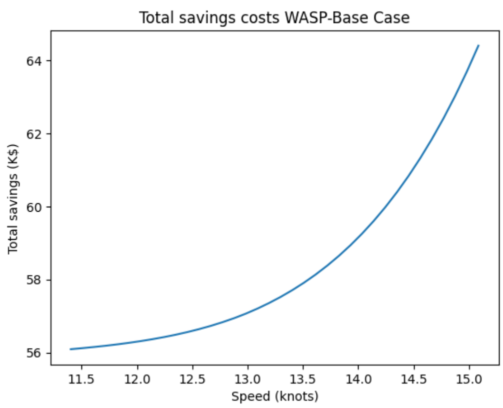
Figure 5.12: Resistance of the water vs total thrust provided by the WASP technology (route 2)

Finally and just as an additional remark, the total time spent in sailing this route ranges from 314 hours (13.08 days) with the lowest speed to 238 hours (9.92 days) with the highest speed.

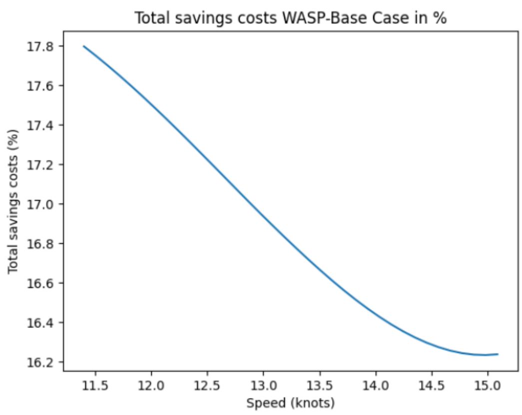
5.2.2 Comparing WASP with Base Case

Both total savings in value and in percentage can be seen in the following figures. As a reminder, the only savings considered here are fuel consumption savings and emissions savings, as the remaining costs will be equal in both scenarios due to the same sailing speed.

It is indeed eye-catching that, even though savings in total value increase with speed, they decrease when calculated as a percentage. This means that when speeds increase, the Base Case increases both fuel consumption and therefore costs and emissions at a much faster pace than the WASP case. Since the percentage of savings is calculated with respect to the consumption in the base case, the denominator of the ratio will increase faster than the numerator, and it will therefore lead to reduced percentages with higher speeds. It must however be kept in mind that savings stay over 16% even in these worse scenarios.



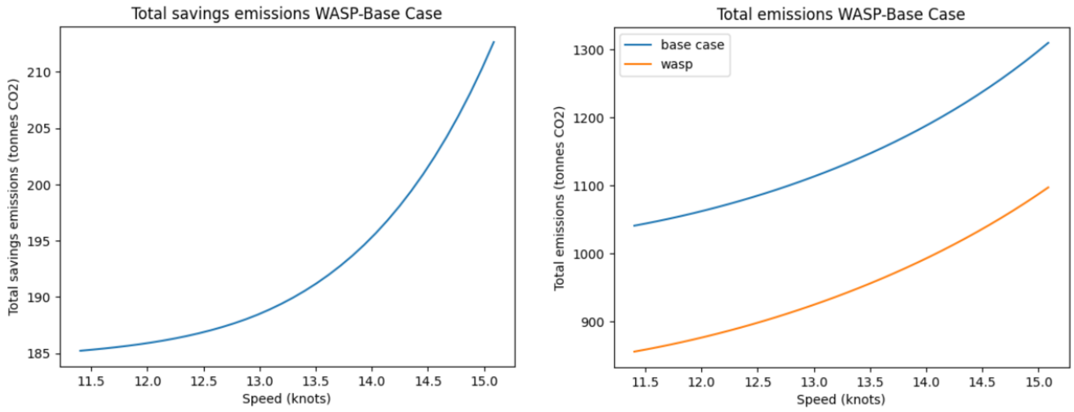
(a) Total savings costs ($)



(b) Total savings costs (%)

Figure 5.13: Total costs savings between the Base Case and WASP (route 2)

Total savings in emissions and total emissions in each of the two scenarios can be seen in Figure 5.14a and 5.14b. In the same way as with costs, savings in total value increase with speed but will decrease in percentage, as the function of the emissions is proportional to the costs.



(a) Total savings emissions (tonnes CO_2) **(b)** Total emissions (tonnes CO_2)

Figure 5.14: Emissions savings in WASP-Base Case and total emissions in each case (route 2)

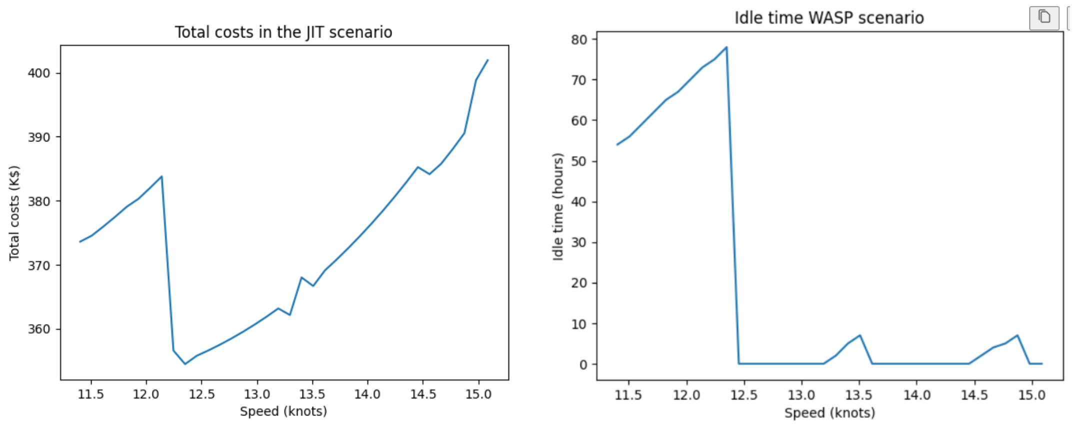
Finally, optimal results can be seen in Table 5.6. Again, since the only costs considered here are fuel and emissions costs, it is reasonable that both economical and environmentally optimal solutions are obtained for the same speed (the highest one).

	Optimal speed [knots]	**Total savings costs [$]**	**Total savings emissions [tonnes CO_2]**	**Total savings costs/emissions [%]**
Minimizing costs	15.08	64,401.22	212.66	16.24
Minimizing emissions	15.08	64,401.22	212.66	16.24

Table 5.6: Economical and environmental optimal results in the WASP-Base Case analysis (route 2)

5.2.3 Total results JIT

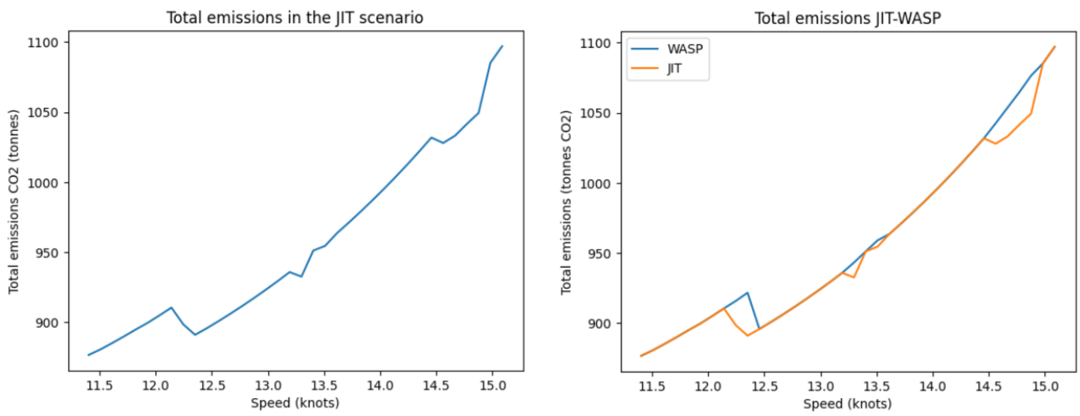
In the same way, as in the previous case study, the first step is figuring out which of the quick and slow scenarios is optimum. It must be noted that several scenarios had to be neglected in this case due to unfeasibility, all of them corresponding to the slowest speeds. Total costs for the chosen option between quick and slow can be seen in Figure 5.15a. The big changes seen in the graph are again due to big speed adjustments in the final section of the route as a result of big idle times, as seen in Figure 5.15b.



(a) Total costs ($) **(b)** Idle time (hours)

Figure 5.15: Total costs and idle time in the JIT scenario (route 2)

Total emissions in the JIT scenario can be seen in Figure 5.16a, and they can be seen compared to the emissions released in the WASP scenario in Figure 5.16b. It can be seen here that savings in emissions are indeed obtained in this case study, as the emissions with JIT are always lower than the ones released in the WASP scenario. Moreover, it can be appreciated that the JIT scenarios for the speeds between 11 and 12 knots are indeed unfeasible and had to be forced to the WASP scenario, as it can be seen that these speeds have idle time but the emissions are however equal to the ones released in the WASP scenario. This is simply due to the fact that the JIT proposed arrival times for which the speed adjustment is either too fast or too slow.



(a) Total emissions JIT (tonnes CO_2) **(b)** Total emissions JIT and WASP

Figure 5.16: Total emissions in the JIT and the WASP scenarios (route 2)

Finally, optimal results can be seen in Table 5.7. It is noteworthy that the speed that minimizes emissions is the slowest one and is therefore one for which JIT is not feasible. Moreover, patterns in this scenario follow what was already found in the WASP scenario, as the economical optimization chooses higher speeds but the environmental one chooses the slowest one.

	Opt speed [knots]	Idle time [hours]	Slow/quick during JIT	Total costs [$]	Total emissions [tonnes CO_2]
Minimizing costs	12.35	78	Quick	354,450.21	891.15
Minimizing emissions	11.40	54	Forced	373,582.05	876.78

Table 5.7: Economical and environmental optimal results in the JIT scenario (route 2)

5.2.4 Comparing JIT with WASP

Savings in total costs as a percentage can be seen in Figure 5.17, where it can be seen that they reach up to almost 12.5% vs the WASP scenario. The non-feasible scenarios when using slower speeds can be found here, as it can be seen that these scenarios present 0 savings.

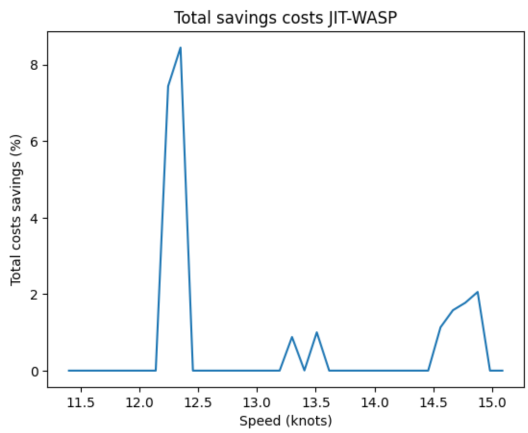


Figure 5.17: Total costs savings between the JIT and WASP scenarios (route 2)

Conversely, total savings in emissions when analyzing these two scenarios can be seen in Figure 5.14a. Remarkably, savings in emissions for higher speeds are almost equal to the savings obtained for smaller speeds, contrary to what happened with the cost savings. This is probably because the savings obtained in fuel with these speeds are higher than the ones obtained in terms of inventory and operation costs.

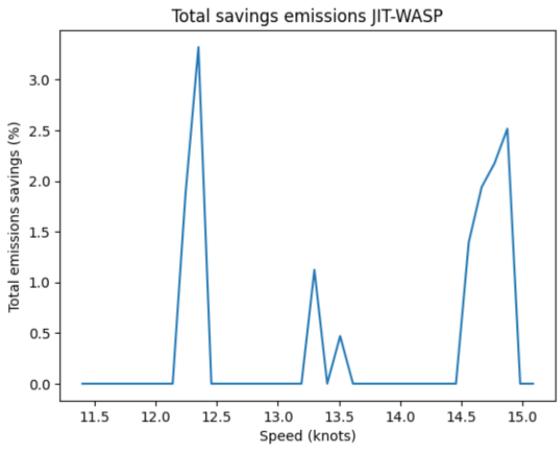


Figure 5.18: Total emissions savings between the JIT and WASP scenarios (route 2)

Taking into consideration everything that has been previously discussed, it is not surprising that both the optimal economical and environmental speeds are equal to 12.35 knots, as can be seen in Table 5.8, which corresponds to the impressive peak in all graphs previously shown. It must be kept in mind that these results depend heavily on the port availability and this logic might not always be true, and that they must be included on top of the previous savings obtained only with implementing WASP.

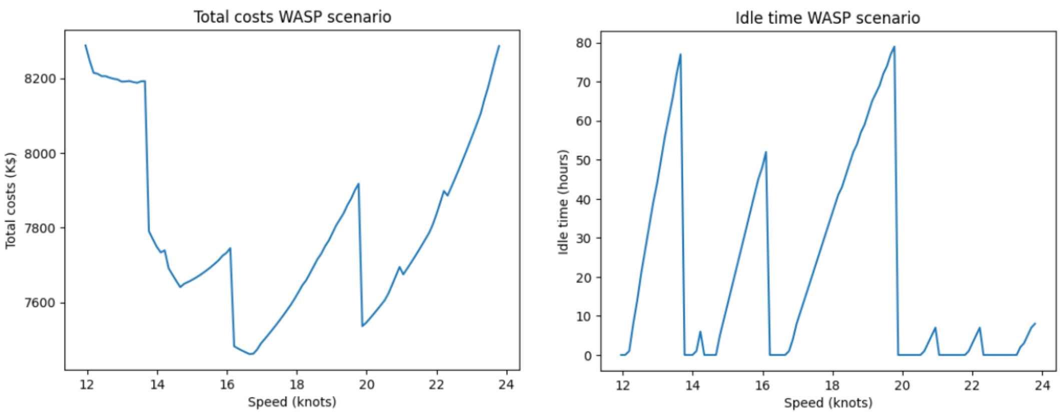
	Opt speed [knots]	**Idle time [hours]**	**Slow/quick during JIT**	**Total costs [%]**	**Total emissions [%]**
Minimizing costs	12.35	78	Quick	8.44	3.32
Minimizing emissions	12.35	78	Quick	8.44	3.32

Table 5.8: Economical and environmental optimal results in the JIT-WASP analysis (route 2)

5.3 Route 3: Hong Kong - Algeciras

5.3.1 Total results WASP

Total costs in the route between Hong Kong and Algeciras using a containership and 8 rigid sails can be seen in Figure 5.19a and idle time can be seen in Figure 5.19b. In the same way, as in the previous case studies, big changes in total costs are due to big changes in idle time. Also in the same way as in the previous case studies, fuel and emission costs are responsible for the increased costs when sailing at higher speeds.



(a) Total costs ($) **(b)** Idle time (hours)

Figure 5.19: Total costs and idle time in the WASP scenario (route 3)

On the other hand, total emissions can be seen in Figure 5.20, which also increases with speed due to increased fuel consumption, in the same way as in the previous case studies. It can be seen that here extra emissions while idling are bigger than in the previous case studies, as the impact of the idle time is more remarkable in the emissions than in the previous cases. This simply depends on the type of vessel that is being modeled in this route.

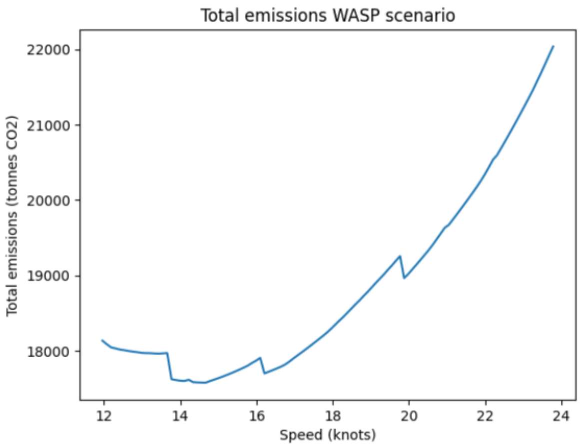


Figure 5.20: Total emissions in the WASP scenario (route 3)

Optimal results can be seen in Table 5.9. Here again, economic and environmental optimal results do not match, as was expected looking at the graphs and again showing the differences in economic and environmental interests. Again, economic optimization is obtained for the highest speeds, while the environmental optimal solution is obtained for slower speeds.

	Optimal speed [knots]	Total costs [$]	Total emissions [tonnes CO_2]	Total WASP [%]
Minimizing costs	16.64	7,461,716.66	17,789.96	0.04
Minimizing emissions	14.67	7,640,758.93	17,576.53	-1.04

Table 5.9: Economical and environmental optimal results in the WASP scenario (route 3)

With respect to the WASP percentage being used, it ranges from -3.37% when using the lowest speed to 1.87% when using the fastest one. Several conclusions can be obtained from these results, the first one being that, as expected, this route does not present favorable wind conditions, as it travels through the Mediterranean Sea and the Suez Canal, which are not windy zones. It must be noted that in cases where the WASP percentage is negative, the engine will be doing all the force needed in order to overcome both the resistance of the water and the resistance of the additional weight.

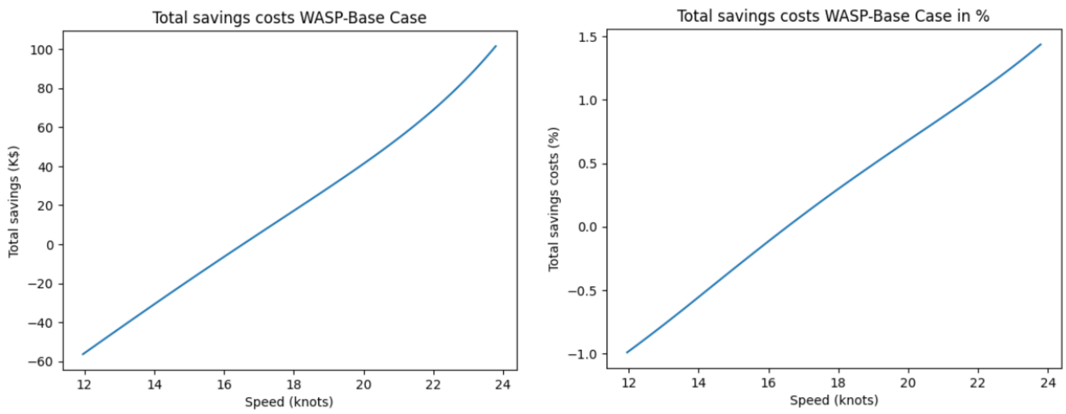
Moreover, negative values of the WASP percentage represents speed options for which installing the WASP technology is not beneficial. This can be explained by keeping in mind that this case study has 8 rigid sails, each one of them with a weight of 200 tonnes. The total thrust that can be obtained from the rigid sails is not enough the make the WASP system beneficial, as the WASP itself is bringing in an additional resistance that ends up in this scenario needing more force from the engine in order to overcome this additional resistance. This additional resistance combined with the poor wind conditions finally results in this implementation not being beneficial when using several of the proposed speeds.

However, this does not mean that this technology cannot be installed in this type of vessel, only that the combination of this system with these wind conditions is not able to obtain savings. In order to prove this point, this technology with this type of vessel has been simulated in the first route, Rotterdam-Trondheim, as it has already been shown that this route presents favorable wind conditions, and results obtained indicate that the WASP percentage reaches up to 32%, proving that this technology can lead to savings if being used in the right conditions. This analysis will be further shown in the following sections.

Finally, the total time in this case study ranges from 717 hours (29.89 days) for the slowest speed to 360 hours (15 days) for the fastest speed.

5.3.2 Comparing WASP with Base Case

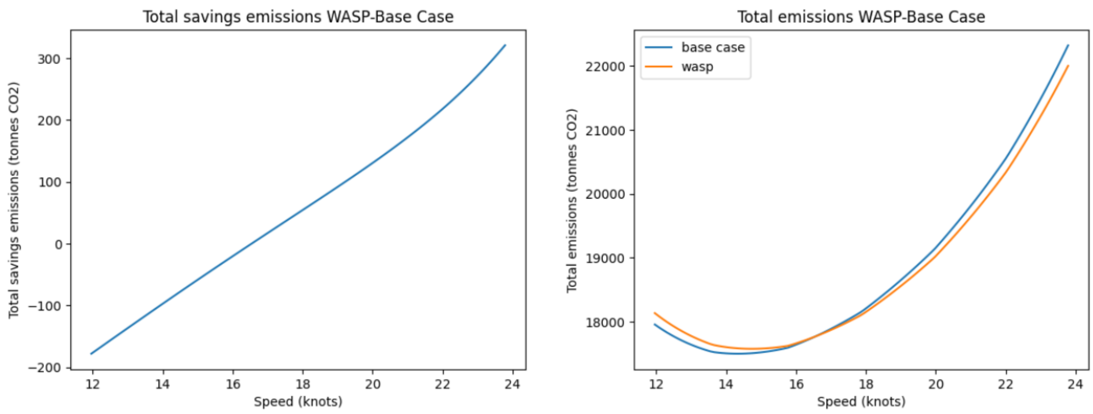
Total savings in value and in percentage can be seen in the following figures. As has just been presented above, implementing this heavy WASP technology in this vessel is not beneficial for slower speeds, as the system will need more force due to the additional resistance of the WASP system and the thrust provided is not big enough. This is the reason why savings are negative in the case of slow speeds. It can however be seen that they turn positive for speeds around 16.5 knots, meaning that savings can be obtained if the vessel is sailing at higher speeds. The savings unfortunately only reach up to 1.5%, which is quite low compared to the previous case studies, and should therefore make the investors careful when considering implementing this technology in similar conditions as the ones analyzed in this case study.



(a) Total savings costs ($) **(b)** Total savings costs (%)

Figure 5.21: Total costs savings between the Base Case and WASP (route 3)

Additionally, total savings in emissions can be seen in Figure 5.22a, while total emissions in each scenario can be seen in Figure 5.22b. In the same way as with costs, savings are negative for slower speeds but turn positive when sailing at higher speeds. Figure 5.22b shows the exact point in which emissions released in the WASP scenario start being lower than the ones released in the Base Case.



(a) Total savings emissions (tonnes CO_2) **(b)** Total emissions (tonnes CO_2)

Figure 5.22: Emissions savings in WASP-Base Case and total emissions in each case (route 3)

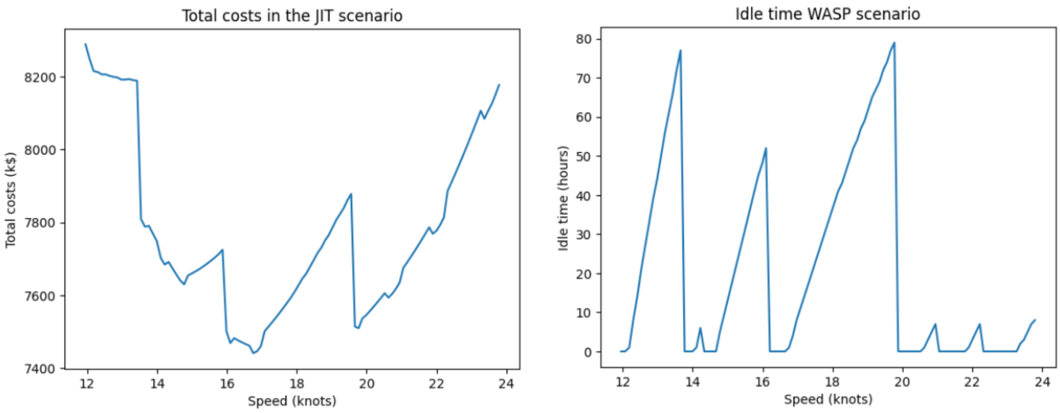
Optimal results can be seen in Table 5.10. As expected, optimal solutions are obtained for higher speeds, as has been previously presented above. The following results confirm that the savings obtained here are indeed quite poor, as only 1.43% of savings with respect to the Base Case can be obtained.

	Optimal speed [knots]	**Total savings costs [$]**	**Total savings emissions [tonnes CO_2]**	**Total savings costs/emissions [%]**
Minimizing costs	23.79	101,542.03	320.66	1.43
Minimizing emissions	23.79	101,542.03	320.66	1.43

Table 5.10: Economical and environmental optimal results in the WASP-Base Case analysis (route 3)

5.3.3 Total results JIT

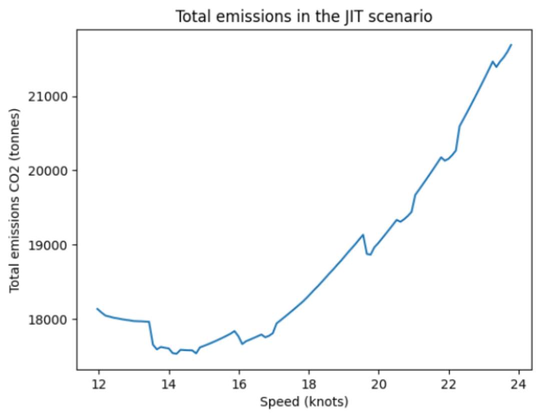
Total costs in the JIT scenario can be seen in Figure 5.23a, as well as idle time in Figure 5.23b. Highlight, that there are almost no solutions that needed to be neglected due to unfeasibility, as it can be seen that sudden peaks in the total costs correspond to the peaks in idle times.



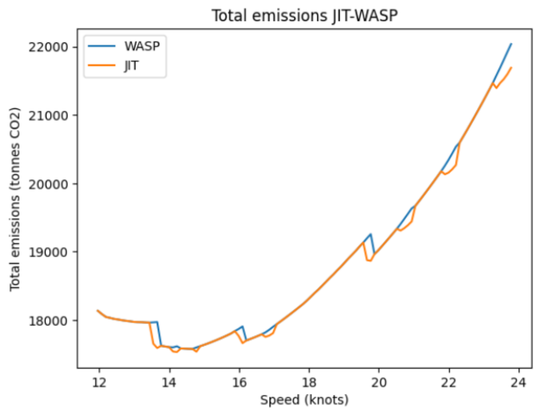
(a) Total costs ($) **(b)** Idle time (hours)

Figure 5.23: Total costs and idle time in the JIT scenario (route 3)

Total emissions in this scenario can be seen in Figure 5.24a, and they can be compared to emissions in the WASP scenario in Figure 5.24b. It can be appreciated that differences in emissions between the two scenarios are significantly low, which will also be shown in the following section.



(a) Total emissions JIT (tonnes CO_2)



(b) Total emissions JIT and WASP

Figure 5.24: Total emissions in the JIT and the WASP scenarios (route 3)

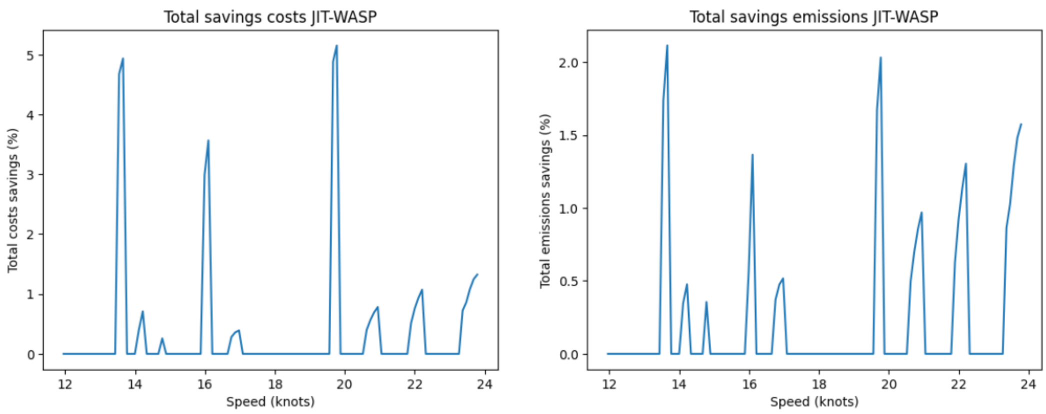
Finally, optimal results can be seen in Table 5.11. In the same way, as in the WASP scenario, the economical optimal solution is obtained for a quite high speed, while the environmental one is obtained for a slow speed.

	Opt speed [knots]	**Idle time [hours]**	**Slow/quick during JIT**	**Total costs [$]**	**Total emissions [tonnes CO_2]**
Minimizing costs	16.75	1	Slow	7,441,496.12	17,752.46
Minimizing emissions	14.22	6	Quick	7,684,350.88	17,530.96

Table 5.11: Economical and environmental optimal results in the JIT scenario (route 3)

5.3.4 Comparing JIT with WASP

Total savings in costs as a percentage can be seen in Figure 5.25a, while total savings in emissions can be seen in Figure 5.25b. Savings in emissions are the lowest one of the three case studies but again, this is highly dependent on the port availability and will probably change for a different input.



(a) Total savings costs JIT-WASP ($) **(b)** Total savings emissions JIT-WASP (tonnes CO_2)

Figure 5.25: Total savings in costs and in emissions between the JIT and the WASP scenarios (route 3)

Finally, optimal results can be seen in Table 5.12. Both optimal solutions are obtained for the quick option, but this is no surprise as it can be seen that the idle time in both cases is 79 and 77 hours, and therefore it is expected that increasing the speed even if it is just a few knots will be more beneficial than sailing for longer times than 79 hours. Again, this depends on the port availability and further conclusions should not be drawn from these results. These savings are obtained on top of the savings obtained simply by installing the WASP technology.

	Opt speed [knots]	**Idle time [hours]**	**Slow/quick during JIT**	**Total costs [%]**	**Total emissions [%]**
Minimizing costs	19.77	79	Quick	5.15	2.03
Minimizing emissions	13.65	77	Quick	4.93	2.11

Table 5.12: Economical and environmental optimal results in the JIT-WASP analysis (route 3)

5.4 General comments

Several conclusions can be obtained from what has been previously presented above. It must be kept in mind that the model has been hugely simplified and several assumptions have been made in order to facilitate calculations, the main one of them being that side forces are not considered and they will bring in an additional resistance in the system.

The first conclusions can be drawn from taking a look at the WASP utilization in each of the case studies. As expected, both the first and second case studies present high WASP percentage utilization, as these present very favorable wind conditions. It is also quite remarkable that the first case study presents percentages that reach up to 41% and provides a total thrust of up to 300kN, while the second one presents percentages up to 35% but is only able to provide around 190kN. These results cannot be compared literally, as each case study has its own wind conditions, but the two case studies indeed present different wind conditions that will be more suitable for different technologies. For instance, the case study with Antwerp-NYC is a route with main headwinds, which makes the sails less efficient, while the case study Rotterdam-Norway presents wind that is mainly sideways, which is more ideal. DynaRigs are in fact one of the best WASP technologies in generating thrust when sailing upwind. Moreover, the KVLCC2 installed in the first case study is much bigger than the bulk carrier simulated in the second one, which also contributes different levels of savings obtained.

On the other hand, it is indeed interesting to analyze what happens in the third case study. Installing rigid sails in this case study lead to remarkable savings, neither in costs nor in emissions, as this WASP system is very heavy and brings in an additional resistance in the system that forces the engine to provide a much higher power to overcome the total resistance. This is due to the combination of the non-favorable wind conditions in this route with the heavy system, and it has already been presented that this system only presents savings when sailing at speeds higher than 16.5 knots. As discussed, it has been proven that installing this technology in this vessel in the first case study does lead to high WASP percentages, meaning that savings will indeed be obtained with this technology if the appropriate wind conditions are present. It would be interesting to analyze this route with a less heavy WASP technology, to see if some of the other technologies are able to achieve savings. This is left for future research.

Regarding the potential savings that can be obtained from simply implementing WASP technologies, it has been shown that both costs and emissions savings can reach up to 17% in the first two case studies. Again, these calculations have been hugely simplified and should not be taken literally, but it has been shown that despite the simplification, the results show how implementing WASP can improve the performance of the vessels and reduce both costs and emissions significantly. These high results were expected given the percentages of WASP utilization presented and the favorable wind conditions in these two routes.

On the other hand, it has been proven that implementing the JIT methodology will always lead to savings both in costs and in emissions compared to the WASP scenario. Implementing JIT leads up to cost savings of up to 8.5% in the second case study, while the first and third cases only reach up to around 5.5%. Savings in emissions are slightly lower than savings in costs, as the maximum here is obtained for the first case study (6%). It must however be kept in mind that these are percentages of huge quantities of CO_2, which ends up in total emissions saved being very remarkable. These savings also will be achieved on top of the additional savings obtained from implementing the WASP technology, and they are associated to 0 additional costs.

However, this analysis has only been carried out for a single one-way journey with several assumptions and simplifications taken along the way, and therefore the conclusions obtained from these individual analyses should not be taken as final results that will always be true. It has also been discussed that these results depend hugely on the availability of the port, and therefore very different results might be obtained when changing this input. These are the main reasons why a validation analysis will be carried out in the following section, in order to carry out a more detailed and statistical analysis with changing inputs that will lead to more realistic results.

6 Normalization

Simulating a route with a specific port availability (although it displays a real-case scenario of the port of Piraeus) does not provide a representative input, hence, in this validation chapter, services are generalized annually. With this in mind, it is assumed that vessels sail 260 days [72] per year, and the simulation will now perform sufficient iterations of the corresponding case studies to obtain a year forecast, specifically 87, 24, and 12 iterations respectively for each of the routes.

Within each of the iterations, a random availability scheme of the terminal is considered and each time the vessel sends the ETA the vessels will accordingly receive a different berth allocation scheme, hence, a different arrangement for the available time slots. In order to find the optimal speed, general costs for WASP and JIT, and general profitability to build a Cost – Benefit Analysis, results must be normalized.

The main objective of this analysis is to examine numerous options for port availability in order to obtain annualized values. The remaining results shown will thus be average values of all the optimal solutions obtained to study the trends of optimal speeds and the savings these generate.

Consequently, the results that will be presented in this analysis are the total average results of the WASP and JIT scenarios, as well as a brief overview of how the JIT methodology modifies the speed. Savings are presented in the form of total savings in a year because these are more representative of average costs in one trip.

Moreover, one initial consideration regarding the improvement of the propeller efficiency when using WASP technologies will be presented in this Section, as the generalized results will be calculated considering these adjustments.

6.1 Variation on Propeller Efficiency and Engine Performance with WASP

The objective of this report is not to make a structural analysis of the implementation of any WASP technology or similar but an optimization of the logistics. This is the main reason why many simplifications have been accounted for when modeling, assumptions like the side forces. Furthermore, this research work has been executed in collaboration with the Ph.D. by Martina Reche-Villanova, and she analyzes in depth the specific effect of the propeller when being unloaded due to WASP contribution, which is the reason why this topic has been included here.

Most Wind Propulsion Systems (WPS) operate in a hybrid mode alongside actual main propulsion units. WPS can achieve a total 100% of thrust gain from the technology. This affects the propeller and engine operating conditions and thus, their performance. For instance, in constant speed operation mode and active WPS contributing to the forward thrust, the propeller and consequently the engine are unloaded. Thus, their operating points are moved away from their design conditions, which may significantly influence the overall performance. In most of the actual PPP (Performance Prediction Programs), these influences are assumed negligible, but on Reche-Vilanova M. et al., [72] a generic tool is developed with only the ship main particulars and general specifications as the minimum input data.

For the studied vessel, the open-source oil tanker KVLCC2, the following Figure 6.1 presents the open water efficiency variation as a function of the WPS net thrust contribution in absolute and in percentage for two simulated propeller plants in constant speed operation mode.

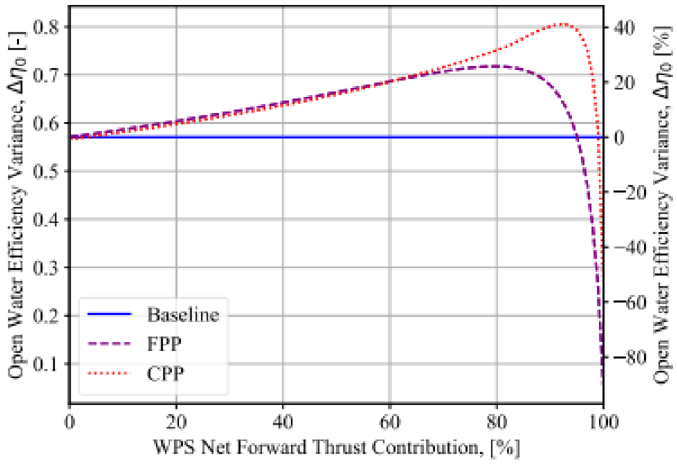


Figure 6.1: Open-water efficiency variance as a function of increasing WPS net forwards thrust contribution compared to a baseline scenario with no WPS. [72]

Now, as seen in Figure 6.2 increasing the WPS thrust contribution in constant speed operation mode results in a lower brake power compared to the baseline scenario. The propulsive efficiency is used to compute the delivered and brake power and is proportional to the open water efficiency with its variation following the same trend but with a higher magnitude. This also results in a detrimental rise in the main engine-specific oil consumption (SFOC).

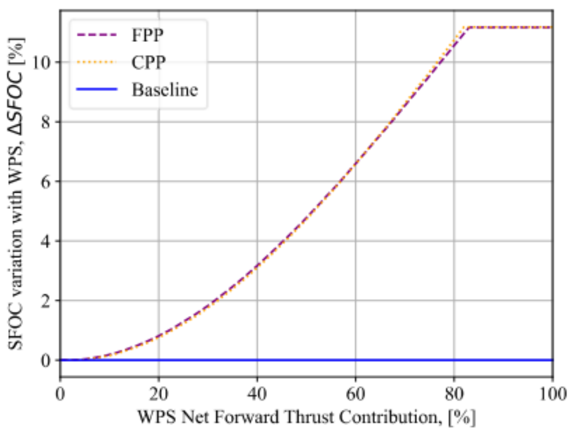


Figure 6.2: SFOC variation as a function of increasing WSP net forwards thrust contribution compared to the baseline scenario with no WPS [72]

Due to a reduction of the main engine load, the SFOC increases. This has a penalty on the fuel savings compared to the scenario where only the good effects of the propulsive efficiency variation are accounted for. However, compared with the scenario where none of these effects are considered, extra savings are achieved. Accounting for propulsive and engine performance variation results in up to 12% higher fuel savings [72]. The beneficial effects of the increase of propulsive efficiencies are higher than the penalty of the increase in SFOC. In addition, the reduction in propeller rotational speed leads to less risk of cavitation and less harmful noise for marine mammals.

6.1.1 Application to case studies

Overall, WPS can significantly reduce the fuel consumption of a ship. As seen, two out of the three simulated routes, being these, one and two, surpass a 10% of WASP % in their maximizing emission saving scenarios.

Route 1 obtains a 36.3% of WASP assistance in the validation of the average annual service performance and route 2 a 35.2%. Figure 6.1 studies an open-source KVLCC2, but a similar function for a tanker and a bulk carrier has been assumed since it is the propeller that is being studied. Plus, there is no need of defining the propeller plants as they only differ from one another when they exceed the 70% WASP threshold. Ergo, from the open water efficiency variation curve, it is collected that:

- A 36.3% or 35.2% (given a 1% difference they are treated both as 36%) WASP net thrust contribution and a constant speed scenario have a 10% open water efficiency variance in the propeller.
- From Figure 6.2 and the SFOC variation curve it is then extracted that the WASP contribution represents a 2.3% variation of the SFOC which will penalize the savings.

It must be noted that the total WASP utilization is not constant over all the way-points and can vary greatly from one way-point to another. However, the propeller efficiency cannot vary hugely in such a short distance, it has been assumed that it varies overall in the whole route or even over the years. The same applies to the SFOC variation.

Concluding, the new parameters can be seen for a new Route 2. The scenario studied is the one that maximizes the emissions savings because it is what the industry is demanding and is the scenario with the highest WASP % usage. The pertinent modifications have also been adjusted in Route 1. Results shown from now on include these adjustments.

	Validation Route 2	**With propeller efficiency**
Average WASP % used	35.30	35.30
Average fuel consumption [tonnes fuel]	298.76	281.92
Average journey duration [hours]	314.92	314.92
Average emissions released [tonnes CO_2]	929.13	876.78

Table 6.1: Results obtained when implementing the improved propeller efficiency

From the numbers procured in Table 6.1, these modifications generate a 5.7% of benefits in the fuel consumption and the emissions while maintaining the WASP contribution and the duration of each journey constant. In an overview, the implementation of WASP unloads the propeller, hence increasing its efficiency, although it has some negative side-effects it is still beneficial to count for this contribution when simulating any scenario.

6.2 Analysis of generalized annual results.

6.2.1 Route 1: Rotterdam - Trondheim

In this particular scenario, and given the total sailing time to travel between ports, the service will be performed a total of 87 times in a year. The following results in Table 6.2 display a comparison of the averages per journey in this given year with the assistance of some WASP technology but without the deployment of the JIT system. The first column shows averaged results of the optimal solutions found when simulating all possible speeds within bounds to find the minimum total cost, while the second one shows the averaged results of the optimal solutions found when working towards minimizing total emissions. The structure is the same as in the previous section, and it is worth mentioning that these simulations already account for the propeller efficiency variations that have already been presented above.

Quite remarkable WASP percentages are obtained in this route, both in the economical solutions and in the environmental ones. These percentages are slightly different from the results that were obtained in Section 5 due to the randomness of the availability, which affects all results. It is expected that the WASP percentage is lower in the economical optimization than in the environmental one, as the economical optimization tries to maximize the speed in order to arrive earlier and, as has been already presented, the total resistance that the vessel needs to overcome will be higher with increased speeds. Even though the WASP technology will also be generating more thrust, the resistance will increase at a faster pace and therefore the total WASP percentage will be lower for increased speeds than for lower ones. This will also be shown below with two figures showing the variation of WASP percentage with respect to the sailing speed.

Following this reasoning, speed only varies a totality of 2 knots between scenarios, which results in an 11-hour difference towards the time of arrival. Again, this difference in the optimal speeds is expected, as shown in Section 5, since the emissions optimization tries to use the minimal speed, while the optimization of the cost uses the maximum one.

	Minimizing costs	**Minimizing emissions**
Average WASP [%]	30.94	35.44
Average speed [knots]	12.78	10.94
Average fuel consumption [tonnes fuel]	250.22	243.92
Average journey duration [hours]	66.69	77.85
Average emissions released [tonnes CO_2]	778.17	758.59

Table 6.2: Average results per journey obtained for the 87 iterations to simulate an annual service in the WASP scenario (Route 1)

Table 6.3 shows the average results obtained when implementing JIT and running the whole annual simulations again. The total number of times that either the slow option or the quick option was chosen is also shown here, and it is worth noting that the sum of slow and quick options chosen in both optimizations adds up to 87, meaning that implementing JIT is always feasible in this case study, which is mostly due to the availability of the port. It can also be seen that emissions in both optimizations decrease with respect to the WASP scenario, showing how implementing JIT can indeed reduce both costs and emissions.

It is remarkable that both optimizations tend to choose the quick option over the slow option. This is highly dependent on the availability of the port and the needed speed adjustments in either the quick/slow options: the slow option might probably decrease the speed quite considerably and therefore increase the total sailing time hugely, while the quick option might only need a small speed adjustment which will not impact the total sailing time that much. Therefore, the slow option might be sailing at a slower speed for a much longer time than the quick option, which ends up in total increased emissions even though the speed is lower.

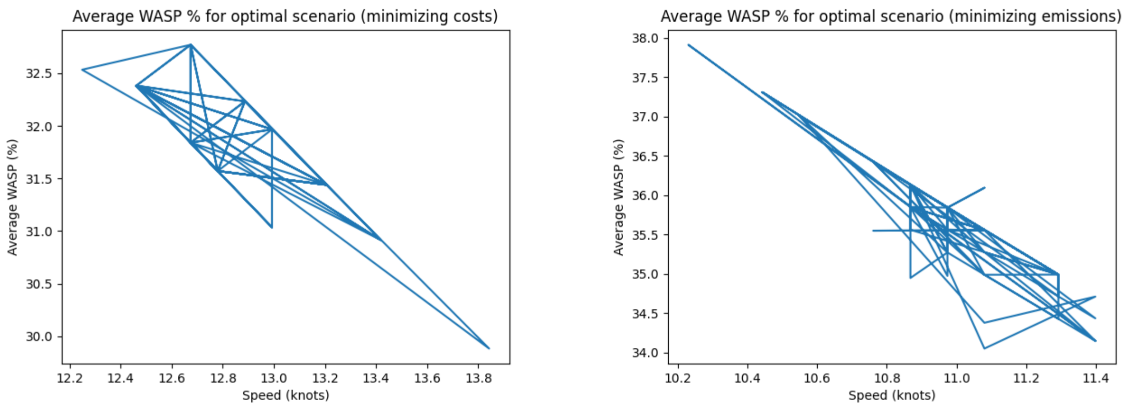
	Minimizing costs	**Minimizing emissions**
Slow option chosen in the JIT	26	0
Quick option chosen in the JIT	61	87
Average WASP [%]	31.85	35.62
Average emissions released [tonnes CO_2]	754.76	745.8

Table 6.3: Average results per journey obtained for the 87 iterations to simulate an annual service in the JIT scenario (Route 1)

Now, in figures 6.3a and 6.3b the average WASP percentage used in the JIT scenario in each of the iterations is drawn. As has been presented above, the WASP percentages in the JIT scenario are slightly higher than the ones obtained in the WASP scenario. On the x-axis, the optimal possible speeds in knots are displayed while on the y-axis the respective WASP percentage is plotted. To plot a representative graph, for these results exclusively, the simulation was iterated 100 times and the results were saved.

Starting, the graph on the right shows the cases where the emissions were minimized and on the left, minimum costs are sought. Next, the semi-constant decreasing rate of the trend line has developed as assumed. All iterations work with the same wind profile, as they are sailing the same route and consequently with the same way-point distribution with the same distances within the whole route. This will result in a close-to-identical thrust obtained from the WASP technology along all iterations and scenarios for this route. On the other hand, while the speed increases linearly, the resistance of the water that the vessels need to overcome also increases exponentially. This was initially seen in figures 4.8 in previous sections. So, given that the WASP percentage is calculated as the percentage of thrust obtained from the WASP technology out of the total force needed to overcome the resistance of the water, then the force the engine needs to generate will also increase with the speed.

Continuing, it is noticeable that both graphs are opposite of one another. Given the semi-straight trend line that crosses the center of the graph diagonally, Figure 6.3b finds other optimal results, due to the randomness added, in the area below the curve while Figure 6.3a finds them above.



(a) Minimizing costs scenario (%) **(b)** Minimizing emissions scenario ($)

Figure 6.3: Average WASP percentage used in each of the iterations for optimal speed in knots for Rotterdam - Trondheim

The last Table 6.4 shows the results of the savings accounted for a year of this scenario. It both compares the WASP vs Base Case and the JIT vs the WASP scenarios. Savings here are presented by NM of the route to facilitate comparison between scenarios. The total length of this scenario is 852 NM. It is noteworthy that both emissions and costs savings in the JIT are quite low compared to the optimal solutions that were found in the previous section, but it must be kept in mind that they are percentages of bigger values and that this methodology is only being implemented in the last 10% section of the route. These savings must also be included on top of the ones obtained when simply implementing the WASP technology, and it is important to remember that there will be no additional costs that will need to be borne when implementing this technology, which makes these savings worth it.

Additionally, the optimal results obtained when implementing the Base Case are obtained for the same speed both in the economical optimization and in the environmental one, as also happened in the previous results shown. This is simply due to the savings increasing with speeds and being maximum for the maximum speed, as the WASP technology will generate more thrust for these increased speeds. It is also expected that the percentages of both emissions and cost savings have the same value, as it has already been explained that the costs function and the emissions function are proportional.

	Minimizing costs			Minimizing emissions		
	Totals	Per NM	Diff. %	Totals	Per NM	Diff. %
Cost savings WASP vs. Base Case [$]	3,822,318	4,486.28	14.03	3,822,318	4,486.28	14.03
Emission savings WASP vs. Base Case [tonnes CO2]	12,404	14.55	14.03	12,404	14.55	14.03
Cost savings JIT vs. WASP [$]	754,506	885.57	0.03	642,254	753.81	0.02
Emission savings JIT vs. WASP [tonnes CO2]	2,276.60	2.67	0.03	1,287.52	1.51	0.02

Table 6.4: Total annual savings obtained between different scenarios (Route 1)

6.2.2 Route 2: Antwerp - New York

As has already been mentioned, assuming that the vessel spends 260 days sailing per year and taking into consideration the total time needed to sail this route, there will approximately be 24 trips per year. Therefore, all the results shown in this section correspond to the averaged values per journey of the optimal results obtained when running 24 simulations of this service, each one of them with a different port availability input randomly generated. It is worth mentioning that the simulations of this case study already account for the propeller efficiency variations that have been already presented in Section 6.1. Results are slightly different from the ones presented in Table 6.1 due to the randomness of the availability.

Again, average results obtained for the optimal results in all the simulations are shown in Table 6.5. It can be seen that the total percentage of WASP utilization reaches up to 38.82% in the environmental optimization, again higher than what was shown before in Section 5 due to the randomness, and the economical optimization also reaches up to very decent values of WASP utilization.

	Minimizing costs	Minimizing emissions
Average WASP [%]	38.62	38.82
Average speed [knots]	11.53	11.40
Average fuel consumption [tonnes fuel]	269.13	268.83
Average journey duration [hours]	313.72	314.89
Average emissions released [tonnes CO_2]	837	836.08

Table 6.5: Average results per journey obtained for the 24 iterations to simulate an annual service in the WASP scenario (Route 2)

Averaged results of consumption and emissions in the optimal JIT scenarios can be seen in Table 6.6, as well as the total number of times where either the slow option or the quick option was chosen. It is noticeable that the sum of chosen slow options and quick scenarios adds up to 24, meaning that all the optimal solutions found do implement the

JIT methodology and there are no unfeasible solutions. Again, all of the optimal solutions choose the quick option over the slow one, which again seems to be due to the needed adjustments of the speed in each of the options.

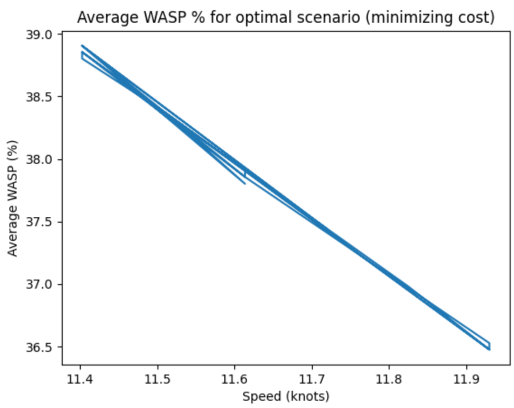
	Minimizing costs	Minimizing emissions
Slow option chosen in the JIT	0	0
Quick option chosen in the JIT	24	12
Average WASP [%]	38.26	38.87
Average emissions released [tonnes CO_2]	837.21	834.9

Table 6.6: Average results per journey obtained for the 24 iterations to simulate an annual service in the JIT scenario (Route 2)

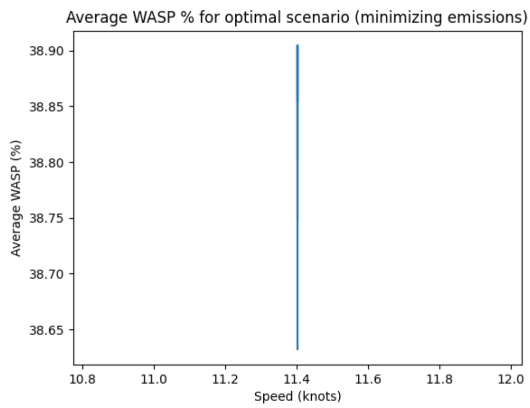
Figures 6.4a and 6.4b show the average WASP percentage that the optimal solutions are using. It is important to mention that this graph has been obtained by running 100 simulations instead of only 24, as results obtained with a lower number of simulations were not representative enough and the variation of the WASP percentage was not remarkable. Clearly, Figure 6.4a follows the logic previously explained decreasing at a semi-constant rate the percentage of WASP while the speed increases.

What is remarkable here is Figure 6.4b, as in this particular case study, the scenario where the simulation is minimizing emissions is fixed to the one with the minimum possible speed, which stuck to the minimum bound established by the vessel design conditions to 11.4 knots. Consequently, when iterating the scenario 24 times to simulate an annual service, different thrust values are obtained from the WASP technologies due to the randomness generated but, again, the speed is constant.

Recalling the results obtained in Section 5, this WASP technology obtained maximum emissions savings when the vessel was sailing at lower speeds and lead to increased emissions when sailing at higher speeds, which matches the results obtained here, as optimal speeds found are relatively small compared to the maximum speed at which the vessel can sail (15 knots).



(a) Minimizing costs scenario (%)



(b) Minimizing emissions scenario ($)

Figure 6.4: Average WASP percentage used in each of the iterations for optimal speed in knots for Antwerp - New York

Savings between the WASP and the Base Case scenarios and between the JIT and the WASP scenarios can be seen in Table 6.7. Again, savings here are total savings in all the trips executed in one year, and they are also presented as total values, as savings per km of the route (this route is 3591 NM), and as a percentage. It is remarkable that the percentage of savings in this case study is slightly higher than the ones obtained in the previous route even with the not-as-favorable wind conditions found in this route, which leads to the conclusion that DynaRigs are very efficient. These comparisons should however be made very carefully, as there are many parameters such as the type of vessel and the particular differences between the technologies that also affect the results, as well as the assumptions that have been made.

In the same way as in the first case study, maximum savings compared to the Base Case are obtained for the maximum speed both in the economic and in the environment optimizations, as this speed is the one that allows the WASP technology to generate the maximum thrust. Again, percentages of emissions and cost savings obtained when implementing JIT are quite low, but this is also highly dependent on the port availability and it must be kept in mind that these low savings will always be worth it, as there will be no additional costs when implementing this methodology.

	Minimizing costs			**Minimizing emissions**		
	Totals	Per NM	Diff. %	Totals	Per NM	Diff. %
Cost savings WASP vs. Base Case [$]	1,429,087	397.96	15.71	1,429,087	397.96	15.71
Emission savings WASP vs. Base Case [tonnes CO2]	4,718	1.31	15.71	4,718	1.31	15.71
Cost savings JIT vs. WASP [$]	34,831.49	9.69	0.0045	13,445.07	3.74	0.0023
Emission savings JIT vs. WASP [tonnes CO2]	60.15	0.016	0.0032	18.28	0.005	0.0014

Table 6.7: Total annual savings obtained between different scenarios (Route 2)

6.2.3 Route 3: Algeciras - Hong Kong

Following the same assumption as in the previous case studies, the selected vessel will make this trip approximately 12 times per year, and hence 12 simulations of this case study will be generated, again each one of them having its own port availability input.

Averaged results of consumption and emissions in the WASP scenario can be seen in Table 6.8, both for the economical and environmental optimal solutions. In the same way, as presented above, the economic optimal solution is found for the highest speeds, while the environmental one is found for the lowest speeds. It has already been shown that traveling this route with this technology at speeds lower than 16 knots will actually end up in increased emissions and costs compared to the Base Case. This is the reason why the WASP percentage in the environmentally optimal solution is negative, showing that the WASP technology is actually not generating any savings but worsening the situation when sailing at lower speeds.

The lower emissions and fuel in the scenario with a negative WASP percentage are only due to the reduced sailing speed, and not due to savings obtained from the WASP technology. In the scenarios with a negative WASP percentage, the engine will be providing all the force needed to overcome both the resistance of the water and the additional resistance of the WASP technology.

	Minimizing costs	**Minimizing emissions**
Average WASP [%]	0.53	-3.06
Average speed [knots]	23.79	14.70
Average fuel consumption [tonnes fuel]	7,150	5,696
Average journey duration [time]	360	584
Average emissions released [tonnes CO_2]	22,238	17,716

Table 6.8: Average results per journey obtained for the 12 iterations to simulate an annual service in the WASP scenario (Route 3)

Table 6.9 shows results obtained in the JIT scenario. The number of times where either the slow or quick option was chosen can be seen below, and it is remarkable that in this case study, the environmental optimization always chooses the quick option over the slow option, as happened in the previous case studies. On the other hand, economical optimization not only neglects several solutions due to unfeasibility but also always chooses the slow option over the quick one. In this case study the optimal sailing speeds between the two optimizations are very different, and therefore the economical scenario will have a completely different arrival time from the environmental one. It might be that this arrival time only allows for decreasing the speed and increasing it might not be feasible, which is the reason why the slow option is chosen.

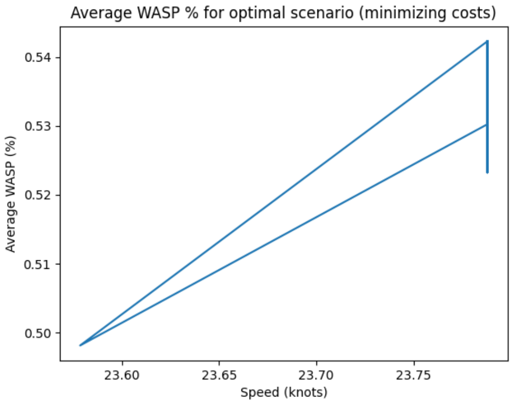
	Minimizing costs	**Minimizing emissions**
Slow option chosen in the JIT	5	0
Quick option chosen in the JIT	0	12
Average WASP [%]	0.54	-3.004
Average emissions released [tonnes CO_2]	22,171	17,659

Table 6.9: Average results per journey obtained for the 12 iterations to simulate an annual service in the JIT scenario (Route 3)

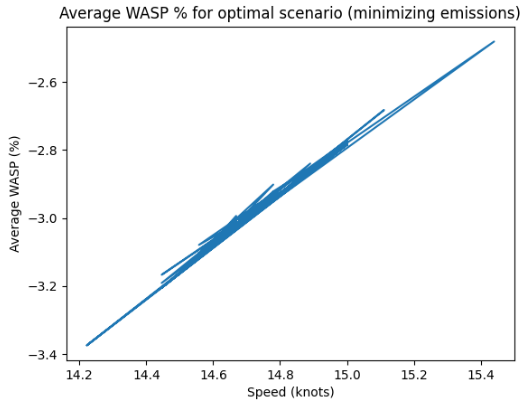
Figure 6.5a and 6.5b show the average WASP percentage that the optimal solution in the JIT scenario is using. Again, this graph has been obtained when running 100 simulations in order to generate enough solutions, even though the numerical results that have been previously presented do correspond to only 12 iterations, as these were realistic enough even with this low number of simulations.

These graphs show a different trend than the one shown in the previous case study, but it must be kept in mind that this scenario does not present savings when installing the WASP technology due to the increased resistance of the system and the poor wind conditions. It has already been presented when showing the results that implementing the WASP technology only achieves savings when sailing at higher speeds, which matches what these graphs show: the WASP percentage will be very low for reduced speeds but will increase for higher ones.

Additionally, it has already been shown that approximately half of the iterations when minimizing costs choose a non-feasible solution (only 5 out of 12 were feasible), and it, therefore, is not surprising that not as many iterations can be seen in Figure 6.5a. Unfeasibility here happens when JIT suggests the quick option, and since the sailing speed is already the maximum one, all the quick solutions will not be feasible and will therefore not be shown in the graph.



(a) Minimizing costs scenario (%)



(b) Minimizing emissions scenario ($)

Figure 6.5: Average WASP percentage used in each of the iterations for optimal speed in knots for Algeciras - Hong Kong

Finally, savings obtained both when comparing WASP vs Base Case and JIT vs WASP can be seen in Table 6.10. The only savings vs the Base Case are obtained for maximum speeds, given that for slower cases the added weight is too much. Then, total savings in costs and in emissions appear to be representative if they are examined as total values, but it is glimpsed that the savings per NM and the percentages are very poor compared to the ones obtained in the previous case studies. It is important to highlight that although the average WASP values are close to zero or negative there still appears to be savings. This is based on two factors.

The first is that a negative value is not representative of a penalty from the wind but it is considering that the technology is switched off or in this case, the sails are retracted. With this assumption, negative effects from the WASP technology do not extremely affect the fuel consumption or the rest of the parameters. The second reason is due to the fact that although the average results are negative, in some particular scenarios out of the 12 iterations simulated for a year the WASP slightly contributes in a positive way, hence the savings in fuel and emissions. Moreover, most of these iterations choose the maximum speed as the sailing speed, and it is of course not realistic to assume that the vessel will be constantly sailing at these high speeds.

It must however be noted that cost savings obtained when implementing JIT are almost as representative as the ones obtained in the first case study. This route is 8570 NM long.

	Minimizing costs			**Minimizing emissions**		
	Totals	Per NM	Dif. %	Totals	Per NM	Dif. %
Cost savings WASP vs. Base Case [$]	330,004	104.10	1.43	330,004	104.10	1.43
Emission savings WASP vs. Base Case [tonnes CO2]	1,042	0.33	0.41	1,042	0.33	0.41
Cost savings JIT vs. WASP [$]	3,467,937	1,094	0.0051	256,374.75	80.88	0.000043
Emission savings JIT vs. WASP [tonnes CO2]	770.34	0.24	0.0036	809.60	0.26	0.0024

Table 6.10: Total annual savings obtained between different scenarios (Route 3)

6.3 General comments

This section aimed to carry out a more realistic analysis of the case studies by simulating the services over one year and by varying the availability of the port, as it has been shown that this is a key parameter that will modify the results obtained. The availability of the port has, thus, been randomized to obtain more general results.

The first conclusion that can be drawn from this analysis is that installing WASP technologies in commercial vessels does lead to savings in both costs and in emissions, which have been proved to reach up to around 15% regardless of the availability of the port. Moreover, they improve the efficiency of the engine by generating additional thrust that will reduce the total power needed from the engine.

The WASP utilization percentage that can be obtained in the first two case studies reaches up to 38%, and it has been shown that these percentages are higher for lower sailing speeds. It has been discussed that this is due to the increased resistance of the water for higher speeds while the WASP technology will generate approximately the same thrust regardless of the speed. This analysis has been shown in the graphs presented in this section. The optimal solutions obtained when minimizing emissions, therefore, present higher WASP percentages than the ones obtained when minimizing costs, as the former solutions will be found for lower speeds while the latter will be found for higher speeds.

In addition, it is important to highlight the graphical characteristics of the second case study, as one of the graphs in this route deviates from the general pattern observed in the others. This is a vertical straight line, which is due to the initial restrictions imposed in the program that did not allow the shipping speed to be less than 11.4 knots when optimizing emissions. This constraint proved to be the unanimously optimal option, as was also happening in Section 5.

Route 3, although it has an efficient and one of the most promising technologies for the future and is the main focus of the current research, turns out to be the route with the smallest WASP savings due to wind conditions. This will be further analyzed in the following section, as it will be shown that the same technology installed in the same type of vessel on the route Rotterdam-Trondheim does lead to savings both in costs and in emissions.

Another interesting finding that can be drawn from this study is that the majority of the optimal solutions in the JIT scenario are obtained when choosing the quick option over the slow one. This has been discussed to be highly dependent on the port availability, which might be suggesting slow solutions that are not feasible.

Additionally, the savings obtained when implementing JIT should be included on top of the savings that are already obtained when simply using the WASP technology, as the results shown here are calculated comparing the JIT scenario with the WASP one. Even though the percentages of savings obtained are not very impressive, it must be kept in mind that they represent percentages of remarkable numbers and will therefore translate into important total savings. It is also noteworthy that JIT is only being applied in the last 10% of the route, which is not representative in terms of distances. Moreover, there are no additional costs when implementing this methodology, as it only requires more communication and organization between the port and the vessel.

Overall savings obtained in each of the case studies cannot be compared with each other due to each one of them using different vessels and different technologies, so there is no way to use these results for concluding which technology is better than the other ones. Further simulations varying the combinations of vessels with each of the different technologies would indeed be interesting and is left for future research.

7 Analysis of alternative scenarios

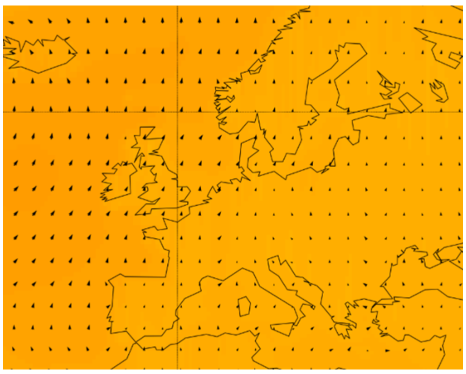
7.1 Wind Profiles: Background

Diving into further analysis of the thrust contributions from the WASP technologies, Routes 1 and 2 are affected by wind flows, so sailing in one direction differs from its counter-service when talking about wind conditions. The wind flows accounted for these routes are "trade winds" and "westerlies".

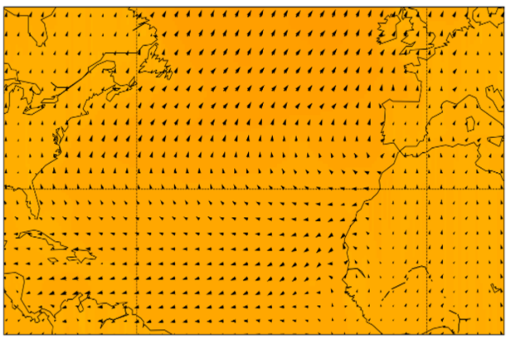
The “trade winds” or “easterlies” are the permanent east-to-west prevailing winds that flow in the Earth’s equatorial region. The trade winds blow mainly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere, strengthening during the winter and when the Arctic oscillation is in its warm phase. [94]

“Westerlies” are prevailing winds that blow from the west at mid-latitudes. They are fed by polar easterlies and winds from the high-pressure horse latitudes, which sandwich them on either side. Westerlies are strongest in the winter, when pressure over the pole is low, and weakest in summer when the polar high creates stronger polar easterlies. The strongest westerlies blow through the “Roaring Forties,” a wind zone between 40- and 50 degrees latitude in the Southern Hemisphere. [95]

Winds tend to follow the same pattern. On the NYC-Antwerp route higher savings are estimated than on the Antwerp-NYC (because it favors the westerlies) and on Rotterdam-Trondheim, the same: higher savings are assumed to be achieved than on its reverse route. Figures 7.1a and 7.1b show the wind profiles in Northern Europe and the Atlantic Ocean. Additionally, a worldwide map is also displayed in Figure 7.2.



(a) Northern Europe’s Wind Profile (Own generation)



(b) Atlantic Ocean’s Wind Profiles (Own generation)

Figure 7.1: Possible Wind Profiles affecting the simulated case studies.

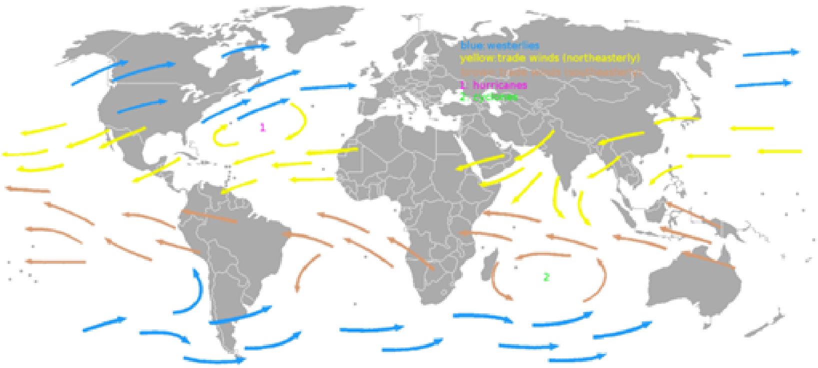


Figure 7.2: The westerlies (blue arrows) and the trade winds (yellow and brown arrows).
[72]

In the following subsections, the WASP% is printed for case studies 1 (Trondheim – Rotterdam) and 2 (Antwerp - New York) for each of the way-points in juxtaposition to the direction in which the wind is blowing (TWA) and the distance in NM of the given way-points. These are analyzed individually to prove the influence of the wind flows. The reversed routes for these two scenarios are simulated in comparison and to finish, an alternative route for the third case study examines the importance of the route vs vessel vs WASP technology implemented.

7.2 Route 1: Rotterdam - Trondheim

The wind map for Route 1 (Figure 7.1a) indicates that increasing vessel speed results in a higher occurrence of AWA near 0 degrees, reducing the force exerted by the rotors. Even though the vessel is sailing in the same direction as the wind, the Flettner rotors perform poorly in upwind conditions due to their significant drag penalties due to lateral forces (the C_D), hence the low WASP percentages obtained when the TWA are in quadrant 1 and 4 (red and blue), as will be shown below. In contrast, the DynaRig and rigid sails excel at sailing against the wind.

Firstly, Table 7.4 collects the WASP contribution for all way-points from Rotterdam to Trondheim and color codes for the TWA depending on the quadrant they fall into. It conveys that winds with a TWA expanding from 300 degrees to 80 degrees (TWAs red and blue) approximately will produce no thrust and have negative values for the WASP %, hence the Flettner rotors are turned off. These cases will however have the added weight in comparison to the Base Case, and therefore the propeller needs enough propulsive power to overcome this too. Higher thrust is acquired from winds with TWA ranging from 170 to 250 degrees, so ranging around 180 degrees. The weighted average that will be used later on has been procured at the bottom of the table.

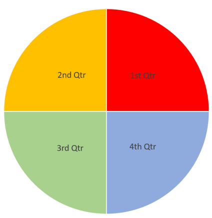


Figure 7.3: Colour Code legend for the TWA angles. (Own Figure)

WP	Distance (NM)	TWA	Spped (kntos)												
			8.74	8.84	8.95	9.06	9.16	9.27	9.38	9.48	9.59	...	15.12	15.22	15.33
			WASP %												
1	29.23	243.6	22.6	22.4	22.2	22	21.8	21.6	21.4	21.2	21.1	...	13.5	13.4	13.3
2	69.35	188.5	35	34.8	34.7	34.5	34.3	34.1	33.9	33.7	33.6	...	24.1	23.9	23.7
3	54.15	175.6	53.2	52.9	52.5	52.2	51.8	51.4	51.1	50.7	50.4	...	34.4	34.1	33.8
4	91.82	210.2	48.5	48.2	47.8	47.4	47.1	46.7	46.4	46	45.7	...	30.6	30.3	30.1
5	91.82	207.9	50.1	49.7	49.3	49	48.6	48.3	47.9	47.5	47.2	...	31.6	31.4	31.1
6	91.82	219.9	47	46.6	46.2	45.8	45.4	45.1	44.7	44.4	44	...	28.9	28.6	28.4
7	37.47	233.1	40.5	40.1	39.8	39.4	39	38.7	38.3	38	37.7	...	23.9	23.7	23.5
8	89.82	198.6	55.7	55.3	54.9	54.5	54.1	53.7	53.3	52.9	52.5	...	35.3	35	34.7
9	89.82	179.7	58.3	57.9	57.5	57.1	56.7	56.3	55.9	55.5	55.1	...	37.2	36.9	36.6
10	81.30	120.3	38.4	38	37.6	37.2	36.8	36.5	36.1	35.8	35.4	...	21.9	21.6	21.4
11	40.16	95.16	5.93	5.83	5.73	5.63	5.54	5.45	5.36	5.27	5.18	...	2.13	2.09	2.05
12	10.53	109.2	2.8	2.82	2.85	2.87	2.89	2.91	2.93	2.94	2.96	...	2.71	2.69	2.67
13	9.28	135.3	24.3	24.2	24	23.9	23.7	23.6	23.5	23.3	23.2	...	16.4	16.3	16.1
14	37.24	119.8	26.9	26.6	26.4	26.2	25.9	25.7	25.5	25.3	25.1	...	16.1	16	15.8
15	0.82	107.1	10.5	10.4	10.4	10.3	10.2	10.1	10	9.94	9.86	...	6.33	6.27	6.21
16	1.54	16.29	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
17	1.40	355.5	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
18	2.40	15.43	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
19	3.27	33.6	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
20	5.89	29.09	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
21	2.26	70.67	-4.73	-4.72	-4.72	-4.72	-4.71	-4.71	-4.7	-4.7	-4.7	...	-4.48	-4.47	-4.46
22	5.93	331.1	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
23	4.71	314	-12.6	-12.3	-12.2	-12	-11.8	-11.6	-11.4	-11.2	-11.1	...	-5.25	-5.18	-5.11
	Total:		Wighted Average												
	852.04		**41.53**	**41.21**	**40.90**	**40.59**	**40.28**	**39.98**	**39.68**	**39.38**	**39.09**	...	**26.06**	**25.83**	**25.60**

Figure 7.4: WASP % results of Route 1 detailed for all way-points and weighted average calculation (Own Figure)

The detailed analysis proves that the given WASP thrust results in percentages ranging from 25% to 42%. It is noted that from the beginning of the route, the vessels receive close to ideal wind conditions. This continues throughout the route until approximately way-point 16 when the thrust decreases. Fortunately, these last seven way-points represent the shortest way-points in length since they are maneuvering to arrive at Trondheim.

7.2.1 Reverse Route: Trondheim - Rotterdam

Now, the reverse route is computed. In this particular case, the reverse route realizes the service in ballast. The original direction was defined depending on commercial synergies. On one hand, the port of Rotterdam is one of the biggest tank terminals in Europe and it exports oil to Trondheim. On the other hand, Rotterdam does not receive any commercial imports from Trondheim, hence, to make a realistic scenario the vessel returns ballast.

Results of the comparison with the reversed route are seen in Table 7.1. The results procured are in the optimizing cost scenario without the JIT procedure. It is laden one-way and ballast in return and has the fixed availability provided by the Terminal usage of the port of Piraeus. The third column reveals the difference in the percentage of the parameters.

	Rot - TH	TH - Rot	Diff. [%]
Average WASP % used	30.94	-9	-125
Average fuel consumption [tonnes fuel]	250.22	287.53	15
Average journey duration [hours]	66.69	80.02	-1
Average emissions released [tonnes CO_2]	779.17	894.23	15
Optimal Speed [knots]	10.58	10.64	1

Table 7.1: Comparison between the route Rotterdam-Trondheim and the reversed one

In view of the findings, it can be highlighted that sailing in the favorable direction of the wind flows increases the WASP percentage a 125% and this is with the vessel in laden status vs a ballast return. In this scenario, the fuel consumption and emissions released also increase by 15% when sailing contrary to the favorable wind.

It is remarkable that the average WASP percentage for Rotterdam Trondheim is negative, so the detailed analysis for each of the way-points is also printed in Figure 7.5 to confirm.

WP	Distance (NM)	TWA	Spped (kntos)												
			8.34	8.45	8.56	8.67	8.78	8.89	9.01	9.11	9.22	...	14.86	14.96	15.07
			WASP %												
1	4.71	135.2	32.33	32.11	31.9	31.7	31.49	31.28	31.08	30.88	30.68	...	21.7	21.5	21.4
2	5.93	150.9	39.17	38.94	38.7	38.47	38.24	38.01	37.79	37.56	37.33	...	26.8	26.6	26.4
3	2.26	251.1	14.84	14.71	14.58	14.46	14.33	14.21	14.09	13.97	13.86	...	9.07	8.99	8.91
4	5.89	208.1	39.24	39	38.77	38.54	38.31	38.08	37.86	37.63	37.41	...	26.9	26.7	26.5
5	3.27	213	37.19	36.96	36.74	36.52	36.3	36.08	35.86	35.65	35.43	...	25.4	25.2	25
6	2.40	195.2	42.18	41.95	41.71	41.48	41.24	41.01	40.78	40.54	40.31	...	29.2	29	28.8
7	1.40	175.5	43.34	43.1	42.87	42.63	42.39	42.16	41.93	41.69	41.46	...	30.1	29.9	29.7
8	1.54	196.1	41.83	41.6	41.37	41.13	40.9	40.67	40.44	40.21	39.98	...	29	28.8	28.6
9	0.82	286.8	-5.06	-5.06	-5.06	-5.06	-5.06	-5.05	-5.05	-5.05	-5.05	...	-5.03	-5.03	-5.02
10	37.24	294.1	-7.66	-7.63	-7.6	-7.57	-7.54	-7.52	-7.49	-7.47	-7.44	...	-6.54	-6.45	-6.37
11	9.28	319	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
12	10.53	293.8	-8.21	-8.17	-8.13	-8.09	-8.05	-8.02	-7.98	-7.95	-7.92	...	-6.54	-6.45	-6.37
13	40.16	272.6	-8.72	-8.63	-8.55	-8.47	-8.39	-8.31	-8.23	-8.16	-8.09	...	-5.96	-5.93	-5.91
14	81.30	299.1	-7.51	-7.49	-7.48	-7.47	-7.46	-7.45	-7.44	-7.43	-7.42	...	-6.54	-6.45	-6.37
15	89.82	350	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
16	89.82	0.188	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
17	37.47	43.21	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
18	91.82	39.15	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
19	91.82	39.45	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
20	91.82	27.46	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
21	54.15	357	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
22	69.35	22.51	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
23	29.23	49.16	-15.72	-15.46	-15.2	-14.95	-14.7	-14.46	-14.23	-14	-13.77	...	-6.54	-6.45	-6.37
	Total:		Wighted Average												
	852.04		**-12.48**	**-12.28**	**-12.08**	**-11.88**	**-11.69**	**-11.51**	**-11.33**	**-11.16**	**-10.98**	...	**-5.50**	**-5.42**	**-5.36**

Figure 7.5: WASP % results of Route 1 reversed for all way-points and weighted average calculation (Own Figure)

From this analysis, it can be drawn that for this specific route a technology that can be turned off with no additional penalty is the most suitable. The added weight of the WASP technology will however be always present in the reversed route, but hopefully savings obtained in the initial route will be able to compensate for the additional emissions released in the reverse route due to this additional weight.

7.3 Route 2: Antwerp - New York

Table 7.6 collects the WASP contribution for all way-points from Antwerp to New York. It conveys that winds with a TWA expanding from 320 degrees to 30 degrees approximately will produce very little thrust or even zero (causing a negative percentage). The weighted average that will be used later has been procured at the bottom of the table.

Note that, similar way-points have been hidden from the table to simplify the results and shorten them, but all way-points are accounted for in the weighted average, without exclusion. Color codes for the TWA angles can also be seen in Figure 7.3.

The detailed analysis suggests that WASP thrust for this scenario indeed is very favorable. It is, out of the three, the highest thrust obtained in the whole service (back and forth) so it is interesting to see in what conditions will the return service operate. The DynaRig demonstrates greater potential in upwind sailing courses (TWA=45°), outperforming other configurations. The commercial synergies for this scenario and given that it is a bulk carrier suggest that the vessel should also return laden. It does not necessarily mean that the cargo has to be the same, but both continents have enough to export and import to one another to second the assumption.

WP	Distance (NM)	TWA	Speed (knots)												
			11.40	11.51	11.61	11.72	11.82	11.93	12.04	12.14	12.25	...	14.88	14.98	15.09
			WPS %												
1	0.54	159.63	100	100	100	100	100	100	100	100	100	...	93.85	93.01	92.18
2	2.16	213.99	100	100	100	100	100	100	100	100	100	...	87.71	86.91	86.12
3	3.37	235.44	91.35	90.62	89.89	89.17	88.45	87.73	87.02	86.31	85.60	...	68.70	68.06	67.42
4	5.58	296.68	30.48	30.10	29.72	29.35	28.98	28.62	28.26	27.91	27.56	...	19.91	19.64	19.38
5	9.89	280.32	23.88	23.60	23.33	23.06	22.79	22.52	22.26	22.00	21.74	...	16.03	15.83	15.63
6	8.11	125.63	72.13	71.62	71.11	70.60	70.09	69.58	69.08	68.57	68.07	...	55.63	55.15	54.66
7	1.13	303.17	16.76	16.55	16.34	16.14	15.94	15.74	15.55	15.35	15.16	...	10.88	10.73	10.58
8	4.90	329.4	3.64	3.56	3.49	3.41	3.34	3.26	3.19	3.12	3.05	...	1.55	1.50	1.45
9	11.22	261.88	34.98	34.68	34.39	34.09	33.80	33.51	33.22	32.93	32.64	...	25.93	25.68	25.43
10	6.43	257.87	48.32	47.89	47.48	47.06	46.65	46.24	45.83	45.42	45.02	...	35.66	35.31	34.96
11	1.14	20.731	0.02	-0.03	-0.08	-0.13	-0.18	-0.22	-0.27	-0.32	-0.36	...	-1.22	-1.24	-1.26
12	27.88	277.35	33.64	33.23	32.82	32.42	32.03	31.64	31.26	30.88	30.50	...	22.31	22.02	21.74
13	34.35	283.7	57.93	57.17	56.42	55.68	54.96	54.24	53.53	52.83	52.14	...	37.38	36.88	36.38
14	53.43	334.76	13.43	13.20	12.98	12.76	12.54	12.33	12.12	11.91	11.71	...	7.44	7.30	7.16
15	76.00	324.55	23.19	22.86	22.54	22.21	21.9	21.58	21.27	20.96	20.66		14.21	13.99	13.77
16	14.39	56.284	48.36	47.72	47.09	46.47	45.86	45.26	44.66	44.07	43.49	...	30.98	30.6	30.1
17	5.12	60.117	47.28	46.66	46.05	45.45	44.86	44.27	43.69	43.12	42.56	...	30.43	30	29.6
18	82.49	244.32	100.00	99.58	98.66	97.75	96.85	95.95	95.06	94.17	93.3	...	73.1	72.4	71.6
19	72.87	298.74	59.8	59	58.22	57.45	56.68	55.93	55.19	54.46	53.73	...	38.28	37.8	37.2
20	72.87	296.02	56.01	55.28	54.55	53.83	53.12	52.43	51.74	51.06	50.39	...	36	35.5	35
21	93.18	264.89	60.89	60.19	59.49	58.81	58.13	57.46	56.8	56.15	55.51	...	41.45	41	40.5
22	93.18	270.01	54.4	53.68	52.97	52.28	51.59	50.91	50.25	49.59	48.94	...	35.15	34.7	34.2
23	93.18	275.16	61	60.19	59.39	58.6	57.82	57.06	56.3	55.56	54.83	...	39.25	38.7	38.2
24	*93.18*	279.00	64.53	63.67	62.82	61.99	61.16	60.35	59.55	58.76	57.98	...	*41.44*	40.9	40.3
51	87.88	280.53	15.68	15.51	15.34	15.17	15	14.84	14.67	14.51	14.35	...	10.66	10.5	10.4
52	87.88	287.85	9.59	9.48	9.38	9.28	9.18	9.07	8.97	8.87	8.77	...	6.44	6.35	6.27
53	87.88	295.44	4.13	4.08	4.03	3.98	3.94	3.89	3.84	3.79	3.74	...	2.58	2.54	2.49
54	43.08	272.17	6.06	6.01	5.96	5.9	5.85	5.8	5.74	5.69	5.63	...	4.25	4.2	4.14
55	4.05	227.69	44.36	44.14	43.93	43.71	43.48	43.26	43.04	42.81	42.58	...	36.26	36	35.7
56	0.96	304.37	4.67	4.61	4.55	4.49	4.43	4.37	4.31	4.25	4.19	...	2.82	2.77	2.72
57	0.37	334.14	-4.65	-4.63	-4.61	-4.59	-4.57	-4.55	-4.52	-4.5	-4.48	...	-3.4	-3.4	-3.3
	Total:		**Weigthed Average:**												
	3590.998		35.27	34.84	34.40	33.96	33.54	33.11	32.70	32.28	31.88	...	23.08	22.8	22.5

Figure 7.6: WASP % results of Route 2 detailed for all way-points and weighted average calculation (Own Figure)

DynaRigs function differently than the Flettner Rotors and this can clearly be seen in the TWAs and the WASP% obtained. DynaRigs do not give big negative numbers when sailing close to the wind compared to the rotors before. That is why they are good with winds from the front: the ideal angle is still sideways, but they perform better upwind than other WASPs. Highlight that the first two points show a 100% of wind propulsion contribution and that the average WASP contribution range from 22 to 36%.

7.3.1 Reverse Route: New York - Antwerp

Results of the comparison with the reversed route are seen in Table 7.2. The results procured are in the optimizing emissions scenario, with four DynaRigs on a bulk carrier, without the JIT function. It is laden both ways and it has the fixed availability provided by the Terminal Usage of the port of Piraeus. The third column reveals the increase in the percentage of the parameters.

	Ant - NY	**NY - Ant**	**Diff. [%]**
Average WASP % used	38.62	72.6	51
Average fuel consumption [tonnes fuel]	269.13	215.71	-31
Average journey duration [hours]	313.72	314.92	-
Average emissions released [tonnes CO_2]	837	670.86	-31
Optimal Speed [knots]	11.40	11.40	-

Table 7.2: Comparison between the route Antwerp - New York and the reversed one

The results attained are very interesting, as they show that the trip with the same overall conditions obtains approximately double the thrust when sailing downwind than upwind. Additionally, both optimal scenarios have identical average journey duration and speed. On the fuel consumption and emission released, a 31% increase is gained by just performing an appropriate routing design.

In Figure 7.7 the detailed way-points are displayed for the reverse route. Again, for simplification and given that there are 57 way-points some similar way-points are hidden but they are all included in the calculations. This table is predominantly yellow in the TWAs code so it is natural to conclude that it is the most favorable route. Additionally, from way-point 41 to 44, the lower speeds obtain a 100% contribution of WPS thrust. This accounts for 149 NM, a 4% of the total route. Way-points 43 and 44 even maintain this percentage for all sailing speeds. Finally, negative values can only be seen at the fastest speeds for the last way-point which matches the angle the wind is blowing.

WP	Distance (NM)	TWA	Speed (knots)												
			11.40	11.51	11.61	11.72	11.82	11.93	12.04	12.14	12.25	...	14.88	14.98	15.09
			WPS %												
1	0.37	154.15	55.14	54.87	54.60	54.32	54.04	53.76	53.47	53.19	52.90	...	44.96	44.62	44.29
2	0.96	124.39	39.7	39.51	39.31	39.11	38.92	38.72	38.51	38.31	38.1	...	32.45	32.2	32
3	4.05	47.496	2.68	2.64	2.59	2.55	2.50	2.46	2.42	2.37	2.33	...	1.33	1.30	1.26
4	43.08	91.537	9.25	9.19	9.12	9.05	8.99	8.92	8.85	8.78	8.72	...	6.97	6.90	6.83
5	87.88	113.53	28.97	28.84	28.71	28.58	28.44	28.31	28.17	28.03	27.89	...	23.92	23.75	23.58
6	87.88	113.02	27.33	27.21	27.10	26.98	26.86	26.73	26.61	26.48	26.35	...	22.68	22.52	22.36
7	87.88	105.46	27.92	27.76	27.61	27.45	27.29	27.13	26.98	26.82	26.66	...	22.42	22.24	22.07
8	86.52	111.87	43.00	42.72	42.44	42.17	41.89	41.61	41.34	41.06	40.78	...	33.76	33.48	33.20
33	93.18	99.985	87.95	86.95	85.97	85	84.03	83.08	82.15	81.22	80.3	...	60.23	59.5	58.8
34	93.18	97.815	82.56	81.59	80.64	79.7	78.78	77.86	76.96	76.06	75.18	...	55.99	55.3	54.7
35	93.18	95.32	75.97	75.05	74.14	73.25	72.37	71.49	70.63	69.79	68.95	...	50.86	50.2	49.6
36	93.18	91.506	63.34	62.52	61.72	60.92	60.14	59.37	58.61	57.86	57.12	...	41.35	40.8	40.3
37	93.18	86.401	55.49	54.76	54.04	53.33	52.63	51.94	51.26	50.59	49.93	...	35.87	35.4	34.9
38	72.87	109.49	89.95	89.08	88.22	87.37	86.52	85.68	84.85	84.02	83.21	...	64.62	64	63.3
39	72.87	113.27	100	100	100	100	100	100	100	100	100	...	77.58	76.8	76
40	82.49	74.58	64.86	64	63.15	62.32	61.49	60.68	59.87	59.08	58.3	...	41.65	41.1	40.5
41	5.12	239.98	100	100	100	100	100	100	100	100	100	...	78.73	78	77.2
42	14.39	233.48	100	100	100	100	100	100	100	100	100	...	87.96	87.1	86.2
43	76.00	143.64	100	100	100	100	100	100	100	100	100	...	100	100	100
44	53.43	154.13	100	100	100	100	100	100	100	100	100	...	100	100	100
45	34.35	106.31	93.37	92.41	91.45	90.51	89.58	88.66	87.74	86.84	85.94	...	65.88	65.2	64.5
46	27.88	100.54	80.61	79.73	78.85	77.99	77.14	76.3	75.46	74.64	73.82	...	55.84	55.2	54.6
47	1.14	200.79	100	100	100	100	100	100	100	100	100	...	89.5	88.7	87.9
48	6.43	77.112	34.21	33.79	33.38	32.97	32.56	32.16	31.77	31.38	30.99	...	22.59	22.3	22
49	11.22	78.645	28.73	28.39	28.05	27.71	27.38	27.06	26.73	26.41	26.1	...	19.13	18.9	18.6
50	4.90	148.81	87.86	87.29	86.72	86.14	85.57	84.99	84.42	83.84	83.26	...	68.67	68.1	67.5
51	1.13	122.91	63.51	63.08	62.65	62.21	61.78	61.35	60.92	60.49	60.05	...	49.33	48.9	48.5
52	8.11	307.33	15.23	15.04	14.85	14.66	14.47	14.29	14.1	13.92	13.74	...	9.77	9.63	9.49
53	9.89	96.321	34.08	33.77	33.46	33.16	32.86	32.56	32.26	31.96	31.67	...	24.88	24.6	24.4
54	5.58	112.22	55.87	55.45	55.03	54.62	54.2	53.79	53.38	52.97	52.56	...	42.66	42.3	41.9
55	3.37	53.602	26.34	26	25.67	25.34	25.01	24.69	24.37	24.06	23.75	...	16.97	16.7	16.5
56	2.16	33.403	13.77	13.57	13.36	13.16	12.96	12.77	12.57	12.38	12.19	...	8.15	8.01	7.88
57	0.54	339.89	0.15	0.1	0.04	-0.01	-0.06	-0.11	-0.16	-0.21	-0.26	...	-1.18	-1.2	-1.2
	Total:		Weigthed Average:												
	3590.998		70.73	70.15	69.57	69.00	68.44	67.88	67.32	66.76	66.21	...	52.92	52.4	51.9

Figure 7.7: WASP % results of Route 2 reversed for all way-points and weighted average calculation (Own Figure)

7.4 Route 3: Algeciras - Hong Kong

On this route, the wind comes from the aft direction, which explains the presence of null and negative values in the wind measurement. Furthermore, the availability of wind is limited compared to, for example, Route 2, which mainly crosses open sea areas. Contrary to Route 2, Route 3 crosses areas such as the Suez Canal and the Mediterranean, known to be relatively calm in terms of wind. The detailed analysis of the way-points in this route is displayed in Figure 7.8. The total 104 way-points are accounted for the weighted average even though they are hidden from this figure.

WP	Distance (NM)	TWA	Speed (knots)												
			11.96	12.07	12.19	12.30	12.42	12.53	12.65	12.76	12.87	...	23.58	23.68	23.79
			WPS %												
1	11.61	42.02	-11.4	-11.3	-11.1	-10.9	-10.7	-10.6	-10.4	-10.3	-10.1	...	-3.22	-3.19	-3.16
2	97.97	107.78	-7.28	-7.1	-6.92	-6.75	-6.58	-6.42	-6.26	-6.11	-5.96	...	0.59	0.61	0.64
4	97.97	84.22	-6.93	-6.8	-6.66	-6.53	-6.41	-6.29	-6.17	-6.05	-5.94	...	-0.96	-0.94	-0.92
7	97.97	83.60	-6.14	-6.01	-5.89	-5.77	-5.65	-5.54	-5.43	-5.32	-5.22	...	-0.63	-0.61	-0.6
8	97.97	111.74	0.08	0.19	0.3	0.41	0.52	0.62	0.72	0.82	0.92	...	4.5	4.51	4.52
11	91.70	116.77	2.06	2.16	2.27	2.37	2.46	2.56	2.65	2.74	2.82	...	5.79	5.8	5.8
12	91.70	72.91	-11.3	-11.1	-10.9	-10.7	-10.6	-10.4	-10.2	-10.1	-9.93	...	-2.96	-2.94	-2.91
13	91.70	98.26	-8.52	-8.34	-8.16	-7.99	-7.83	-7.67	-7.52	-7.36	-7.22	...	-0.63	-0.6	-0.57
22	91.70	129.22	4.15	4.26	4.36	4.46	4.55	4.65	4.74	4.83	4.91	...	7.53	7.53	7.53
23	39.38	54.67	-8.34	-8.19	-8.04	-7.9	-7.76	-7.63	-7.5	-7.37	-7.25	...	-1.75	-1.73	-1.71
28	17.81	50.91	-9.55	-9.39	-9.23	-9.08	-8.93	-8.78	-8.64	-8.5	-8.37	...	-2.31	-2.29	-2.26
29	9.34	107.86	-3.83	-3.68	-3.53	-3.39	-3.26	-3.12	-2.99	-2.87	-2.74	...	2.37	2.38	2.4
30	3.68	61.22	-8.41	-8.26	-8.11	-7.97	-7.83	-7.7	-7.56	-7.43	-7.31	...	-1.73	-1.71	-1.69
31	13.84	48.48	-9.21	-9.05	-8.89	-8.74	-8.6	-8.46	-8.32	-8.18	-8.05	...	-2.18	-2.16	-2.13
32	3.71	353.40	-15.1	-14.9	-14.7	-14.5	-14.3	-14.1	-13.9	-13.8	-13.6	...	-4.92	-4.89	-4.85
33	77.73	71.83	-8.25	-8.1	-7.95	-7.8	-7.67	-7.53	-7.4	-7.27	-7.15	...	-1.58	-1.56	-1.54
34	77.73	145.43	7.75	7.84	7.93	8.02	8.1	8.18	8.26	8.34	8.41	...	10	10	10.03
40	92.16	98.00	-5.22	-5.08	-4.94	-4.81	-4.68	-4.55	-4.43	-4.31	-4.19	...	0.89	0.91	0.93
41	92.16	83.69	-7.79	-7.65	-7.5	-7.36	-7.23	-7.1	-6.97	-6.85	-6.73	...	-1.32	-1.3	-1.28
52	65.88	2.24	-15.2	-15	-14.8	-14.6	-14.4	-14.2	-14	-13.8	-13.6	...	-4.92	-4.89	-4.85
53	70.18	345.13	-12.4	-12.2	-12	-11.9	-11.7	-11.5	-11.4	-11.2	-11.1	...	-3.93	-3.9	-3.87
54	97.63	36.83	-5.63	-5.52	-5.41	-5.3	-5.2	-5.1	-5	-4.91	-4.81	...	-0.83	-0.82	-0.8
63	97.63	80.69	-7.45	-7.31	-7.17	-7.04	-6.91	-6.78	-6.65	-6.53	-6.42	...	-1.19	-1.17	-1.15
64	97.63	92.49	-7.48	-7.33	-7.18	-7.04	-6.9	-6.76	-6.63	-6.5	-6.37	...	-0.76	-0.74	-0.72
77	96.57	89.64	-6.32	-6.19	-6.06	-5.94	-5.83	-5.71	-5.6	-5.49	-5.39	...	-0.69	-0.67	-0.65
88	92.82	27.33	-13	-12.8	-12.6	-12.4	-12.2	-12	-11.9	-11.7	-11.5	...	-4.02	-3.99	-3.96
89	94.98	143.71	1.27	1.42	1.56	1.69	1.82	1.95	2.07	2.19	2.31	...	6.45	6.46	6.47
98	94.98	90.84	-4	-3.9	-3.8	-3.7	-3.61	-3.52	-3.43	-3.35	-3.26	...	0.38	0.4	0.41
99	94.98	86.95	-4.1	-4	-3.9	-3.81	-3.72	-3.63	-3.54	-3.46	-3.37	...	0.19	0.2	0.21
100	84.50	112.20	4.07	4.15	4.22	4.29	4.35	4.42	4.48	4.55	4.61	...	6.37	6.37	6.37
104	84.50	103.91	1.68	1.76	1.83	1.91	1.98	2.05	2.11	2.18	2.25	...	4.5	4.51	4.51
	Total:		Wighted Average:												
	8,570.72		-3.37	-3.25	-3.12	-3.00	-2.88	-2.77	-2.66	-2.55	-2.45	...	1.84	1.86	1.87

Figure 7.8: WASP % results of Route 3 detailed for all way-points and weighted average calculation (Own Figure)

Additionally, it should be noted that the vessel in question is large and requires considerable thrust force. The multiple rigid sails installed on the vessel also add weight and generate additional resistance that must be overcome. It is therefore clear that on this route it would be more appropriate to consider the installation of lighter and more versatile technology.

Higher speeds are required to make the use of these sails cost-effective in terms of efficiency, but this in turn significantly increases fuel consumption. It is therefore proposed to test this same configuration on another route to assess its performance and determine whether it is more viable.

The reverse route is not analyzed for Route 3 because this combination is not optimal and the studied wind profiles do not affect the route. It has been decided that no further analysis should be developed.

7.4.1 Special routes for KCS

A KCS container ship is simulated with 8 rigid sails like in Route 3 but changing the origin and destiny ports. On one hand, the results in Figure 7.9 show this service going from Antwerp to New York and crossing the Atlantic. The connection between these two ports displays a suitable environment for this technology to excel and can replicate a reasonable route given the current commercial synergies worldwide.

WP	Distance (NM)	TWA	Speed (knots)												
			14.10	14.20	14.30	14.40	14.50	14.60	14.70	14.80	14.90	...	24.80	24.90	25.00
			WPS %												
1	0.54	159.63	27.8	27.6	27.4	27.21	27.02	26.84	26.67	26.5	26.33	...	16.62	16.56	16.51
2	2.16	213.989	26.2	26	25.81	25.62	25.45	25.27	25.1	24.94	24.78	...	15.53	15.48	15.43
3	3.37	235.436	21.1	20.94	20.78	20.62	20.47	20.32	20.18	20.04	19.91	...	12.3	12.26	12.22
4	5.58	296.683	8.32	8.23	8.14	8.05	7.97	7.89	7.81	7.74	7.66	...	3.71	3.69	3.67
5	9.89	280.323	6.72	6.65	6.59	6.52	6.46	6.39	6.33	6.28	6.22	...	3.13	3.12	3.1
6	8.11	125.633	17.36	17.23	17.11	16.99	16.88	16.77	16.66	16.55	16.45	...	10.52	10.48	10.45
7	1.13	303.171	5.59	5.53	5.48	5.42	5.37	5.31	5.26	5.21	5.16	...	2.5	2.49	2.47
8	4.90	329.401	3.28	3.24	3.21	3.17	3.14	3.1	3.07	3.04	3.01	...	1.32	1.31	1.31
9	11.22	261.883	9.22	9.14	9.07	9	8.93	8.86	8.79	8.73	8.67	...	5.22	5.2	5.19
10	6.43	257.872	11.99	11.89	11.79	11.69	11.6	11.51	11.43	11.34	11.26	...	6.79	6.77	6.75
11	1.14	20.7307	2.99	2.95	2.91	2.88	2.85	2.81	2.78	2.75	2.72	...	1.11	1.1	1.09
12	27.88	277.346	8.58	8.49	8.4	8.32	8.23	8.15	8.07	8	7.92	...	3.94	3.92	3.9
13	34.35	283.697	13.4	13.25	13.1	12.96	12.82	12.68	12.55	12.42	12.3	...	5.83	5.8	5.77
14	53.43	334.764	6.12	6.04	5.97	5.9	5.84	5.77	5.71	5.64	5.58	...	2.43	2.41	2.39
15	76.00	324.547	7.65	7.57	7.48	7.4	7.31	7.23	7.16	7.08	7.01		3.18	3.16	3.14
16	14.39	56.2842	12.14	12	11.87	11.74	11.61	11.48	11.36	11.25	11.13	...	5.19	5.16	5.14
17	5.12	60.1169	11.8	11.66	11.53	11.41	11.28	11.16	11.05	10.93	10.82	...	5.09	5.06	5.04
18	82.49	244.317	22.56	22.36	22.17	21.99	21.81	21.64	21.47	21.31	21.15	...	12.47	12.43	12.38
19	72.87	298.742	14.26	14.09	13.93	13.78	13.63	13.48	13.34	13.2	13.06	...	6.07	6.03	6
20	72.87	296.022	13.42	13.26	13.11	12.97	12.83	12.69	12.56	12.43	12.3	...	5.76	5.73	5.7
21	93.18	264.895	13.96	13.82	13.68	13.54	13.41	13.29	13.16	13.05	12.93	...	6.9	6.87	6.84
22	93.18	270.011	12.33	12.19	12.05	11.92	11.79	11.67	11.54	11.43	11.31	...	5.45	5.42	5.4
35	99.33	296.552	10.34	10.23	10.11	10.01	9.9	9.8	9.7	9.6	9.51	...	4.54	4.51	4.49
37	99.33	303.401	8.66	8.57	8.48	8.38	8.3	8.21	8.13	8.05	7.97	...	3.8	3.77	3.75
43	90.51	350.216	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	...	0	0	0
44	90.51	354.776	0	0	0	0	0	0	0	0	0	...	0	0	0
45	86.52	298.481	4.72	4.67	4.62	4.57	4.53	4.48	4.44	4.4	4.36	...	2.14	2.13	2.12
54	43.08	272.168	3.05	3.02	2.99	2.96	2.94	2.91	2.89	2.86	2.84	...	1.46	1.45	1.44
55	4.05	227.687	11.82	11.75	11.68	11.61	11.55	11.48	11.42	11.36	11.3	...	7.71	7.69	7.67
56	0.96	304.371	3	2.97	2.94	2.91	2.88	2.85	2.82	2.8	2.77	...	1.32	1.31	1.31
57	0.37	334.135	1.28	1.27	1.25	1.24	1.22	1.21	1.19	1.18	1.16	...	0.42	0.41	0.41
	Total:		Weigthed Average:												
	3591		9.11	9.01	8.91	8.82	8.73	8.64	8.55	8.47	8.38	...	4.069	4.048	4.027

Figure 7.9: WASP % results of KCS and 8 rigid sails detailed for all way-points from Antwerp-NY

No negative percentages are shown in this scenario and only way-point 44 displays 0 contribution to the thrust from the WASP technology. This proves that the only issue was the combination of technology and the route, as assumed.

Furthermore, WASP percentages are still relatively low so the KCS configuration is also simulated in the North Atlantic route, from Rotterdam to Trondheim. This route is just for study purposes because a container ship this big would never sail from Rotterdam to Trondheim but the wind conditions are believed to be similar for other northern services that could be studied if interested. As presented in Figure 7.10 up to a 33% in this route is obtained if optimized appropriately.

WP	Distance	TWA	Spped (kntos)											
			14.10	14.20	14.30	14.40	14.50	14.60	14.70	14.80	14.90	...	24.80	24.90	25.00
	(NM)		WASP %												
1	29.23	243.63	23.39	23.19	22.99	22.8	22.62	22.44	22.26	22.09	21.93	...	12.89	12.85	12.8
2	69.35	188.48	30.45	30.22	30.01	29.79	29.59	29.39	29.2	29.01	28.83	...	18.1	18.04	17.99
3	54.15	175.63	38.75	38.45	38.16	37.87	37.6	37.33	37.07	36.82	36.57	...	22.34	22.26	22.18
4	91.82	210.21	36.39	36.1	35.82	35.54	35.27	35.01	34.76	34.51	34.27	...	20.66	20.58	20.51
5	91.82	207.88	37.13	36.84	36.55	36.27	35.99	35.73	35.47	35.22	34.98	...	21.1	21.02	20.95
6	91.82	219.91	35.49	35.2	34.91	34.63	34.36	34.1	33.85	33.6	33.36	...	19.82	19.75	19.68
7	37.47	233.06	32.2	31.91	31.64	31.38	31.12	30.87	30.63	30.39	30.16	...	17.54	17.48	17.41
8	89.82	198.59	39.74	39.42	39.11	38.82	38.53	38.25	37.97	37.71	37.45	...	22.63	22.55	22.47
9	89.82	179.74	40.99	40.67	40.36	40.06	39.76	39.48	39.2	38.93	38.66	...	23.47	23.39	23.3
10	81.30	120.34	30.98	30.7	30.43	30.16	29.91	29.66	29.41	29.18	28.95	...	16.52	16.45	16.39
11	40.16	95.16	13.93	13.79	13.65	13.52	13.39	13.26	13.14	13.02	12.9	...	6.9	6.87	6.84
12	10.53	109.19	13.05	12.95	12.86	12.76	12.67	12.58	12.49	12.41	12.33	...	7.73	7.71	7.68
13	9.28	135.26	24.83	24.64	24.45	24.27	24.1	23.93	23.76	23.6	23.44	...	14.53	14.48	14.43
14	37.24	119.80	25.58	25.36	25.15	24.94	24.74	24.54	24.35	24.16	23.98	...	14.1	14.05	14
15	0.82	107.13	17.01	16.86	16.72	16.58	16.45	16.32	16.19	16.07	15.94	...	9.4	9.37	9.34
16	1.54	16.29	2.52	2.48	2.45	2.42	2.39	2.36	2.33	2.3	2.28	...	0.86	0.86	0.85
17	1.40	355.46	0	0	0	0	0	0	0	0	0	...	0	0	0
18	2.40	15.43	2.32	2.29	2.26	2.23	2.2	2.17	2.14	2.12	2.09	...	0.77	0.77	0.76
19	3.27	33.60	6.34	6.26	6.19	6.12	6.05	5.99	5.93	5.86	5.8	...	2.62	2.61	2.59
20	5.89	29.09	5.45	5.38	5.32	5.26	5.2	5.14	5.09	5.03	4.98	...	2.21	2.19	2.18
21	2.26	70.67	10.42	10.3	10.19	10.08	9.98	9.87	9.77	9.68	9.58	...	4.62	4.59	4.57
22	5.93	331.09	5.47	5.41	5.34	5.28	5.22	5.17	5.11	5.06	5	...	2.22	2.2	2.19
23	4.71	314.05	8.52	8.42	8.33	8.24	8.15	8.06	7.98	7.9	7.82	...	3.64	3.62	3.6
	Total:		Wighted Average												
	852.04		**32.78**	**32.52**	**32.26**	**32.00**	**31.76**	**31.52**	**31.29**	**31.06**	**30.84**	**...**	**18.46**	**18.39**	**18.33**

Figure 7.10: WASP % results of KCS and 8 rigid sails detailed for all way-points Rotterdam - Trondheim(Own Figure)

8 Business Case

As additional validation, some economic analysis is carried out in order to assess the profitability and feasibility of the project. This evaluation will be executed by simulating total costs and incomes over 25 years, accounting for fluctuation of prices but keeping the same fuel consumption and emissions released that have been previously calculated for a year of service. The approach taken is the Net Present Value, calculated for both the Base Case and the WASP scenario, in order to analyze the benefits between them.

These calculations will be executed by simulating the services during one year and therefore keeping the assumption that a commercial vessel is sailing on average 260 days per year [72]. As presented in the previous section, this corresponds to approximately 87, 24, and 12 trips respectively in each of the case studies. Total costs obtained for a single one-way journey will be multiplied by this number to calculate the total costs in one year.

Before starting, it is worth mentioning that all parameters used are highly dependent on the direction of trade. With respect to economical parameters, several studies have shown that cost and freight rates depend on the selected origin and destiny ports [79]. Given the intrinsic difficulty of global trades and price fluctuations, this analysis has only considered the global averages presented below. Furthermore, thrust obtained from the WASP technology will also undoubtedly change depending on the direction of the travel, as the performance outcomes are different depending on the TWA, heading... etc. that affect their interactions with the wind. Another general assumption is to consider one-way journeys as defined in the case studies of previous chapters rather than the back-and-forth service they are probably completing. The returning voyage to the origin port is left out of scope since it composes a completely different configuration, hence a new case study.

8.1 Net Present Value

The Net Present Value (NPV) is a calculation used to understand how much an investment is worth throughout its life taking into consideration the time value of money, meaning that future cash flows are discounted to today's value. This calculation is generally used to determine the profitability of an investment [96].

On one hand, its main advantage over other investment calculations is that it considers the time value of money, based on the principle that the value of a dollar today is worth more than its value in the future. Thanks to this consideration, inflation can be taken into account, unlike some other analyses such as the payback period. On the other hand, one of its main disadvantages is that it requires accurately assessing the future cash flows.

Essentially, the NPV can be interpreted as follows:

- A positive NPV represents a profitable and a worth-pursuing investment
- While a negative NPV represents a project that is unlikely to be profitable and its pursuit should be questioned.

It can be simply calculated as follows:

$$NPV = \sum_{t=1}^{T} \frac{CF_t}{(1+i)^t} - IInv \tag{8.1}$$

Where:

- CF_t: cash flow in each of the periods, they represent the total money earned in each period (profit in each period). They will be calculated as total income minus total costs.
- i: it is the rate of interest that is used to discount all future cash flows. It represents the time value of money and the rate of return that companies expect from their investments. This can be seen as one of the drawbacks of the NPV calculation, since first a specific discount rate (which might not always be available) must be selected and it is then assumed to remain constant during the whole lifetime of the project (which might not always be true). In this project, this discount rate has been assumed to be 3%.
- t: it represents the number of periods that the project lasts for, which has been defined as 25 years to represent the average lifetime of a vessel. T represents the last year considered in the project, which will be 25 years.
- IInv: it represents the initial investment at the beginning of the project in USD.

8.1.1 Calculation of costs over the time periods

All the costs that have been considered as input here certainly depend on the moment of time in which the analysis is carried out, and therefore this variability of the parameters must be accounted for when calculating costs in times different than the present. Due to difficulties in finding future trends for specific costs, an average of the respective values over the last five years (2019-2023) has been used in future cash flows. Even though the impact of COVID-19 and the war in Ukraine are reflected in these values, this has been found to be the most accurate way of estimating future costs. These averaged values have been assumed to remain constant in all the periods.

The costs accounted for are the same as presented in the previous sections except for the operating costs, since these will have the same value in both the WASP scenario and the Base Case. Emissions and fuel consumption at the port and their associated costs will also not be accounted for, as they will be equal in both scenarios. The sources for each of the parameters used and the final considered value are presented here:

- Fuel consumption: the cost of the MGO has undoubtedly varied during the last few years and will indeed keep varying. Values of the fuel price over these last five years have been obtained from the database found in ShipBunker for the port of Hong Kong [41]. It has been obtained from a different source than the one that was mentioned in Section 4.4.1 because the former did not show historical data. These prices change depending on the port of origin, and the corresponding ones have been considered in each of the case studies, as can be seen in Table 8.1 expressed in \$/tonne of fuel [41]. The final averaged values that have been used for the calculations can be seen in the last column.

Port of origin	2019	2020	2021	2022	2023	Final averaged value
Rotterdam	984	329	578	1,317	689	779.39
Antwerp	970	344	635	1,501	739	837.8
Hong Kong	846	399	611	1,359	687	780.4

Table 8.1: Average fuel prices in \$/tonne in each port over the years

- Carbon emissions: the carbon price has been directly obtained from trading economics, and the trend of this price can be seen in Figure **??** [97]. The averaged value considered in this analysis can be seen in the last column in Table 8.2 in \$/tonne of CO_2. This value is assumed to be equal in all three case studies.

Figure 8.1: Fluctuation of the carbon price.

	2019	2020	2021	2022	2023	Final averaged value
Carbon price [\$/tonne CO_2]	22.79	22.21	54.23	77.89	93.56	54.135

Table 8.2: Average carbon prices over the years

- Inventory costs of the cargo: the CIF value of the cargo that is being transported also fluctuates with time and this trend also needs to be captured in the analysis. These values have been obtained from the same source that was shown in Section 4.4.1 [86] [87] [83], and values considered for each of the cargo being transported and the final averaged values included in the calculations can be seen in Table 8.3, all of them expressed in \$/tonne of cargo.

Cargo	2019	2020	2021	2022	2023	Final averaged value
Crude oil	532.25	631.02	1,238.26	1,636.26	927.5	993.19
Iron ore	111.94	105.64	213.43	127.87	112.65	134.31
Industrial products	19,873.95	18,755.44	37,892.59	22,702.17	20,000	23,844.83

Table 8.3: Average CIF values of the cargo over the years in \$/tonne of cargo

- Initial investment: the initial investment is essentially represented by the CAPEX, and these costs will only be borne in the first year. There is therefore no need to analyze how this cost fluctuates over time, and it has been set to the value shown in Section 4.4.1.
- Maintenance cost of the WASP technology: this cost has been assumed once a year, which is the reason why it has not been included in the previous analysis, as all of them have been carried out for a maximum time span of one year. It however needs to be included in this analysis, as here the costs will be calculated over 5 years. It has been assumed to remain constant over the 5 years, with a total value of 50000 $/year [98].

With respect to the fuel consumption, emissions released, and time spent sailing, these values have been defined as the results obtained from the validation analysis previously presented, both for the WASP scenario and for the Base Case, as these are annualized values and will be more representative than the results presented in Section 5. It is worth mentioning that the results that have been used are the ones obtained when minimizing costs and without including JIT, as the objective of this study is to analyze the economical viability of the WASP technology and not the one of implementing the JIT methodology. Moreover, the results of both the first and the second case study correspond to after implementing the propeller efficiency. The results of the Base Case correspond to the speed for which the optimal results are obtained in the WASP scenario, in order to compare situations that are as similar as possible.

It is important to mention that these consumption, emissions, and time are route-dependent, as they have directly been obtained from the routes simulated in the case studies. These will of course will not be representative of all routes around the world, as one specific vessel will not only sail one specific route over a year but calculations have been based on these consumption due to a lack of other input data.

Fuel consumption, emissions, and time have however been assumed to remain constant throughout the 25 years, and they can be seen in Table 8.4. The difference between the consumption in the Base Case and the WASP scenario can be noticed. It is also identified how the total sailing time remains the same due to equal speed. Total costs per trip are calculated as per the following equation to then be multiplied by the total number of trips per year and capture annual costs, including the maintenance costs once per year and the CAPEX in t=0 (only for the WASP scenario). Again, all the costs shown here are the averaged values of the last 5 years, and operating costs have not been considered because they are equal in both scenarios.

$$C_T = FC \cdot F_p \ + E \cdot C_p + h \cdot Total\ time \tag{8.2}$$

$$C_{T.year} = C_T \cdot Number\ of\ trips \tag{8.3}$$

Where:

- C_T is the total cost in USD per trip
- $C_{T.year}$ is the annual total cost in USD.
- FC is the fuel consumption per trip in tonnes of fuel.
- F_p is the fuel price in USD/tonne of fuel (average).
- E is the emissions released per trip in tonnes of CO_2.

- C_p is the carbon price in USD/tonne of CO_2 (average).
- h is the inventory holding costs in USD/hour of trip (average).

	Trondheim - Rotterdam	**Antwerp - New York**	**Hong Kong - Algeciras**
Fuel consumption WASP scenario [tonnes fuel]	250.22	269.13	7,150
Fuel consumption Base Case [tonnes fuel]	308.19	348.12	7,178
Emissions released WASP scenario [tonnes CO_2]	778.17	837	22,238
Emissions released Base Case [tonnes CO_2]	958.47	1,082.66	22,323
Total time [hours]	66.69	360	365

Table 8.4: Average fuel, emissions and sailing time per trip

Coincidentally, the fuel consumption for Antwerp-New York looks very similar to Rotterdam-Trondheim for a much longer trip. The reason for this is that the KVLCC2 simulated in the first case study has an MCR of 32MW while the bulk carrier for this case study has an MCR of 9MW. The KVLCC2 is a much bigger vessel, thus the higher fuel consumption. Plus, the resistance of the calm water of the KVLCC2 is higher, reaching up to 25kN in comparison to the bulk carrier corresponding to 1.5kN.

For the NPV calculations, there is a need to compute the per-year values, so they are collected in the following Table 8.5.

	Trondheim - Rotterdam	**Antwerp - New York**	**Hong Kong - Algeciras**
Fuel consumption WASP scenario [tonnes fuel]	21,769.14	6,459.12	85,800
Fuel consumption Base Case [tonnes fuel]	26,812.53	8,3548.88	68,658
Emissions released WASP scenario [tonnes CO_2]	67,700.79	20,088	266,856
Emissions released Base Case [tonnes CO_2]	83,386.89	25,968	213,526.80

Table 8.5: Average fuel and emissions in a year

8.1.2 Calculation of incomes over the time periods

The total income of one journey has been calculated differently for each of the case studies given the data availability for each of the types of vessels and routes. The first and second case study have been calculated in the same way, using the average earnings for the specific types of vessels, while the third has been calculated using the container freight rate. Again, future earnings have been obtained using the averaged values of the last 5 years,

Data on average earnings per day of a tanker can be glimpsed in Figure 8.2, while the ones corresponding to a bulk carrier are collected in Figure 8.3 [89] [99]. The average value of the earnings of a tanker over the last five years is 2,375 $/hour, while one of the bulk carriers is 2,460 \$/hour. Total average earnings per trip have then easily been calculated by multiplying these hourly earnings by the total sailing time, and total average earnings per year have been calculated using the estimated number of annual trips.

It is worth mentioning that, to account for the deck weight consumed by the WASP technology, the total earnings in the WASP scenarios have been reduced by the percentage of the WASP technology's weight out of the total payload of the vessel.

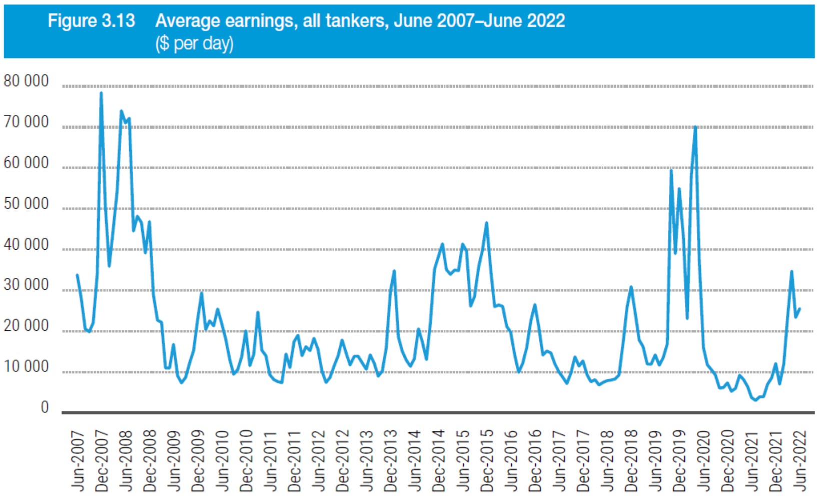


Figure 8.2: Global Tanker Index Rates
[89]

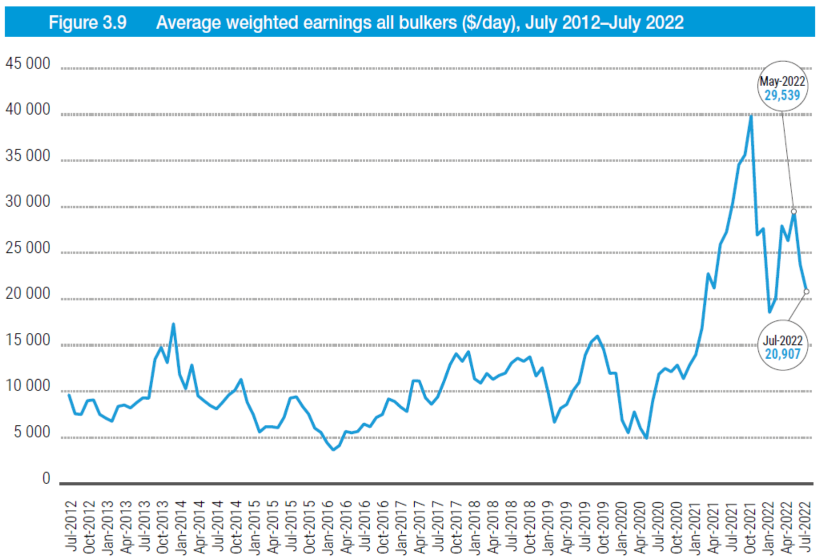


Figure 8.3: Global Bulk Carrier Index Rates
[89]

On the other hand, the total income of one journey of the third case study has been simply calculated as seen in Equation 8.4. Total income in one year has been calculated by multiplying the income in one journey by the total number of trips per year.

$$Inc = Payload \cdot s_r \tag{8.4}$$

Where:

- payload is the maximum cargo weight capacity of the vessel. Again, this has been assumed to be approximately 95% of the vessel's deadweight, and the weight of the WASP technology has been subtracted from the total cargo weight capacity. It has also been assumed that one TEU carries approximately 24 tonnes of cargo, which translates into the KCS having a total container capacity of 2,100 TEUs [100].
- s_r is the current freight market price at which the shipper pays to have their cargo shipped.

The freight rates have been defined as exogenous, meaning that they are dictated by the supply and demand of the cargo and are out of the operator's control [79]. Moreover, these have also shown fluctuations mainly due to the COVID pandemic as shown in Figure 8.4. The freight rate used here is the Shanghai Containerized Freight Index (SCFI) from Shanghai to Europe, expressed in $/TEU. The final average value of this freight rate is 4,184$/TEU.

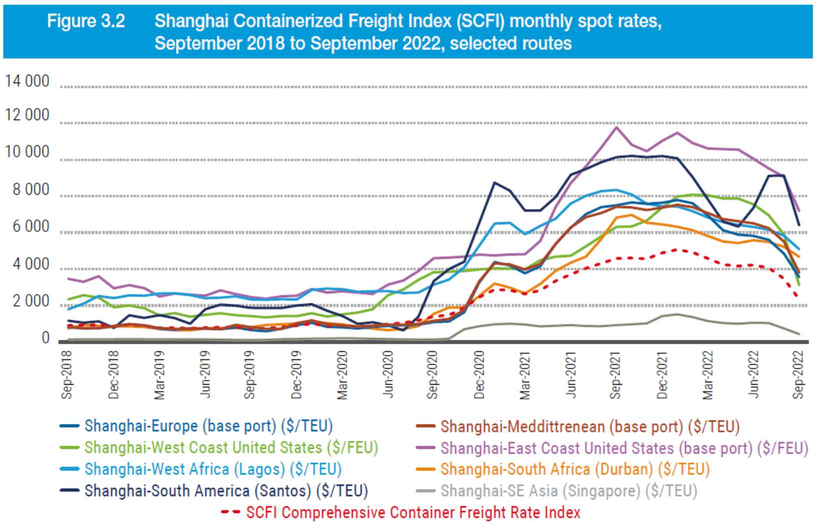


Figure 8.4: Global Container Index Rates in $/TEU [89]

8.1.3 NPV results

In a preliminary overview, it is expected to have the main differences between the Base Case and the WASP scenarios in the fuel consumption and emissions released and their associated costs, which will both be higher in the Base Case; and in the CAPEX and maintenance costs of the WASP technologies, which will not be included in the Base Case. Next, the income in the WASP scenarios will be slightly lower than in the Base Case, as the added weight of the WASP technology will limit the cargo capacity of the vessel.

Finally, the total profit in each year is calculated in the present time with equation 8.1, both for the WASP scenario and for the Base Case. The difference between the Base Case's NPV and the WASP's can be seen in Table 8.6.

	NPV difference Base Case - WASP [M$]
Rotterdam - Trondheim	73.52
Antwerp - New York	18.86
Hong Kong - Algeciras	-4,922.44

Table 8.6: NPV difference for each of the case studies in M$

Taking into consideration what has been explained above, all the positive NPVs represent profitable and worth pursuing investments, and therefore a positive difference between the Base Case's NPV and the WASP's will represent a project where the installation of the WASP technology is promising. It can then be concluded that installing the WASP technology in both the first and second case study will lead to cost savings, as has already been presented above.

Concerning the third case study, it was expected that it would not lead to cost savings, given what has been discussed about the route not having good wind conditions and the remarkable weight of the WASP technology. Even though fuel consumption and emissions are slightly lower in the WASP scenario compared to the Base Case, it can be seen that these solutions are obtained for the maximum speed, which means that the vessel would need to always sail at this maximum speed to obtain savings, which is not realistic. Consequently, the NPV of this case study shows that this will probably not be a profitable investment.

Comparisons between the NPV of the different case studies should not be made regarding which one of them seems more reasonable, as it is important to keep in mind that they use different types of vessels transporting different cargo and using different WASP technologies. The only conclusion that should be drawn from these results is that both the first and the second case study seem to be profitable investments since they show a positive NPV difference when compared to their respective Base Cases. A higher difference in the first case study than in the second one might probably mean that installing the selected WASP technology in the first route and with the selected type of vessel will be more profitable than what is presented in the second case study, but further in-depth calculations should be executed to prove this point.

Moreover, it must be kept in mind that several simplifications regarding neglected costs (such as the propeller maintenance costs), neglected forces (such as the side forces), or assumed fixed consumption and emissions released over the years have been done for the sake of simplicity, which also reassures the idea that these results should not be taken literally. These results have also been shown to be route-dependent, and therefore the conclusions obtained should not be generalized to different case studies.

Consequently, a more detailed profitability analysis should be executed if more thorough results are sought, but these results can be taken as good signs of how implementing WASP technologies in two out of the three cases studied does not bear impressive supplementary costs, which has been proven to be one of the main concerns of the stakeholders. Furthermore, additional profit from using WASP technologies could be achieved once these technologies are further developed and benefits from emissions trading systems can be obtained.

9 Discussion

Rarely has the importance of maritime logistics for trade and development been more evident than during the last year. Historically high and volatile freight rates, congestion, closed ports, and new demands for shipping following COVID-19 and the war in Ukraine have all had measurable impacts on people's lives. With ships carrying over 80% of the global trade volume, higher shipping costs and lower maritime connectivity lead to higher inflation, shortages of food, and interruptions of supply chains – all of which are among the features of the current global crisis [89].

Concretely, higher grain prices and dry bulk freight rates in early 2022 contributed to a 1.2% increase in consumer food prices. Container ships spent 13.7% longer in ports in 2021 compared to 2020, exacerbating delays and shortages. During the last year, total GHG emissions from the world's fleet increased by 4.7% [89]. so it is evident that actions need to be taken while new waves are yet to come.

This thesis has been the result of arduous research and analysis work on WASP technologies, the implementation of a JIT protocol, and a multilateral framework for decarbonizing maritime transport to reduce uncertainty for policymakers and industry alike. Throughout this study, various aspects related to sustainability in naval logistics have been addressed, to deepen existing knowledge and bring new perspectives to the field.

The primary purpose of this final discussion is to evaluate the contribution of this thesis to the field of WASP technologies, highlighting the main achievements and limitations of the work carried out. It will also seek to establish connections between the findings and the KPIs identified for evaluation. Besides, new questions and issues arising from the results obtained will be uncovered, thus opening the door to future research.

In addition, the limitations of the study will be addressed, as possible sources of error or bias might have influenced the results. This will allow for a critical and objective view of the research conducted.

This research could have explored any of the unknown parameters that have appeared in the report and exploited them, ending in a completely different approach. The WASP implementation and deployment of new technologies is such a broad topic that the path is marked by constant trial and error, and with the guidance of supervisors, it has culminated in the analysis presented here. If any interested academic would wish to follow this approach at a different point in time it can be concluded that other aspects should be prioritized rather than neglected, hence the open-research method implemented.

To address the first proposed objective in the introduction, little information was found on the current wind-related regulations in the shipping industry. While there are a variety of MBMs established by the IMO to decarbonize the shipping sector, as well as efficiency indices such as the EEDI and the CII, it is clear that more drastic measures are required if the IMO is to achieve its sustainability and emission reduction targets for 2030 or 2050.

In the future, when stronger regulations such as the EU ETS start being implemented for excessive emissions, these will need to be added to the scope to narrow the scenarios. This project only tries to simulate a limit on carbon emissions by setting a carbon price, since the EU ETS has very specific and complex requirements depending on the route to be implemented in a general analysis such as the one executed in this project.

A major opportunity is identified for WASP technologies in shipping. Although it is an emerging and still developing technology, its potential can be glimpsed. Those actors who decide to adopt this technology will face a steep learning curve, as an extensive testing phase is still required. However, once optimal operation is achieved, WASPs could reduce emissions on routes with favorable winds by up to 90%. It is worth mentioning that the remaining 10% would be for maneuvering in and out of port, where the near-shore wind strength may not be sufficient, or the maneuverability required would not be adequate to rely solely on WASPs as they do not give the liberty some of these operations require.

Moreover, engines, hull design, materials, and other related aspects have been under optimization and development for years, and there is little scope for significant large-scale improvements in these aspects without external technologies. The majority of current emissions come from the consumption and burning of fuels, and reducing dependence on fuels is a priority. While various biofuels have been investigated as possible solutions, this alternative still has the problem of being a finite source. Wind, on the other hand, is a renewable and abundant source of energy that can broaden the field of vessel architecture to another level.

Concerning the second objective, an investigation of the available WASP technologies was carried out. The focus is not on a detailed mechanical or architectural study of these technologies, so aspects such as vessel forces, buoyancy, or stability have not been accounted for. However, the analysis of force triangles in a single plane to assess the driving force generated by the wind, the unloading of the engine, and its possible impact on engine life, as well as the analysis of different wind profiles in terms of the level of thrust that can be obtained when sailing in different directions, have been extensively considered. Furthermore, a limitation of this thesis has been the structural requirements of these WASP technologies and the weather routing system that will be later addressed during this discussion.

WASP technologies seem to be a promising solution for accelerating the shipping industry's decarbonization efforts. The status quo of the WASP technological growth within the maritime transport sector reveals that despite the existing limited number of WASP installations, there is a promising trend of diffusion of the technology within the industry, so is that stopping it?

A survey aiming to gather insights from stakeholders in the shipping and logistics sector regarding the potential of wind propulsion in decarbonizing shipping was circulated through social platforms and communication channels. The findings align with the hypothesis that the WASP market is still in its early stages and requires further exploration to fully leverage its potential. It emphasizes the need to navigate this emerging market for innovative technologies, addressing stakeholders' resistance and capitalizing on the advantages of being an early adopter. By understanding the dynamics of the market and managing stakeholders' perspectives strategically, successful implementation and widespread adoption of WASP technology can be facilitated.

Gathering the next two goals together, an analytical model was developed to find the optimal speed of a dual engine and analyze its performance. Several limitations can be further developed in this model and are left as future work. The first and main one is that it is computed to overcome the resistance of calm water. No waves are accounted for in this thesis because scenarios are compared one to another, so the same conditions are assumed in both and they would be compensated. If individual routes and technologies are selected and focused on, then a wind model of up to 6 degrees of freedom like the one in current development under Martina Reche-Villanova's Ph.D. is needed.

Another assumption linked to the above is related to the side forces. These forces have been neglected for the sake of simplicity. They are however responsible for an additional resistance in the whole system and should therefore be accounted for if more realistic studies were to be executed, making it the next logical step. It is noteworthy that Flettner rotors excel at performing with side forces, contrary to what happens with other WASP technologies.

Moreover, an in-depth analysis of how each of the considered costs per hour affects the costs function would also be interesting, to find which one of the costs should be prioritized. WASP technologies can play a significant role in reducing both fuel and emissions, and there is still room for further optimizing them if other costs should be accounted for.

Related to this, one of the current trends in decarbonizing the maritime industry is slow steaming, which ends up in longer sailing times and additional inventory and operating costs. If the functioning of WASP technologies were to be upgraded and to be implemented in commercial vessels instead of practicing slow steaming, sailing times hence inventory and operating costs could be reduced. Given that the main reason for slow steaming is fuel reduction, routes transporting perishable goods such as cherries from Chile would not have to switch to other modes of transport due to their inability to meet the new emissions bounds. Besides, other dangers like piracy due to slower speeds can also be avoided.

Another interesting topic that this model addresses is how each of the WASP technologies will perform differently depending on the wind conditions, and the fourth objective directly tackles this. Computations shown in this project show that Flettner rotors perform better with side forces, while DynaRigs can generate impressive savings when sailing upwind compared to what other WASP technologies can produce. When working under these correct weather conditions, the simulations run by this model have proven that the WASP technologies can generate up to 38% of the total force needed, which can lead to costs and emissions savings of approximately 15%.

A few combinations of how these technologies perform under different wind conditions have been briefly presented, but there is room for a more realistic analysis of how technologies should be combined with wind conditions to find the optimal solution. An interesting finding in this project is that the notable weight of some of the WASP technologies can become a penalty in terms of increased costs and emissions if it is working under poor wind conditions, since it will bring in additional resistance to the system but will not be able to generate enough thrust to compensate for this additional resistance.

Connected to how differently WASP technologies perform depending on the wind conditions, another important topic that could also lead to increased savings when implementing WASP technologies is route optimization, which aims to find the best route legs that will maximize wind conditions. This is directly linked to what has been discussed above, as working with optimal wind conditions will indeed lead to higher savings. This analysis should however be careful in not hugely increasing sailing times at the expense of finding the optimal weather conditions, and a balance between how much the route can be modified and the desirable savings should be defined. It is worth mentioning that the North Atlantic area presents excellent wind profiles, and therefore this should be the place to start when working on route optimization.

Finally, JIT has proven to achieve additional savings both in emissions and in costs when it is implemented in combination with WASP technologies. It is noteworthy that using this methodology will not bear any additional costs and only some communication and coordination between the port and the vessel will be required. Consequently, even though the savings achieved with this methodology are not as impressive as the ones obtained when implementing the WASP technology, they are associated with 0 additional costs and should be considered a very promising decarbonization solution.

10 Conclusion

The model that has been developed in this research project has proved to be useful in analyzing how the implementation of different WASP technologies in large commercial vessels can lead to both savings in costs and emissions and can find the optimal speed that maximizes them. Three different WASP technologies have been simulated, Flettner rotors, DynaRigs, and rigid sails, which have been installed in three commercial vessels, a tanker, a bulk carrier, and a container ship. Even though this model is hugely simplified in terms of mechanical considerations of both the vessels and the installed technologies, it can be used to draw general conclusions on how the logistics of these fittings can be optimized and how the technologies can perform depending on the wind conditions.

Results derived from this model show that cost savings can lead up to 17% and that appropriate technologies mounted on the appropriate vessel under the appropriate wind conditions are indeed crucial in obtaining the optimal deployment. Even though some right combinations of technology and wind conditions have been briefly presented in this project, further in-depth analysis of these optimal combinations is left as future research.

From a management perspective, such a green transition entails significant challenges and transformations for organizations and their strategy, the design of viable business cases, and business models. In addition, an important aspect that deserves study is safety when using these technologies. However, evidence on this subject is still limited, and future studies should focus on a structural safety assessment of each wind technology. This could be complemented by an empirical review of the reliability and durability of the WASP technologies. It is crucial to start bringing WASP technologies out into the market to compare results.

On another note, the JIT is a measure that without initial investment returns a decrease in fuel consumption and emissions. It can reach up to a 6% of savings and the only need for its achievement is a general organization and cooperation within ports, vessels, captains... etc. A structured managerial scheme can be slow to implement but is proven highly beneficial.

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A Sustainable Developgment Goals

The Sustainable Development Goals were adopted in 2015 by the United Nations Member States as a way of calling to action to all countries to achieve a more sustainable and better world. There are 17 goals in total which recognize the importance of collaborating to fight climate change, improve health and education, reduce inequality and trigger economic growth.

The main reason behind this project is to analyze the implementation of renewable energies and technologies to reduce emissions associated with maritime trade, and the research that has been carried out in this project is therefore certainly aligned with the Sustainable Development Goals. Ideally, the results obtained from this project would contribute to bringing innovative and more sustainable technologies one step closer to being implemented in the global maritime trade.

This project relates to the following three main goals, which can be seen in Figure A.1:

- **Goal 13:** Climate Action.
- **Goal 9:** Industry, Innovation and Infrastructure.
- **Goal 14:** Life Below Water.

Figure A.1: Sustainable Development Goals linked to this project.

The main goal linked to this project is Goal n. 13, which is defined as "Take urgent action to combat climate change and its impacts". It has been shown in this project that notable emissions savings can be achieved if WASP technologies are correctly implemented, with these savings reaching up to 17%. These savings in emissions would indeed help in the fight against climate change and would help reduce its impact if these technologies are correctly implemented.

On the other hand, Goal n. 9 is defined as "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation". Thanks to this project, innovative and more sustainable technologies will be one step closer to being implemented in the global maritime trade, as the optimal deployment has been deeply reviewed while carrying out this project. As has been continually discussed and proven in this project, these technologies come with high associated installation costs, but savings both in costs and in emissions should make them profitable and should therefore help in making the industry more sustainable.

There is of course a need for further improving and optimizing these technologies, as they are still on their very early stages of development, but they indeed seem to be promising solutions for helping achieve the IMO targets for 2050. It must be kept in mind that results of the achieved savings are extremely reliant on the wind conditions, which are not always as reliable as we would like them to be, and this is the reason why these technologies must be optimized to generate the desirable results even working under not that favorable conditions.

Finally, this project aims to find an optimal way in which the engines of the vessel and the WASP technology can be combined to reduce the emissions. This will probably imply minimizing the use of the engines and maximizing the output obtained from the WASP technology, which will directly have an impact on the marine ecosystems. By reducing the use of the engines, underwater ecosystems will be less disturbed by noises, vibrations and pollution of the oceans, so this project is also connected to Goal n. 14, whose objective is to "Conserve and sustainably use the oceans, seas and marine resources for sustainable development".