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 ship 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 decarbonisation 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**

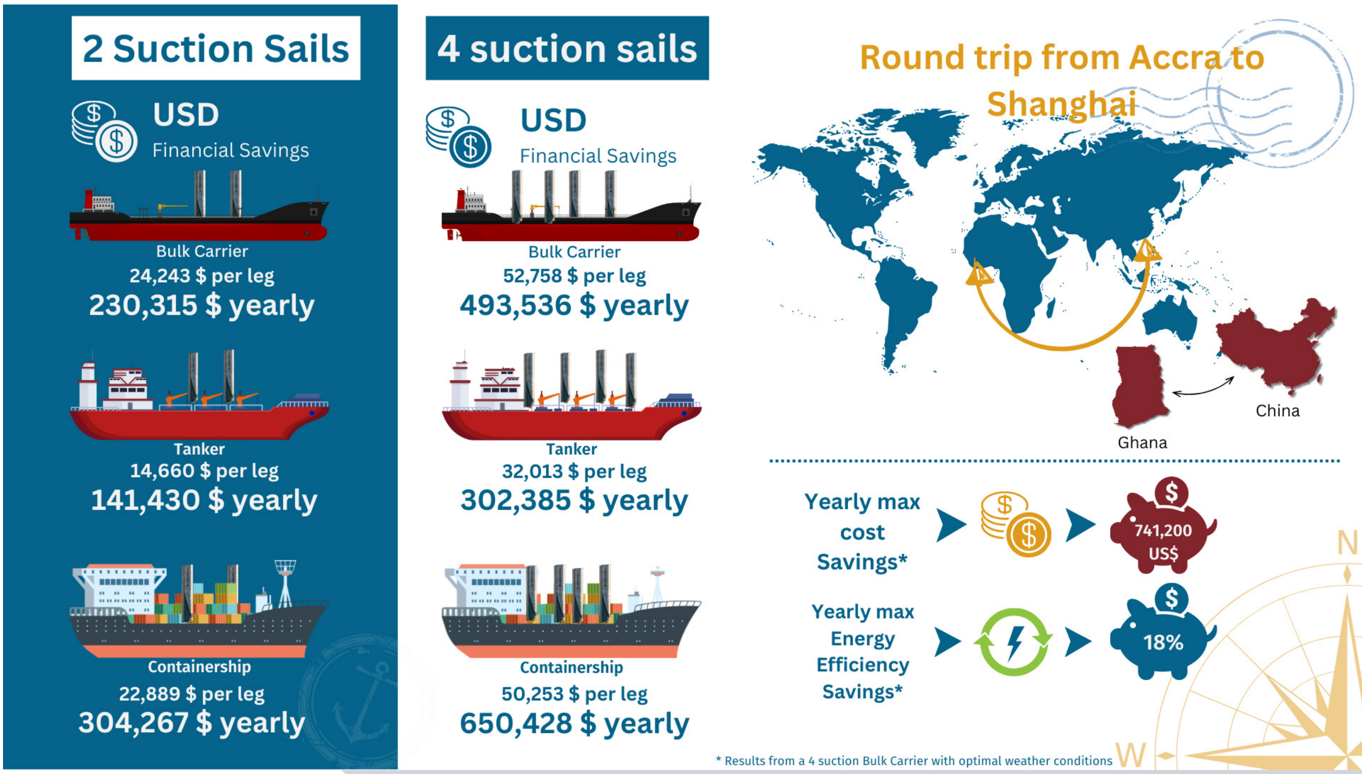
Main results

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.

Want to know more? [You can play around with the shipping routes, sail installations, and type of vessel to configure your own data.]

Statement for Clarity

In this study, suction wings were selected as the Wind-Assisted Ship Propulsion (WASP) technology in order to ensure methodological consistency and because reliable performance data were available for this configuration. This selection was made solely for modeling purposes and should not be interpreted as an endorsement or indication of superiority over other WASP solutions such as rotor sails, kites, or rigid sails.

No comparative assessment between different WASP technologies was undertaken. Rather, the focus was placed on quantifying the potential benefits of integrating a wind propulsion system within a statistical weather routing framework. The same methodology may be applied to alternative WASP technologies, provided that appropriate performance data are available.

Disclaimer

D-ICE Engineering has made every effort to ensure that all studies and analyses are correct, and that it reflects the vessel or operational capabilities most likely to be attained during operations. However, the results must not be considered as a guarantee of performance and D-ICE Engineering cannot be held responsible for any inaccuracies in the calculations.

2. Applicable documents and references

Ref	Reference
Holtrop 1984	A statistical re-analysis of resistance and propulsion data. International ship-building progress, 31(363), 272-276.
Yasukawa 2015	Introduction of MMG standard method for ship maneuvering predictions. Journal of Marine Science and Technology, 20(1), 37-52.
Fujii 1960	Experimental researches on rudder performance (1) (in Japanese). J. Zosen Kiokai 107, 105–111.
Liu 2017	Liu, J., & Hekkenberg, R. (2017). Sixty years of research on ship rudders: Effects of design choices on rudder performance. Ships and Offshore Structures
Yoshimura 2012	Hydrodynamic database and manoeuvring prediction method with medium high-speed merchant ships and fi shing vessels. In International MARSIM Con-ference (pp. 1-9).
Fujiwara 2005	A new estimation method of wind forces and moments acting on ships on the basis of physical component models, Journal of the Japan society of naval archi-tects and ocean engineers, 2, 243–255
Pianc 2014	PIANC Report No. 121 - 2014, Harbour Approach Channels - Design Guidelines
ROM 3.1 2007	Puertos del Estado. (2007). ROM 3.1-99: Recommendations for the Design of the Maritime Confi guration of Ports, Approach Channels and Harbour Basins. Madrid, Spain.

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, comes 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	Optimised route, optimised speed

3. Context of the study

This 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 clear findings and recommendations to help shipping grow in a way that protects the planet and benefits people. Particularly, it focuses on three major environmental regulations, shaping the future of maritime transport: the **IMO Carbon Levy**, the **EU Emissions Trading System**, and the **Carbon Intensity Indicator.** To assess the impact of these policies, the study focused on realistic voyage data, historical weather conditions, and three major global routes - **Accra to Shanghai**, **Mombasa to Shanghai**, and **Rotterdam to Santos**. Three vessels, a 50,000 DWT **MR tanker**, an 80,000 DWT **Panamax bulk carrier,** and a 125,000 DWT **Post-Panamax containership,** are taken from a representative database of ships used in the marine transport industry. This database was established based on a collection of typical ship dimensions, by [PIANC 2014], from [ROM 3.1 2007] and other statistical analysis.

Suction wings were selected as the Wind-Assisted Ship Propulsion (WASP) technology to maintain methodological consistency and because reliable performance data were available for this system. This choice was made solely for modeling purposes and should not be seen as an endorsement of suction wings over other WASP technologies, such as rotor sails, kites, or rigid sails. Digital twins of conventional and hybrid vessels were defined using semi-empirical formulas to model the hydrodynamic and aerodynamic loads applied to the ship, as well as the propeller design and engine power. A generic model of the suction sail is used, based on the state of the art. No interactions between sails or with the ship were considered.

Over **16,000 simulations were conducted from 2020 to 2023** to compare conventional mechanical propulsion with hybrid wind-assisted systems. The results highlight the environmental and economic benefits of WASP, showing how it can support compliance with upcoming regulations and contribute to more sustainable maritime transport

4. Methodology

4.1 Vessel setup and performance polar tables

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 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.

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.

All hydrodynamic and aerodynamics forces listed elow have been modelled using semi-empirical formulae taken from the literature which will not be detailed:

- Calm water resistance
- Maneuvring coefficients
- Added wave resistance
- Propeller propulsion
- Propeller and rudders characteristics
- Wind loads

Wind propulsion system

Suction sails are lifting profiles with active boundary layer control to shift the stall to larger angles. A movable flap is used to control the side of the aspiration zone. They were first designed by Malavard and Charrier, from the Cousteau Foundation R&D team, known as the Turbovoile.[1]

4.2 Introduction to D-ICE statistical 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. The details of our multi-objective shortest path algorithm won't be explained here.

A statistical weather routing study uses a vessel's digital twin to simulate its performance across a large set of historical weather and ocean conditions. It evaluates how different routes affect fuel consumption, speed, and voyage time.

1 Malavard, L. Un nouveau propulseur éolien de navire. La vie des Sciences, 1, 57-72, 1984

4.3 Environmental regulations

To assess environmental compliance, the study incorporates key regulatory metrics such as the IMO's CII, the proposed IMO carbon levy, and the EU ETS. These frameworks provide standardized measures for evaluating the vessel's carbon footprint and economic impact under different routing scenarios.

IMO 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 CO_2, 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 CO_2e emissions per ton of HFO burned is ~3.3 tons of CO_2e.

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[1].

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

In this study, the IMO levy for CO_2e 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:

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

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 8.

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[2].

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.

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2 "IMO's Newly revised GHG Strategy: what it means for shipping and the Paris Agreement" (Source: ICCT20, July 2023)

3 "Reducing emissions from the shipping sector" (Source: European Commission, Climate Action)

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 1: Emission Factor of the specific fuel type

Table 1 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**.**

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

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

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

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 8.

CII

The CII is a metric used by the IMO to assess the carbon efficiency of ships, as per MEPC 354(78)[3], which is part of the IMO's regulations to reduce the greenhouse gas emissions from ships. The CII is part of the IMO Strategy to reduce GHG emissions and is calculated for each individual vessel using the formula:

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

, 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 specific vessel (deadweight or gross tonnage depending on the vessel's type). The result is the CO_2 emissions per ton-mile, expressed in4 grams of CO_2 per nautical mile per ton of deadweight (g CO_2 /ton-mile). This value of the attained CII helps rate the ship's carbon efficiency, with lower values indicating better performance. In the next step, the reference CII is calculated. It represents the carbon intensity of the ship based on its type, size, and operational profile, and is determined by a formula specified by the IMO[4].

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, the attained CII and required CII are obtained, the CII class is determined as follows[5] :

4 "Annex16 - Resolution MEPC 354(78) - 2022 Guidelines on the operational carbon intensity rating of ships" (Source: MEPC 354(78))

5 "Parameters for determining the 2019 ship type specifi c reference lines" (Source: Annex 15, page 4 - MEPC 78/17/Add.1)

6 "dd vectors for determining the rating boundaries of ship types" (Source: MEPC 78/17/Add/1 Annex 16, page 6)

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

5. Study definition

5.1 Vessel setup

Table 3 summarizes the main particulars for each ship.

Table 3 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 3: Vessels technical characteristics

5.2 Sails configuration

In the statistical weather routing study assessing the performance of WASP, Suction Wings were selected for evaluation among other technologies based on their sustainability for diverse vessel types and operation profiles.

The study covers three major routes: Accra - Shanghai, Mombasa - Shanghai, and Rotterdam - Santos, which represent a range of wind patterns and sailing conditions. Simulations are conducted for 3 typical cargo vessels presented above. Therefore, suction wings were selected due to their defi ned aerodynamic performance data, compatibility with structural and operational constraints of all three vessels, and their ability to generate usable thrust across a broad range of wind angles. In addition, drag and lift coeffi cients and lift-induced drag of suction wings are available in the literature and were used to model these suction wings. These characteristics made them technically feasible for modeling in long-range routing simulations. In no way does this represent an advertisement for a wasp system in particular because each system (kite, wing, flettner rotor, suction wing) has its own pros and cons.

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

5.2.1 Set up on tanker

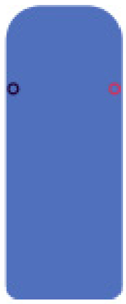
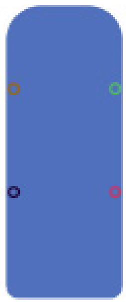
Suction Wings' onboard positions		
Number	2	4
Span	24m	24m
Position (from aft)	150m	75m / 150m

Table 4: tanker with two WASP configurations

5.2.2 Set up on bulk carrier

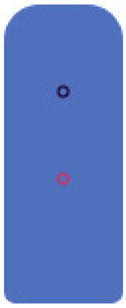
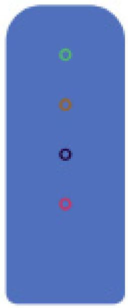
Suction Wings' onboard positions		
Number	2	4
Span	30m	30m
Position (from aft)	100m / 170m	80m / 120m / 160m / 200m

Table 5: bulk carrier with two WASP configurations

5.2.3 Set up on containership

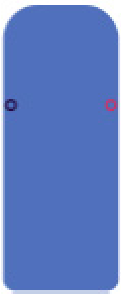
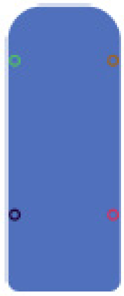
Suction Wings' onboard positions		
Number	2	4
Span	30m	30m
Position (from aft)	240m	100m / 300m

Table 6: containership with two WASP configurations

5.3 Polar tables

figure 1 below presents the polar visualization of the BrakePower of the bulker carrier with no sails (solid lines) and with 2 suction wings (dotted lines) on the left and on the right with no sails and with 4 suction wings.

In order to view a 5D polar, some coordinates are fixed and two are displayed. Here the wave height is fixed to 0m, the wave angle is 0 degrees. On the left figure, the isosurface curves are the speed through water (ranging from 8kt to 16kt) and the true wind speed is fixed to 15kt. On the right fi gure the isosurface curves are the true wind speed (ranging from 0kt to 50kt).

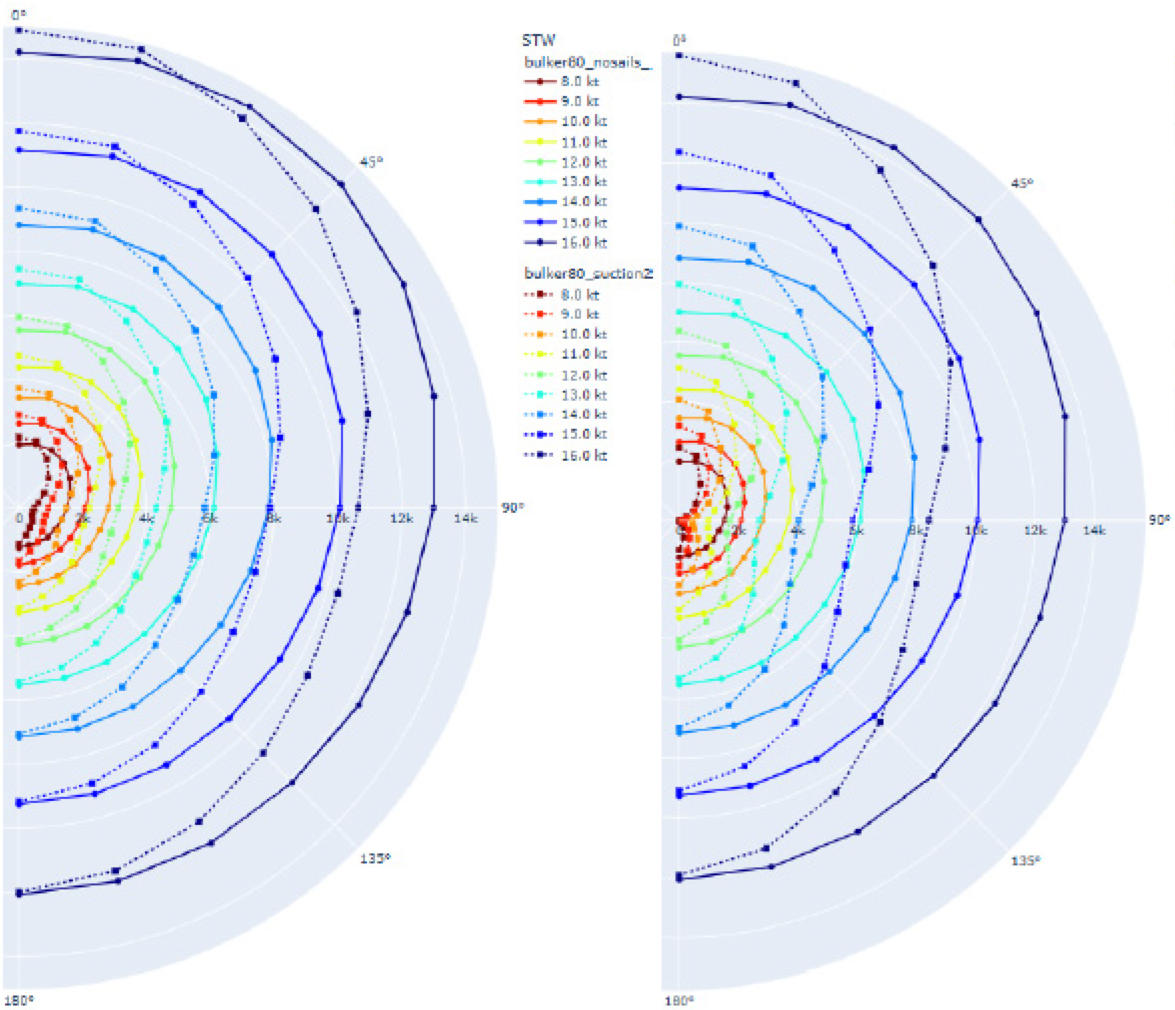


Figure 1: BrakePower visualization for the Bulker with no sails and 2 suction wings on the left and the Bulker with no sails and 4 suction wings on the right

On both left and right diagrams it appears that for wind angles of 30 to 180 degrees the power of the boat equipped with sails is lower than the power of the boat without sails. For wind angle from 0 to 30 degrees it is the opposite because of the additional drag of the wings. The same visuals for the containership and tanker are available in the appendix.

5.4 Routes configuration

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 specific waypoints to call, some route pass gates, canals, stopovers where specific 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 7 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	10 906 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	20 526 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	12 266 nm	12 kt	42.1 days
	Tanker				
	Containership			16 kt	31.6 days

Table 7: Routes description

The number of round trips per year is estimated by dividing 365 days by the mean trip duration for each ship and subtracting ~10% margin for port operations, anchoring, maintenance (see Table 8).

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 8: Estimated number of round trips per year per vessel per route

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.

5.5 Statistical Study

5.5.1 Run definition

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 optimised 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 benefits of adding WASP compared to Run 1.

In Table 9, we propose notations for these runs, and, in Table 10 - associated benefits 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 9: 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 10: 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.

5.5.2 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 influence. The longer the routes are - the more flexibility 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.

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 the surface (m/s) - Zonal velocity of current at surface (m/s)	Mercator Ocean	HR Global	24h	1/12°

Table 11: Weather models used

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[1]. Among other information, temporal 7 and spatial resolutions are defined in the Table 11.

7 "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)

6. Results and analysis

6.1. Case study: Bulk carrier with 4 WASPs on the route Rotterdam > Santos

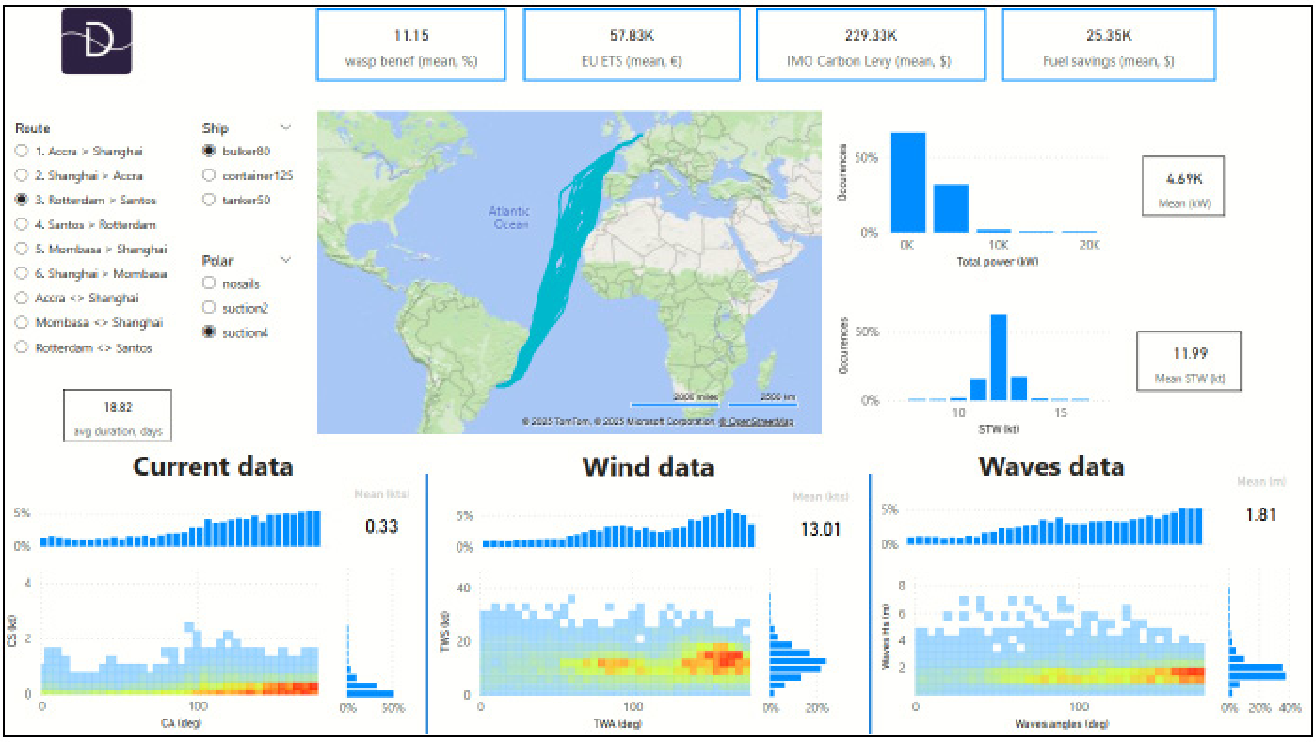


Figure 2: Synthetic results for bulk carrier equipped with four 30-meter-high suction wings on the route from Rotterdam to Santos, with a reference STW of 12 knots.

Statistical weather routing results for the route Rotterdam > Santos with the 4 suction wings at 12kt are given in Figure 2. A set of optimised routes seen on the map - represents the optimised 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 colours 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 confi guration. These results can also be found in the Power BI report.

Figure 3 summarizes the annual impact of using 4 WASPs on board of the bulk carrier on the round route Rotterdam - Santos. On average, using wind-assistance technology improves efficiency by 9.71%, saving around 825 tons of fuel, which translates to 412,500 $ in cost savings and reduces CO_2 emissions by 2569 tons. These savings also reflect potential environmental compliance benefits, including **1.09 M€ under the EU ETS and 4.34 M$ in IMO carbon levy** avoidance. The data range shows variability depending on operational conditions, but overall impact is clearly positive.

	Min	Mean	Max
WASP Benefits, %	4.94	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 3: key indicators for the bulk carrier with 4 WASPs on the route Rotterdam <> Santos during annual operations

6.2 General results

6.2.1. Vessel's performance per round route

Remembering the notation of runs in Table 9, and the benefits notation in Table 10, in Figure 4 (left) the average total energy consumption of the motor vessel and hybrid vessels in two WASP configurations for the different routes and respective vessel service speeds can be seen.

As expected, compared to the motor ship on the optimised route at optimised 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 4 (right), the benefits calculated on fuel consumption of the three vessels equipped with two different WASP confi gurations over three round trips, compared to the motor ship, are observed. All motor or hybrid vessels are operated on optimised routes at optimised speeds.

The colour legend is as followed:

- adding 2 WASPs: **suction2**

- adding 4 WASPs: **suction4**

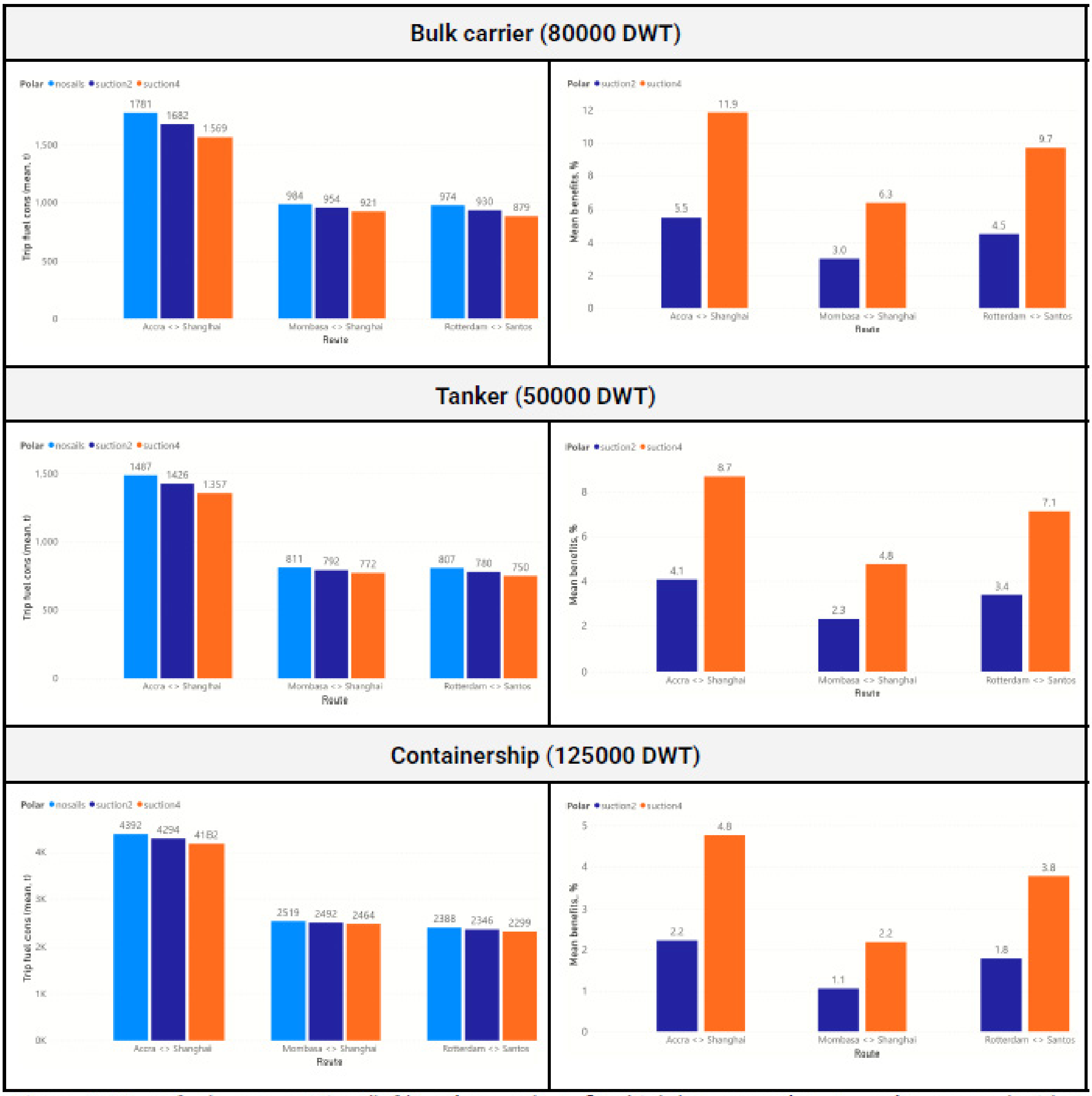


Figure 4: Mean fuel consumption (left) and mean benefits (right) per round route and per vessel with 3 different configurations: no sails, with 2 suction wings, and with 4 suction wings (see in the legend)

The greatest benefits 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 benefits 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.

Then, in Figure 5, a reduction in CO_2 emissions is found when hybrid vessels with two or four WASPs installed are used, compared to motor vessels. Over three round trips, the hybrid vessels emitted less CO_2 than the motor ship. All 3 vessel types (motor, hybrid with 2 or 4 WASPs) operated on optimised routes at optimised speeds:

- adding 2 WASPs: **suction2**

- adding 4 WASPs: **suction4**

All vessels across all routes demonstrate a significant reduction in CO_2 emissions when suction wings are added. When four systems are used, the reduction in CO_2 emissions is doubled compared to the two-suction wing confi guration. This pattern is consistent for all vessels and routes.

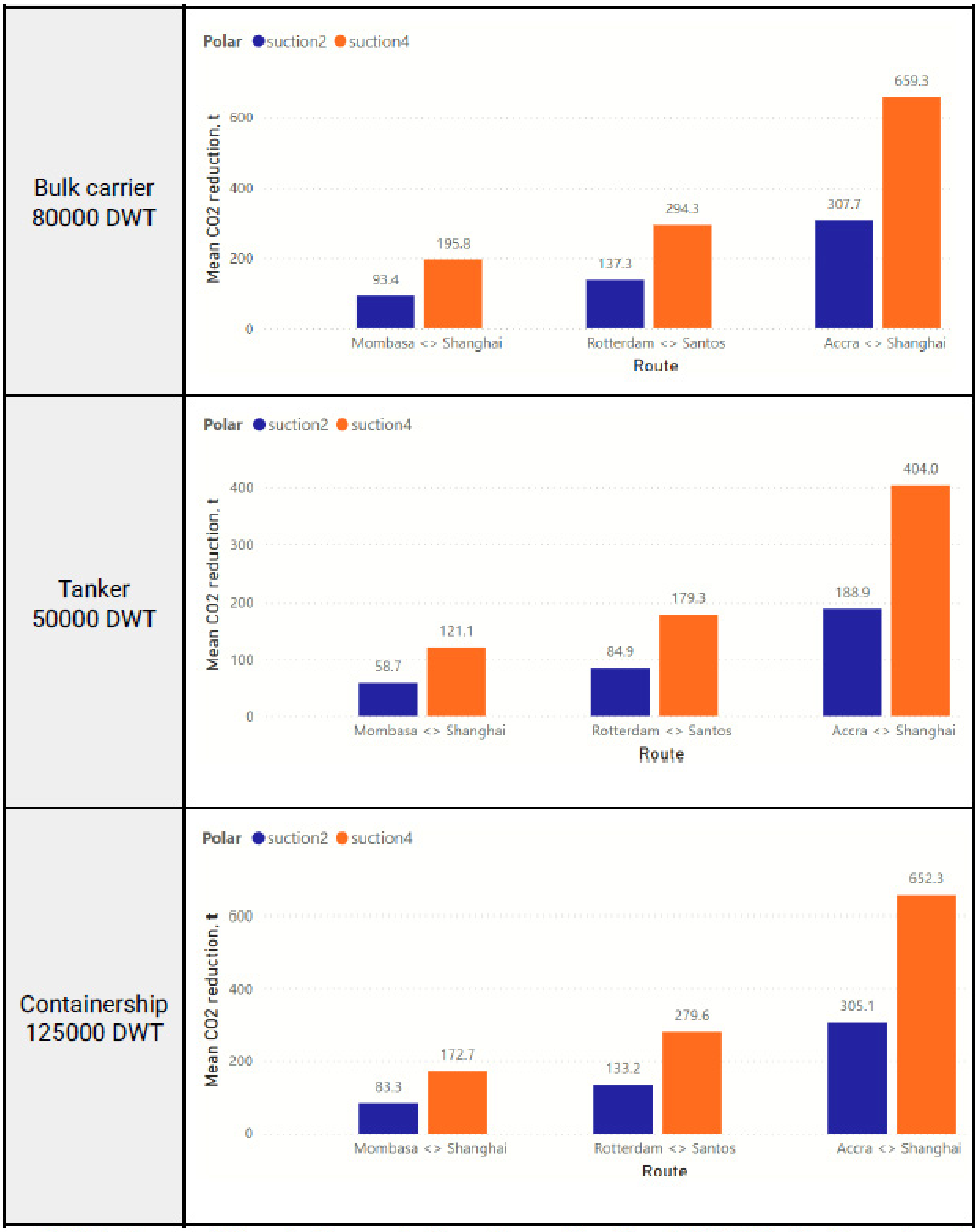


Figure 5: Global mean CO_2 emissions reduction when adding 2 and 4 WASPs, for 3 round routes for (top): bulk carrier, (middle): tanker, and (bottom) containership

6.2.2. Annual vessel's performance

Figure 6 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 optimised speed and route strategies.

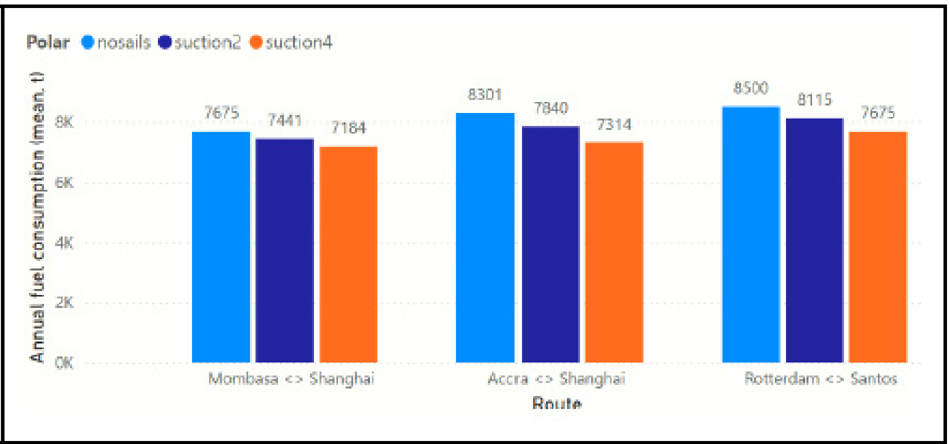
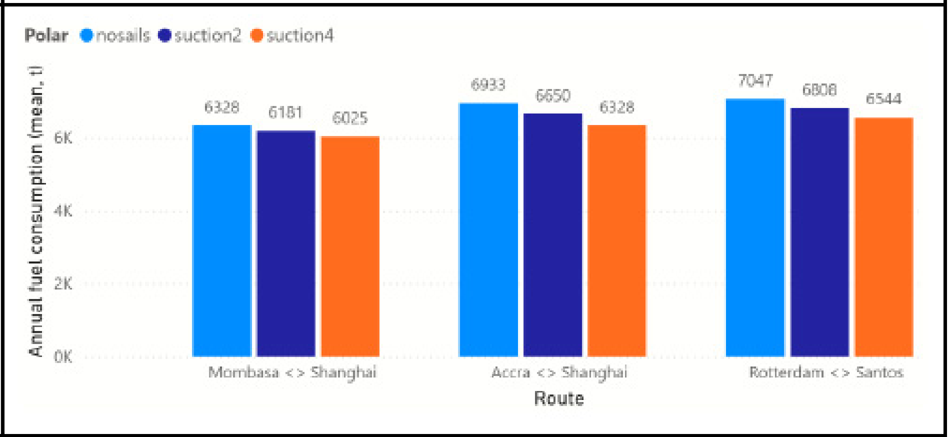
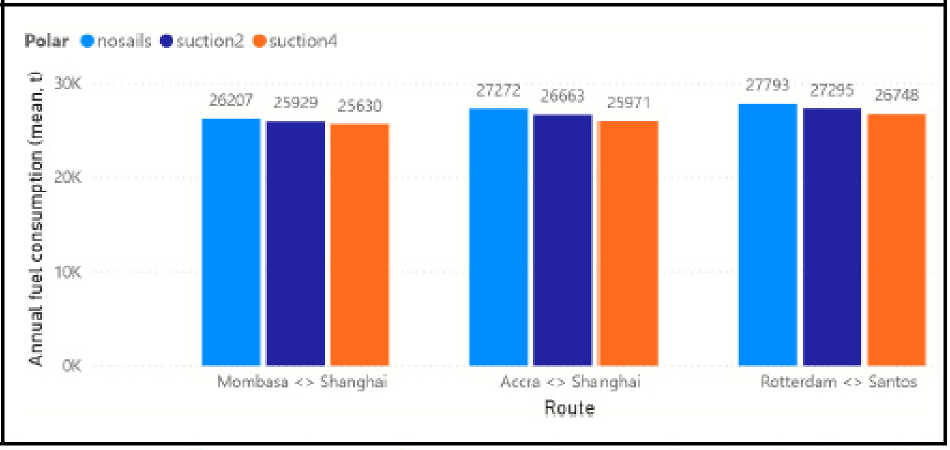
Bulk carrier 80000 DWT	
Tanker 50000 DWT	
Containership 125000 DWT	

Figure 6: 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.

6.2.3. CII rating

Table 12 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 optimised routing and speed. Column GCR_CS shows the CII for the motor vessel (without WASP) on the conventional navigation (Great Circle route with fixed service speed), where the tanker performs best (**A** rating) on all routes. Without route and speed optimisation, 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 confi gurations 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 12: average CII rating per vessel per WASP configuration per round route

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

6.2.4. IMO Carbon Levy

As we see from Figure 7 and Figure 8, installation of suction wings technologies reduces the IMO carbon levy, with 4 WASPs providing the highest savings. The results indicate that IMO levy varies significantly 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 fitted 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 figures 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 profile.

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

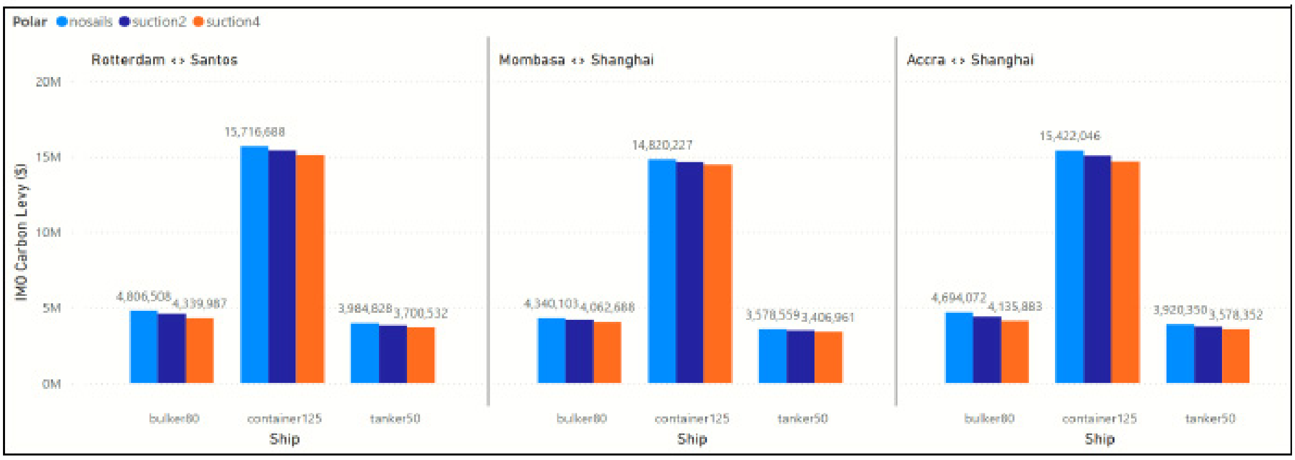


Figure 7: Mean annual IMO carbon levy per vessel type in 3 configurations (no wasp, 2 wasps, 4 wasps) on 3 round routes

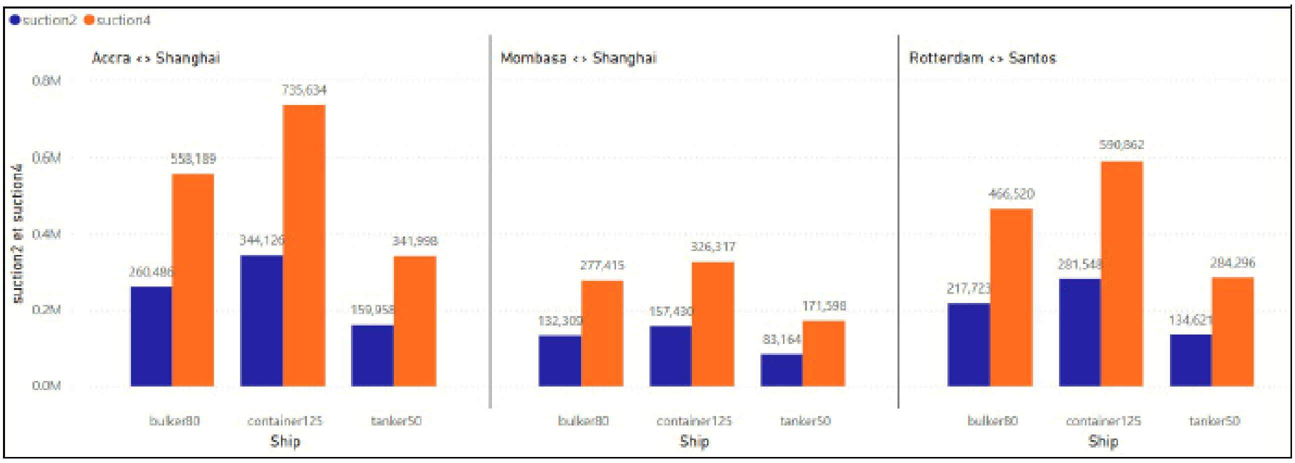


Figure 8: Reduction of mean annual IMO carbon levy per ship when installing WASPs in two different configurations for 3 routes

6.2.5. EU ETS

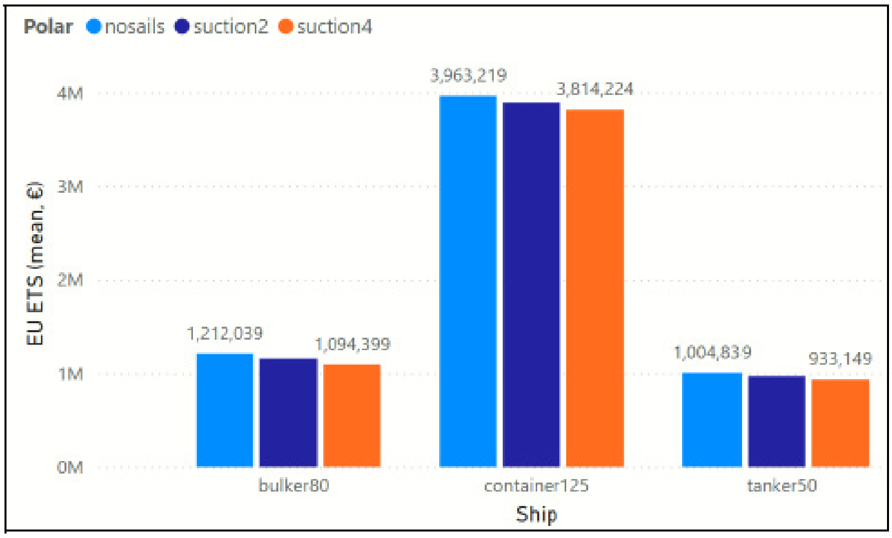


Figure 9: Mean annual EU ETS per ship without and with WASPs in two different configurations on the route Rotterdam <> Santos

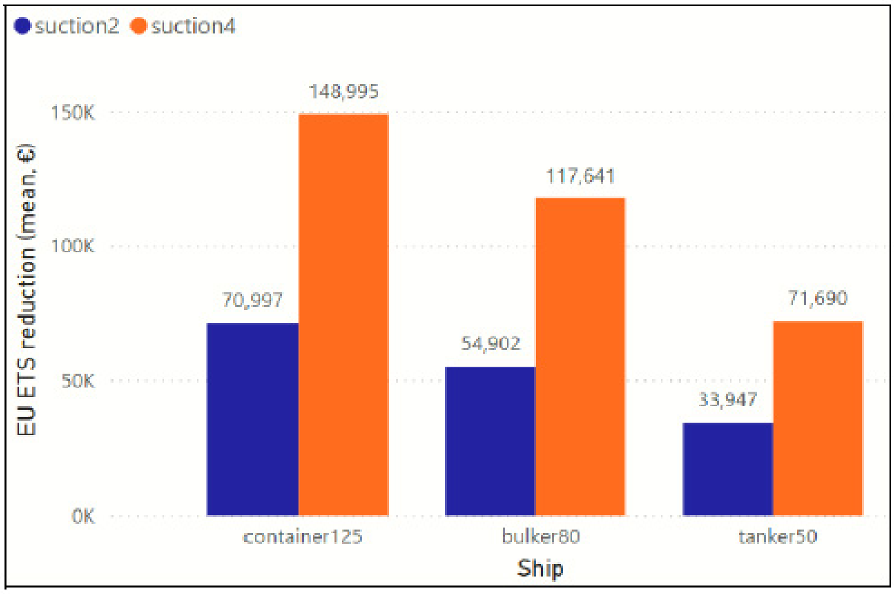


Figure 10: Reduction of mean annual EU ETS per ship when installing WASPs in two different configurations on the route Rotterdam <> Santos

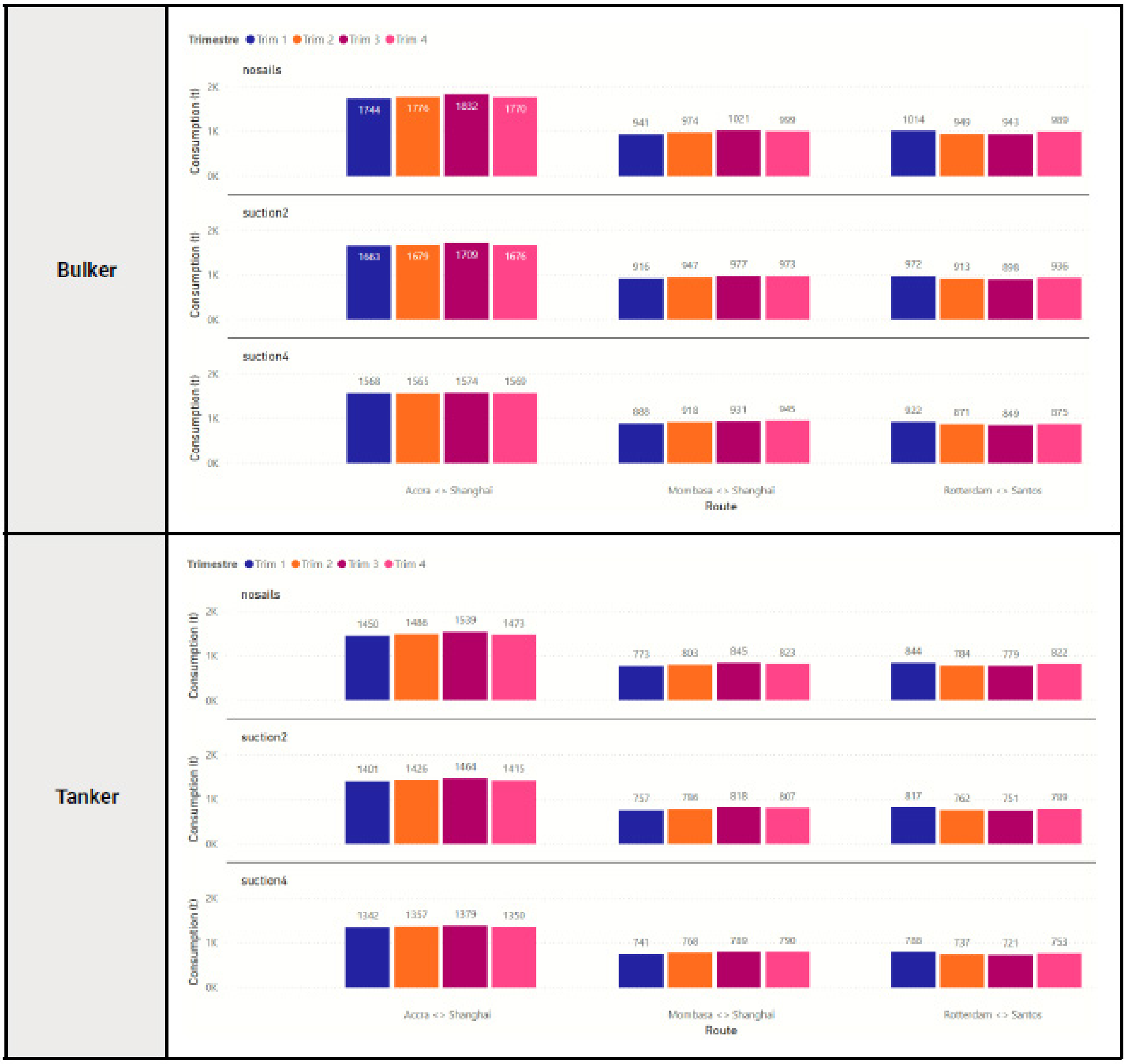
Figure 9 and Figure 10 are implemented only for the route Rotterdam <> Santos. As a reminder, only 50% of emissions were considered as this route is between EEA and non-EEA ports. The highest average annual EU ETS is 3,963,219 € for a container ship using only conventional propulsion.

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 significantly reduces EU ETC costs, with a higher number of wind-assisted technologies being the most effective.

6.2.6. Seasonal variation

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



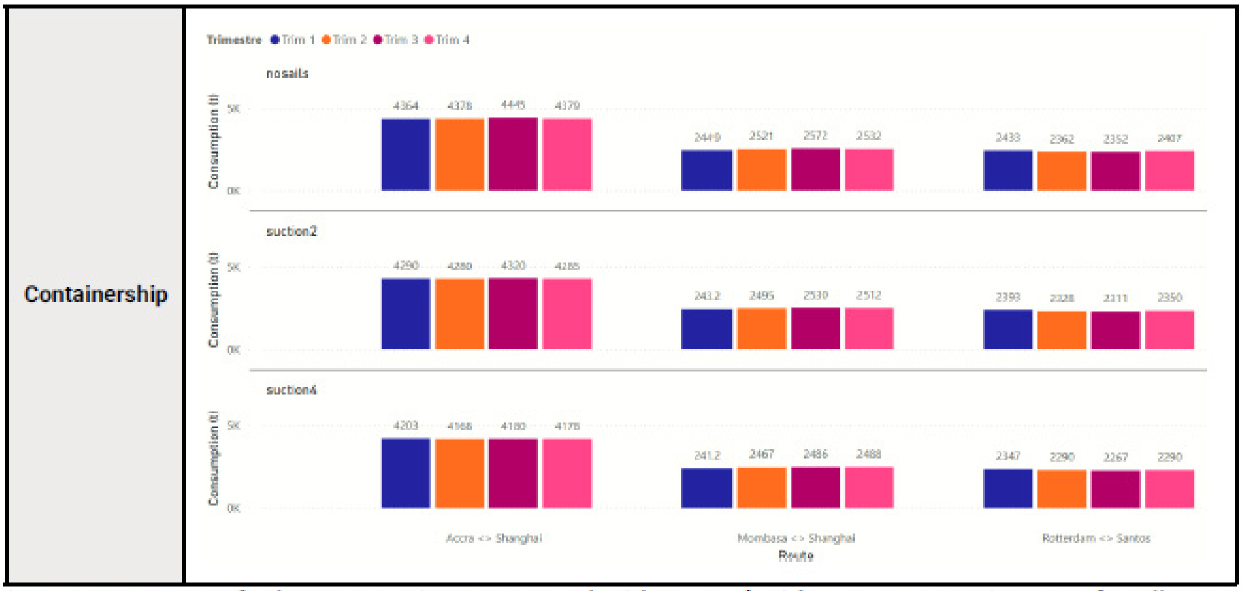
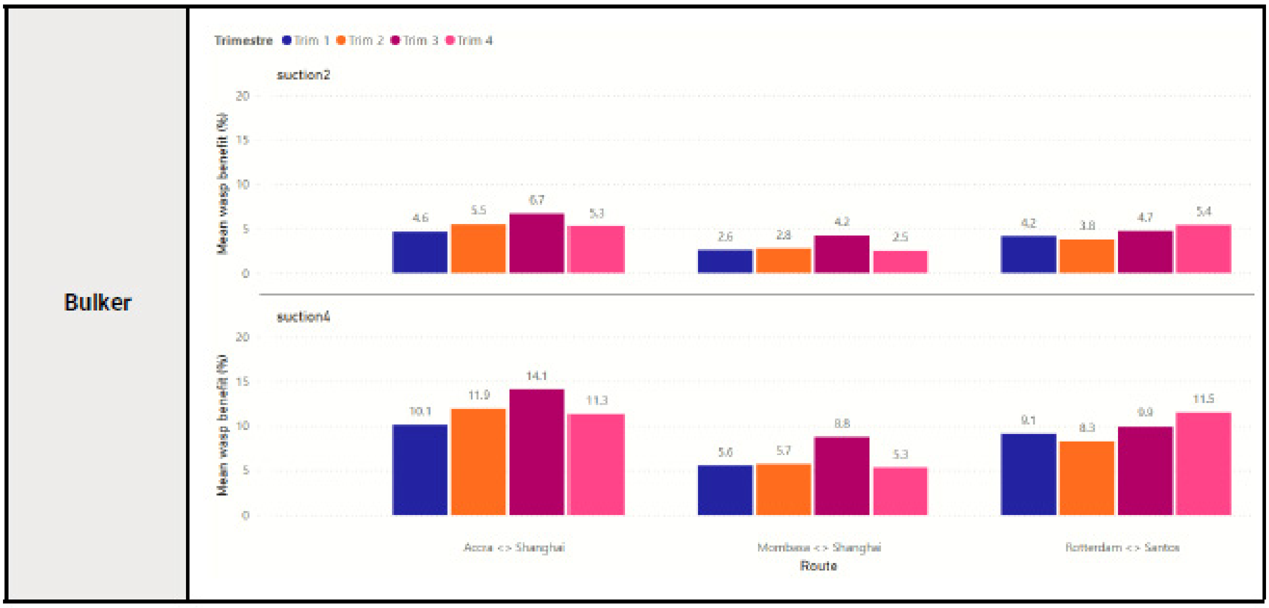
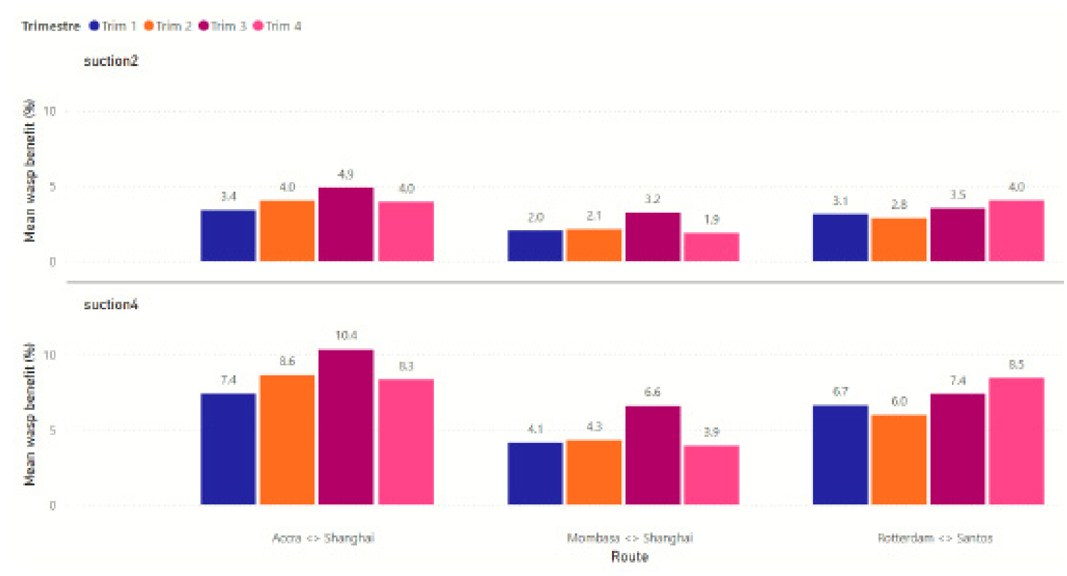


Figure 11: Average fuel consumption per vessel without and with WASPs per trimester for all routes

Figure 11 and Figure 12 show the seasonal variation of the mean trip consumption and WASP benefits for all three vessels in various propulsion configurations on three round trips respectively. On the routes Accra <> Shanghai and Mombasa <> Shanghai, the most beneficial season is Trimester 3, and for the route Rotterdam <> Santos - Trimester 4.



Tanker



Containership

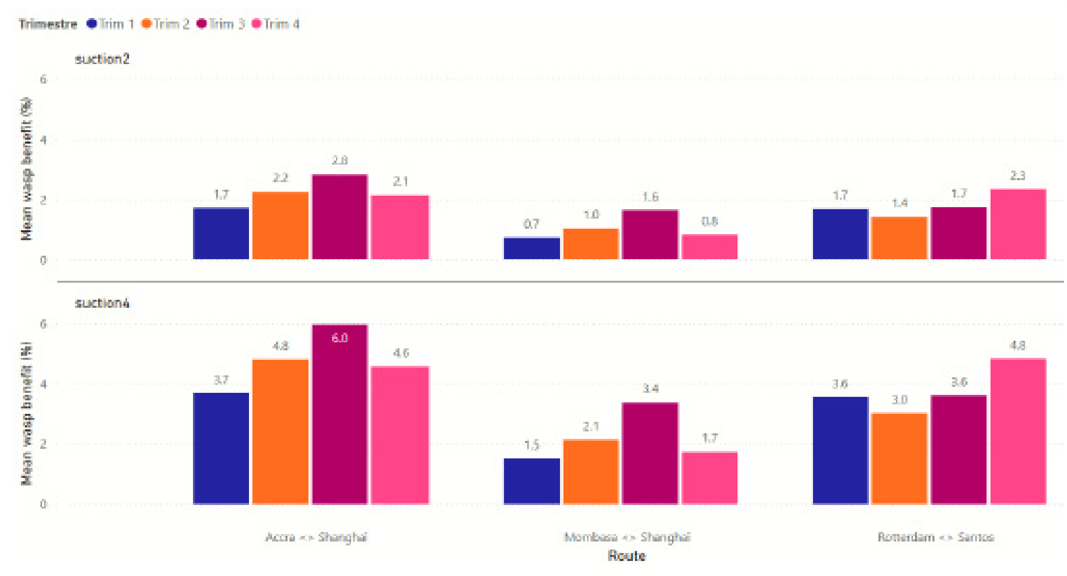


Figure 12: Average WASP benefits per vessel without and with WASPs per trimester for all routes

7. Conclusion

This historical weather routing study examines the benefits 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 efficiency. 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 efficiency for specific 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 optimisation strategy to enhance shipping efficiency and reduce environmental impact. In particular, section Results and analysis describes in detail per route and per vessel the total fuel benefits 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 reduction (987 tonnes of fuel), and 3,074 tonnes of CO_2 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 CO_2 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 benefits** on the route Rotterdam <> Santos.

Among three routes, the Accra - Shanghai route is the most favorable for WASP benefits, 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 optimisation.

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**, reflecting 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 configuration. 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 decarbonisation targets, particularly when combined with route optimisation. Prioritizing a vessel's confi guration with 4 WASPs on long routes maximizes benefits, though vessel-specific factors (e.g. service speed, fuel baseline) must be considered.

Key findings 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 fi nancial 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.

This report was commissioned and published by Seas At Risk

Please reference as follows: Seas At Risk et al, (2025). Wind First! How wind-assisted ship propulsion is the zero-emission fuel for shipping's future. Brussels, Belgium

Acknowledgements

Photos courtesy of International Windship Association
Authors: Dmytro Dudka, Sylvain Fuguet (D-ICE Engineering)
Executive Summary written by Seas At Risk
Thanks to: Anaïs Rios, Louisa Gray, Sian Prior (Seas At Risk)
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