Wind First!

How wind-assisted ship propulsion is the zero-emission fuel for shipping's future

SEAS AT RISK

Contents

Executive Summary

Shipping currently contributes around 3% of global greenhouse gas (GHG) emissions, which is roughly the amount produced by a country the size of Germany, and it is growing. The International Maritime Organization (IMO) now has the opportunity to pave the way for change by prioritising energy efficiency and providing a framework to enable the shipping industry to become climate-neutral – and the solution is wind propulsion. Technologies harnessing wind power, from modern sails to rotor systems, are already available and ready to be deployed, offering an immediate way to cut emissions and reduce reliance on fossil fuels.

The 'Wind First!' study investigates the integration of wind-assisted propulsion (WASP) with statistical weather routing with the aim of reducing ships' fuel consumption and supporting the IMO's GHG emissions strategy to reach full decarbonisation by 2050, with targets along the way: 30% by 2030 and 80% by 2040. This can be done by optimising routes and leveraging favourable winds for greater shipping efficiency and decarbonisation.

This report presents concrete findings and recommendations to ensure that shipping develops within planetary boundaries and to the benefit of people.

Adopting wind assisted propulsion – a true zero emission technology – can help drive the IMO to its zero or near-zero energy goal. Retrofitting existing vessels with two to four suction sails can deliver energy savings of up to two to twelve percent, which will be critical to meet the IMO's 2030 zero to near zero energy target. Wind propulsion is ready and available now.

Wind assisted propulsion can deliver one third of IMO's greenhouse gas emissions reduction target for 2030. Retrofitting vessels offers a proven and immediate solution to reaching the IMO's target of a 30% reduction in emissions by 2030.

Wind Propulsion can save money. The 'Wind First!' report offers many different routes with different vessels, and each has been proven to be financially beneficial. An average round trip from Accra (Ghana) to Shanghai (China) can save up to 105,864 USD for a bulk carrier when retrofitted with 4 sails. That means a yearly saving of nearly half a million US dollars (493,500 USD) per vessel. It is clear that WASP is not only climate-friendly – it is also a smart financial move, freeing-up funds for other investments to complete the transition to decarbonisation.

The shipping sector must phase out fossil fuels and adopt and fund wind propulsion innovation

Strong regulation needs to be adopted and implemented by IMO Member States to clean up the shipping industry and support the transition to decarbonisation must be equitable and just.

> **It is clear that wind-assisted propulsion is not only climate-friendly but also a smart financial move.**

The Carbon Index Indicator (CII)

The CII must be strengthened to drive real emission reductions:

- **Increase Post-2026 Reduction Factors** to CII reduction targets to align with the IMO's decarbonization goals
- **Improve data transparency and integrity:** Include the CII with the IMO Data Collection System (DCS), while making it more public to increase transparency, third-party verification, and public accessibility of emissions data

Global Fuel Standard (GFS)

Ensuring the uptake of truly sustainable marine fuels and incentivising true zero-emission technologies:

- **Adopt/retain a "well-to-wake" (WtW) methodology** which accounts for emissions from the production, transport, and use of fuels, offering a more comprehensive view and ensuring that alternative fuels are compared on a level playing field.
- **Provide a reward factor for wind assisted technology:** this would reward the use of WASP technologies by counting the energy saved from wind propulsion more favorably in the compliance calculation of the GFS. How does it work? The reward factor, a multiplier of 2 would mean that the energy generated and/or saved from WASP would be counted twice when calculating a ship's GHG intensity and fuel usage. This would effectively boost compliance with emissions reduction target. As a result this multiplier acts as an incentive for shipowners/operators to invest in WASP, which in return, accelerates its adoption and plays a critical role in scaling up the technology.
- **Recognise the full impact of fuel choices:** Ensure sustainability criteria respect land rights, food security, the environment, and human health.

Universal Levy

- Support the **adoption of a universal levy** for shipping of at least 150 USD
- Ensure that the revenue mechanism is built in a way that **redistributes the revenues equitably** – necessary to balance the economic impacts of the energy transition
- Ensure that a portion of the revenue is **allocated to funding the development of WASP**

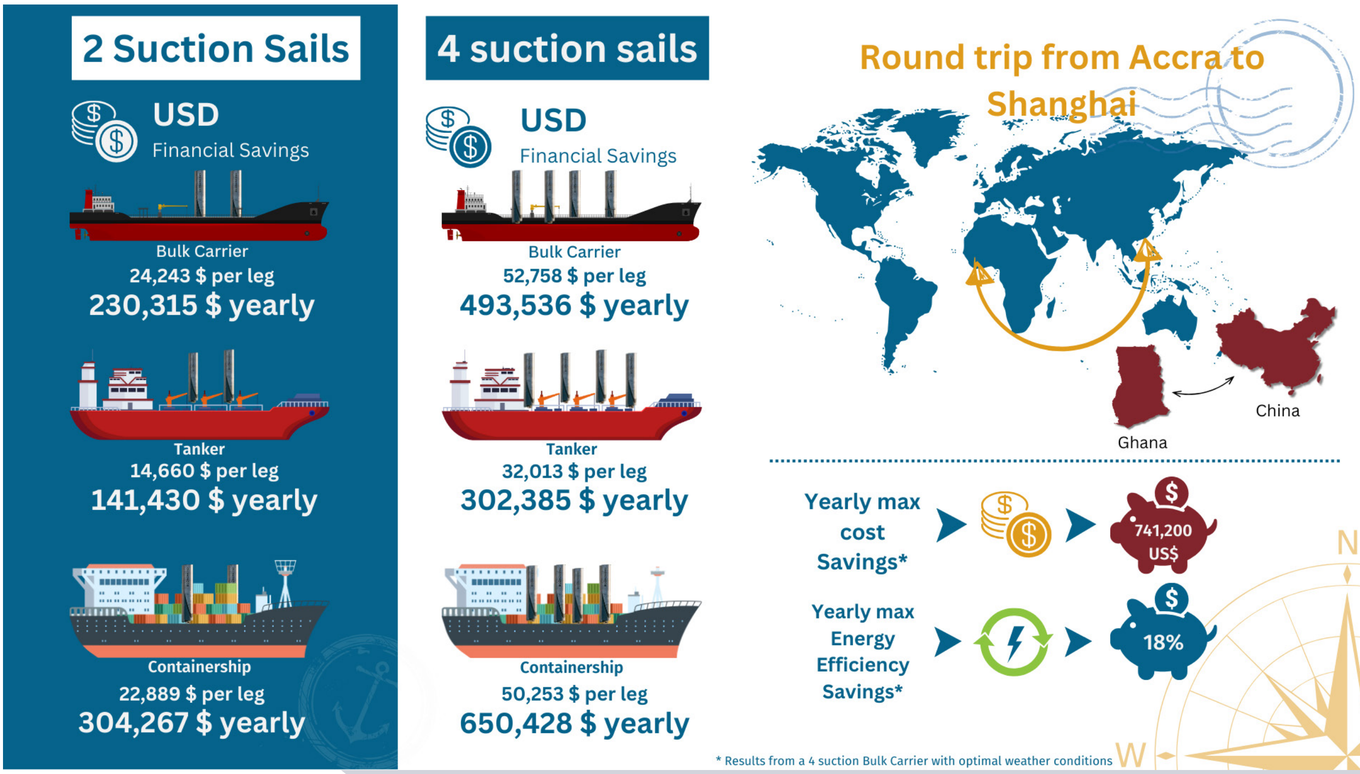
Main results

Case study of the Accra – Shanghai route.

On this route the modelled scenarios were based on three different types of vessels, a Panamax bulker (80,000 DWT), a MR Tanker (50,000 DWT), and a Post-Panamax (125,000 DWT and 14,000 TEU).

The study ran two options of wind assisted propulsion (WASP) per ship, one with 2 suction wings and one with four suction wings.

The results show **an annual maximum cost saving of up to 741,200 USD** with **an annual energy efficiency saving of up to 18%** when fitting four suction wings on a bulk carrier, with optimal weather conditions on route.



While containerships see the total greatest CO2 reduction and money savings on this model, it is important to note that 30m suction sails on the deck of a containership, would in practice negatively affect the aerodynamics, or if raised on a stub mast could interfere with port operations. These interactions need to be further researched.

Conclusion

The Wind First! Study confirms that adopting wind-assisted propulsion - particularly suction wings – alongside optimised weather routing can significantly reduce greenhouse gas emissions and operational costs. Financial benefits include a lower carbon levy, reduced EU ETS, and improved energy efficiency ratings, leading to even more savings. The installation of WASP requires strategic navigation to leverage favourable weather routes, while meeting schedules and safety requirements.

Among vessel types, Panamax bulkers consistently achieve the highest fuel savings percentage. It is critical to understand that the results are done on current oil prices. General understanding is that fuel cost savings will quadruple over the period to ~2040 (when majority fuel needs to be e-fuel).

Installing four suction wings is generally more beneficial than two but shipowners must weigh fuel savings against capacity and investment costs.

Introduction

Vessel & WASP Configuration

Three vessel types were studied, each with varying WASP configurations:

- 50,000 DWT MR tanker (2 or 4 suction wings, 24m tall)
- 80,000 DWT Panamax bulker (2 or 4 suction wings, 30m tall)
- 125,000 DWT Post-Panamax containership (14,000 TEU, 2 or 4 suction wings, 30m tall)

Service speeds are 12 knots for tankers and bulkers, and 16 knots for the containership. Maximum brake powers are 14,865.4 kW for the tanker, 19,347.8 kW for the bulker, and 55,408.57 kW for the containership.

Performance polar tables can be visualised with the following link :

Bulker	Bulker with 2 Suction Wings	Bulker with 4 Suction Wings
Tanker	Tanker with 2 Suction Wings	Tanker with 4 Suction Wings
Containership	Containership with 2 Suction Wings	Containership with 4 Suction Wings

Table 1: Clickable links to the vessels' polar tables: bulker, tanker, and containership without/with WASP and 2 or 4 systems configurations.

Polar Tables & Performance Prediction

Digital twins of these vessels were modeled using semi-empirical formulas and averaged data. Suction sails with active boundary layer control enhance performance, and D-ICE Engineering's Power Prediction Program (PPP) predicts vessel performance based on wind, waves, and vessel conditions, producing polar tables describing ship behavior under various conditions.

Weather Routing Methodology

D-ICE Engineering's weather routing solution optimises vessel routes and propulsion to minimise fuel consumption, transit time, and operational costs while ensuring environmental compliance. The ocean is modeled as a directed graph, with hammock meshing optimally adjusting deviations from the Great Circle route for mechanical propulsion vessels.

Route Configurations

Three round-trip routes were considered: Rotterdam-Santos, Accra-Shanghai, and Mombasa-Shanghai. ETA were calculated based on Great Circle Route distance divided by the vessel's service speed. Two types of scenarios were evaluated: Scenario 1: a motor vessel following an optimised route with speed optimisation, and Scenario 2: a hybrid vessel (motor vessel equipped with WASP) on the optimised route at the optimised speed.

Weather Models & Statistical Study

Weather routing relies on high-resolution ECMWF ERA 5 reanalysis model for the wind and waves, and the ocean current is from CMEMS model. A 3-year statistical study (2020-2023) compares two simulations: Scenario 1 and Scenario 2, evaluating the energy savings and fuel reductions achieved with the hybrid configuration.

The study aims to optimise fuel consumption, reduce CO2 emissions, and assess the financial impact of carbon levies and EU ETS (Emissions Trading System) on shipping operations.

Main results

Here are the results for each vessel, without sails or equipped with the 2 suction wings or with the 4 suction wings:

WASP Benefits, Fuel savings and CO2 reduction:

4 suction wings consistently outperform 2 suction wings in terms of fuel savings, CO2 reduction, and financial benefits across all vessel types and routes. The bulk carrier equipped with 4 suction wings, shows the highest mean benefits especially on the route Accra <> Shanghai (11.87%) which corresponds to 987 mt of fuel savings. The Containership vessel has the largest absolute fuel savings per year (650,427 tonnes) on the route Accra <> Shanghai, but its percentage savings are lower because of its higher initial fuel consumption and high reference speed. The CO2 reduction on this route is also the largest - 4051 tonnes. In the meantime, the lowest fuel savings are obtained with the containership equipped with 2 suction wings on the round trip Mombasa <> Shanghai: 1.06% (or 278 t of fuel). Tanker equipped with 4 suction wings demonstrates moderate fuel savings, with its highest fuel savings on the route Accra <> Shanghai (8.7%). A Tanker equipped with 2 suction wings on the route Mombasa <> Shanghai shows the smallest CO2 emissions reduction per year - 458 t.

Route-specific:

The Rotterdam <> Shanghai route is the only one where the EU ETS apply, but only to 50% of the emissions, as it is a route between the EU and a non-EU/EEA country. The route Accra <> Shanghai shows the highest fuel savings for all vessels, particularly for bulk carrier and tanker, both equipped with 4 suction wings. The route Mombasa <> Shanghai shows moderate fuel savings, with containership benefiting the least from WASP. Note that the containership's reference speed is 16 knots, which is higher than for the other two vessels. A higher reference speed results in a shorter trip duration, which limits the time available to search for favorable weather conditions and affects the ability to optimise the route.

CII Rating, EU ETS and IMO Carbon Levy:

Vessels with WASP (both 2 and 4 suction wings) generally achieve better CII ratings (A and B) rather than without sails, indicating improved carbon intensity. Both Scenario1 and Scenario2 use the route optimisation strategy, so for all vessels, even without WASP, the CII remains below a C rating, achieving A or B.

The IMO carbon levy on GHG emissions from the shipping industry used in this study is 150 USD per 1 tonne of CO2e.

The EU ETS applies only to routes calling at EU/EEA ports. Therefore, we have only analysed the results for the round trip Rotterdam<>Santos, where only 50% of emissions have been considered.

The highest EU ETS reduction in absolute terms is for the containership with four suction wings, amounting to 148,995 €. The EU ETS covers routes involving EU/EEA ports, so only the Rotterdam<>Santos round trip (50% of emissions) were considered. The containership with four suction wings achieved the highest EU ETS cost reduction: €148,995.

Table 2 presents key indicators related to fuel savings, CO2 emissions reduction, financial benefits for different routes and vessel types with installed WASP.

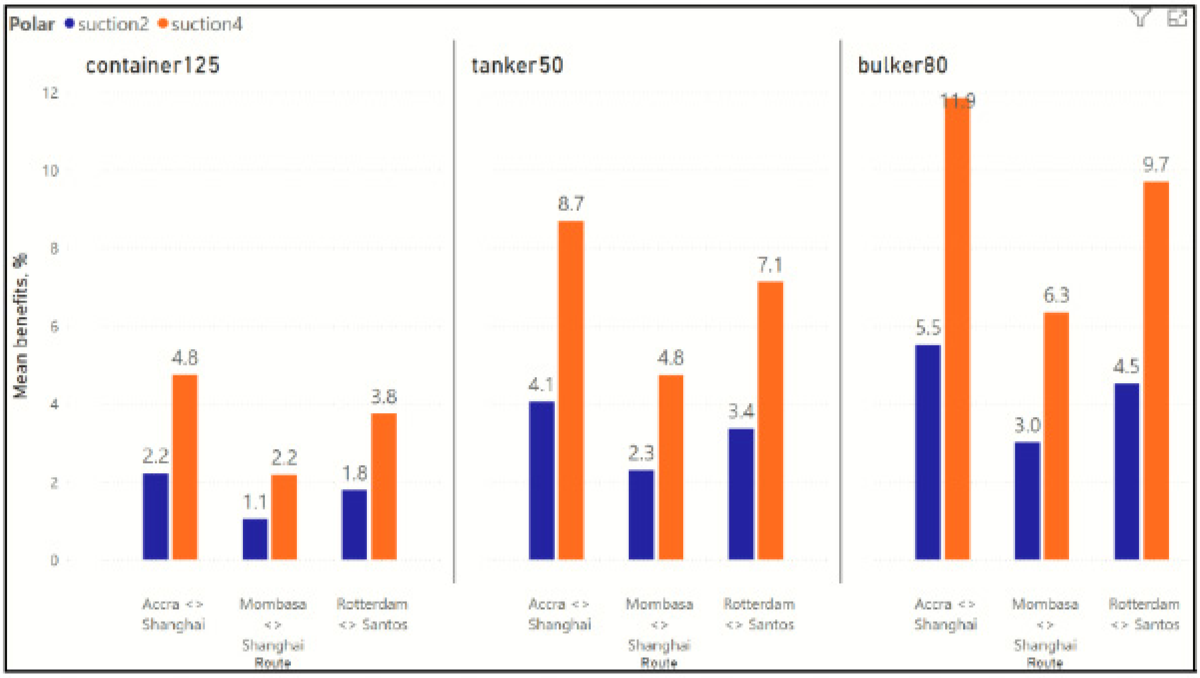


Figure 1: *mean WASP benefits per round route per vessel per WASP configuration*

Route	Ship	Polar	Fuel Consumption (t)	Fuel Savings (t)	Fuel savings ($)	CO2 emissions (t)	CO2 emissions reduction (t)	WASP benef (%)	IMO Levy ($)	EU ETS (€)	CII
Rotterdam <> Santos	Bulker 80	no sails	8 499,57	0	0	26 468	0	0	4 806 508	1 212 039	B
		2 suction wings	8 114,56	385	192 505	25 269	1 199	4,5	4 588 785	1 157 137	A
		4 suction wings	7 674,6	825	412 485	23 899	2 569	9,7	4 339 987	1 094 399	A
	Container 125	no sails	27 792,55	0	0	86 546	0	0	15 716 688	3 963 219	B
		2 suction wings	27 294,68	498	248 937	84 996	1 550	1,8	15 435 139	3 892 222	B
		4 suction wings	26 747,7	1045	522 424	83 292	3 254	3,8	15 125 826	3 814 224	B
	tanker 50	no sails	7 046,56	0	0	21 943	0	0	3 984 828	1 004 839	A
		2 suction wings	6 808,5	238	119 029	21 202	741	3,4	3 850 207	970 892	A
		4 suction wings	6 543,82	503	251 367	20 377	1 566	7,1	3 700 532	933 149	A
Monbasa <> Shanghai	Bulker 80	no sails	7 674,81	0	0	23 899	0	0	4 340 103		A
		2 suction wings	7 440,84	234	116 984	23 171	729	3	4 207 794		A
		4 suction wings	7 184,24	491	245 283	22 372	1 528	6,3	4 062 688		A
	Container 125	no sails	26 207,3	0	0	81 610	0	0	14 820 227		B
		2 suction wings	25 928,91	278	139 195	80 743	867	1	14 662 797		B
		4 suction wings	25 630,26	577	288 520	79 813	1 797	2,2	14 493 910		B
	tanker 50	no sails	6 328,13	0	0	19 706	0	0	3 578 559		A
		2 suction wings	6 181,07	147	73 531	19 248	458	2,3	3 495 395		A
		4 suction wings	6 024,69	303	151 722	18 761	945	4,8	3 406 961		A
Accra <> Shanghai	Bulker 80	no sails	8 300,75	0	0	25 849	0	0	4 694 072		B
		2 suction wings	7 840,12	461	230 315	24 414	1 434	5,5	4 433 586		A
		4 suction wings	7 313,68	987	493 536	22 775	3 074	11,9	4 135 883		A
	Container 125	no sails	27 271,52	0	0	84 924	0	0	15 422 046		B
		2 suction wings	26 662,99	609	304 267	83 029	1 895	2,2	15 077 920		B
		4 suction wings	25 970,67	1301	650 428	80 873	4 051	4,8	14 686 411		B
	tanker 50	no sails	6 932,54	0	0	21 588	0	0	3 920 350		A
		2 suction wings	6 649,68	283	141 430	20 707	881	4,1	3 760 392		A
		4 suction wings	6 327,77	605	302 385	19 905	1 883	8,7	3 578 352		A

Table 2: *Main indicators of the statistical weather routing study per route per vessel per WASP configuration*

Figure 2 contains various data visualizations that analyse the impact of different variables on the route from Rotterdam to Santos for the bulk carrier equipped with 4 suction wings.

On the left side, there are 3 filtering options: by route (including individual legs and 3 round trips), by ship type (bulker, tanker and containership), and by WASP configuration, referred to as "polar" (nosails - without WASP, suction2 - 2 suction wings, suction4 - 4 suction wings). The selected filter combination will adjust the statistical data for all dashboard metrics accordingly.

At the top, 4 key metrics are given: mean WASP benefit = 11.15%, mean EU ETS Cost (EU carbon pricing) = 57 830 €, Mean IMO Carbon Levy (CO_2 emissions cost) =$229,330 $, and mean Fuel Savings (via wind-assisted propulsion) = 25 350 $.

A map in the center displays all shipping routes from Rotterdam to Santos identified through weather routing simulations over three years, with weekly departures totaling 156 voyages.

On the right side, there are distributions of total power over three years of simulations, along with the average total power per trip being

4.69 MW. Below, a histogram displays the occurrences of STW over the same simulation period, accompanied by its mean value of 11.99 knots.

Current data:

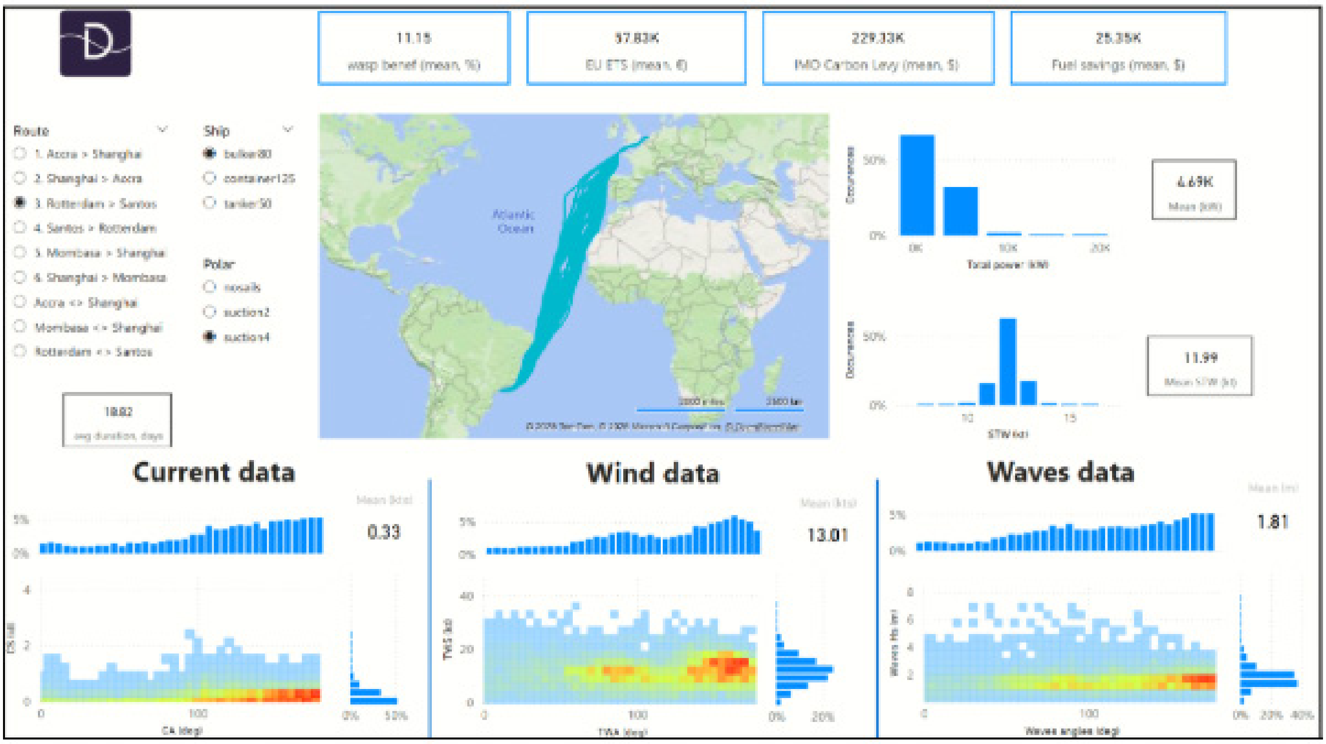
A graph plots marine current speed (CS) against current angle (CA) (relative to the vessel's axis), with color-coded intensities highlighting the most frequent values. The average current speed is 0.33 knots, indicating relatively weak ocean currents along this route.

Wind data:

the plot represents the distribution of True Wind Speed (TWS) and True Wind Angle (TWA), while a heatmap visualizes TWA versus TWS, showing where stronger winds occur more frequently.

Waves data:

The average wave height (HS) is 1.81 meters. A heatmap and histogram illustrate the distribution of wave angles (WA) and heights, revealing that waves are more frequent from astern (150-180 degrees relative to the vessel's axis) and tend to be higher at these angles.



Abbreviations

Abbreviation	Description
STW	Speed Through Water, also known as Boat Speed (BS)
TWS	True Wind Speed
AWS	Apparent Wind Speed
TWA	True Wind Angle, wrt bow / wrt vessel's advance direction
AWA	Apparent Wind Angle, wrt bow / wrt vessel's advance direction
TWC	True Wind angle, wrt vessel's Course
AWC	Apparent Wind angle, wrt vessel's Course
Hs	Significant wave height of a sea state
WA	Waves mean angle (wrt bow, come from convention)
DOF	Degree of Freedom
NED	North East Down (frame convention)
MMG	Manoeuvring Model Group
ITTC	International Towing Tank Conference
FPP	Fixed Pitch Propeller
CPP	Controllable Pitch Propeller
SWL	Sea Water Level
AP	Aft Perpendicular
BP	Brake Power
HFO	Heavy Fuel Oil
CO_2e	Carbon dioxide equivalent
GWP	Global Warming Potential
IMO	International Maritime Organisation
EU ETS	European Union Emissions Trading System
EF	Emissions factor
GCR_CS	Great Circle route, constant speed
OR_OS	Optimized route, optimized speed

Vessels set up and performance polar tables

3.1 Methodology

In order to assess the performances of the hybrid vessels, static kinematic equilibriums are solved for different wind, waves and vessel conditions, along the surge, sway and yaw degrees of freedom. It results in 5 dimensions (STW, TWS, TWA, HSWA) polar tables, required by the weather routing solver, containing all solved quantities (brake power and propeller rotational velocity, heeling and leeway angle, rudder angle for course keeping, etc.) and force components.

Based on the model decomposition and superposition principle, loads applying on the vessel are supposed independent. Special dedicated interaction models are considered when interactions between models are required. All load and interaction models are described in the Models section.

Drift behaviour, through leeway angle, can only be evaluated by computing a force balance between the lateral force applied by the wind (on both vessel superstructures and sails) and anti-drift hydrodynamic force. While lateral aerodynamic forces are generally given, lateral hydrodynamic forces can be obtained through a manoeuvring model.

In order to ensure the vessel course keeping, a static equilibrium in yaw torque can be solved, provided a steering device (rudder) is modelled. This refines the modelling as the drag from the rudders is included in the static surge equation too. In other terms, the rudder angle to achieve a static equilibrium in yaw torque is solved.

The static kinematic equilibrium equations are then:

$$\sum X(STW, TWS, TWA, H_S, WA, \beta, \delta_r, \lambda_p) = 0$$

$$\sum Y(STW, TWS, TWA, H_S, WA, \beta, \delta_r, \lambda_p) = 0$$

$$\sum N(STW, TWS, TWA, H_S, WA, \beta, \delta_r, \lambda_p) = 0$$

X, Y, N are respectively the surge, sway and yaw model loads, while $\beta, \delta_r, \lambda_p,$ respectively the leeway angle, the rudder deflection angle and the propeller loading, are the unknowns to be solved

3.2 Models

3.2.1. Calm water resistance

The calm water resistance and hull/propeller interaction coefficients have been computed with Holtrop and Mennen [HoltropMennen1894] semi-empirical method on speed ranging from [service speed - 4 kts ; service speed + 4 kts].

3.2.2. Manoeuvring

Hydrodynamic derivatives and hull/propeller/rudder interaction coefficients were identified from Yoshimura's [Yoshimura2012] empirical relations.

3.2.3. Added resistance in waves

The added resistance in waves is estimated using the SNNM empirical model ([LiuPapanikolaou2016], [LiuPapanikolaou2020]). The input data required are the vessel's main characteristics, that can be found in table 2. The spectrum is composed of an ITTC wave spectrum with a 30 frequencies discretization, along with a cos^{2s} directional spectrum, with s = 10, and a 30 directions discretization.

3.2.4. Propellers and rudders

The propellers and rudders characteristics are estimated using naval architecture's rules of thumbs. The simplified rudder model is used, only requiring the chord and span. Wageningen B-series are used for the propellers' open water curve.

3.2.5. Wind loads

Wind loads on the hull and superstructure are given by the Fujiwara [Fujiwara2005] semi empirical method.

3.3 Vessels setup

Table 2 summarizes the main particulars for each ship.

Vessel	Tanker	Bulk carrier	Containership
DWT (t)	50 000	80 000	125 000
LPP (m)	200	228	351
Beam (m)	32.2	36.5	45.8
Draft (m)	12.6	14	15
MCR (kW)	14865	19348	55409
Service speed (kt)	12	12	16

Table 2: Vessels technical characteristics

3.4 Hybrid vessels

Following tables recap the position of the suction wings onboard the vessels in both confi gurations 2 or 4 suction wings.

3.3.1. Tanker

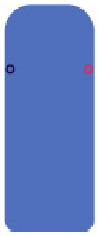
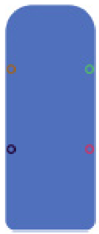
Suction Wings' onboard positions		
Number	2	4
Span	24m	24m
Position (from aft)	150m	75m / 150m

Table 3: tanker with 2 WASP configurations

3.3.2. Bulker

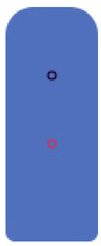
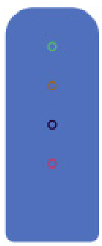
Suction Wings' onboard positions		
Number	2	4
Span	30m	30m
Position (from aft)	100m / 170m	80m / 120m / 160m / 200m

Table 4: bulk carrier with 2 WASP configurations

3.3.3. Containership

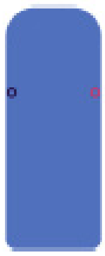
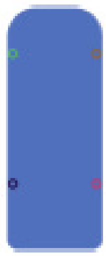
Suction Wings' onboard positions		
Number	2	4
Span	30m	30m
Position (from aft)	240m	100m / 300m

Table 5: containership with 2 WASP configurations

3.4. Polar tables

his table recaps for each vessel and each configuration the link to the online polar visualizer.

Vessel	Tanker	Bulk carrier	Container
No sails	Tanker_nosails	Bulk_nosails	container_nosails
2 suction wings	Tanker_2suctions	Bulk_2suctions	container_2suctions
4 suction wings	Tanker_4suctions	Bulk_4suctions	container_4suctions

Table 6: Links to polar visualizer

Statistical weather routing methodology

4.1 Introducing D-ICE weather routing solution

Today's weather routing solutions are becoming obsolete (lack of model accuracy for motor ships, and different constraints for sailing ships because of the foils) and use totally independent approaches depending on the ship propulsion.

Due to new regulations and environmental consciousness, hybrid propelled ships are studied carefully and also need weather routing solutions adapted for their wind propulsion combined with their motor propulsion.

Lots of improvements have been done in the graph theory community (google maps, waze, social networks analysis, internet routing). It led us to evaluate this approach with attention.

The goal of our developments is to have a single tool for motor, sailing and hybrid propulsion, able to make mono and multi-objective optimisation.

D-ICE solution optimises both the route and the propulsion of the ship during the voyage, to minimise one or multiple objectives (time, consumption, etc). Various operational constraints are taken into account such as maximal environmental conditions or estimated time of arrival (ETA). The solution is used to make statistical studies (large amounts of routing calculations, to evaluate ship performances, consumption prediction, validate a business model, etc), and also operationally through the D-ICE OCEANiCS platform.

Graphs are a mathematical representation of the context on which calculations have to be performed (networks, data, etc). It is a set of nodes, connected with each other with edges on which weights will be attributed. A graph is called directed if its edges have orientations (different edge weights from A to B than B to A).

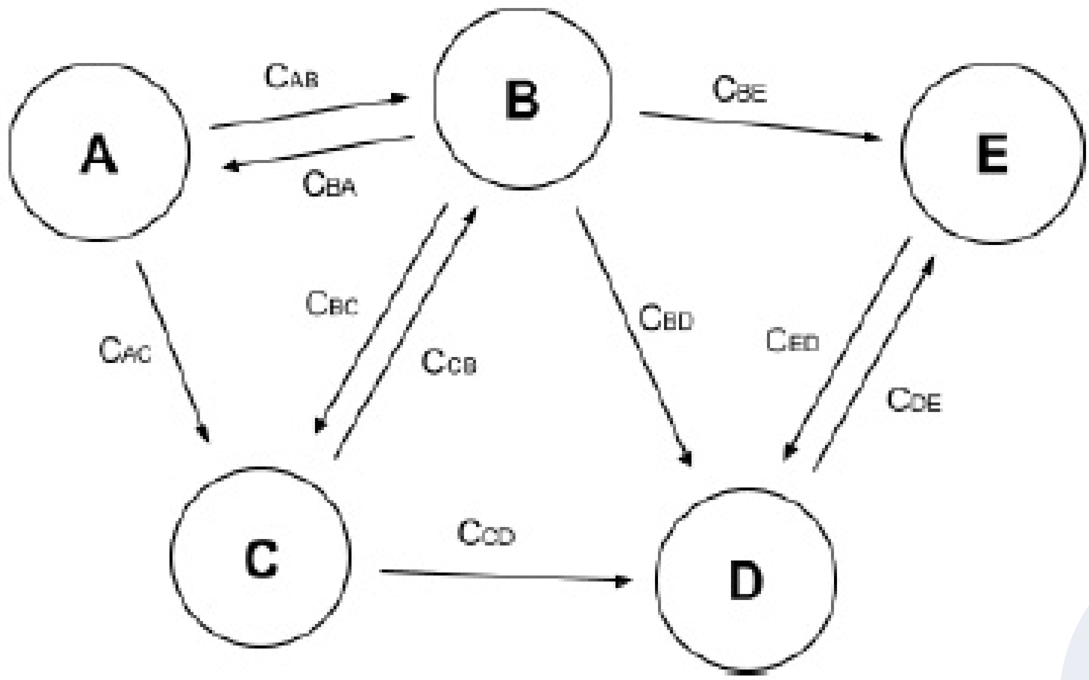


Figure 1: Directed graph illustration

Once set, it will be a support for algorithms, such as shortest paths whose objective is to find the path that minimises the accumulated sum of edge weights.

The main difficulties we are facing are first to optimise multiple objectives (often conflictive), then the fact that the weights are time dependent, then the simultaneous optimisation of both route and ship propulsion, and finally, the fact that the ocean is a continuous space that needs to be discretized.

Depending on the kind of ship, we use different ways to mesh the ocean:

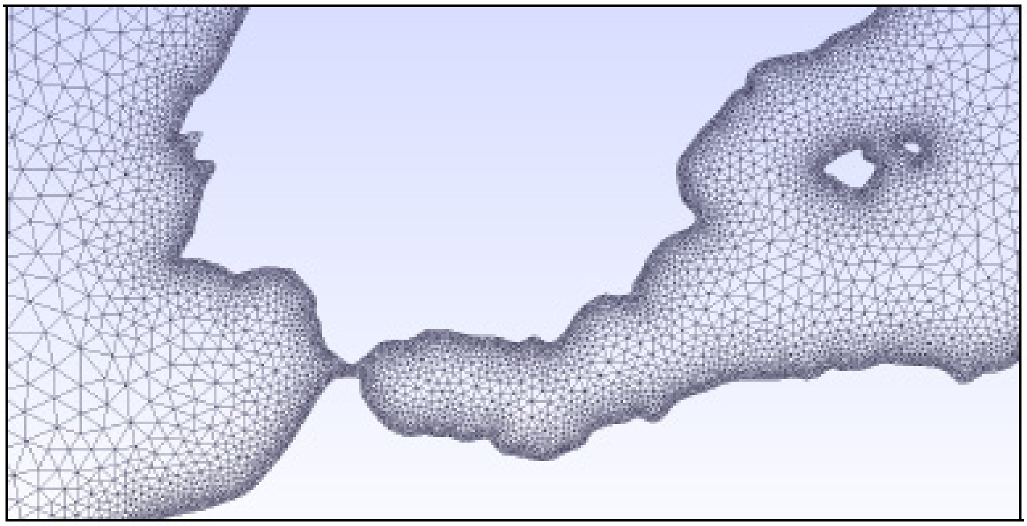


Figure 2: Ocean unstructured mesh around Gibraltar

This mesh is generally used for sailing and hybrid ships, which need to evaluate routes far from great circle routes.

Hammock Mesh:

For motor ships and hybrid ships whose main propulsion remains mechanical, whose route won't be far from the great circle line, the following mesh is used, that enables small route variations around the direct one.

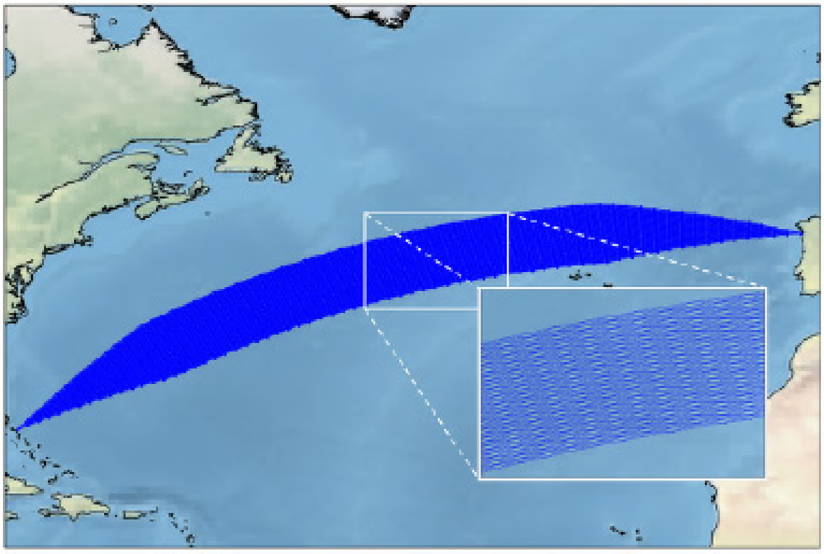


Figure 3: Transatlantic hammock graph illustration

The details of our multi-objective shortest path algorithm won't be explained here.

4.2 Input data

The input information for the historical routing needs the basic things: the mathematical model of the vessel - a so-called polar table or polar fi le and weather data from an existing weather model.

4.2.1 Ship polar tables

To accurately estimate ship speed and consumption depending on weather conditions, D-ICE algorithms need so-called ship “polar” tables as produced in a previous study. For each wind propulsion system evaluated, a polar table is generated, composed of engine power needed to navigate in wind/waves conditions at a specifi c speed through water, that have discrete values.

The limitations of using WASP systems are directly taken into account in the polar generation of ships. Then, the brake power limit is taken into account in the weather routing algorithms.

4.2.2 Weather data

A complex marine environment strongly impacts a vessel’s behaviour. Therefore, it is important to consider these factors when planning a voyage and to try to minimise its negative infl uence. The longer the routes are - the more fl exibility the ship has for avoiding unwanted weather. The following parameters are measured and analysed: winds, waves, currents. Extreme weather conditions make constraints for safety reasons. Many years of observations and storing complex weather data allow us to predict the future weather behaviour and therefore ship performances from a statistical analysis.

D-ICE Engineering carried out routing studies using weather data from the European Center for Medium Range Weather Forecast (ECMWF) for wind and waves and from Mercator Ocean for ocean currents. More precisely, all environmental dataset are reanalysis. Among other information, temporal [1] and spatial resolutions are defi ned in the Table 7.

Environmental field	Source	Model	Time res.	Space res.
Wind - *Meridional velocity of wind at 10m (m/s)* - *Zonal velocity of wind at 10m (m/s)*	ECMWF	ERA-5	6h	0.5°
Waves - *Significant height of combined wind waves and swell (m)* - *Mean wave period (s)* - *Mean wave direction (deg)*	ECMWF	ERA-5	6h	0.5°
Current - The meridional velocity of current at surface (m/s) - Zonal velocity of current at surface (m/s)	Mercator Ocean	HR Global	24h	1/12°

Table 7: Weather models used

1 “Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics” (Source: copernicus marine service)

4.2.3 Environmental Regulations: CII, IMO Carbon Levy, and EU ETS

Carbon Levy

The IMO Carbon Levy aims to reduce the maritime industry's carbon footprint by charging ships based on their CO_2 emissions. When burning 1 ton of Heavy Fuel Oil (HFO), emissions include CO2, CH_4 (methane), and N_2O (nitrous oxide), each contributing to global warming. There are two emission assessment methods: Tank-to-Wake (TTW) and Well-to-Wake (WTW).

TTW considers only direct emissions from fuel combustion. For HFO, this results in 3.114 tons of CO_2 per ton burned. CH_4 and N_2O are not included in TTW calculations. WHile the standard calculation may omit them, these gases are considered in some papers. Estimation of the emissions per GHG gases is:

- CO_2 emissions: ~3.114 tons of CO_2 per ton of HFO burned.
- CH_4 emissions: ~0.004 tons of CH_4 per ton of HFO, with a Global Warming Potential (GWP) of 28-30, contributing 0.112 tons of CO_2e.
- N_2O emissions: ~0.0003 tons of N_2O per ton of HFO, with a GWP of 265-298, contributing 0.08 tons of CO_2e.

When CH_4 and N_2O are considered, we sum all greenhouse gas contributions, and thus the total CO2e emissions per ton of HFO burned is ~3.3 tons of CO2e.

WTW takes into account the full lifecycle of fuel, including production, transport, and combustion. The WTW CO_2e / TTW CO_2 ratio is 1.21, meaning the total CO_2e emissions per ton of HFO burned are 3.77 tons of CO_2e. 2

$$\text{otal } CO_2e\ (\$/t) = 3.114 \times 1.21 = 3.77\ t\ CO_2e \quad (1)$$

In this study, the IMO levy for CO2e emissions is 150 per ton and the WTW method was considered. $Therefore, to calculate the total IMO carbon levy for the voyage, we used the formula below:

$$IMO\ levy\ per\ trip\ (\$) = 3.77\ t\ CO_2e \times 150\$/t \times Trip\ Fuel\ consumption(t) \quad (2)$$

The average IMO levy per year is estimated by multiplying the IMO levy per trip by the estimated number of voyages per year from Table 11.precisely, all environmental dataset are reanalysis. Among other information, temporal 1and spatial resolutions are defi ned in the Table 7.

EU ETS

The European Union Emissions Trading System (EU ETS) is a key tool used by the European Union to reduce GHG emissions. It sets a limit on total emissions from industries, including CO_2 emissions from marine transportation since 2024. From 2026 onwards CH_4 and N_2O are also included. 100% of emissions are considered from voyages within the EEA navigation zone, and 50% of emissions are considered from voyages between EEA and non-EEA ports. The EU ETS is phased gradually: in 2024 emissions were multiplied by 40%. In 2025 - by 70%, and since 2026 - 100% of emissions apply. All vessels over 5000 gross tons are required to comply with emissions regulations under this system. 3

A shipping company must calculate its annual emissions based on fuel consumption. If it exceeds its allowances, it must purchase extra credits. If it emits less, it can sell allowances. In this study, we focus on the estimated EU ETS results based on trips or annual fuel consumption, without considering allowances per vessel. We also assume that 100% of emissions are accounted for as if it were 2026.

Type of Fuel	EF_CO2 [t CO_2/t]	EF_CH4 [t CH_4/t]	EF_N2O [t N_2O/t]	Cj [%]
Marine Diesel Oil (MDO)	3.206	0.00005	0.00018	-
Heavy Fuel Oil (HFO)	3.114	0.00005	0.00018	-
Hydrotreated Vegetable Oil (HVO)	3.115	0.00005	0.00018	-
Liquified Natural Gas (LNG)	2.750	0	0.0011	3.1%
Ammonia (NH_3)	0	0	0	-
Methanol (CH_3OH)	0.0007	0	0.00002	-

Table 8: Emission Factor of the specific fuel type

Table 8 presents the emission factor for different gases that make part of GHG for different fuel types. For the sake of simplicity, this study considered only HFO.

$$EF_{fuel} = EF_{CO_2} + (EF_{CH_4} \times GWP_{CH_4}) + (EF_{N_2O} \times GWP_{N_2O}) \tag{3}$$

In this study, one European Union Allowance per ton of CO_2e is set at 90€. Therefore,

$$\text{EU ETS per trip} = EF_{fuel} \times Trip\ Fuel\ consumption(t) \times 90€/t\ CO_2e \tag{4}$$

The average EU ETS per year is estimated by multiplying the EU ETS per trip by the estimated number of voyages per year from Table 11.

CII

The Carbon Intensity Indicator (CII) is a metric used by the IMO to assess the carbon effi ciency of ships, as per MEPC 354(78), which is part of the IMO's regulations to reduce the greenhouse gas emissions [4]

from ships. The CII is part of the IMO Strategy to reduce GHG emissions and is calculated for each individual vessel using the formula:

$$\text{Attained CII} = \frac{CO_2\ emissions}{Distance\ traveled \times DWT(or\ GT)} \tag{5}$$

where CO_2 emissions are the total greenhouse gas emissions resulting from the combustion of fuel used by the vessel; distance traveled - is the total distance the vessel traveled in nautical miles during the reporting period (1 year); DWT (or GT) - is the capacity of the specifi c vessel (deadweight or gross tonnage depending on the vessel's type).

In the next step, the reference CII is calculated. It represents the carbon intensity of the ship based on its type, size, and operational profi le, and is determined by a formula specifi ed by the IMO. [5]

Then, the required CII is to be calculated. It is the target carbon intensity for the vessel to meet in future years, in line with IMO's emissions reduction targets. It is calculated as a percentage reduction of the reference CII from the current year onward.

Once, we have the attained CII and required CII, we determine the CII class as follows:

Class	Description
A	Excellent (Attained CII ≤ 20% better than the Required CII)
B	Good (Attained CII ≤ Required CII)
C	Needs Improvement (Attained CII > Required CII but within acceptable limits)
D	Requires Corrective Action (Attained CII significantly above Required CII)
E	Very Poor (Attained CII well above the Required CII)

Table 9: CII classes to be assigned for each vessel after its annual performance evaluation

4.3 Workflow

4.3.1 Routes definition

Depending on the application, there could be various constraints on the route from the navigational point of view: TSS (traffi c separation scheme), SECA zones, restricted areas, minimum & maximum distance to coast through the entire trip, minimum sailing time at a minimum distance to the coast, etc. In addition, the ship owner or charter can suggest specifi c waypoints to call, some route pass gates, canals, stopovers where specifi c rules are implemented. Other important constraints are ETA (estimated arrival time), maximum ship speed, weather conditions, maneuver penalties. For the chosen routes, the mean speed (in laden or ballast) can be set. Thus, it is possible to give the exact arrival date time or the range of possible ETA.

The hammock route is built by specifying particular waypoints the vessel has to pass through and the routing type between the given waypoints.

Table 10 represents the 3 routes that have been studied here. If the route has to avoid lands, passing some restricted area, canals, etc. - then the resolution is reduced for higher precision and more accurate routing. This high resolution will cost more computational time. On the other hand, long transocean routing allows to reduce resolution and thus computation time without compromising the quality of the routing.

For all routes, an ETA constraint is applied. This allows the calculated route duration to be between 15% shorter and 1% longer than the expected duration. This reference duration is computed as the direct route distance divided by the reference STW. Values of the duration for three routes are given in the following table.

Route	Vessel	Description	GCR distance	Reference STW	Estimated duration
Rotterdam <> Santos	Bulker	Route from the Netherlands through the English Channel and the Atlantic Ocean to Brazil	10906 nm	12 kt	37.6 days
	Tanker				
	Containership			16 kt	28.2 days
Accra <> Shanghai	Bulker	Route from West Africa to East China passing by the Sunda Strait	20526 nm	12 kt	70.4 days
	Tanker				
	Containership			16 kt	52.8 days
Mombasa <> Shanghai	Bulker	Route from East Africa to East China passing by the Malacca Channel	12266 nm	12 kt	42.1 days
	Tanker				
	Containership			16 kt	31.6 days

Table 10: Routes description

The number of round trips per year is estimated by dividing 365 days by the average trip duration for each vessel and substructing ~10% margin for port operations, anchoring, and maintenance (see Table 11).

Vessel	Accra <> Shanghai	Mombasa <> Shanghai	Rotterdam <> Santos
Tanker	4.7 trips	7.8 trips	8.7 trips
Bulker	4.7 trips	7.8 trips	8.7 trips
Containership	6.2 trips	10.4 trips	11.6 trips

Table 11: Estimated number of round trips per year per vessel per route

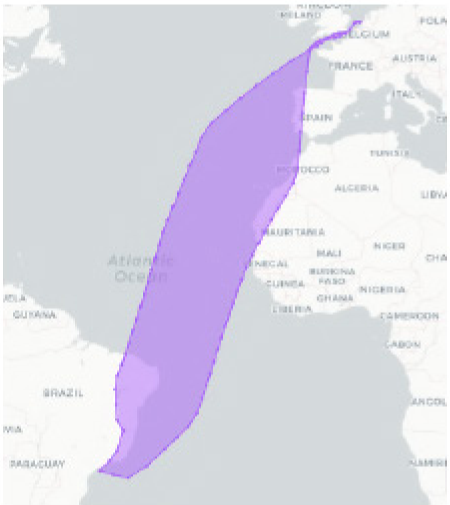
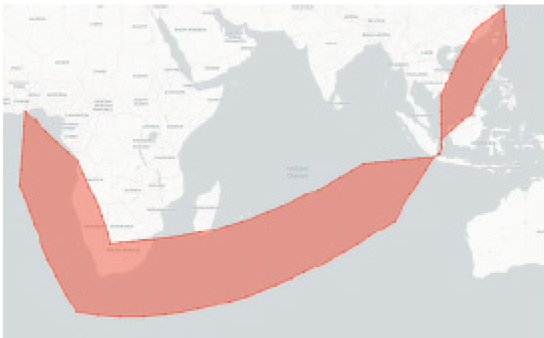
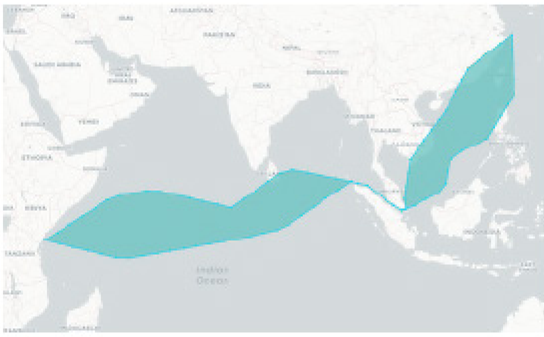
Rotterdam - Santos	
Accra - Shanghai	
Mombasa - Shanghai	

Figure 4: Envelopes for the routes meshes (top): Rotterdam - Santos, (center): Accra - Shanghai, (bottom): Mombasa - Shanghai

For the route Rotterdam <> Santos, the longitudinal resolution is 150 nautical miles, which is equivalent to one control change (heading and/or vessel speed) every 12 hours at 12 knots (every 9h at 16 knots).

For the route Accra <> Shanghai, the longitudinal resolution is 200 nautical miles in the Atlantic and Indian Oceans, which is equivalent to one control change (heading and/or vessel speed) every 16 hours at 12 knots (every 12h at 16 knots); in the South China Sea, the longitudinal resolution is 180 nautical miles, which is equivalent to one control change (heading and/or vessel speed) every 15 hours at 12 knots (every 11h at 16 knots).

For the route Mombasa <> Shanghai, the longitudinal resolution is 150 nautical miles in the Indian Ocean, which is equivalent to one control change (heading and/or vessel speed) every 16 hours at 12 knots (every 12h at 16 knots); in the South China Sea the longitudinal resolution is 120 nautical miles, which is equivalent to one control change (heading and/or vessel speed) every 10 hours at 12 knots (every 7.5h at 16 knots). An exclusion zone has been added to avoid the Maldives, here is why the graph is truncated in the Indian ocean.

4.3.2 Statistical Study

The study that has been carried out by D-ICE Engineering consists of launching a large amount of deterministic weather routing computations, based on weather hindcast data. Then, from the resulting optimal paths, statistics on ship performances and wind-assisted system fuel savings are calculated.

To do so, various computations have been done:

- Run 0: Ship under mechanical propulsion, at constant speed on the great circle route.
- Run 1: Ship under mechanical propulsion, with variable speed and variable route during the voyage.
- Run 2: Hybrid ship, with variable speed and variable route during the voyage.

The results from Run 0 provide insights into traditional navigation, where the vessel operates under mechanical propulsion at a constant Speed Through Water (STW) along the shortest route (the Great Circle route).

NB: Run 0 strategy is not considered in this study except for the evaluation of the CII ratings.

A set of results from Run 1 represents a ship operating under mechanical propulsion with an optimized route and speed, serving as the reference run.

Finally, Run 2 is an optimised set of simulations, where the algorithm optimises the STW and the route for the hybrid vessel. It demonstrates the benefi ts of adding WASP compared to Run 1.

In Table 12, we propose notations for these runs, and, in Table 13 - associated benefi ts computation.

Run	Run 0	Run 1	Run 2	Run 2
Notation	ref_gcr_cs	nosails	suction2	suction4
Description	*Motor ship, great circle route and constant speed*	*Motor ship, optimised route and optimised speed*	*Hybrid ship with 2 WASPs, optimised route and optimised speed*	*Hybrid ship with 4 WASPs, optimised route and optimised speed*

Table 12: Resume of Run descriptions and notations.

Reference for the benefit	Run 1	
Run Name	Run 2	Run 2
Notation	wasp_benef (suction2)	wasp_benef (suction4)
Description	*Benefits of adding 2 WASPs*	*Benefits of adding 4 WASPs*

Table 13: Resume of Run benefit descriptions and notations.

Statistical studies are composed of one departure each 7 days, from 01.01.2020 to 01.01.2023. Study takes into account 3 vessels, 2 WASP confi gurations + no sails confi guration, 1 reference speed per vessel type, 3 routes with two directions: forward and backward and 2 run types for each ship confi guration, the total number of runs is 156 x 3 x 3 x 1 x 2 x 2 = 16848.

Weather routing results and analysis

5.1 Study case: Bulk carrier with 4 WASPs on the route Rotterdam > Santos

Statistical weather routing results for the route Rotterdam > Santos with the 4 suction wings at 12kt are given in Figure 5. A set of optimized routes seen on the map - represents the optimized route per departure date during 3 years of simulation departing once a week. The average trip duration is 18.82 days. Key performance indicators show that installing four Wind-Assisted Ship Propulsion (WASP) systems provides on average 11.15% benefits (fuel savings). The mean EU ETS cost is 57,830€, while the average IMO carbon levy amounts to 229,330$. Additionally, mean fuel consumption reductions lead to saving 25,350$, highlighting both the financial and environmental benefits of wind-assisted propulsion. The average total power consumption is 4.69 MW, while the speed through water (STW) is 11.99 knots.

At the bottom of the dashboard, we see statistics on environmental conditions. The heatmaps play a crucial role in interpreting data, where warmer colors indicate more frequent occurrences. The average current speed (CS) is 0.33 knots, with currents most commonly flowing from 100° to 180° relative to the vessel's course. The true wind speed (TWS) averages 13.01 knots, with wind most frequently coming from behind (astern), which helps improve efficiency. Similarly, the average significant wave height (HS) is 1.81 meters, with waves also predominantly coming from astern, contributing positively to the vessel's performance.

The same type of results are presented in the section "Appendices" for each route, vessel, and WASP configuration. These results can also be found in the Power BI report.

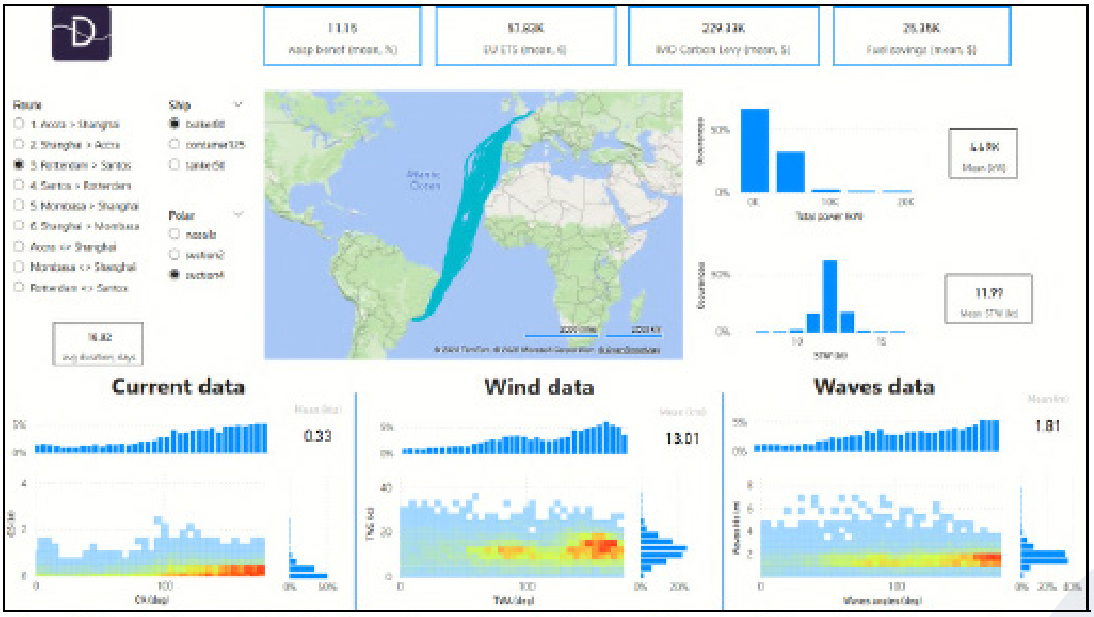


Figure 5: Synthetic results for bulk carrier equipped with four 30-meter-high suction wings on the route from Rotterdam to Santos, with a reference STW of 12 knots.

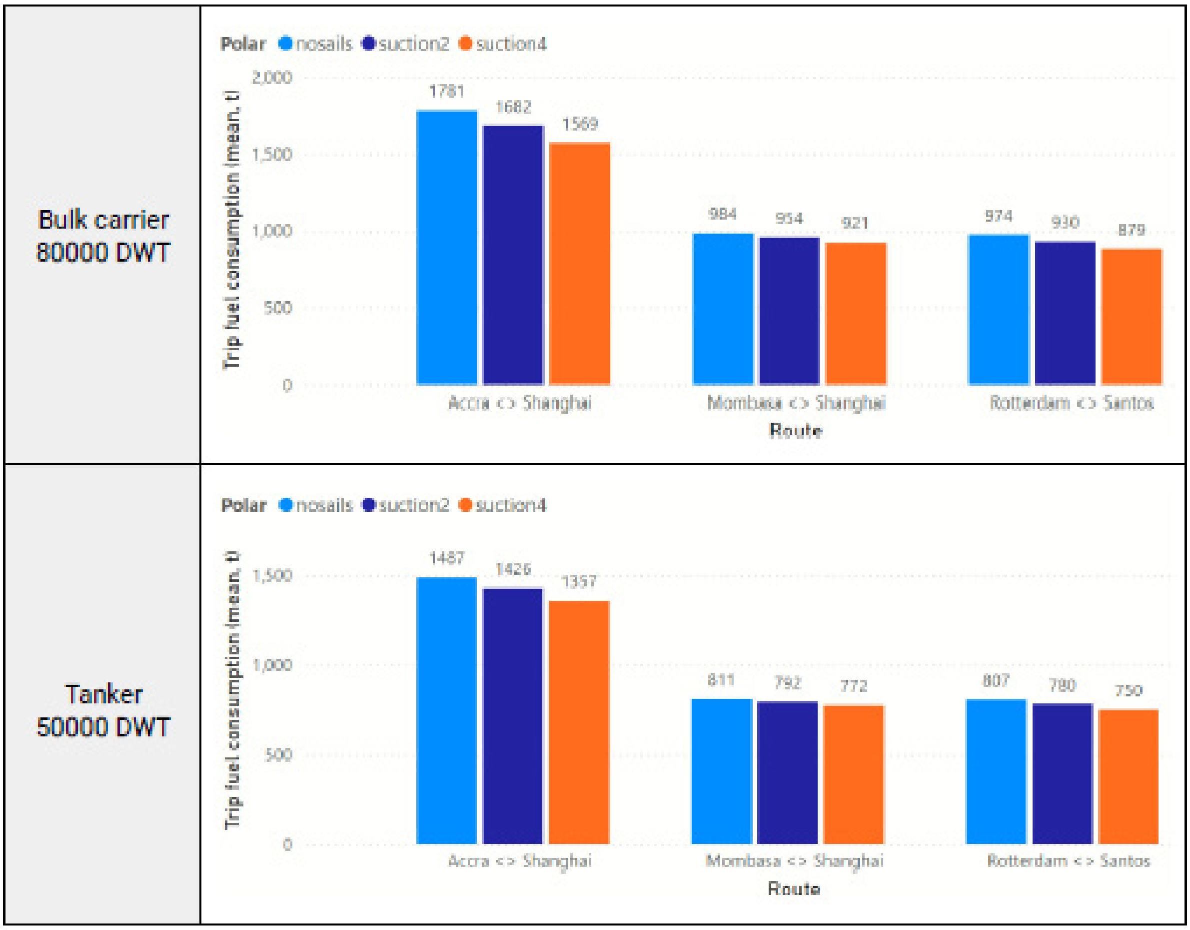
5.2 General results

5.2.1. Vessel's performance comparison in weather routing per round route

Remembering the notation of runs in Table 12, and the benefi ts notation in Table 13, we can see in Figure 6 the average total energy consumption of the motor vessel and hybrid vessels in two WASP confi gurations for the different routes and respective vessels service speeds.

Finally, Run 2 is an optimised set of simulations, where the algorithm optimises the STW and the route for the hybrid vessel. It demonstrates the benefi ts of adding WASP compared to Run 1.

In Table 12, we propose notations for these runs, and, in Table 13 - associated benefi ts computation.



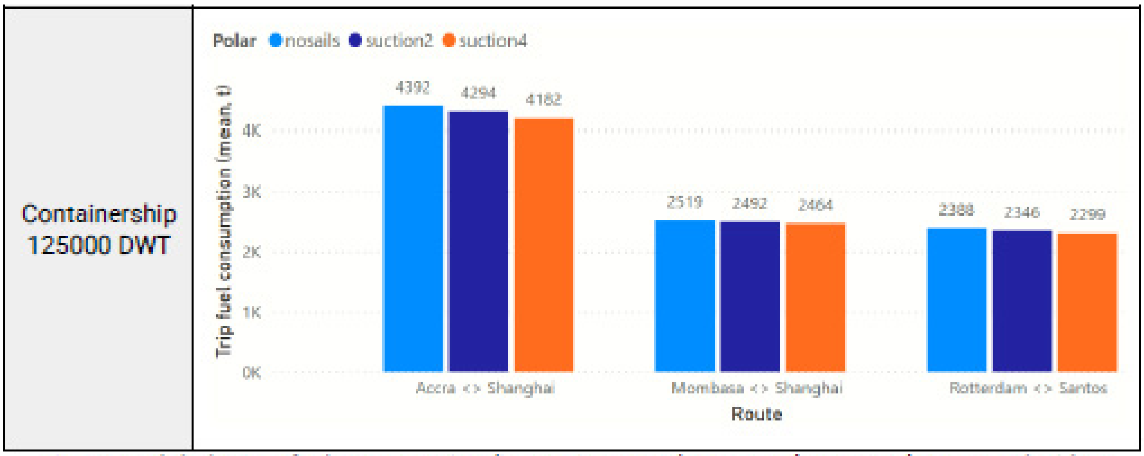


Figure 6: Global mean fuel consumption (in metric tonnes) per round route and per vessel with 3 different configurations: no sails, with 2 suction wings, and with 4 suction wings (see in the legend)

As expected, compared to the motor ship on the optimized route at optimized speed (light blue), the total fuel consumption per round trip decreases by adding 2 WASP systems (dark blue) and even more if the vessels are equipped with 4 WASP (orange).

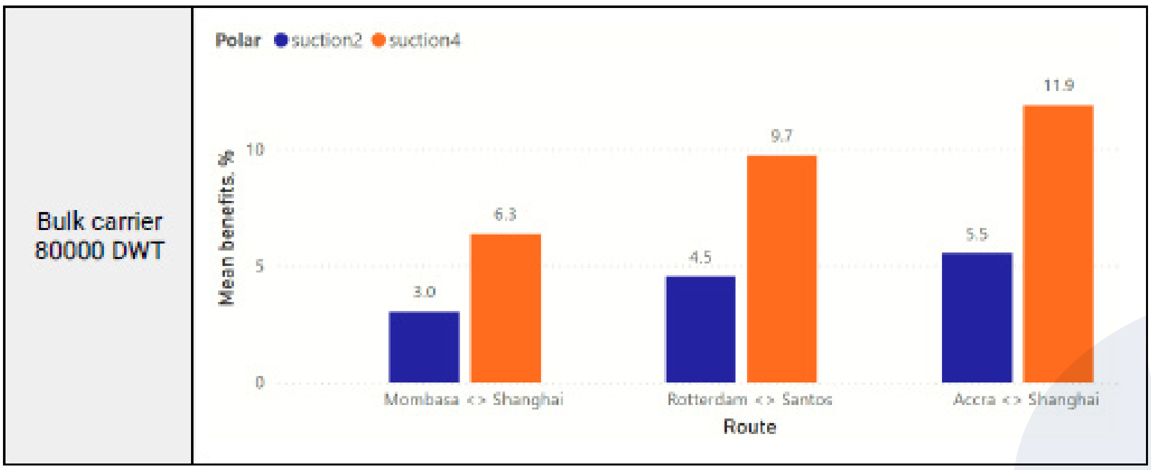
Then, in Figure 7, we observe the benefi ts calculated on fuel consumption of the three vessels equipped with two different WASP confi gurations over three round trips, compared to the motor ship. All motor or hybrid vessels are operated on optimized routes at optimized speeds.

The color legend is as followed:

- adding 2 WASPs: suction2
- adding 4 WASPs: suction4

The greatest benefi ts are achieved by installing four suction wings on the bulk carrier, a pattern observed across all three routes. On the longest route, Accra <> Shanghai, the bulk carrier equipped with four suction wings, each 30 meters in height, can save up to 11.9% in fuel on average.

The lowest benefi ts are observed when WASPs are installed on a post-Panamax containership, with a 1.1% to 2.2% reduction in fuel consumption using two 30-meter suction wings, and a 2.2% to 4.8% reduction with four 30-meter suction wings installed.



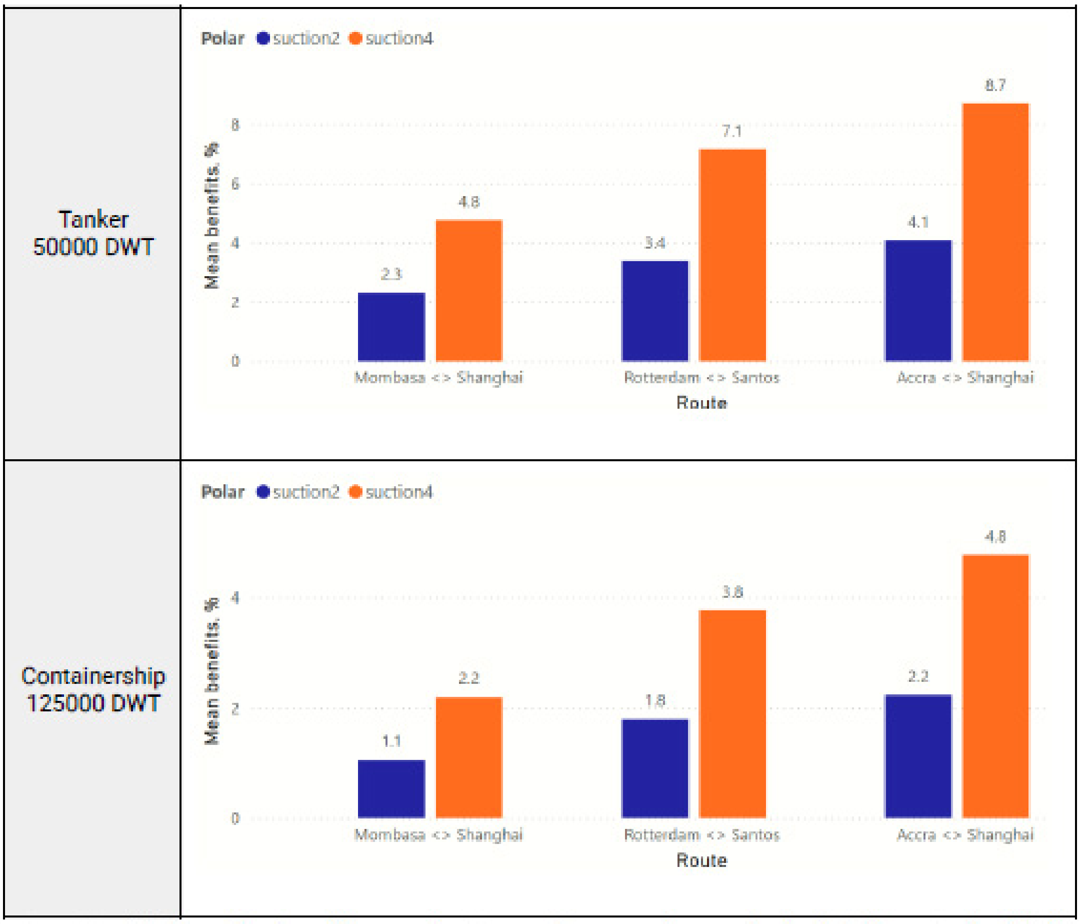


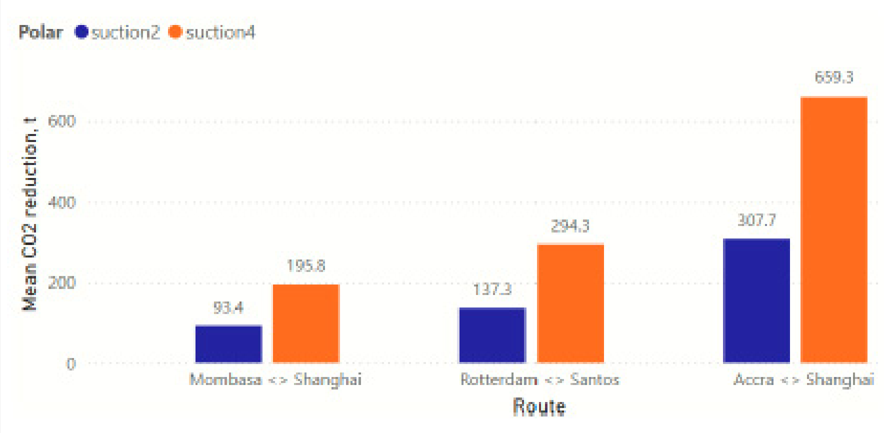
Figure 7: Global benefits for adding 2 and 4 WASPs, for 3 round routes for (top): bulk carrier, (middle): tanker, and (bottom) containership

Then, in Figure 8, we fi nd a reduction in CO2 emissions when using hybrid vessels with two or four WASPs installed, compared to motor vessels. Over three round trips, the hybrid vessels emitted less CO2 than the motor ship. All 3 vessel types (motor, hybrid with 2 or 4 WASPs) operated on optimized routes at optimized speeds:

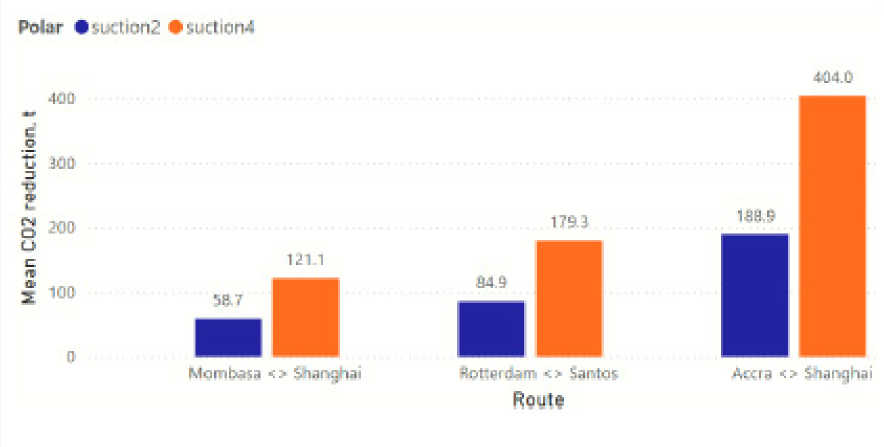
- adding 2 WASPs: suction2
- adding 4 WASPs: suction4

All vessels across all routes demonstrate a signifi cant reduction in CO2 emissions when suction wings are added. When four systems are used, the reduction in CO2 emissions is doubled compared to the two-suction wing confi guration. This pattern is consistent for all vessels and routes.

Bulk carrier
80000 DWT



Tanker
50000 DWT



Containership
125000 DWT

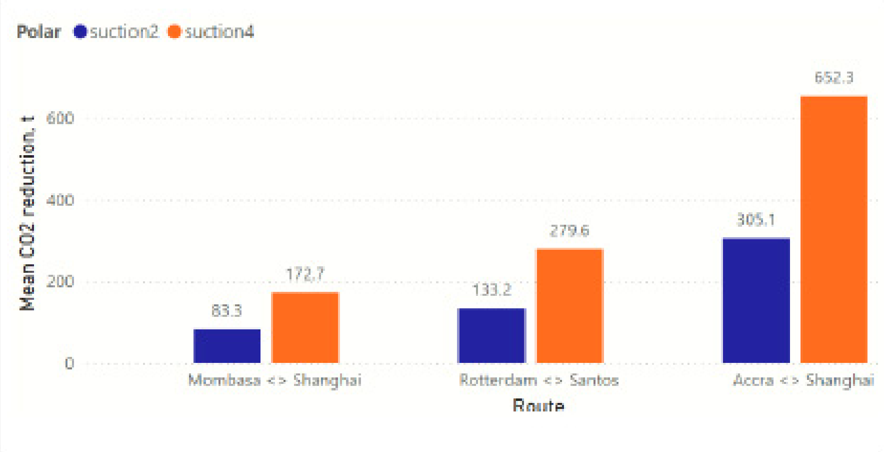


Figure 8: Global mean CO_2 emissions reduction when adding 2 and 4 WASPs, for 3 round routes for (top): bulk carrier, (middle): tanker, and (bottom) containership

5.2.2. Annual vessel's performance comparison in weather routing

Figure 9 compares mean performance of three vessel's confi gurations - a motor vessel, a hybrid vessel with two WASPs, and a hybrid vessel with four WASPs - by estimating their average fuel consumption over a full year of operations on three key trading routes, all using optimized speed and route strategies.

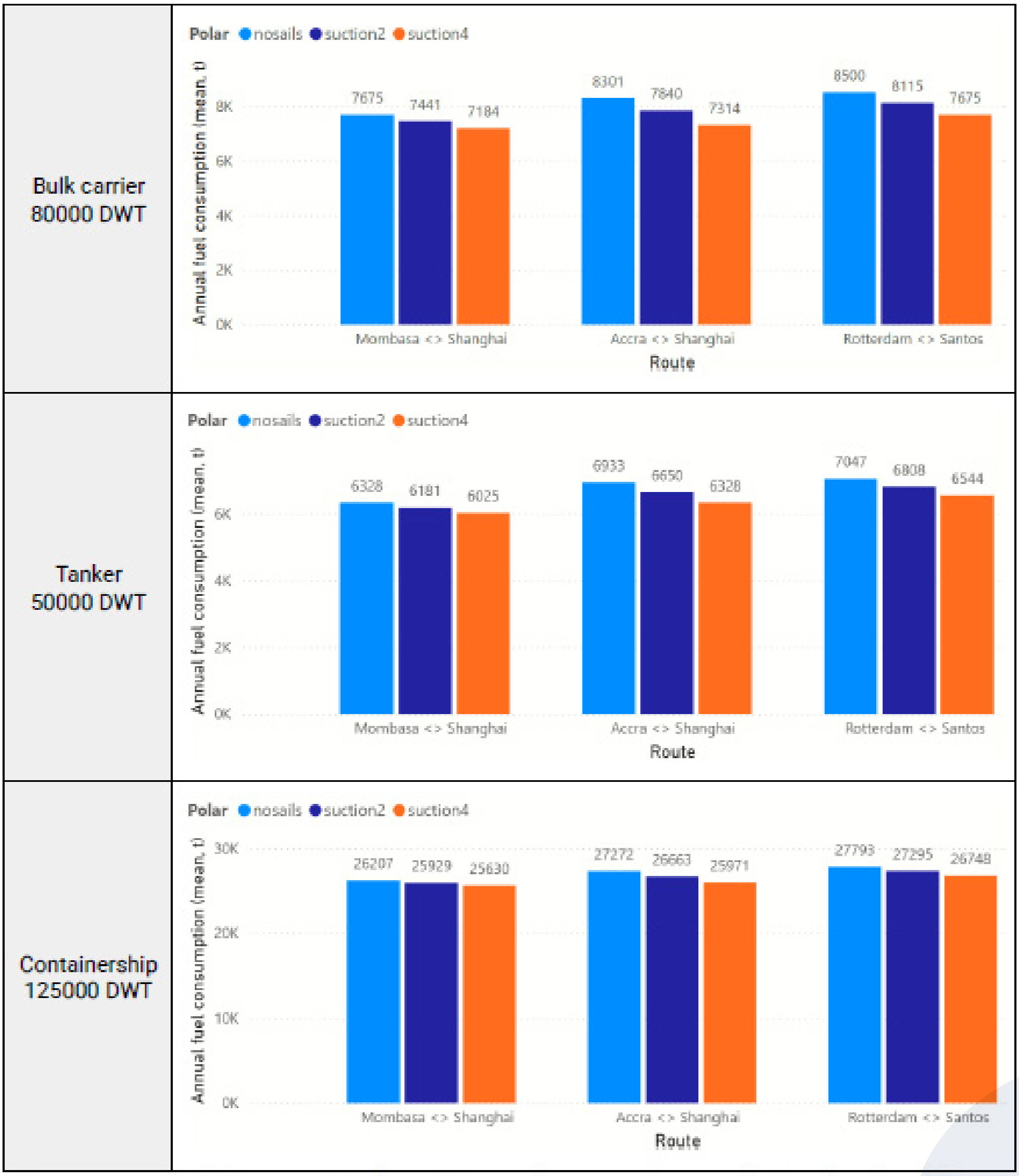


Figure 9: Average fuel consumption (in metric tonnes) per vessel per round trip under three different configurations: no sails, two suction wings, and four suction wings over a year of operation.

5.2.2.1. Key indicators for Bulk carrier performance

Figure 10 to Figure 15 highlight the key annual operational indicators (minimum, mean, and maximum) for a bulk carrier fi tted with 2 and 4 Suction Wings across three round-trip routes.

	Min	Mean	Max
WASP Benefits, %	3.16	5.54	8.60
Fuel consumption, t	7,338	7,840	8,602
Fuel savings, t	261.5	460.6	727.5
Money savings, $	130.7K	230.3K	363.8K
CO2 emissions reduction, t	814	1,434	2,265
EU ETS, €	0	0	0
IMO Carbon Levy, $	4,149,816	4,433,586	4,864,676

Figure 10: key indicators for the bulk carrier with 2 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	7.56	11.87	17.93
Fuel consumption, t	6,783	7,316	7,965
Fuel savings, t	621.3	987.1	1.5K
Money savings, $	310.7K	493.5K	741.2K
CO2 emissions reduction, t	1,935	3,076	4,616
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,835,917	4,135,883	4,503,980

Figure 11: key indicators for the bulk carrier with 4 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.44	3.03	7.43
Fuel consumption, t	6,594	7,441	8,356
Fuel savings, t	32.7	234.0	616.0
Money savings, $	16.4K	117.0K	307.0K
CO2 emissions reduction, t	102	729	1,912
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,728,633	4,207,794	4,725,335

Figure 12: key indicators for the bulk carrier with 2 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	1.33	6.35	15.56
Fuel consumption, t	6,226	7,186	8,105
Fuel savings, t	96.0	490.6	1.3K
Money savings, $	68.0K	245.3K	662.6K
CO2 emissions reduction, t	299	1,528	4,002
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,528,936	4,062,688	4,583,114

Figure 13: key indicators for the bulk carrier with 4 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	1.93	4.53	9.12
Fuel consumption, t	7,279	8,115	9,523
Fuel savings, t	161.0	385.0	792.8
Money savings, $	80.5K	192.5K	396.4K
CO2 emissions reduction, t	501	1,199	2,469
EU ETS, €	1,037,943	1,157,137	1,357,917
IMO Carbon Levy, $	4,116,104	4,588,785	5,385,007

Figure 14: key indicators for the bulk carrier with 2 WASPs on the route Rotterdam <> Santos during annual operations

	Min	Mean	Max
WASP Benefits, %	4.96	9.71	19.01
Fuel consumption, t	6,845	7,675	8,999
Fuel savings, t	411.8	825.0	1.7K
Money savings, $	205.9K	412.5K	826.8K
CO2 emissions reduction, t	1,282	2,569	5,149
EU ETS, €	976,077	1,094,399	1,283,200
IMO Carbon Levy, $	3,870,768	4,339,987	5,088,705

Figure 15: key indicators for the bulk carrier with 4 WASPs on the route Rotterdam <> Santos during annual operations

5.2.2.2. Key indicators for Tanker performance

Figure 16 to Figure 21 present the main indicators (minimum, mean, and maximum) during annual operation of the tanker fi tted with 2 and 4 Suction Wings across three round-trip routes.

	Min	Mean	Max
WASP Benefits, %	2.68	4.07	6.38
Fuel consumption, t	6,185	6,650	7,402
Fuel savings, t	169.4	282.9	453.7
Money savings, $	84.7K	141.4K	226.9K
CO2 emissions reduction, t	528	881	1,413
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,497,715	3,760,392	4,186,098

Figure 16: key indicators for a tanker with 2 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	5.57	8.70	13.15
Fuel consumption, t	5,905	6,328	6,956
Fuel savings, t	372.1	604.8	966.5
Money savings, $	186.0K	302.6K	473.2K
CO2 emissions reduction, t	1,159	1,883	2,967
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,339,262	3,578,352	3,933,679

Figure 17: key indicators for a tanker with 4 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.28	2.30	5.98
Fuel consumption, t	5,450	6,181	6,966
Fuel savings, t	17.6	147.1	411.2
Money savings, $	8.7K	73.5K	205.6K
CO2 emissions reduction, t	56	458	1,280
EU ETS, €	0	0	0
IMO Carbon Levy, $	3,082,209	3,495,395	3,927,924

Figure 18: key indicators for a tanker with 2 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.66	4.76	11.73
Fuel consumption, t	5,292	6,025	6,776
Fuel savings, t	38.7	303.4	807.1
Money savings, $	19.3K	151.7K	403.5K
CO2 emissions reduction, t	120	945	2,513
EU ETS, €	0	0	0
IMO Carbon Levy, $	2,992,406	3,406,961	3,832,021

Figure 19: key indicators for a tanker with 4 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	1.43	3.38	6.79
Fuel consumption, t	6,090	6,808	8,080
Fuel savings, t	98.4	238.1	493.8
Money savings, $	49.2K	119.0K	246.9K
CO2 emissions reduction, t	306	741	1,538
EU ETS, €	868,480	970,892	1,160,747
IMO Carbon Levy, $	3,444,075	3,850,207	4,523,789

Figure 20: key indicators for a tanker with 2 WASPs on the route Rotterdam <> Santos during annual operations

	Min	Mean	Max
WASP Benefits, %	3.21	7.14	14.14
Fuel consumption, t	5,807	6,544	7,712
Fuel savings, t	221.1	502.7	1.0K
Money savings, $	110.6K	251.4K	514.3K
CO2 emissions reduction, t	689	1,566	3,203
EU ETS, €	828,041	933,169	1,099,733
IMO Carbon Levy, $	3,283,709	3,700,532	4,361,141

Figure 21: key indicators for a tanker with 4 WASPs on the route Rotterdam <> Santos during annual operations

5.2.2.3. Key indicators for Containership performance

Figure 22 to Figure 27 identify the key annual operational metrics (minimum, average, and maximum) for a containership equipped with 2 and 4 Suction Wings over three round-trip routes.

	Min	Mean	Max
WASP Benefits, %	0.66	2.23	3.85
Fuel consumption, t	25,662	26,663	27,661
Fuel savings, t	176.4	608.5	1.1K
Money savings, $	88.2K	304.3K	534.3K
CO2 emissions reduction, t	549	1,895	3,328
EU ETS, €	0	0	0
IMO Carbon Levy, $	14,512,014	15,077,920	15,642,192

Figure 22: key indicators for containership with 2 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	1.96	4.76	8.04
Fuel consumption, t	24,684	25,971	27,244
Fuel savings, t	526.2	1.3K	2.2K
Money savings, $	263.1K	650.4K	1.1M
CO2 emissions reduction, t	1,639	4,051	6,947
EU ETS, €	0	0	0
IMO Carbon Levy, $	13,958,623	14,686,411	15,406,321

Figure 23: key indicators for containership with 4 WASPs on the route Accra <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.00	1.06	2.91
Fuel consumption, t	24,149	25,929	27,726
Fuel savings, t	0.0	278.4	793.9
Money savings, $	0.0	139.2K	396.9K
CO2 emissions reduction, t	0	867	2,472
EU ETS, €	0	0	0
IMO Carbon Levy, $	(Vide)	14,662,797	(Vide)

Figure 24: key indicators for containership with 2 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.00	2.19	5.91
Fuel consumption, t	23,864	25,630	27,579
Fuel savings, t	0.0	577.0	1.6K
Money savings, $	0.0	288.5K	804.9K
CO2 emissions reduction, t	0	1,797	5,013
EU ETS, €	0	0	0
IMO Carbon Levy, $	13,494,882	14,493,910	15,596,123

Figure 25: key indicators for containership with 4 WASPs on the route Mombasa <> Shanghai during annual operations

	Min	Mean	Max
WASP Benefits, %	0.41	1.79	3.93
Fuel consumption, t	25,727	27,295	30,034
Fuel savings, t	112.5	497.9	1.1K
Money savings, $	56.3K	268.9K	545.3K
CO2 emissions reduction, t	350	1,550	3,396
EU ETS, €	3,668,631	3,892,222	4,282,812
IMO Carbon Levy, $	14,548,458	15,435,139	16,984,078

Figure 26: key indicators for containership with 2 WASPs on the route Rotterdam <> Santos during annual operations

	Min	Mean	Max
WASP Benefits, %	1.66	3.76	7.90
Fuel consumption, t	25,229	26,768	29,437
Fuel savings, t	409.1	1.0K	2.2K
Money savings, $	204.5K	522.6K	1.1M
CO2 emissions reduction, t	1,276	3,254	6,835
EU ETS, €	3,597,651	3,814,224	4,226,286
IMO Carbon Levy, $	14,266,978	15,125,826	16,759,908

Figure 27: key indicators for containership with 4 WASPs on the route Rotterdam <> Santos during annual operations

5.2.3. CII rating

Table 14 illustrates the average CII rating for each vessel type across three round-trips under different WASP confi gurations. It compares conventional motor vessel operation with hybrid ships equipped with either 2 or 4 Suction Wings, all operating with optimized routing and speed. Column GCR_CS shows the CII for the motor vessel (without WASP) on the conventional navigation (Great Circle route with fi xed service speed), where the tanker performs best (**A** rating) on all routes. Without route and speed optimization, containerships and bulk carriers relying solely on motor propulsion receive a **C** CII rating on the Rotterdam <> Santos and Accra <> Shanghai routes. Optimizing the route and speed (OR_OS - NO WASP) improves ratings from **B** to **A** for a containership and a bulk carrier. Adding 2 WASPs further enhances performance, with a bulk carrier switching a **B** rating to **A** rating on the routes Rotterdam <> Santos and Accra <> Shanghai. With 4 WASPs, a bulk carrier and tanker consistently achieve **A** rating, while a containership remains with both WASPs configurations at CII rating **B**.

Route	Vessel	GCR_CS	OR_OS		
		No WASP	No WASP	2 WASPs	4 WASPs
Rotterdam - Santos	tanker	A	A	A	A
	containership	C	B	B	B
	bulker	C	B	A	A
Mombasa - Shanghai	tanker	A	A	A	A
	containership	B	B	B	B
	bulker	B	A	A	A
Accra - Shanghai	tanker	A	A	A	A
	containership	C	B	B	B
	bulker	C	B	A	A

Table 14: average CII rating per vessel per WASP configuration per round route

This suggests that optimizing route and speed signifi cantly improves the vessel's effi ciency, and wind-assisted propulsion further enhances performance, particularly for the bulk carrier.

5.2.4. IMO Carbon Levy

As we see from Figure 28 and Figure 29, installation of suction wings technologies reduces the IMO carbon levy, with 4 WASPs providing the highest savings. The results indicate that IMO levy varies signifi cantly across ship type and size and number and size of suction wings. For example, on Mombasa <> Shanghai, a tanker without wind-assisted technologies incurs a levy of 3,578,559 $ while implementing 2 suction wings 24 meters tall reduces it to 3,495,395 $ (a reduction of 83,164 $), and if the vessel is equipped with 4 suction wings of the same size, it further lowers it to 3,406,901 $ (a reduction of 171,598 $).

Similarly, a bulk carrier on the same route faces a levy of 4,340,103 $ without WASPs. When fi tted with two 30-meter suction wings, the levy decreases to 4,207,794 $, saving 132,309 $. With four suction wings, it drops further to 4,062,688 $, resulting in a total reduction of 277,415 $.

These fi gures highlight some key insights:

First, using four suction wings consistently delivers greater cost savings compared to only two.

Second, wind-assisted propulsion offers signifi cant levy reductions across different vessel types, though the absolute savings vary depending on ship type and size, operational speed, and emissions profi le.

Third, the impact of wind-assisted technologies varies by route, indicating that factors like wind patterns, voyage conditions, and operational effi ciency also play a crucial role in determining levy reductions.

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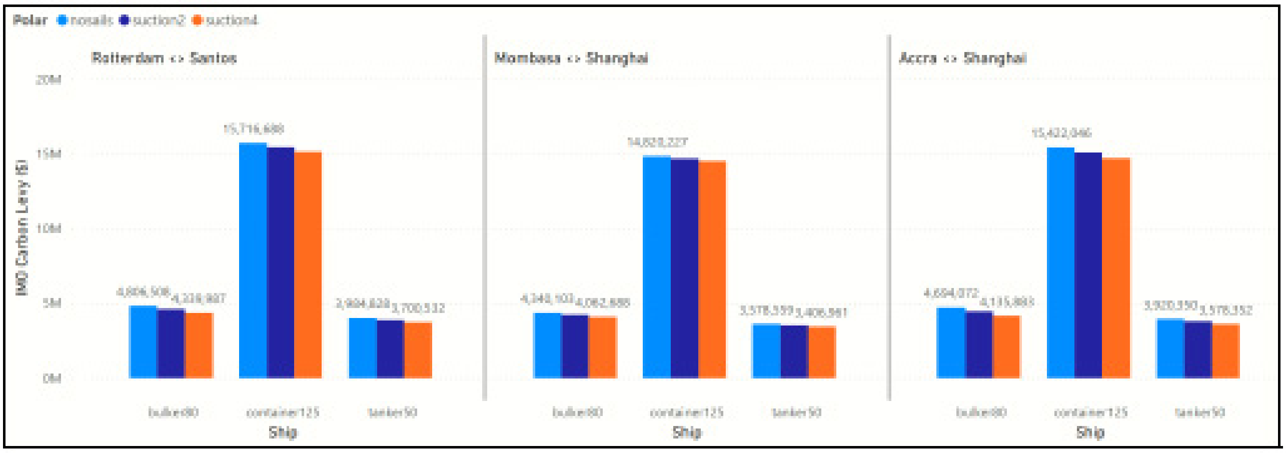

Figure 28: Mean annual IMO carbon levy per vessel type in 3 configurations (no wasp, 2 wasps, 4 wasps) on 3 round routes

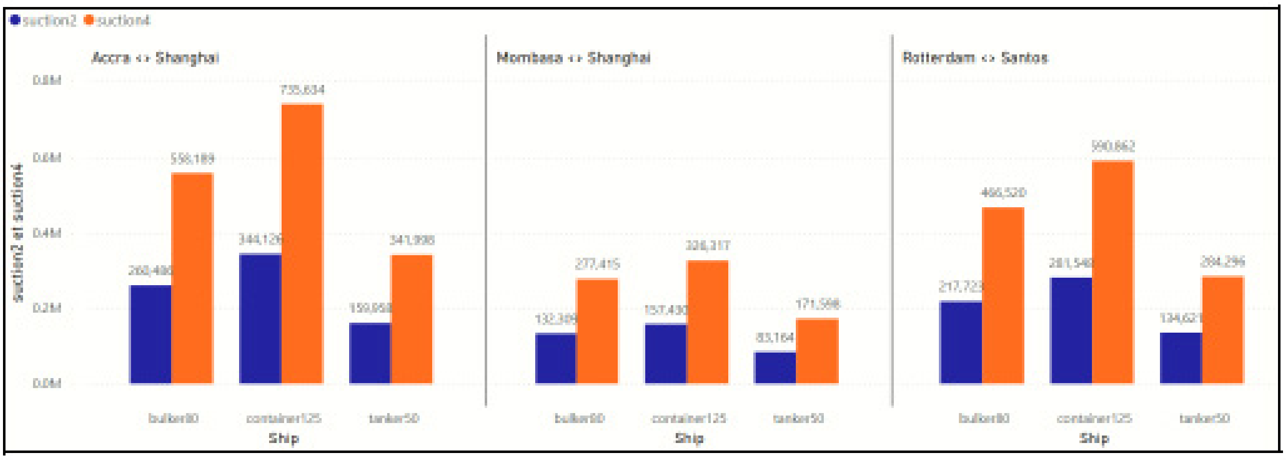

Figure 29: Reduction of mean annual IMO carbon levy per ship when installing WASPs in two different configurations for 3 routes

5.2.5. EU ETS

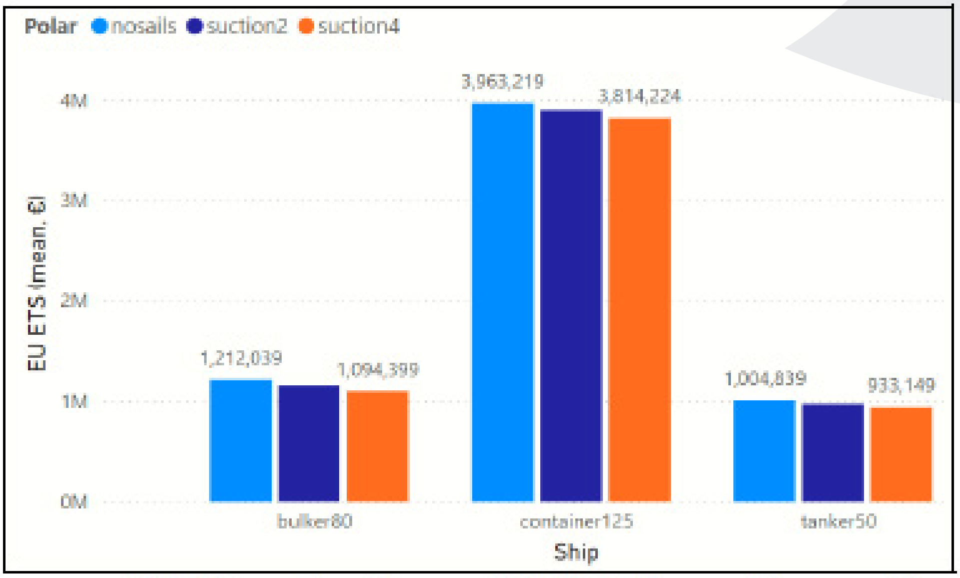

Figure 30: Mean annual EU ETS per ship without and with WASPs in two different configurations on the route Rotterdam <> Santos

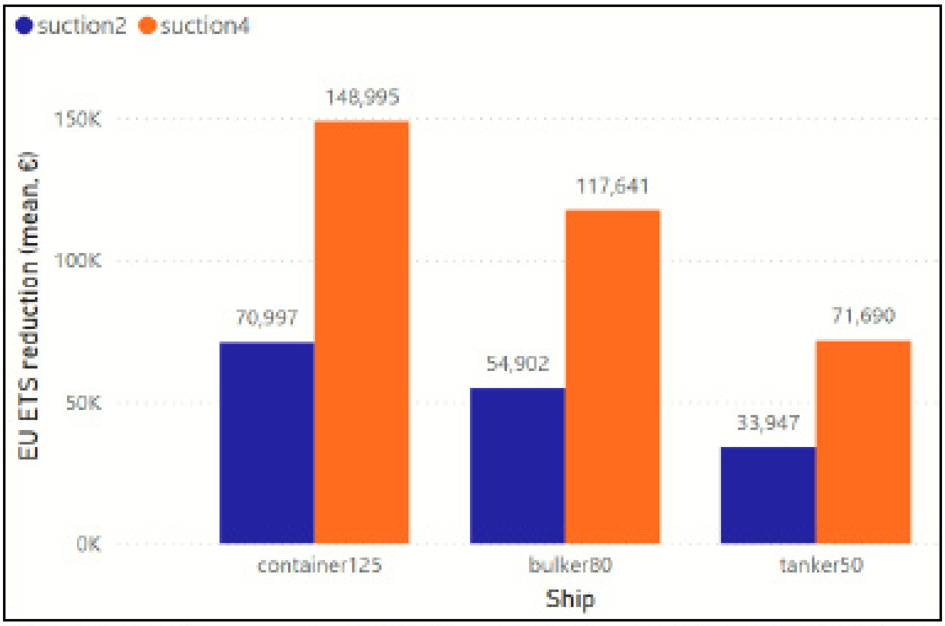

Figure 31: Reduction of mean annual EU ETS per ship when installing WASPs in two different configurations on the route Rotterdam <> Santos

Figure 30 and Figure 31 are implemented only for the route Rotterdam <> Santos. As a reminder, only 50% of emissions were considered as this route is between EEA and non-EEA ports. The highest average annual EU ETS is 3,963,219 € for a container ship using only conventional propulsion.

Using 2 suction wings reduces mean costs by 70,997 € on containership, and 54,902 € on bulk carriers.

Using 4 WASPs achieves greater reduction, up to 148,995 € on the containership and 117,641 € on the bulk carrier.

Overall, the implementation of WASPs signifi cantly reduces EU ETC costs, with a higher number of wind-assisted technologies being the most effective.

5.2.6. Seasonal variation

In the following fi gures, we report the seasonal variation of the total energy consumption per route with various WASP systems. Here we only consider the benefi t obtained in the most optimised scenario (hybrid vessel, optimised speed and optimised route).

Table 15 represents the four quarters of the year, commonly used in Figure 32 and Figure 33

Trim1	Trim2	Trim3	Trim4
01/01 - 31/03	01/04 - 30/06	01/07 - 30/09	01/10 - 31/12

Table 15: Quarterly divisions corresponding to the seasons of the year

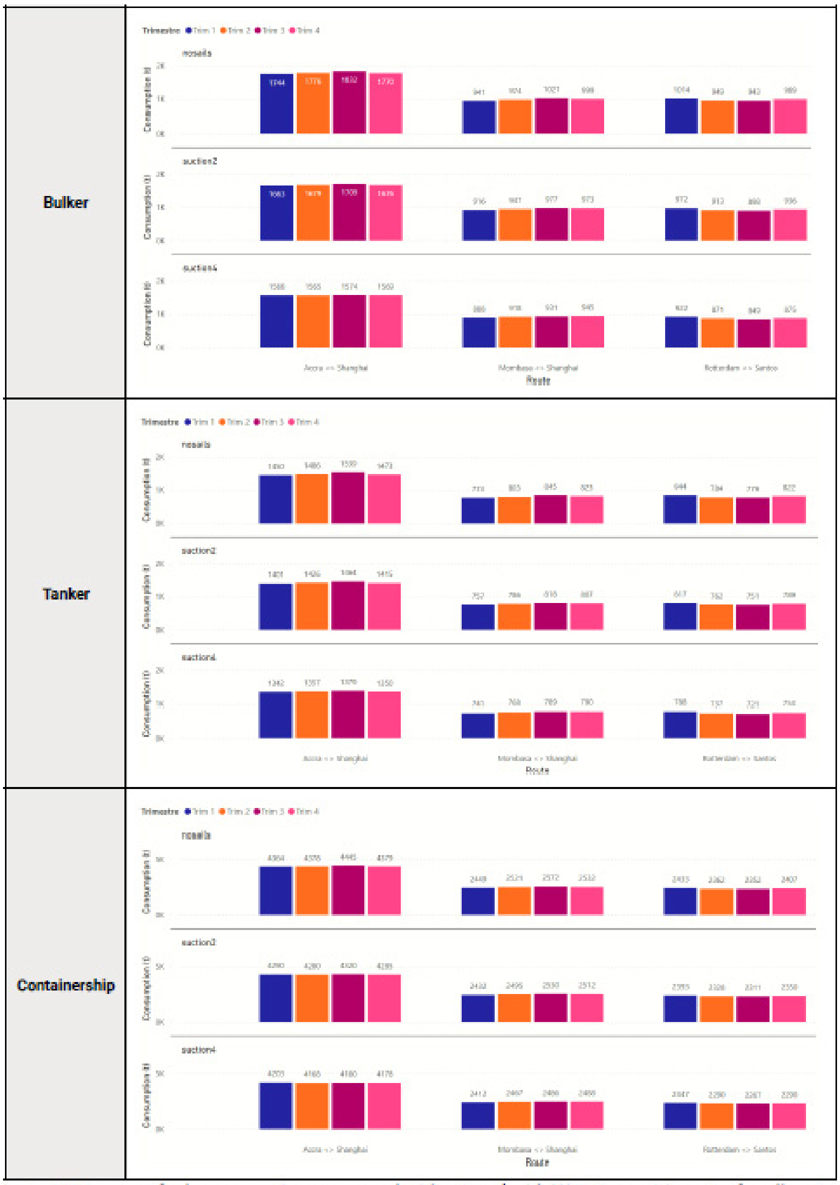

Figure 32: Average fuel consumption per vessel without and with WASPs per trimester for all routes.

Figure 32 and Figure 33 show the seasonal (per quarter) variation of the mean trip consumption and WASP benefi ts for all three vessels in various propulsion confi gurations on three round trips. On the routes Accra<> Shanghai and Mombasa <> Shanghai, the most benefi cial season is Trimester 3, and for the route Rotterdam <> Santos - Trimester 4.

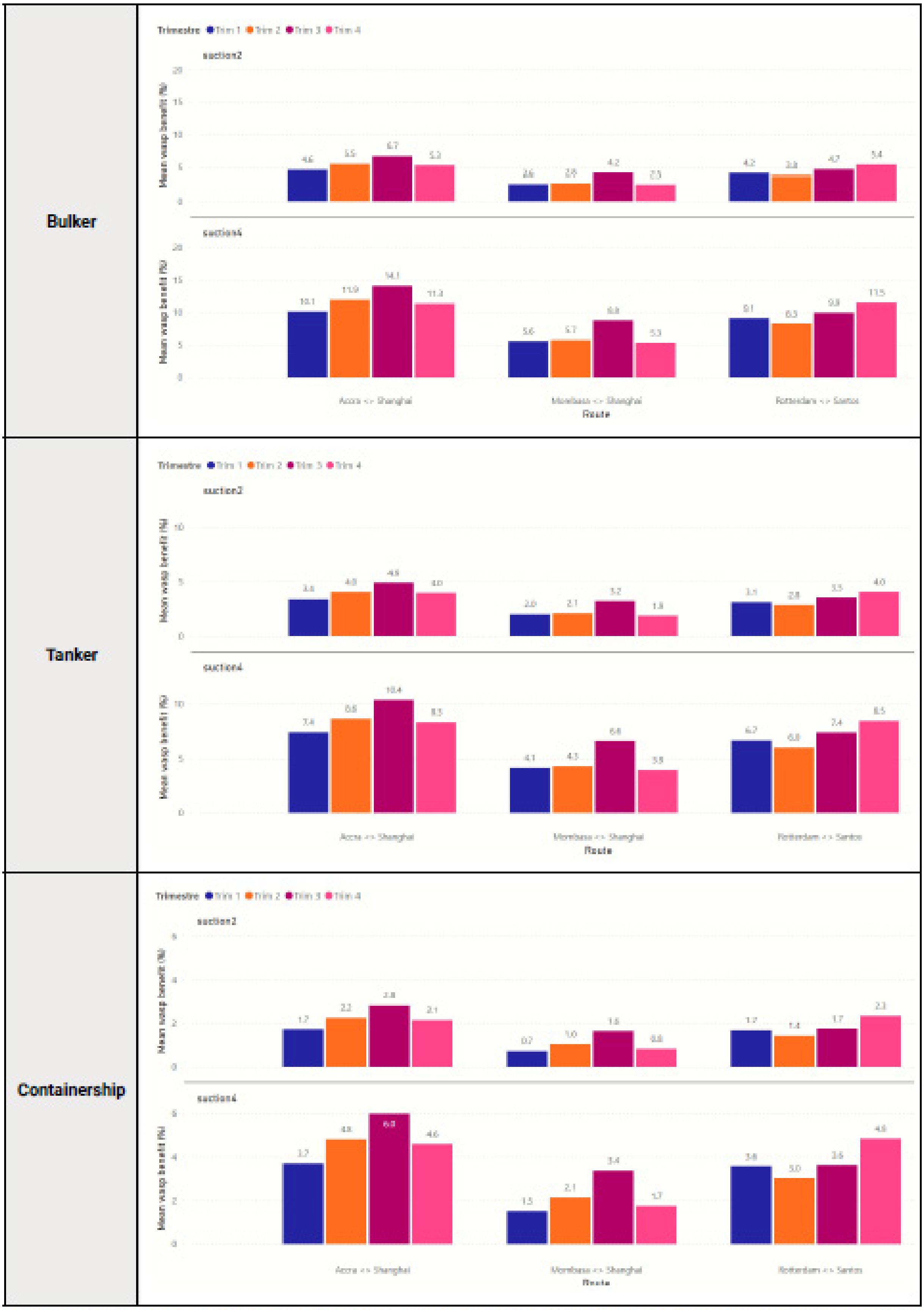

Figure 33: Average WASP benefits per vessel without and with WASPs per trimester for all routes.

Conclusion

This historical weather routing study examines the benefi ts of integrating WASPs (either 2 or 4 suction wings) on three vessels - an MR tanker, a Panamax bulker, and a Post-Panamax containership - across three key round-trip routes: Rotterdam - Santos, Accra - Shanghai, and Mombasa - Shanghai, using simulations over a 3-year period (2020-2023) with a departure frequency of one week.

The polar tables of the used vessels were created using semi-empirical formulas, integrating suction sails with active boundary layer control to improve aerodynamic effi ciency. D-ICE Engineering's Power Prediction Program (PPP) produced polar tables, which map vessel behavior under various wind, wave, and operational conditions.WASP installation (with 2 or 4 suction wings of 24 and 30 meters tall) is based on existing cases of similar vessel types. The polar tables enable precise fuel savings predictions and support optimizing fuel effi ciency for specifi c routes while validating hybrid propulsion feasibility.

The results of the statistical study demonstrate the signifi cant potential of integrating wind-assisted propulsion with weather routing and speed optimization strategy to enhance shipping effi ciency and reduce environmental impact. In particular, section Weather routing results and analysis describes in detail per route and per vessel the total fuel benefi ts observed.

The 80,000 DWT Bulker on the route Accra - Shanghai with 4 suction wings yielded the **highest mean relative savings: 11.87% of fuel consumption r**eduction (987 tonnes of fuel), and 3,074 tonnes of CO2 reduction, translating to 493,536 $ in fuel cost savings.

The 125,000 DWT containership, despite its higher baseline fuel consumption and service speed (16 knots), achieved the **largest absolute fuel savings (1,301 tonnes and CO2 reduction (4,051 tonnes)** on the Accra - Shanghai route when 4 suction wings were installed, although these savings represented a lower mean percentage gain of 4.76%.

The 50,000 DWT tanker showed quite good performance as well, especially with 4 suction wings installed, with its **highest average savings (8.7%)** on the longest route Accra - Shanghai, and 7.14% of mean benefi ts on the route Rotterdam <> Santos.

Among three routes, the Accra - Shanghai route is the most favorable for WASP benefi ts, while Rotterdam - Santos incurred EU ETS costs, with the containership achieving the highest mean ETS reduction in absolute values (148,995 €). The Mombasa - Shanghai route exhibited lower savings, particularly for the containership, attributed to shorter voyage durations limiting weather optimization.

Sections CII rating, IMO Carbon Levy, and EU ETS present the economical and regulatory improvements thanks to implementation of WASPs. Financial incentives, including the IMO Carbon Levy (150$/tonne

CO_2) and EU ETS, further underscored the economic viability of WASPs. Studied vessels equipped with 2 and 4 suction wings consistently achieved **CII ratings of A and B**, refl ecting improved carbon intensity.Whereas, if a bulker and a containership without wind-assisted propulsion followed a traditional navigation strategy (direct route and constant speed), their average **CII rating** would fall into class **C**.

Section Seasonal variation shows a seasonal analysis of fuel consumption per route and per vessel, and per WASP confi guration. For the routes Accra - Shanghai and Mombasa - Shanghai, the best performances were observed in **Trimester 3** mainly due to favorable wind conditions. On the route Rotterdam - Santos, the best results were shown in **Trimester 4**.

In conclusion, WASP integration offers a robust pathway to meet the IMO's decarbonization targets, particularly when combined with route optimization. Prioritizing a vessel's configuration with 4 WASPs on long routes maximizes benefits, though vessel-specific factors (e.g. service speed, fuel baseline) must be considered.

Key fi ndings reveal that the vessels equipped with 4 suction wings consistently outperform those with two suction wings across all metrics, achieving higher fuel savings, greater CO_2 reductions, and improved financial and regulatory returns.

As a reminder, the Power BI report can be found here. For the best visualization of routes on slide 2, it is recommended to use the Google Chrome browser.

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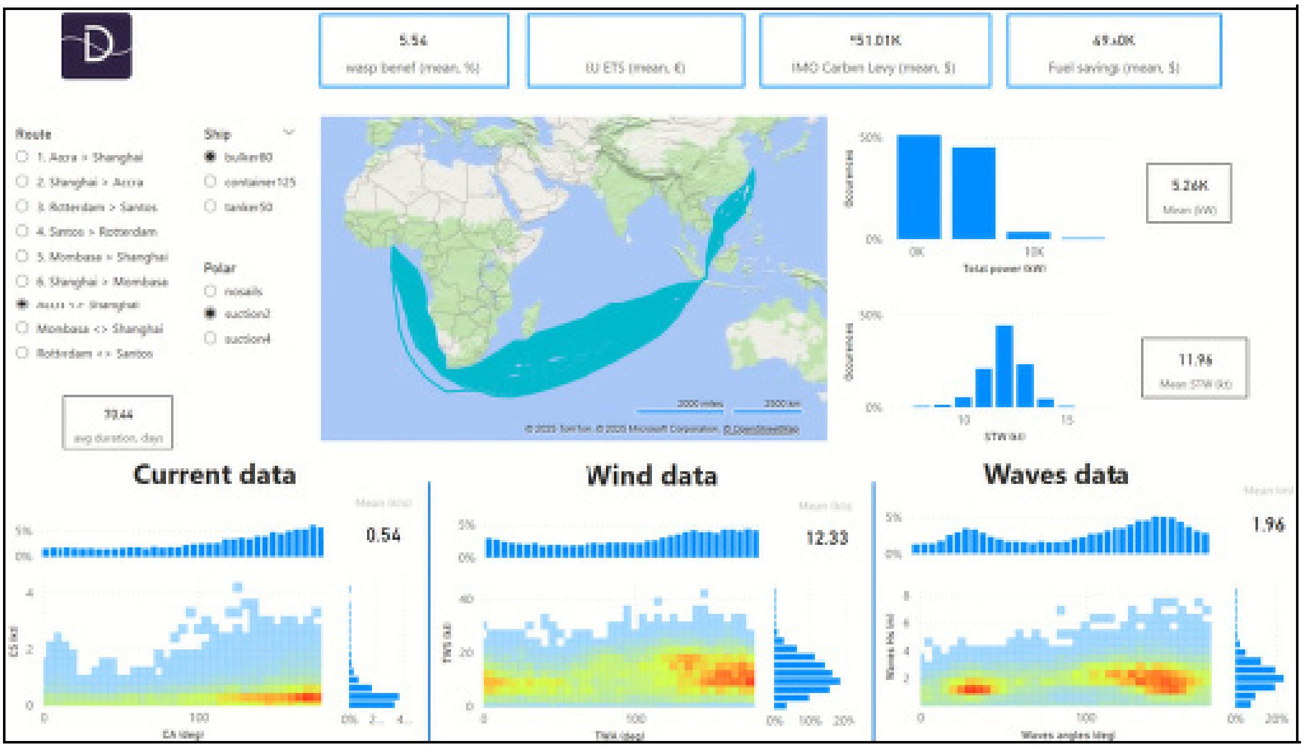
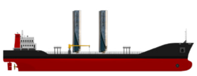
Appendices

In this section, we summarise the main weather routing results for each route, vessel, and WASP system.

Bulker with 2 WASPs

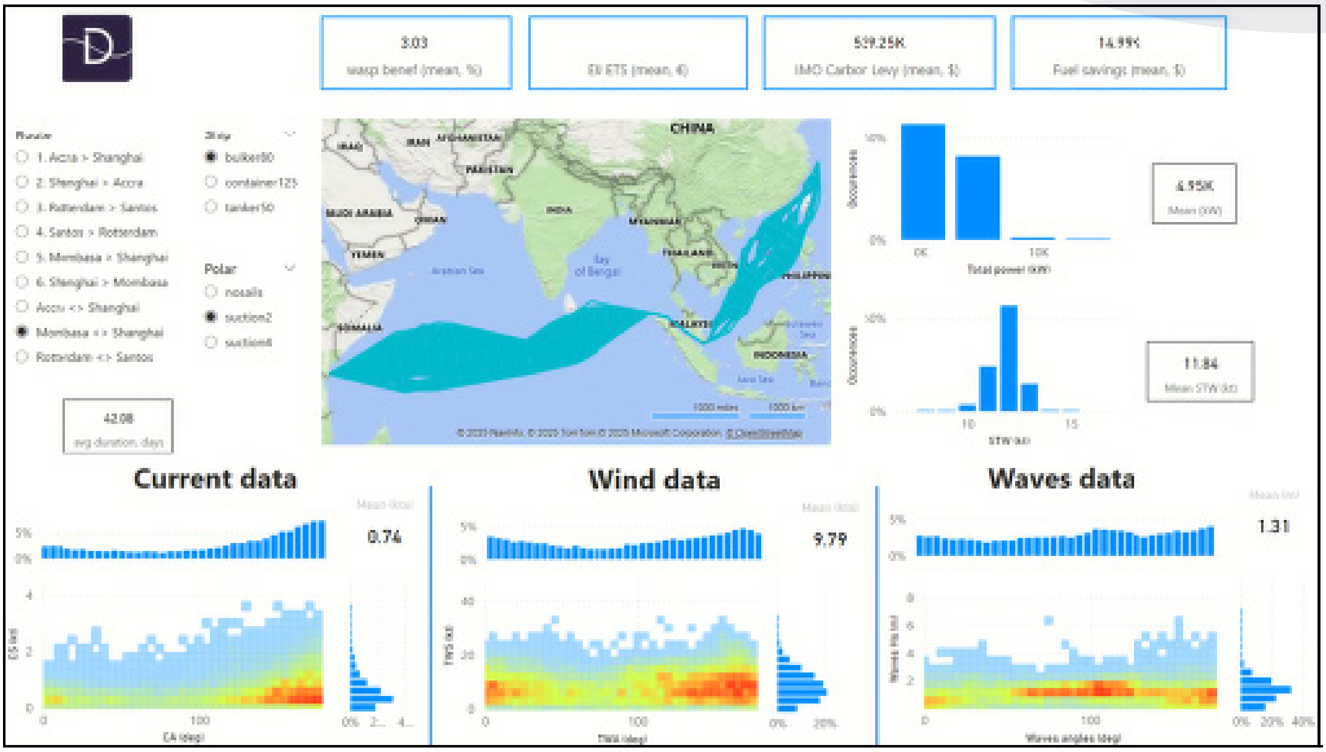
Weather routing on Accra <> Shanghai



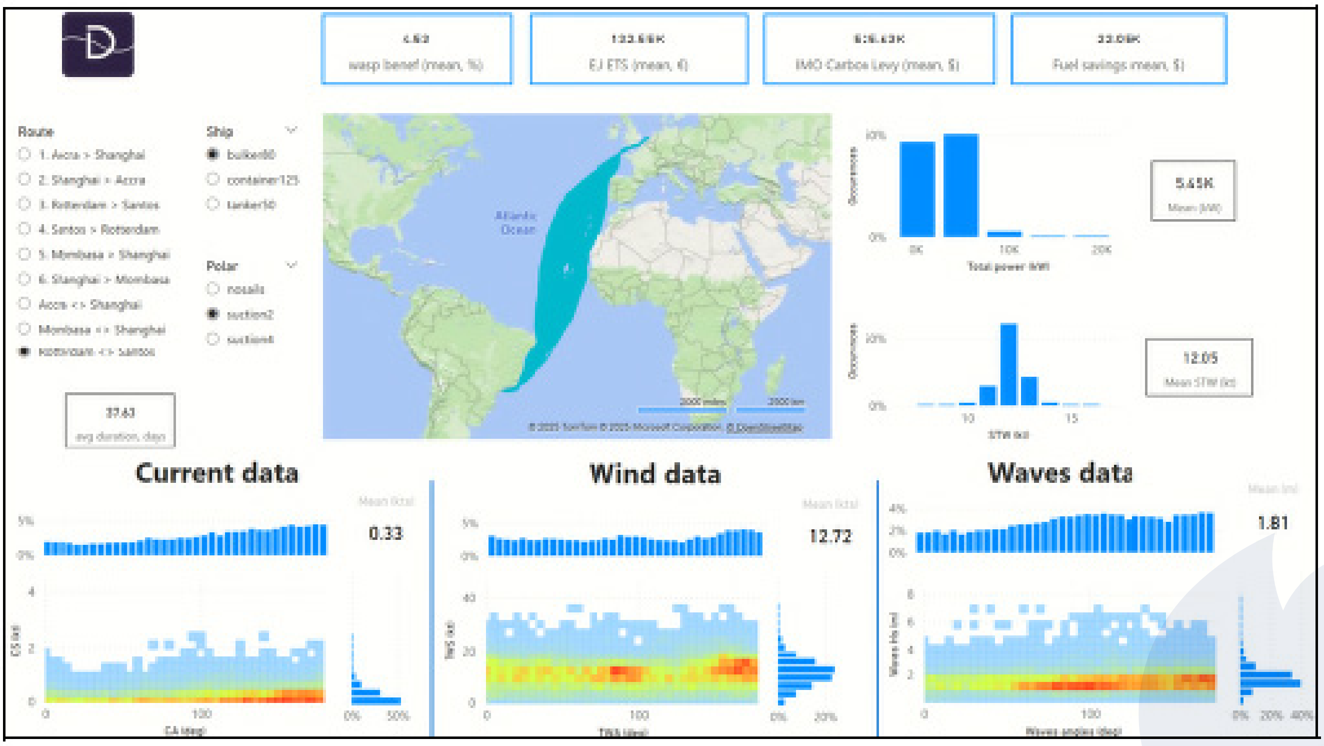


Bulker with 2 WASPs

Weather routing on Mombasa <> Shanghai

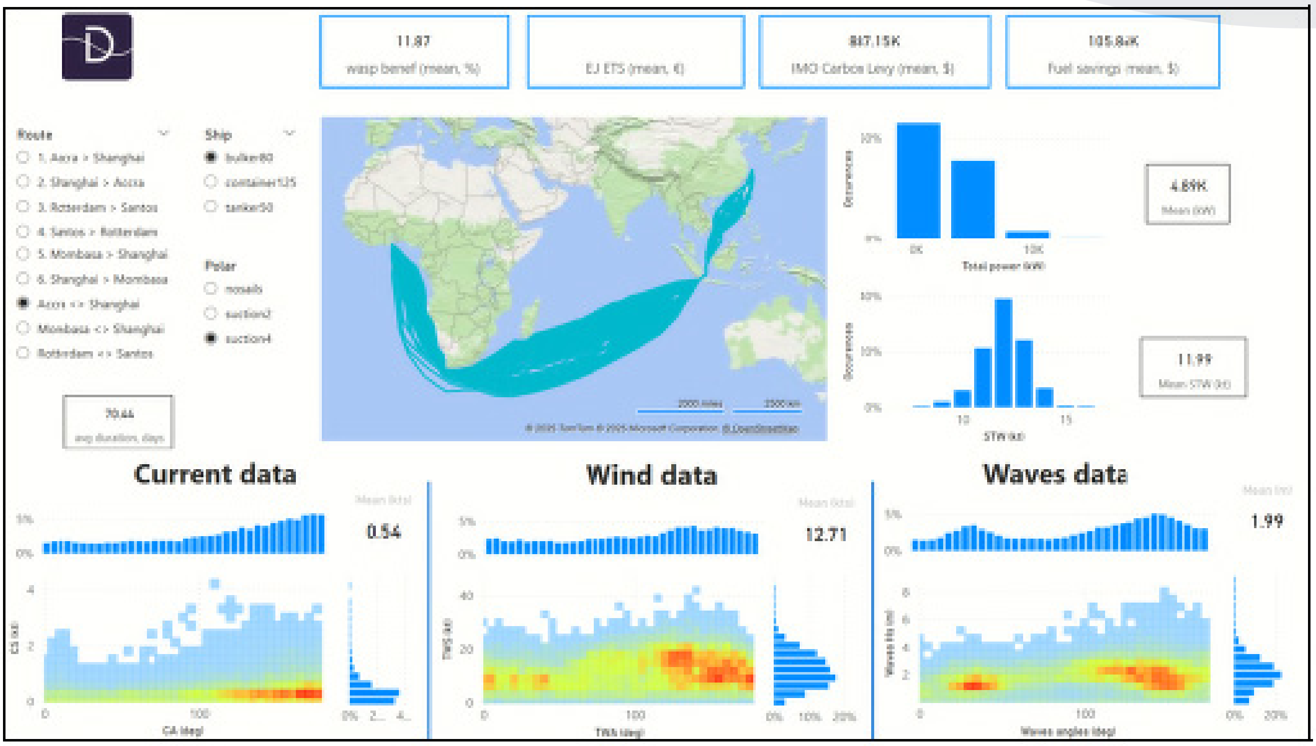


Weather routing on Rotterdam <> Santos

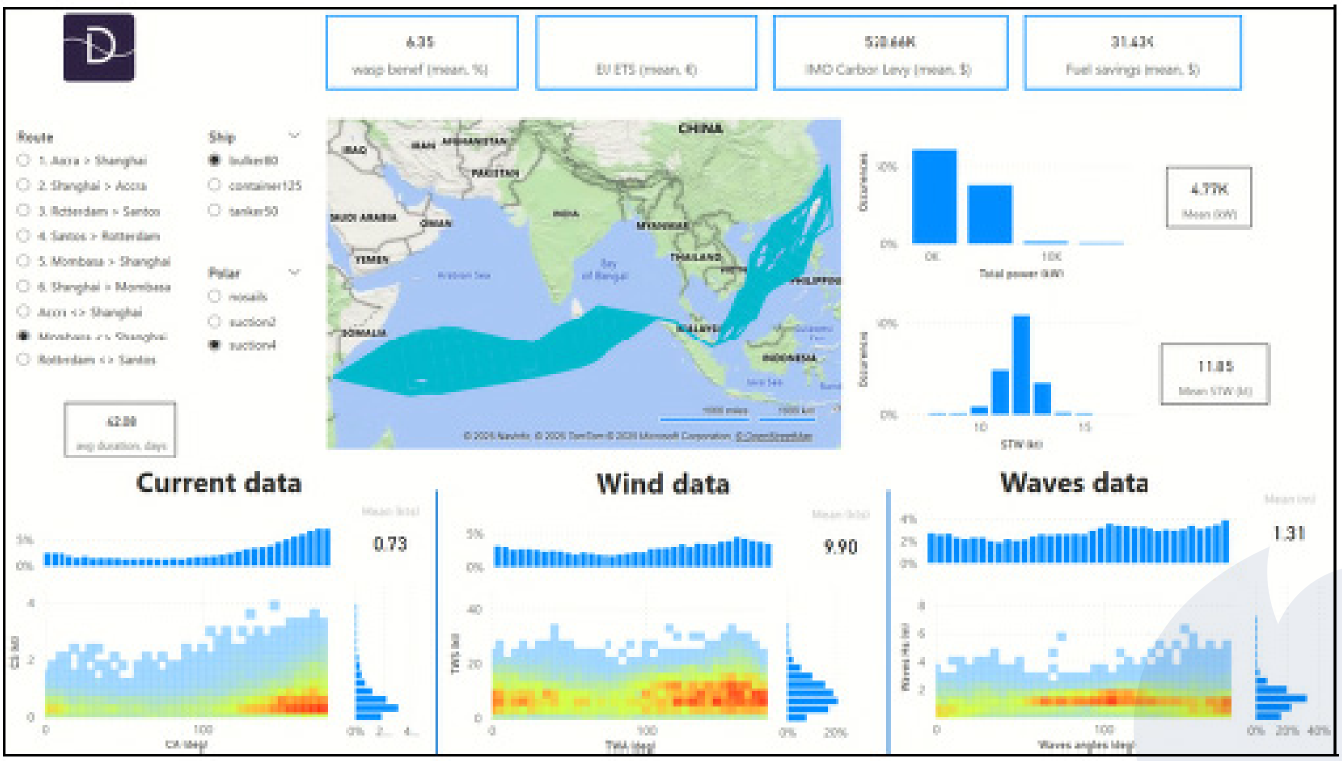


Bulker with 4 WASPs

Weather routing on Accra <> Shanghai

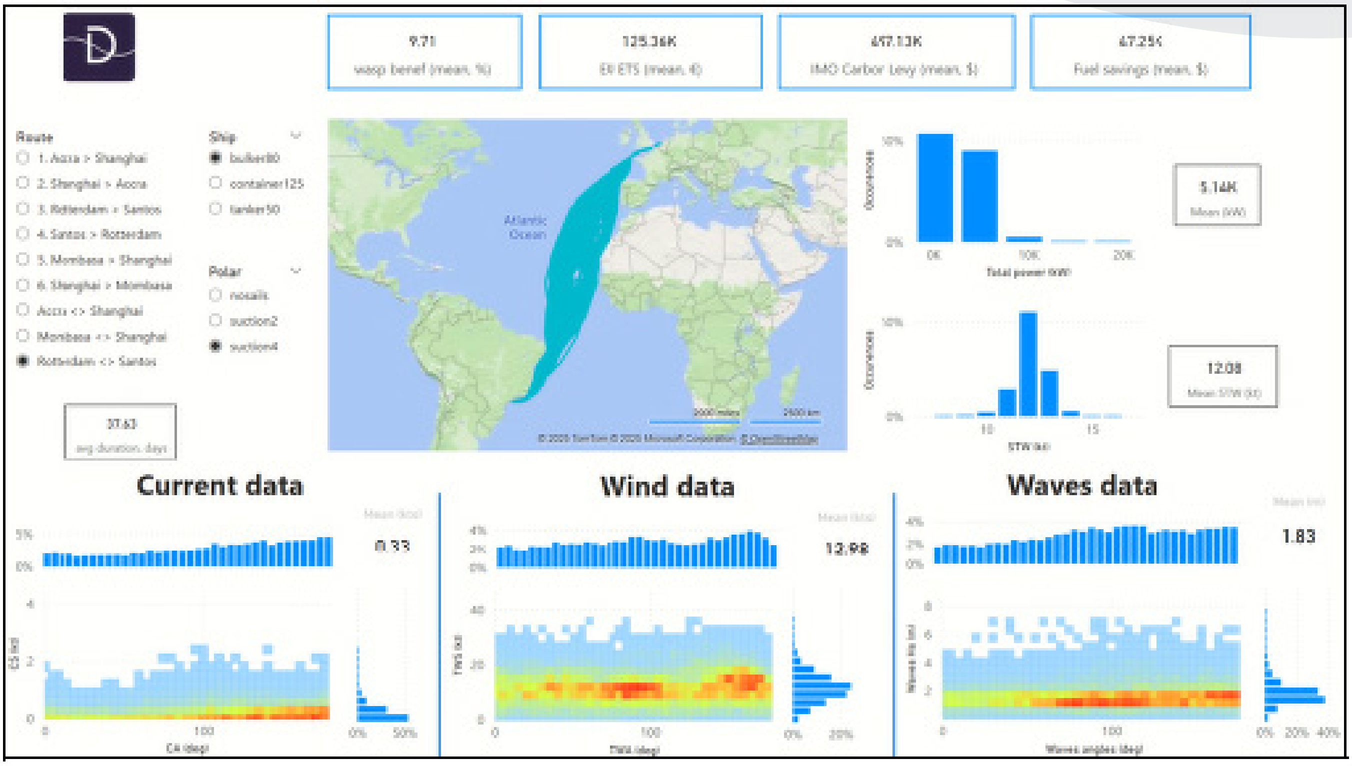


Weather routing on Mombasa <> Shanghai



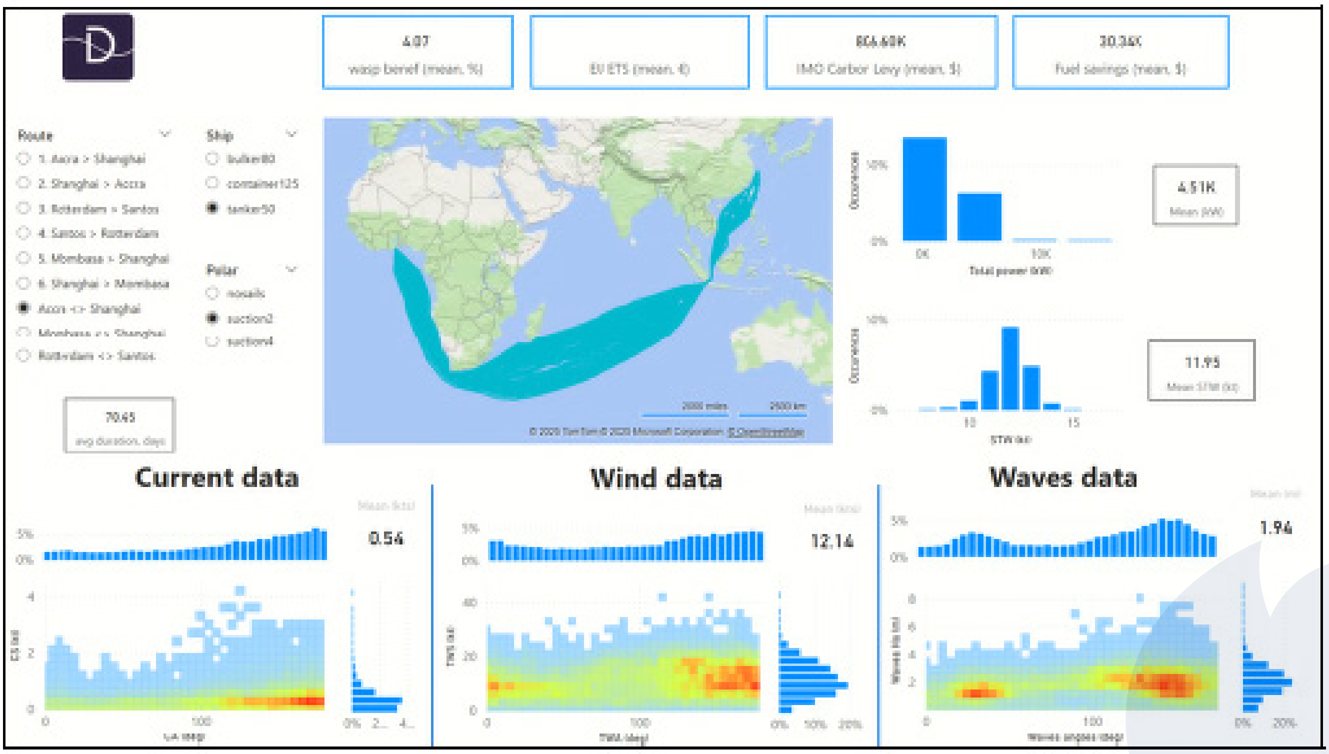
Bulker with 4 WASPs

Weather routing on Rotterdam <> Santos



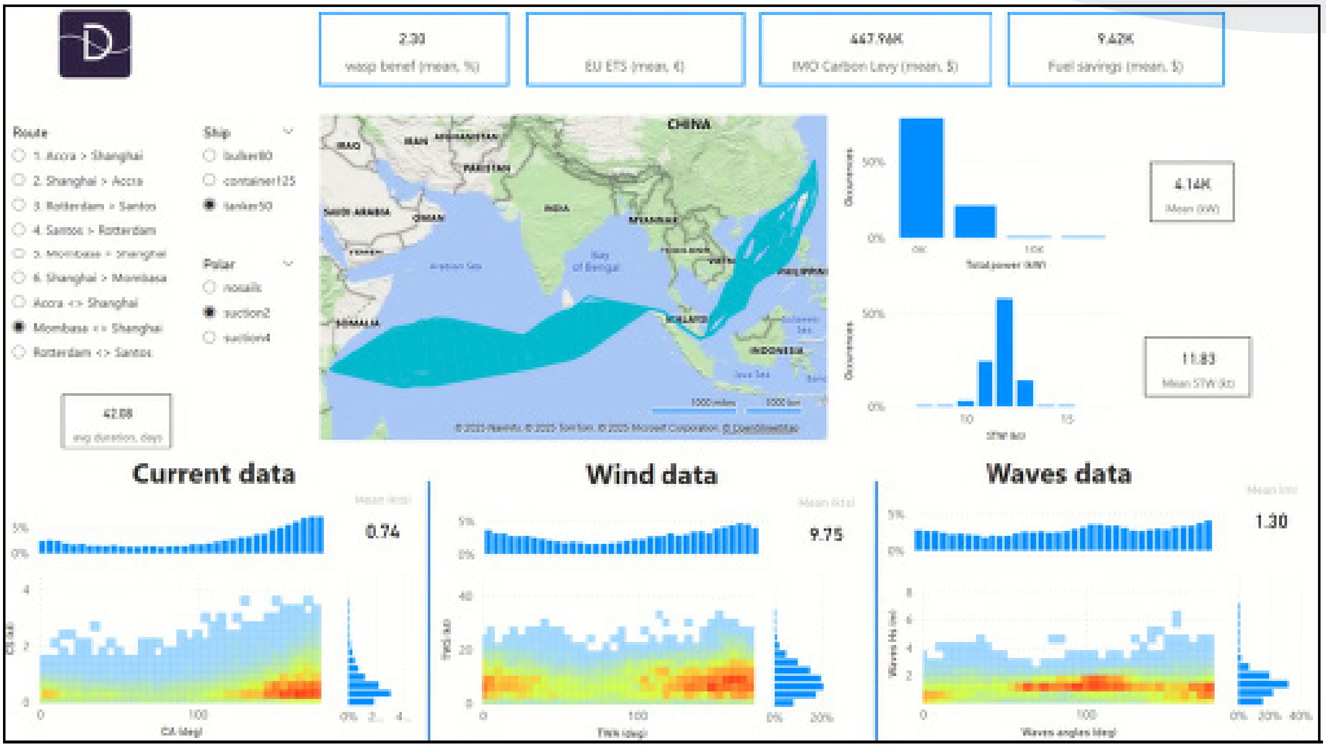
Tanker with 2 WASPs

Weather routing on Accra <> Shanghai

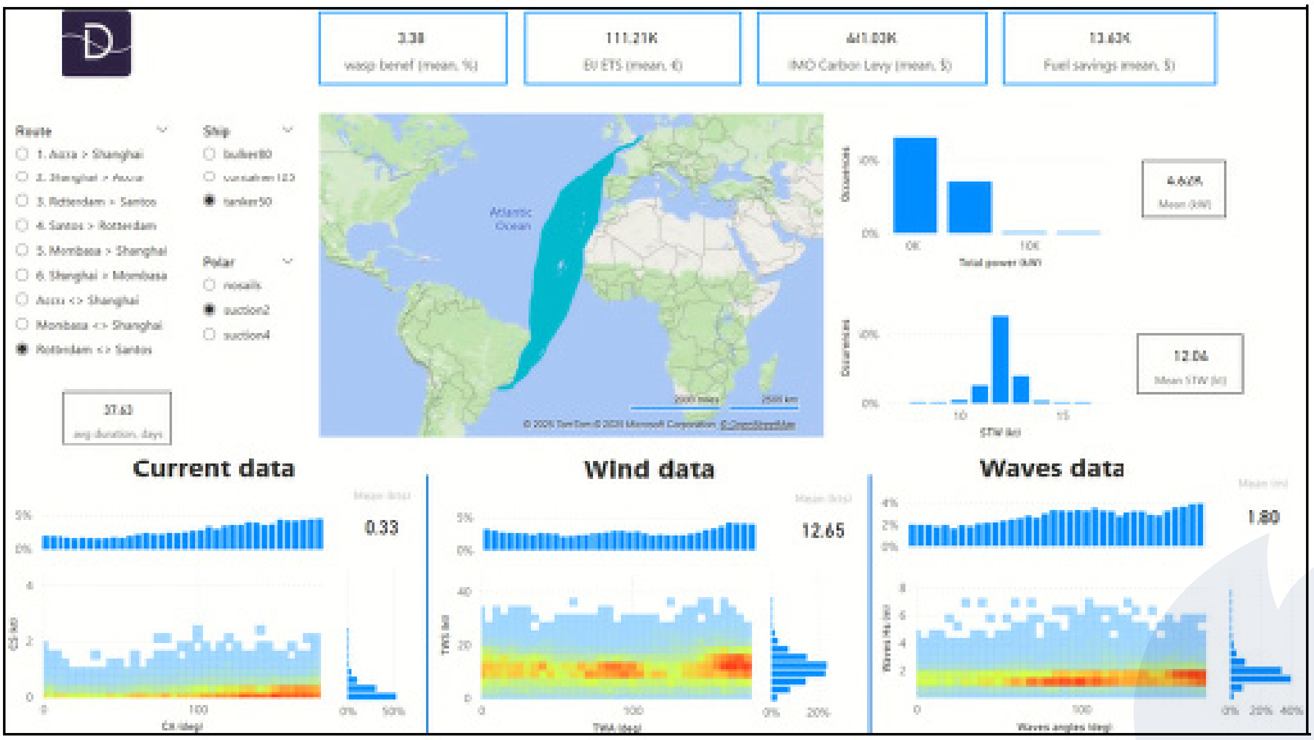


Tanker with 2 WASPs

Weather routing on Mombasa <> Shanghai

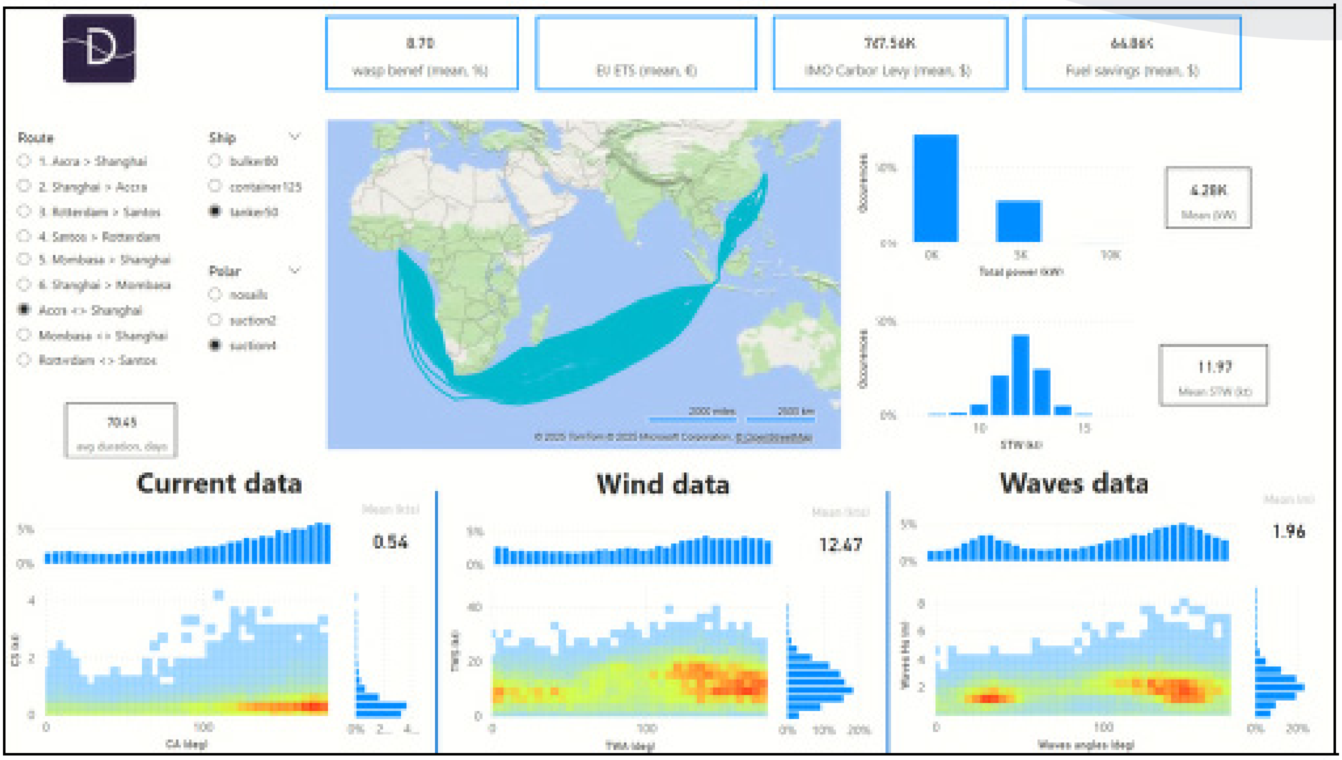


Weather routing on Rotterdam <> Santos

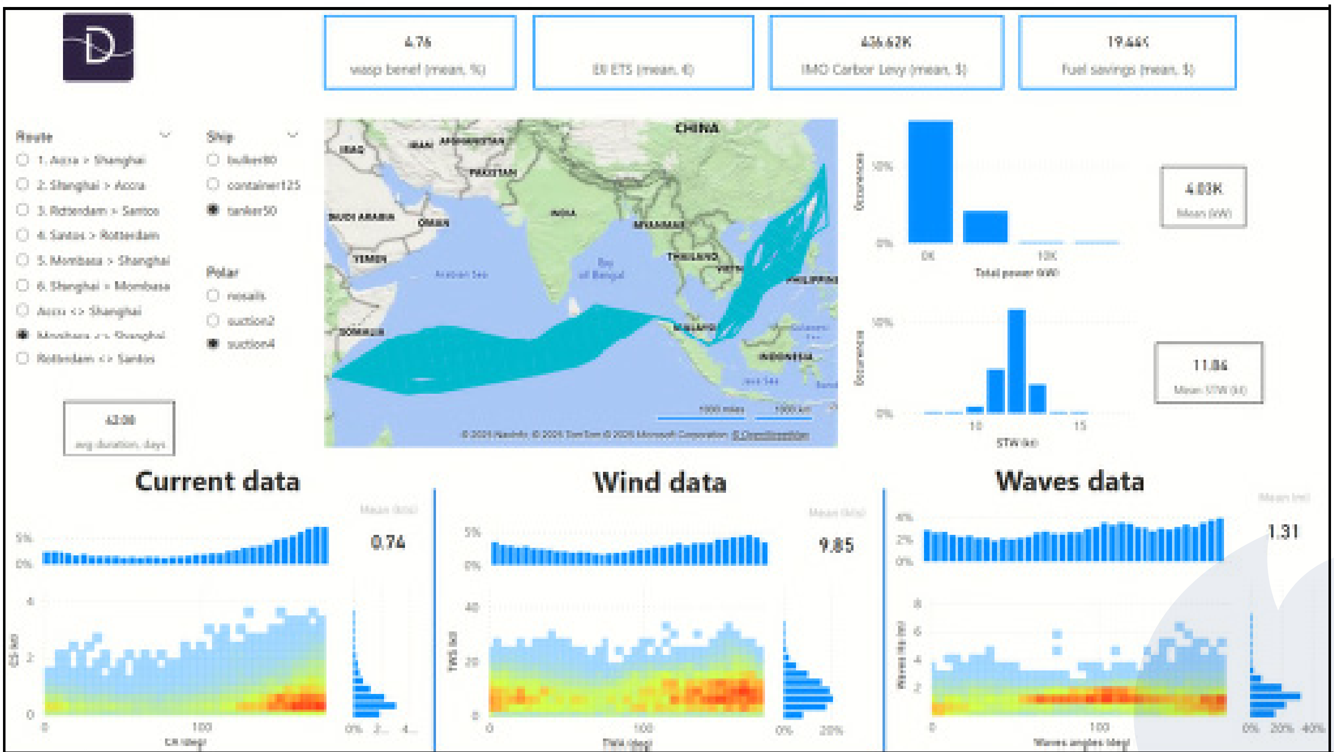


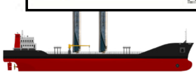
Tanker with 4 WASPs

Weather routing on Accra <> Shanghai



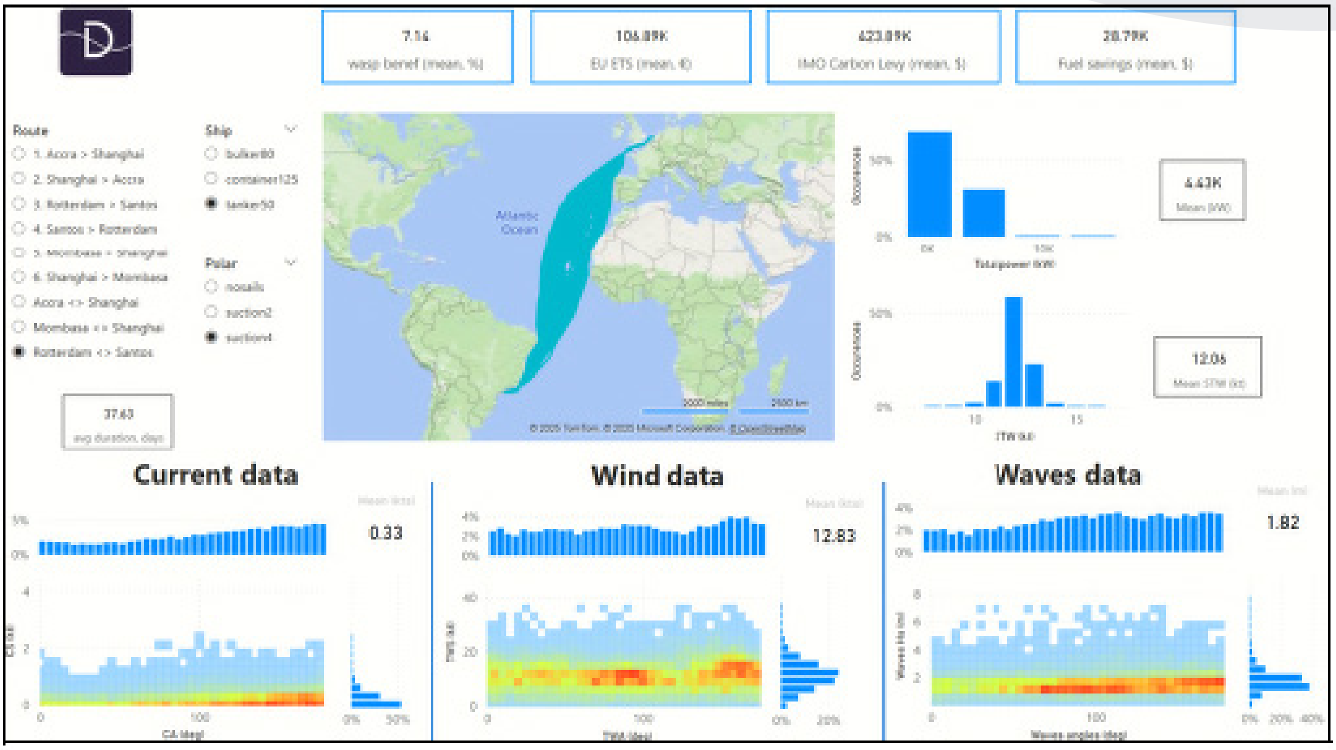
Weather routing on Mombasa <> Shanghai





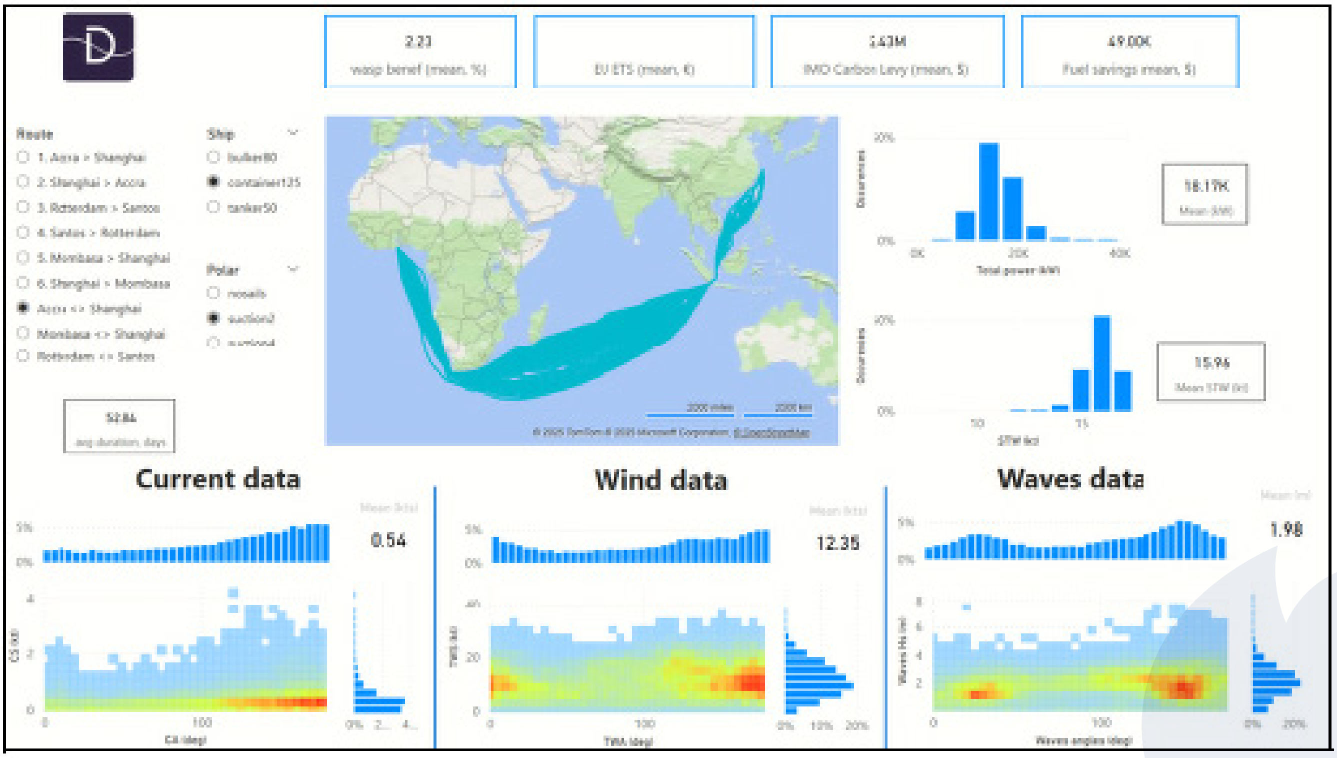
Tanker with 4 WASPs

Weather routing on Rotterdam <> Santos



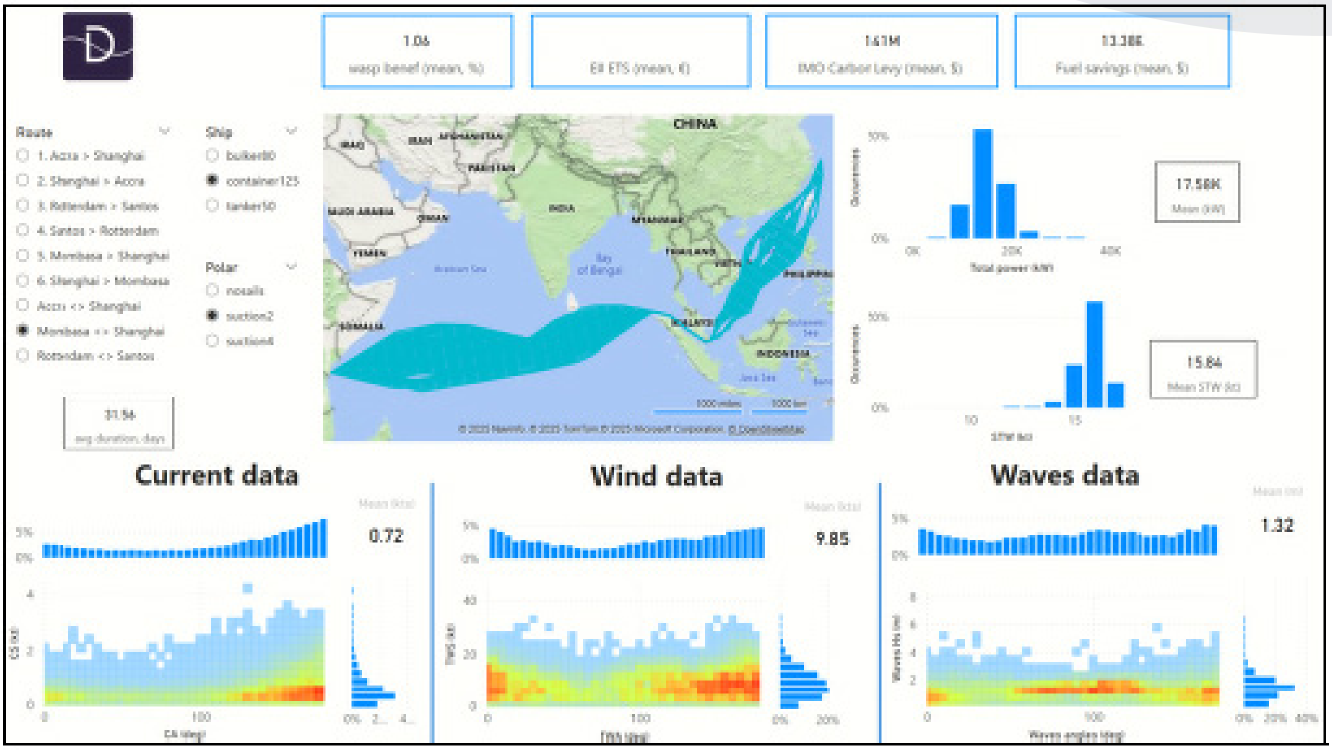
Containership with 2 WASPs

Weather routing on Accra <> Shanghai

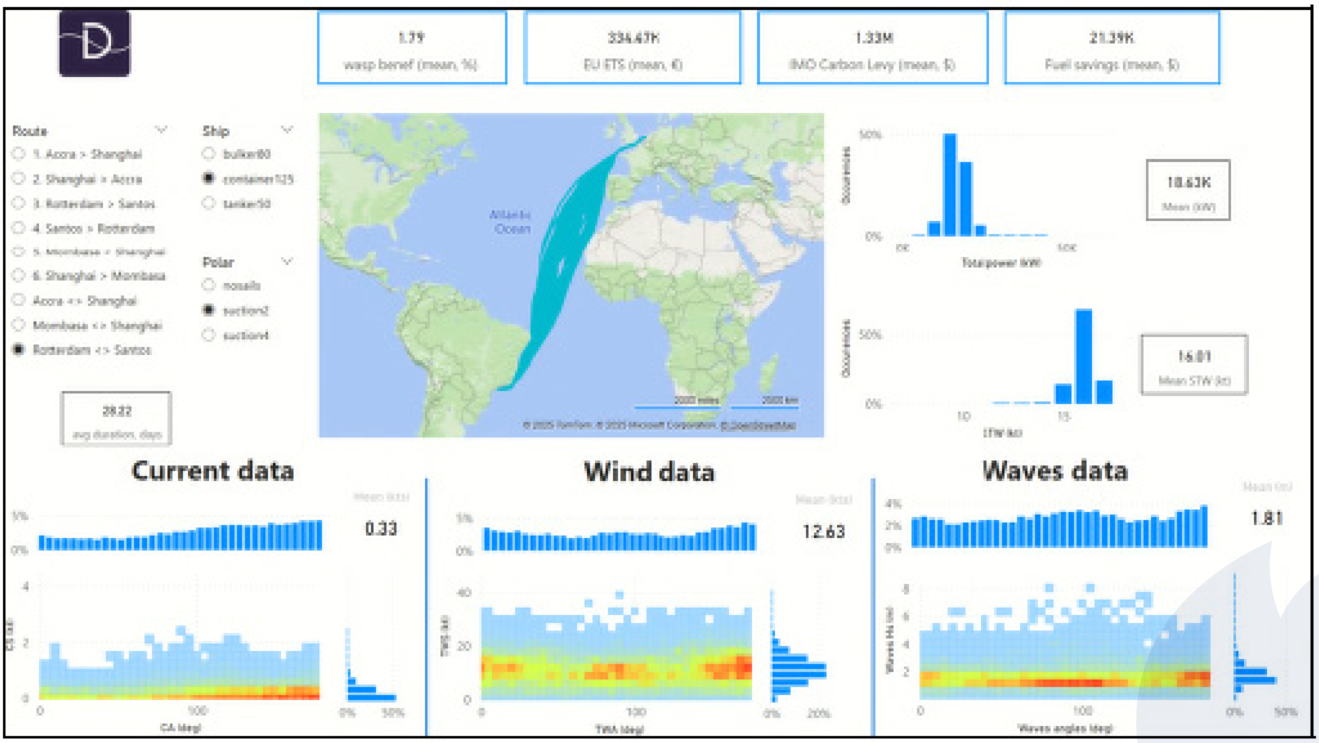


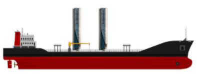
Containership with 2 WASPs

Weather routing on Mombasa <> Shanghai



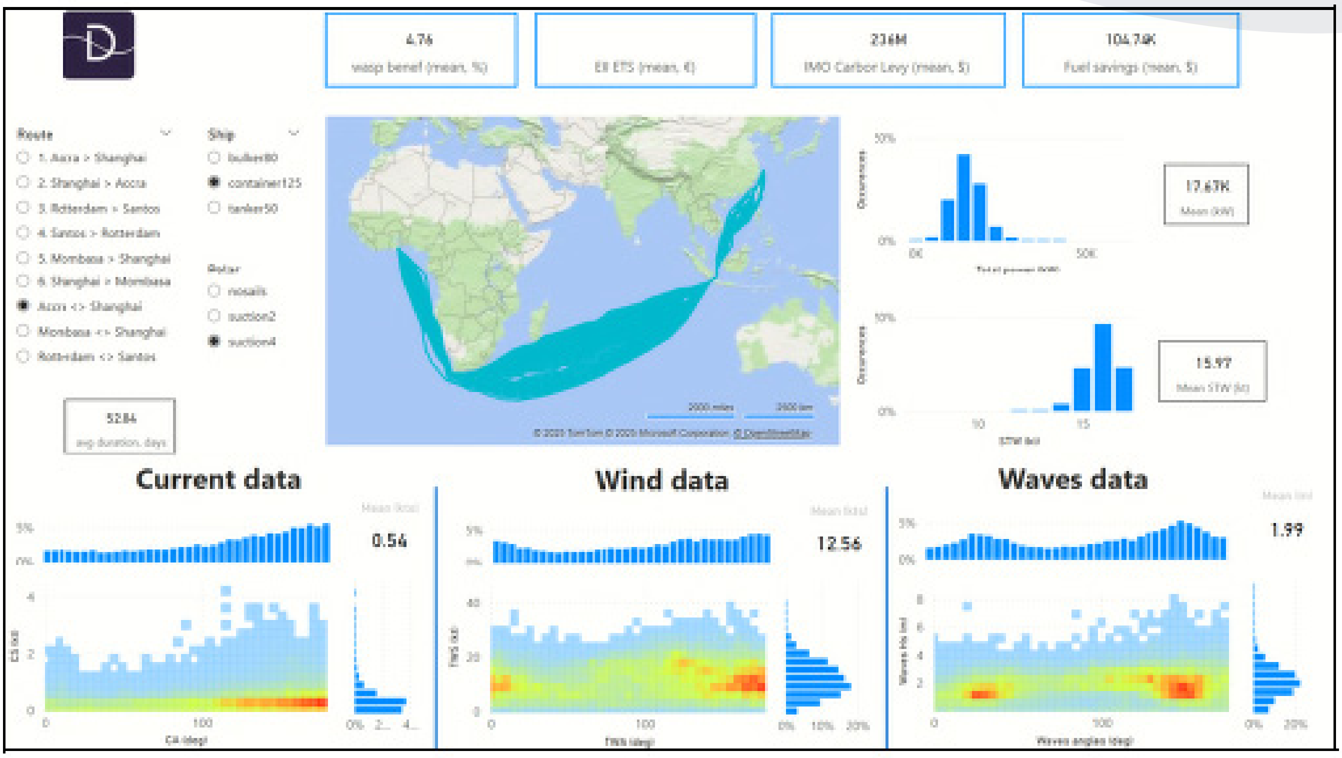
Weather routing on Rotterdam <> Santos



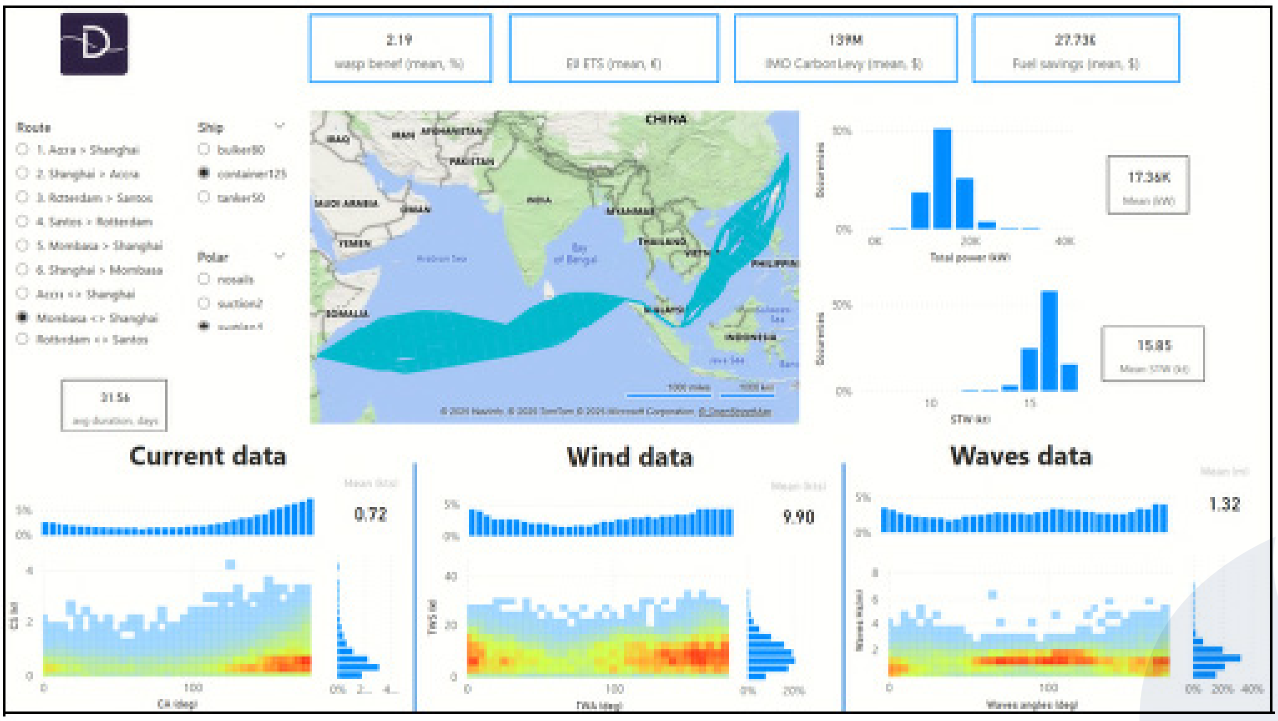


Containership with 4 WASPs

Weather routing on Accra <> Shanghai

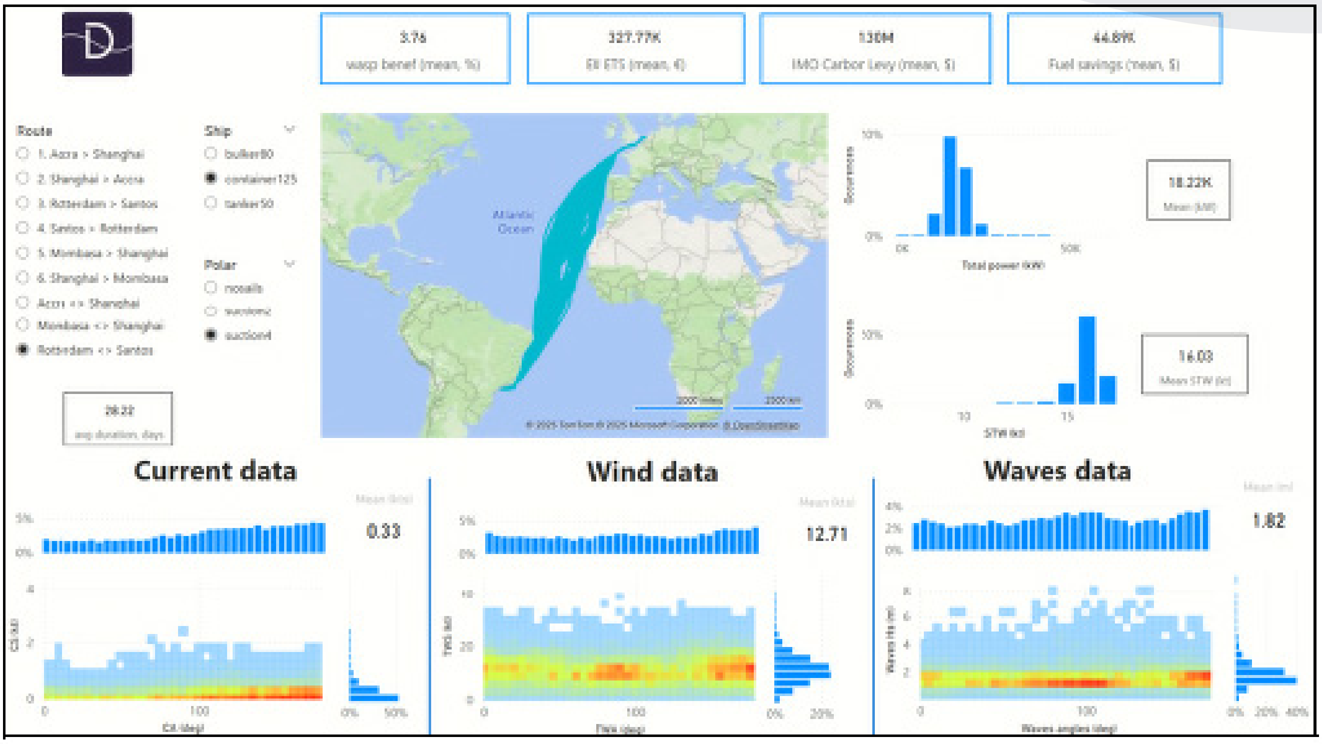


Weather routing on Mombasa <> Shanghai



Containership with 4 WASPs

Weather routing on Rotterdam <> Santos



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