Wind Assisted Ship Propulsion (WASP)

Work Package 3 - Engineering of Wind Propulsion Technologies

This technical report is submitted in completion of work package 3 tasks **3.1.1**, **3.1.2** and **3.3**.

Overview of the report

This technical report provides a summary of the experimental measurements and numerical simulation results from the five vessels associated with the Wind Assisted Ship Propulsion (WASP) project. Industrial-scale experiments were conducted during a series of so-called 'sea trials', which consisted of several short-term tests with each of the vessels both with and without the wind propulsion technologies (WPT) enabled and in wind conditions representative of real world operations.

The report is divided into three main sections. The first is concerned with the procedure employed in the sea trials and the subsequent strategy used to evaluate the performance of the WPTs. Both the second and third sections each focus on the numerical simulations efforts of Chalmers and KU Leuven, providing verification methodologies and further calculations using the numerical tools. This includes an evaluation of three vessel use cases with the ShipCLEAN tool of Chalmers University and two use cases with the digital twins developed by KU Leuven. Using a combustion of models verified with experimental data, statistical wind matrices and historical position data of ships, estimations of fuel savings and CO_2 avoided through the use of WPT are calculated on an annual basis.

Sea Trials

General procedure

Five sea trials were conducted within the WAPS project. The details of each sea trial are given in the following reports:

- RE40201042-01-00-A Speed trial of Copenhagen
- RE40201042-02-00-A Speed trial of Frisian Sea
- RE40201042-03-00-A Speed trial of Annika Braren
- RE40201042-04-00-A Speed trial of Ankie
- RE40201042-05-00-A Speed trial of Tharsis

Here follows a general procedure of the sea trials.

The sea trials were planned and conducted by Sofia Werner, RISE (former SSPA), in cooperation with the ship's masters and in the case of the ferry Copenhagen, also in cooperation with Scandlines' naval architect Rasmus Nielsen. For Frisian Sea and Ankie, a representative of the wing provider was onboard as observer. The trials took 5-6 hours and were conducted on-route between two load ports in the Baltic Sea and the North Sea.

The trials were conducted as close as possible according to the well recognised standards for speed-trials ISO 15016 / ITTC 7.5-04-01-01.1. The trial programs included short runs, 10-15 minutes long. Constant heading was kept during the runs using the ships' autopilots. Before the measurements started for each run, it was checked that the heading and speed was steady with an external GPS by plotting over time.

The rotor and wing settings were adjusted automatically by the control system throughout the trial. The wings were activated and dis-activated by raising and lowering them down, which takes just a few minutes. The two rotors were activated by turning the spinning on or off.

Current

Since the purpose of the trials was to measure speed-power *differences* (with and without wind propulsor), no correction for current was needed. Hence, the speed though water measured with the log is used, not the speed over ground from the GPS.

Superstructure and idling rotor air resistance

The measured power for each single run is corrected for the resistance of the superstructure based on ISO/ITTC standard procedure. Since the purpose is to derive the effect of the wind propulsor compared to the ship without any wind propulsor, the resistance of the idling propulsor must be subtracted from the runs when the wind propulsor was not used. For Frisian Sea, Tharsis and Ankie, the wings were folded down when idling, so this is only required for the two ships with rotors. For the two rotor ships, the rotor resistance is estimated as:

$$R_{rotor} = C_{\mathrm{D\ rotor}} \frac{1}{2} \rho_{air} \cdot H \cdot D \cdot {AWS_x}^2$$

The resistance coefficient of the idling rotor is estimated to be 0.5 [13]. AWSx is the apparent wind speed in the ship's longitudinal direction at the height of the rotor.

Power correction

The correction of propulsive efficiency due to the added resistance corrections and idling rotor resistance is derived according to the ISO/ITTC standard using the Direct Power Method, see [14] for details.

Strategy to evaluate operational performance of WPTs

Chalmers ShipCLEAN

Introduction

Chalmers University of Technology has developed a generic power prediction model called ShipCLEAN. The purpose of the model is to provide reliable power predictions while requiring a minimum of input data. The model includes modules for power prediction in real life conditions (including waves, wind, current etc.), a weather database for the whole world and a sail module including a four degrees of freedom solver to get accurate prediction of the effects of wind-assisted propulsion including the yaw moments and side forces from the sails and the hydrodynamic response of the ship. The model does not require any more input than the main dimensions and does not require calibration. Thus, it shall be seen as a generic prediction model and not as a digital twin. All coefficients, e.g. resistance and side force coefficients of the hull and the lift and drag of the sails, are evaluated in ShipCLEAN and based on analytical or empirical methods. The resistance prediction is based on several empirical models and a numerical standard hull series which was evaluated using CFD. The propeller coefficients are estimated using a standard propeller series which is evaluated using OpenProp. Hydrodynamic coefficients for drifting, i.e. the lift and drag coefficients of the hull, are based on wing theory for low aspect ratio wings, see [2]. Sail forces are based on pre-defined lift and drag forces which are based on CFD, model tests and full-scale measurements, if available. Finally, the sail-sail interaction is evaluated using a simplified Navier-Stokes equation to quantify the influence of the sails on the local wind angel and speed.

The model is component based, as illustrated in Figure 1.

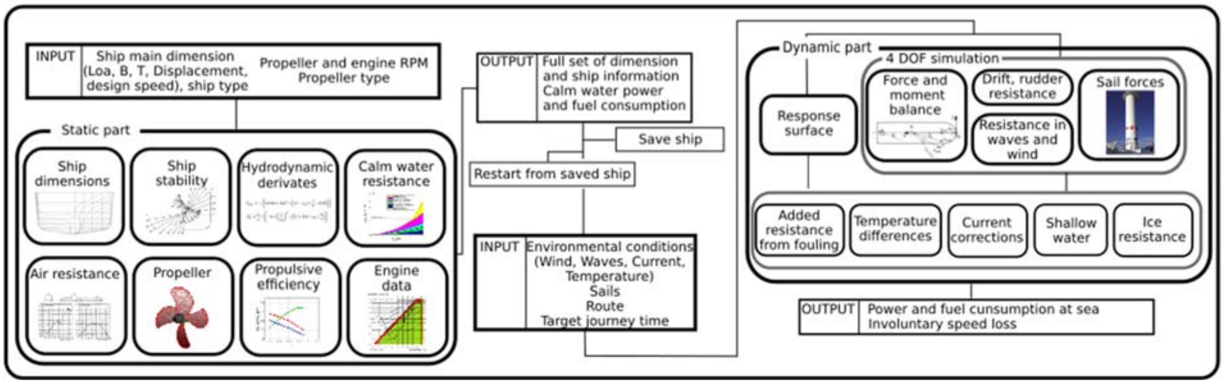

Figure 1. Components of the performance prediction model ShipCLEAN.

The input to the model is reduced to the main dimensions (Length overall, beam, draft, displacement or deadweight, ship type), the design speed and the propeller rpm. Additionally, the propeller diameter can be defined which significantly increases accuracy.

Details about the model and its modules are extensively published in [1-5] and summarized in [3]. The uncertainties and the reduction of uncertainties in the model are studied in [4].

Study cases, available input, and measurement data

Three ships are studied using ShipCLEAN, M/V Annika Braren (equipped with one rotor sail), M/V Ankie (equipped with two suction wings), and M/V Copenhagen (equipped with one Flettner rotor). The ship's particulars and received measurement data are summarized in Table 1.

Table 1. Ship particulars and available measurement data

		M/V Annika Braren	M/V Ankie	M/V Copenhagen
Ship particulars	Loa [m]	86.93	89.99	169.5
	B [m]	15.00	12.50	25.40
	T [m]	6.35	5.30	5.20
	Δ [t]	6706	4785	11870
	Speed [kn] (design/operation)	12.5 / 10.5	11 / -	18 / 16
	Propeller rpm	-	-	-
	Propeller diameter	-	2.70	-
Sails	Type	Rotor sail (1 pcs)	Suction Wing (2 pcs)	Flettner rotor (1 pcs)
	Position	81.4 m from AP 6.6 m from DWL	Bow, same longitudinal position	Around midship 17.2 m from DWL
	Size	3x18m	3x10 m	5x30m
	cL/ cD curves	-	1 point	-
Operation/ reports	Sea Trials	Received	-	Received
	Operation	Speeds/ positions (22-04-2021 – 20-01-2022)	Speeds/ positions/ drafts (2020-2022)	Route/ Schedule

Methodology

The performance prediction for all three ships is performed in three steps. Firstly, a power prediction without sails is performed, to give a baseline for power and fuel saving computations. Afterwards, polar diagrams for the power savings in three different wind speeds and 19 different wind angles are produced as a standardized comparison. Finally, the fuel and power savings in real operation are predicted using measurement data (position and speed) or weather statistics for the route.

The power predictions are performed using the data presented in Table 1, i.e., main dimensions for all ships and the propeller diameter for M/V Ankie. As shown in [4], uncertainties are increased when little information is known about the ship. However, since the power and fuel consumption are of interest in this study, it is more important to use a suitable baseline for comparison. Fuel and power consumption reductions are not as affected by such uncertainties as the total power demand.

The polar diagrams are created for 10 and 20 kn true wind speed and the service (or design speed) or the ship for 9 true wind angles, 0-180 deg. All sail arrangements in this study are symmetric, thus modelling wind angles between 0 and 180 deg is sufficient.

Results

This section presents the prediction results using ShipCLEAN for each of the three ships. Since well documented sea trials are available for the M/V Copenhagen, some validation is performed for this ship. More validation cases and uncertainty evaluation can be found in [1-5].

As a basis for the prediction of the effects of the WASP systems, the lift and drag curves of the employed systems are defined. For the Flettner rotor, the lift and drag curves in ShipCLEAN are based on available CFD results, model tests and full-scale measurements, as reported in [2]. The current lift to drag curve of Flettner rotors in ShipCLEAN is slightly changed compared to the one reported in [2], which mainly affects the lift at high spin ratio, which was found to be lower than shown in [2]. The current lift model reaches its maximum (of around 8.5) at a spin ratio of around 3.5 and is kept almost constant with further increasing spin ratios. This update mainly affects conditions with low apparent wind speeds, i.e., mainly downwind conditions. The updated lift and drag curves are presented in Figure 2. Since both Flettner rotors used in this study have identical aspect ratios, the lift and drag coefficients are identical.

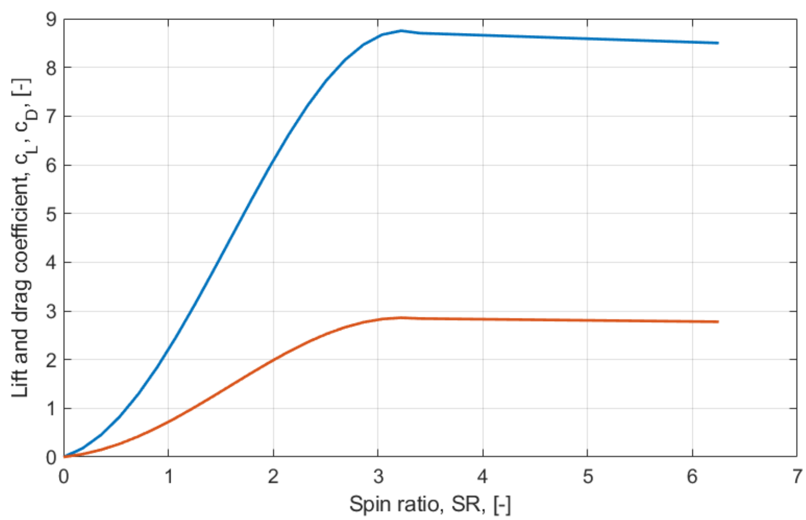

Figure 2. Lift and drag coefficients of the Flettner rotors.

The lift and drag curves of the suction sail are based on information received from Econowind. This information was limited to one combination of lift and drag, which is assumed to be the maximum lift point. Based on this, a typical lift and drag curve for wing sections is scaled to match this input. Naturally, this procedure introduces high uncertainty, but no better data was available. The assumed lift and drag curves of the suction sails are presented in Figure 3.

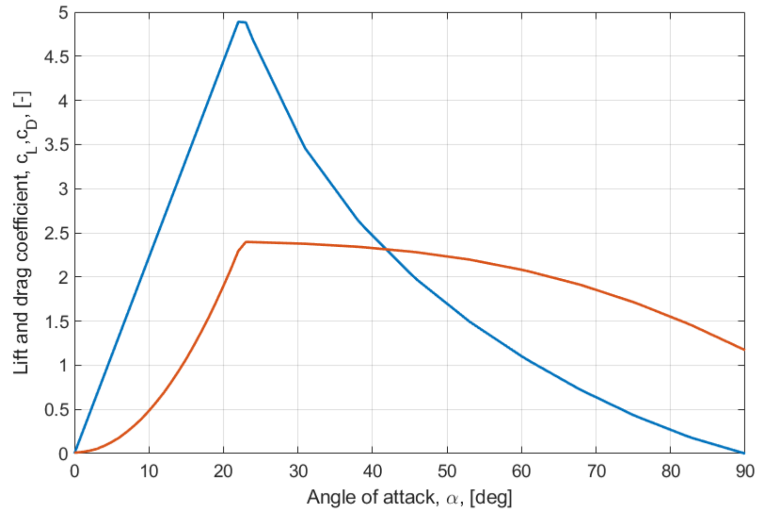

Figure 3. Lift and drag coefficients of the suction sail.

Scandlines – M/V Copenhagen

The RoPax ferry M/V Copenhagen is equipped with one 5m x 30m Flettner rotor, position at midships. The ship has three propellers, but no information about the operational procedure for these propellers are available. Since the full thrust could easily be delivered by two propellers, the ship is modelled as two-propeller ship in ShipCLEAN. Figure 4 presents the speed power curves as evaluated in ShipCLEAN. It must be kept in mind, that only the data presented in Table 1 is used for the prediction.

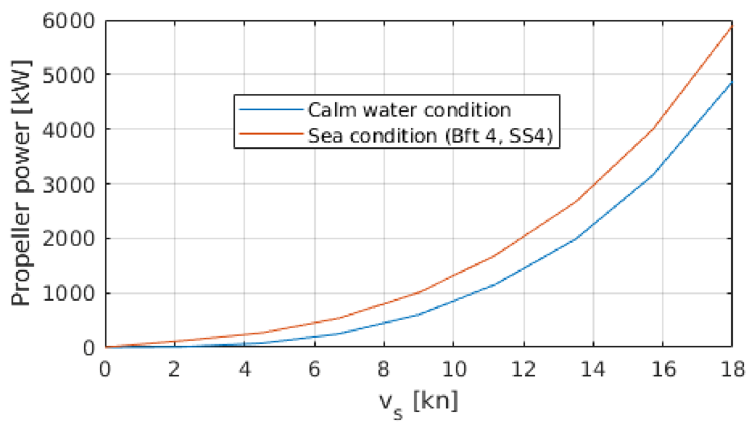

Figure 4. Speed power curves for the M/V Copenghagen.

The performance of the WASP systems is predicted in 4, 8 and 10 m/s true wind speed (TWS) from 0 to 180 degrees true wind angles (TWA). Figure 5 presents the results in terms of absolute propulsion power savings at 16 kn of ship speed. The figure includes the results from sea trial tests reported earlier. A very good agreement of the predicted and measured power savings can be observed. In fact, the difference is much lower than expected from uncertainty evaluations in the sea trial reports and in [5]. Naturally, this can be pure coincidence. Additionally, most of the effects that introduce the highest uncertainties in ShipCLEAN (see [6]), i.e., the drift and sail interaction, are small or non-existing for this ship, since it only has one rotor.

Figure 6 presents the power savings related to the propulsion power without sails. It can be seen, that up to 30% power saving is achievable for this ship with one Flettner rotor, a ship speed of 16 kn and a true wind speed of 10 m/s.

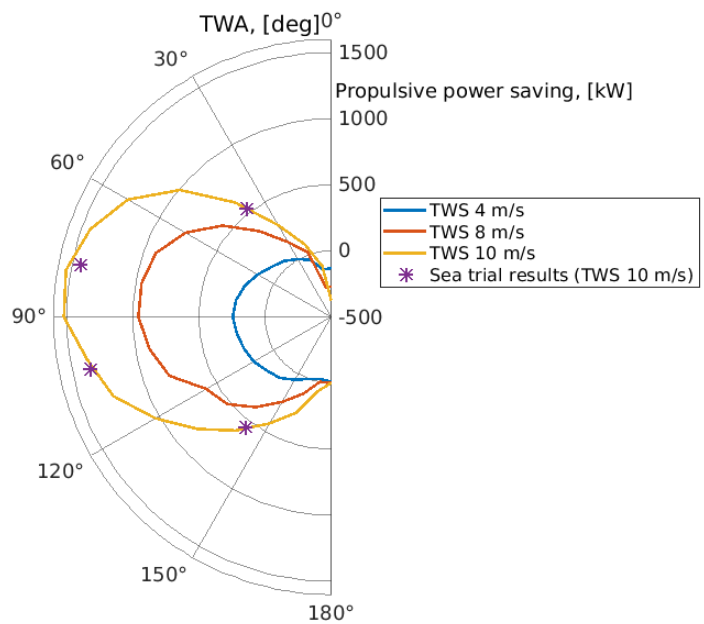

Figure 5. Propulsion power savings (kW) for the M/V Copenhagen, including results from the sea trials.

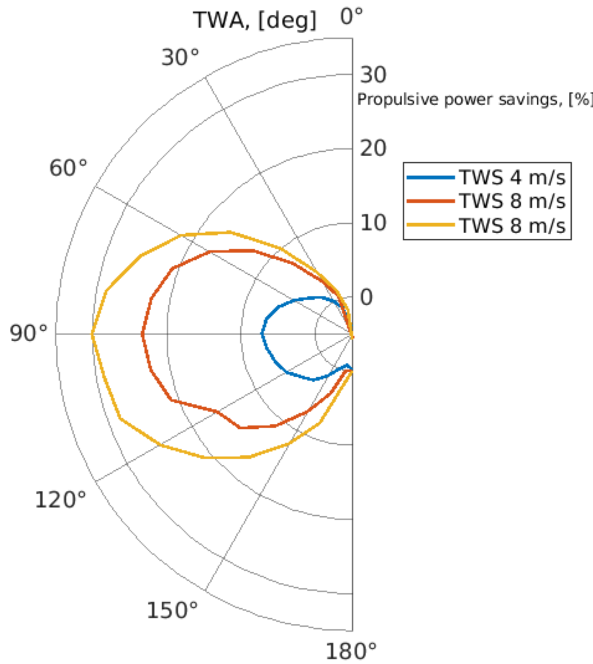

Figure 6. Percentual power savings for the M/V Copenhagen.

To predict the long-term fuel savings, a statistical approach is used since no operational data or measurements were available. The statistical approach is described in detail in [2]. Generally, the distribution of wind speeds and angles along the route are used to formulate weighting functions which are applied to the values of the polar analysis. In that way a mean value of the expected fuel consumption can easily be evaluated. The weather statistics are based on data from the Copernicus Marine Environment Monitoring Service (CMEMS). The wind strength and direction are presented in the form of a wind scatter plot in Figure 7. Using this approach, the long-term savings are estimated to be about 7.5%.

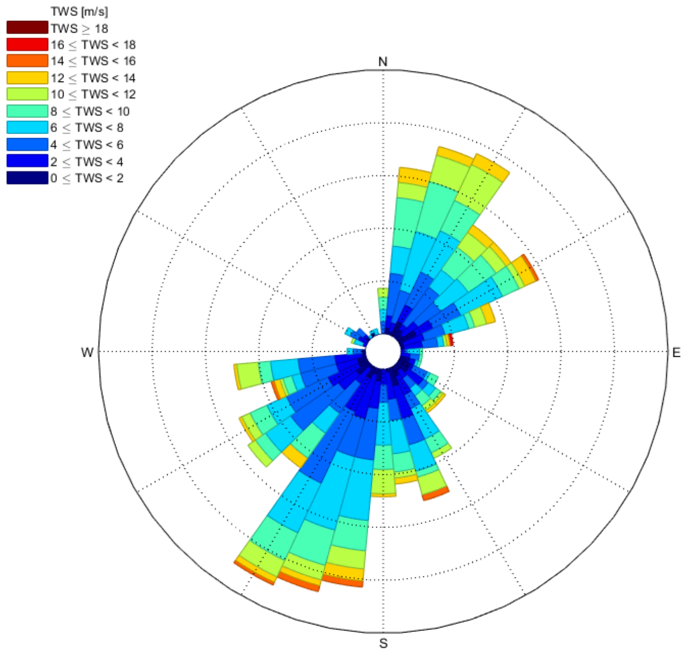

Figure 7. Wind scatter plot based on weather statistics from 2016-2018.

Rord Braren – M/S Annika Braren

The general cargo vessel M/S Annika Braren was equipped with one 3X18m Flettner rotor, installed at the bow.

The power curves as evaluated by ShipCLEAN are presented in Figure 8.

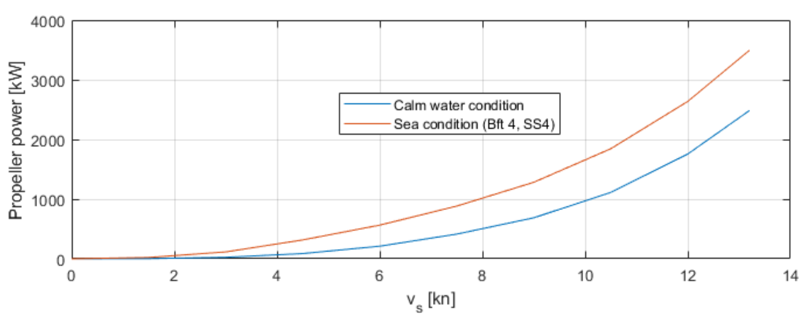

Figure 8. Speed power curves of M/S Annika Braren.

Polar plots of the power savings at 11.5 kn ship speed are presented in Figure 9 (absolute) and Figure 10 (relative). Figure 9a presents the results for the sea trial condition (ballast draft), with the sea trial results included in the figure. Figure 9b presents the results for design draft. It can be seen that ShipCLEAN agrees well with the sea trial results up to a TWA of 90 degrees. In more following winds, the sea trial results show higher savings than predicted by ShipCLEAN. However, the large spread, i.e., uncertainties, in the sea trial results are also obvious.

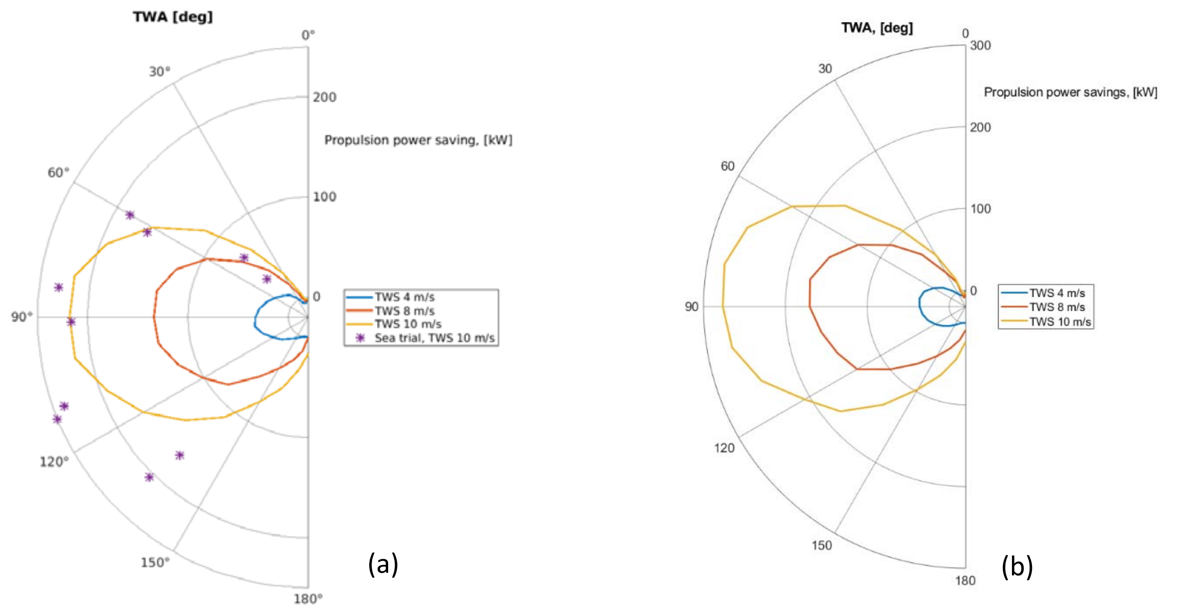

Figure 9. Power savings from WASP on the M/S Annika Braren, in trial conditions (a) and in design draft (b)

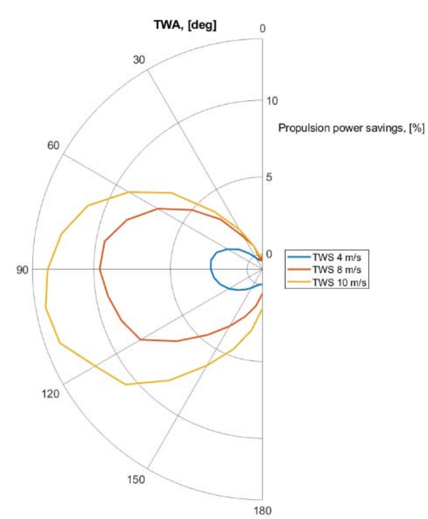

Figure 10. Relative power savings on M/S Annika Braren.

Operational data (positions, speed and course) were available for M/S Annika Braren. The positions during the analyzed time are presented in Figure 11. The ship mainly operates in short sea traffic in rather sheltered waters. Each data point is analyzed using the 4 degrees of freedom solver in ShipCLEAN, with and without sail. As a result, the achievable fuel savings during the analyzed time can be predicted. In total, 1689 points were analyzed. Reports start on the 29th of April 2021 and end on the 31st of December 2021.

Figure 11. Positions of M/S Annika Braren.

The experience true wind angle and true wind speed during that time are summarized in the wind scatter plot in Figure 12. The true wind angle is rather equally distributed, but that the wind speed is rather low, with only a small part of the time above 6 m/s. The ship speeds are presented as a histogram in Figure 13. The ship was often travelling at 11 kn or more. The mean ship speed was about 10 kn.

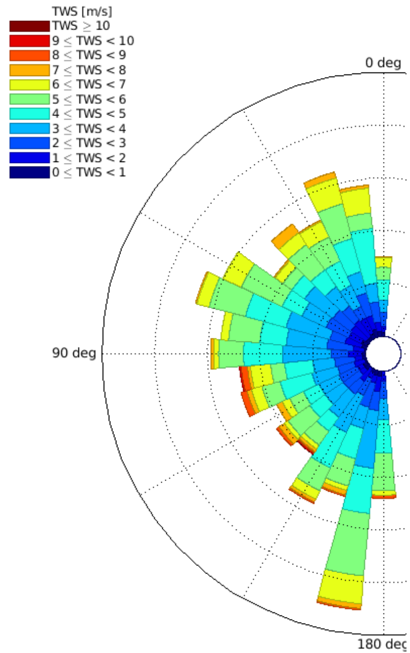

Figure 12. Wind scatter plot of the experienced TWA and TWS during operation of M/S Annika Braren.

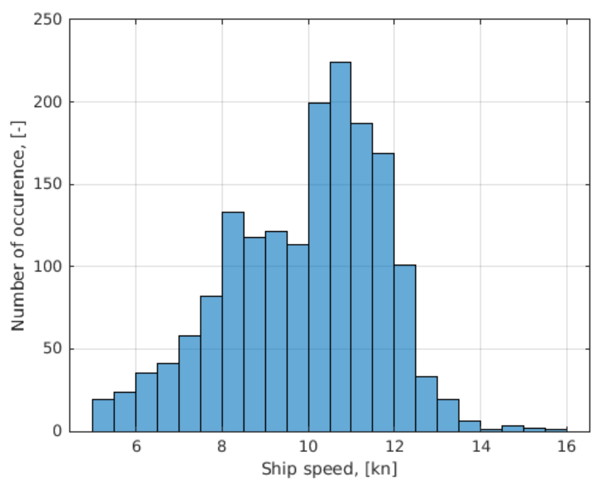

Figure 13. Ship speeds of M/S Annika Braren.

The predicted fuel saving over this period was about 3.6 %. The distribution of the fuel savings is presented in the histogram in Figure 14. In about 4% of the time, the Flettner rotor caused additional fuel consumption, with the maximum additional consumption being 1.2%. At about 22% of the time, the fuel savings were higher than 5%.

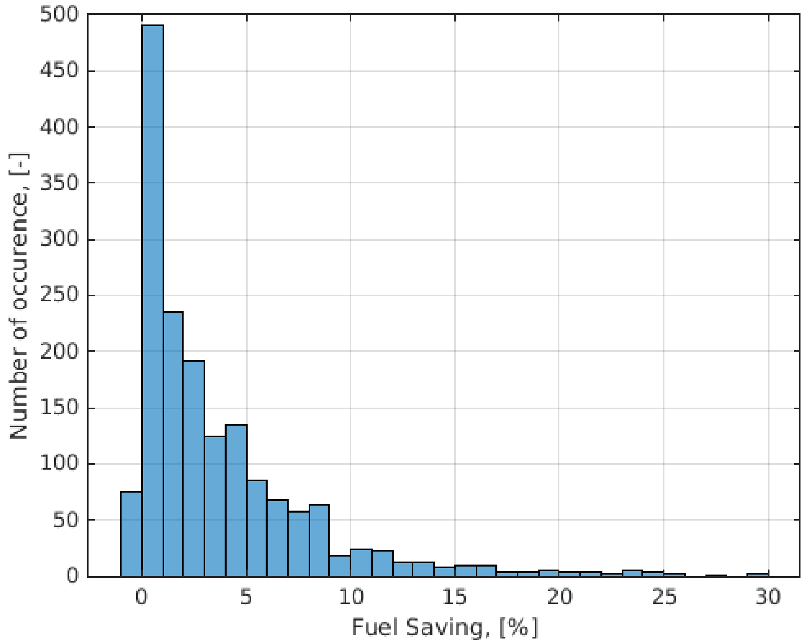

Figure 14. Distribution of predicted fuel savings for M/S Annika Braren.

To estimate the absolute fuel savings, engine curves must be assumed in ShipCLEAN. Since no information about the type of engine and fuel is available for Chalmers University of Technology, this includes high uncertainties. Using an engine consumption curve with a specific fuel oil consumption of 190 g/kWhr at the design point, the absolute fuel saving with the WASP system is estimated to about 17 tons during the time of analysis (April through December) of. Since no information about the fuel type is available, the CO_2 saving cannot be evaluated.

Van Dam Shipping – M/V Ankie

The general cargo vessel M/V Ankie was equipped with two Ventifoil sails, positioned next to each other at the bow. As stated above, the lift and drag curves for these sails are not validated. Uncertainties in the prediction are thus much higher than for the Flettner rotor cases.

The power curves evaluated by ShipCLEAN are presented Figure 15.

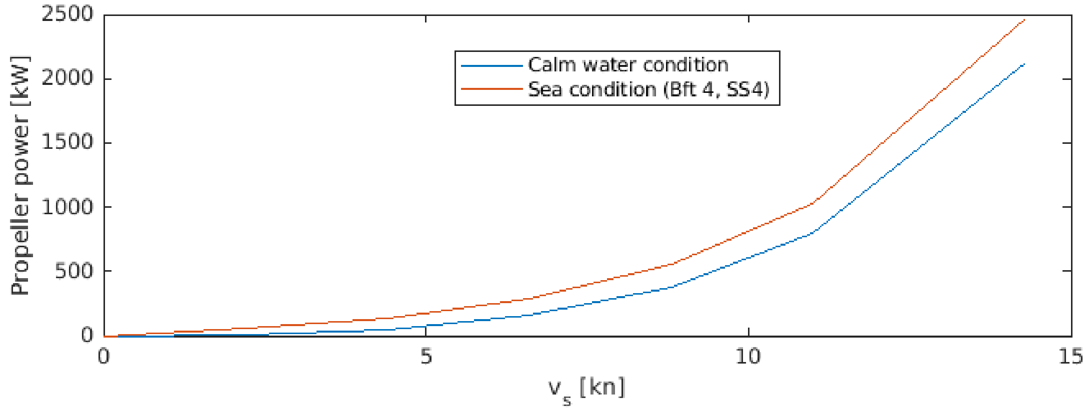

Figure 15. Speed power curves M/V Ankie.

Polar plots of the power savings at 11 kn ship speed are presented in Figure 16 (absolute) and Figure 17 (relative).

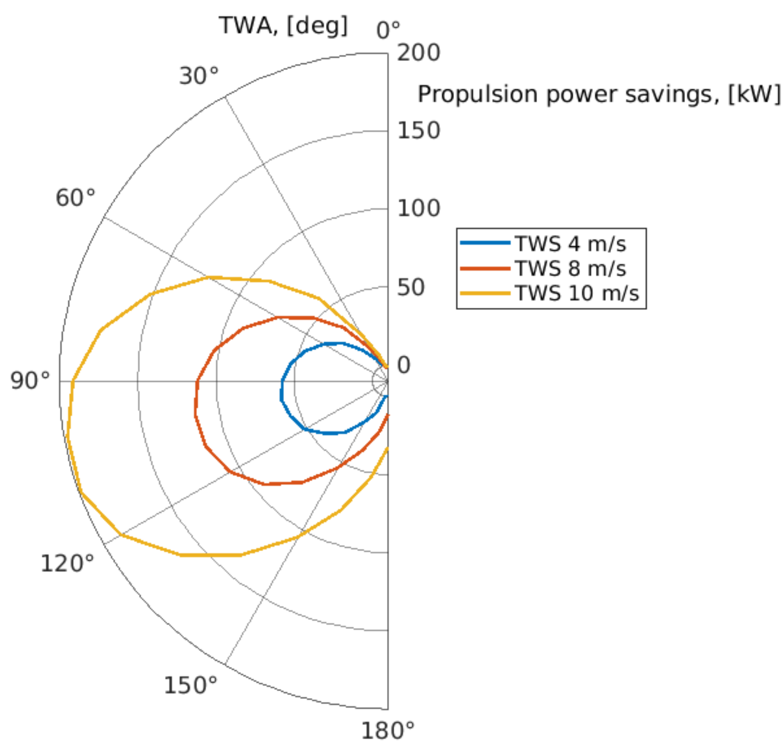

Figure 16. Propulsive power savings on M/V Ankie.

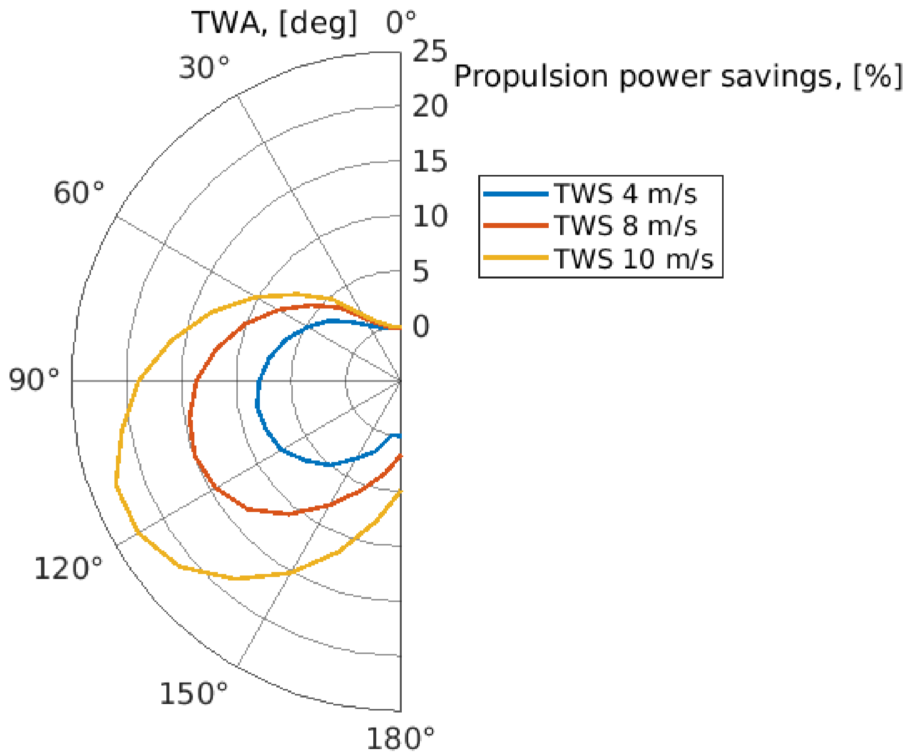

Figure 17. Relative propulsion power savings on M/V Ankie.

Operational data (positions, speed and course) were available for M/S Ankie (Figure 18). The positions during the analyzed time are presented in. The ship mainly operates in short sea traffic in rather sheltered waters. Each data point is analyzed using the 4 degrees of freedom solver in ShipCLEAN, with and without sails. As a result, the achievable fuel savings during the analyzed time can be predicted. In total, 50974 valid points with ship speeds above 5 kn were available. This high number is because of a high sampling frequency, with 1 point every 5 minutes. Since the weather conditions and ship operational conditions do not change that quickly, only every tenth point was analyzed. Reports start on the 15th of January 2021 and end on the 29th of December 2021.

The wind scatter plot of true wind speeds and true wind angles is presented in Figure 19. The ship speeds are presented in Figure 20. The mean ship speed was 9.5 kn.

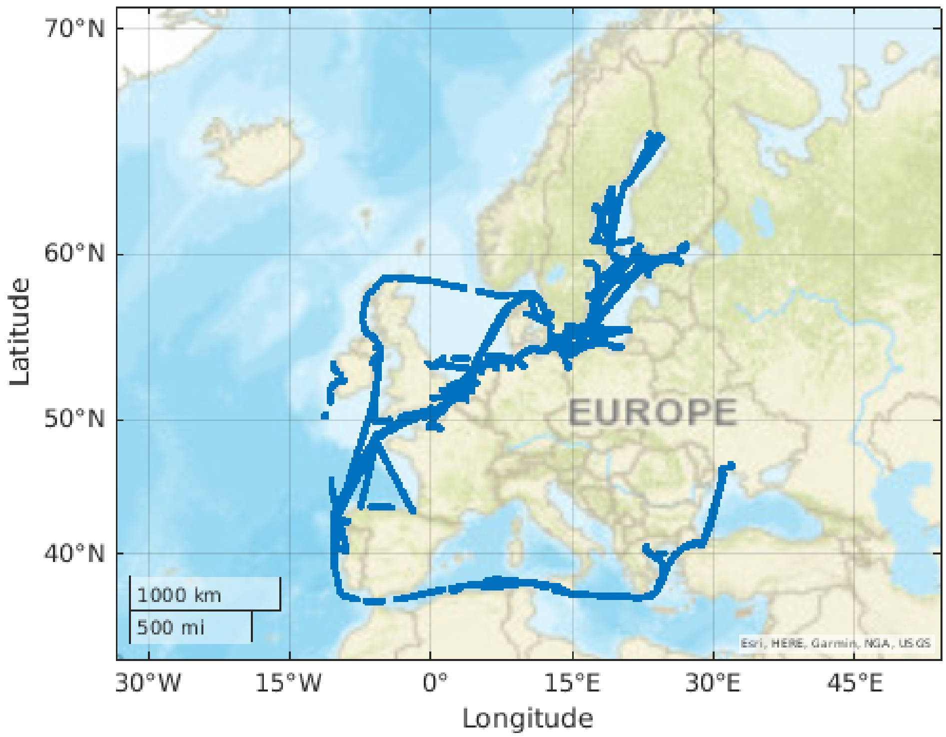

Figure 18. Positions of M/V Ankie.

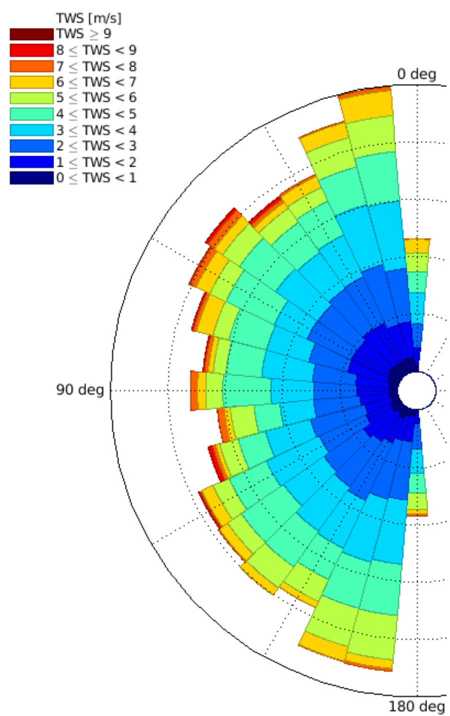

Figure 19. Wind scatter plot for M/V Ankie.

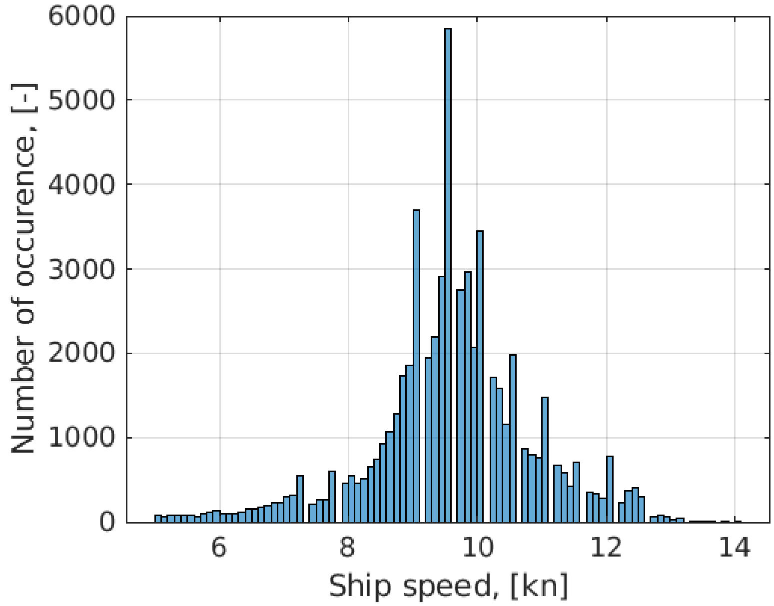

Figure 20. Ship speeds of M/V Ankie.

The predicted fuel saving over this period was about 8.1 %. The distribution of the fuel savings is presented in the histogram in Figure 21. In about 8 % of the time, the Suction sail caused additional fuel consumption, with the maximum additional consumption being 3.7%. At about 43% of the time, the fuel savings were higher than 5%.

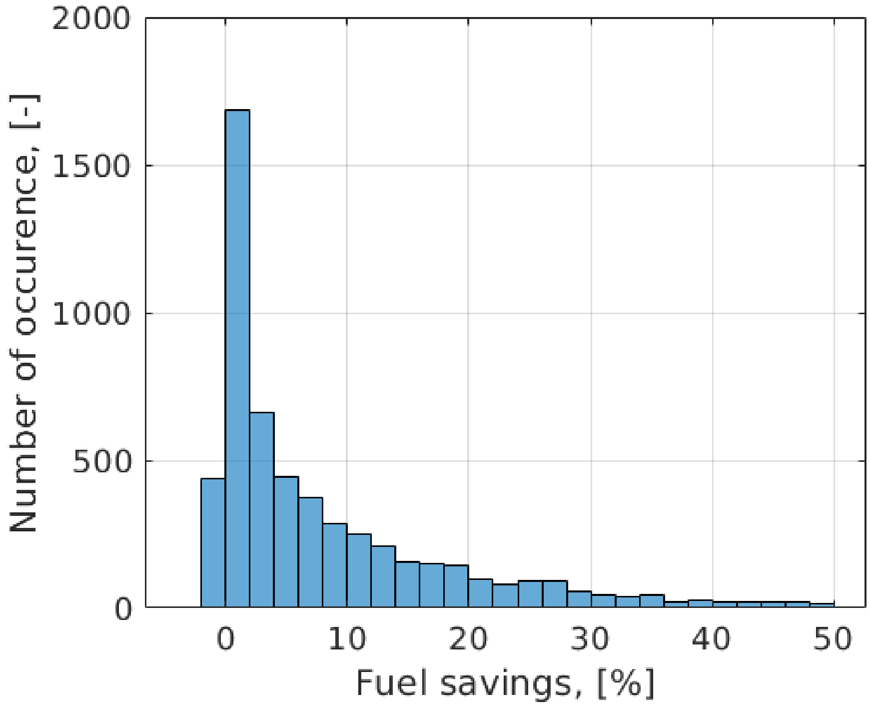

Figure 21. Histogram of fuel savings during operation of M/V Ankie.

To estimate the absolute fuel savings, engine curves must be assumed in ShipCLEAN. Since no information about the type of engine and fuel is available for Chalmers University of Technology, this includes high uncertainties. Using an engine consumption curve with a specific fuel oil consumption of 174 g/kWhr at the design point, the absolute fuel saving with the WASP system is estimated to about 31 tons during 2021. Since no information about the fuel type is available, the CO_2 saving cannot be evaluated.

ShipCLEAN References

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[2] TILLIG, F., RINGSBERG, J.W. (2020) *Design, operation and analysis of wind-assisted cargo ships.* Ocean Engineering, Volume 211, DOI: 10.1016/j.oceaneng.2020.107603

[3] TILLIG, F. (2020) *Simulation model of a ship's energy performance and transportation costs.* Doctoral thesis (New series, no. 4750). Chalmers University of Technology, Gothenburg, Sweden

[4] TILLIG, F., RINGSBERG, J.W., MAO, W., RAMNE, B.J. (2018) Analysis of the reduction of uncertainties in the prediction of ships' fuel consumption – from early design to operation conditions. Ships and Offshore Structures, 13:sup1, pp 13-24, DOI: 10.1080/17445302.2018.1425519

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KU Leuven Digital Twins

Introduction

The digital twin dynamical model of the vessel is developed in-house within a Python environment and is based on a generic 4 DoF (heave and pitch are not considered) cargo ship model based on earlier works. The focus of this model is twofold: 1) capture the longitudinal dynamics in the surge direction to assess fuel savings from the WPT and 2) evaluate the lateral dynamics of the ship when a WPT unit is present and generates side forces on the vessel. The details about the modeling framework, assumptions and the specifications are available in [1].

The ship model comprises all hydrodynamic and aerodynamic forces and moments exerted on the wind-assisted cargo ship. These are subdivided into two: the hull model and the WPT model. All forces and moments are described via force modules which will be applied on the vessel dynamics and expressed in 4 DoF. In the upcoming sections, the hull and WPT model is briefly explained.

Hull model

This section describes the hull model, which includes all forces acting on the hull and the superstructure of the ship.

• The forces acting on the hull are expressed in the vessel body fixed frame which is located at the center of gravity of the cargo ship.

• The hull resistance is based on Kristensen work [2] which is an update to the Harvald method in the sense that it considers the statistical data of more recent vessels to compute the resistance coefficients. Hull efficiency is approximated based on the hull type using Kristensen work [2].

• The side force, which is not significant in the investigated vessels, in response to the WPT aerodynamic loads, and the associated drag are computed according to the ISO standard [3].

• The rudder hydrodynamic forces and moments are calculated based on the lift and drag of the rudder according to the method of Lewis [4]. The added rudder resistance has been corrected to account the rudder-propeller interaction according to Bertram [5].

• The propeller thrust is assumed to be a Wageningen B-Screw series propeller following Kuiper [6]. For Frisian Sea vessel, the available onboard power and speed over ground (SOG) measurements are used to estimate the propeller thrust and torque coefficients and open water efficiencies. For this purpose, only the logged data in calmer sea conditions are considered.

• The added wind forces and moments on ship superstructure are computed according to the proposed formula by Fossen [7]. The wind induced drag coefficients, C_X, are adopted according to the reported values from SSPA company. We obtained the true wind speed and direction relative to the north at 10 m above sea level from the ERA5 reanalysis hindcast dataset available in CDS [8]. To calculate the true wind speed and direction for a specific date and vessel location, the hourly data were extracted for a specific geographical area of the vessels operations and then those variables are interpolated based on the nearest ERA5 data to vessel location and time of voyage.

• The added resistance in waves is calculated according to STAwave-1 formula proposed by ITTC 7.5-04 -01-01.2 [3]. The proposed formula estimates the resistance increase in head waves provided that heave and pitching are small. The application is restricted to waves in the bow sector (within +/- 45 deg. off bow). The wave induced forces and moments are expressed in the body frame based on the wave direction following the method of Zuidweg [9]. The significant wave height over a fetch is approximated as a function of the true wind speed based on SMB method of Parle [10]. The wave direction is assumed to be collinear with the true wind direction.

WPT model

The working principle of all used wind thrust generation technologies is explained through the mathematical lift and drag equations expressed in vessel's body-fixed frame [11]. The side force and yaw and roll moments generated by units are also incorporated in our digital twin model. The lift and drag coefficients of each used technology are identified from Econowind database. The maximum thrust coefficient ($C_{T,\, max}$) identified from the Econowind dataset is 6.

Power and fuel consumption calculation

The engine brake power is calculated considering all inefficiencies between the engine crankshaft and the power to overcome total resistance (effective power) in addition to any shaft generator power that the engine itself provides. The engines specific fuel oil consumption (SFOC) is then used to estimate the fuel consumption rate.

Results

The following sections highlight the simulation results and estimated savings from the digital twin models for the Frisian Sea and Tharsis vessels.

Boomsma Shipping – M/V Frisian Sea

We considered the Frisian Sea vessel (IMO: 9534547). This ship is regarded as a potential candidate to benefit from WPT installation, and the potential for wind capture from two flatrack suction sail is considered here. Table 2 Frisian Sea particulars shows the main characteristics of the ship. It is a general cargo vessel that mainly operates in the North Sea region and the Baltic Sea.

Table 2. Frisian Sea particulars

Parameter	Symbol	Value	Units
Length overall	L_{OA}	118.19	m
Breadth on water line	B	13.35	m
Mean draft	T	3 to 6.2	m
Displacement mass	Δ	4000 to 8000	ton

Figure 22 shows the ship bare hull resistance in its design draft.

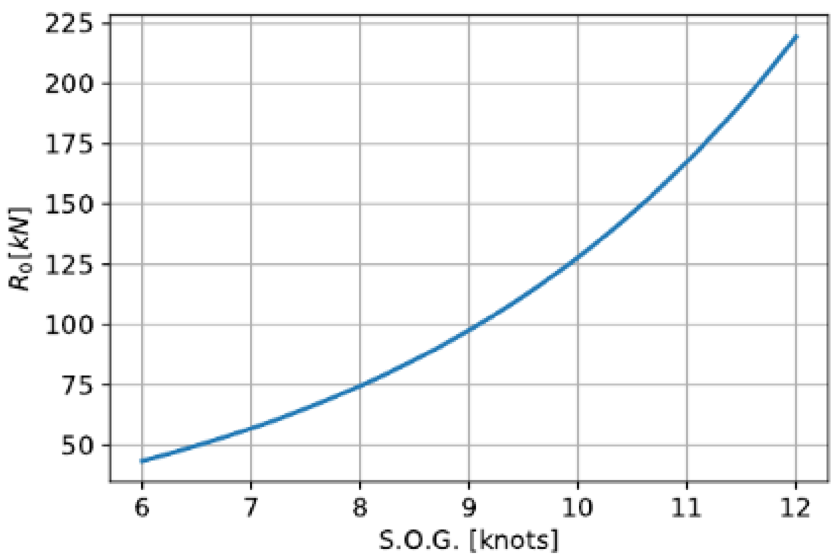

Figure 22. Frisian Sea bare-hull resistance vs. SOG.

Table 3 shows the main parameters of the vessel propeller in its 100% pitch ratio. The propeller pitch setting changes during trials. Through the logged data we identified the vessel propeller characteristics assuming that the vessel's propeller is similar to the Wageningen B-series with four blades and expanded aria ratio of 0.45.

Table 3 Frisian Sea propeller characteristics

Parameter	Symbol	Value	Units
Propeller diameter	D	2.95	m
Number of blades	Z	4	-
Identified expanded area ratio	A_E/A_0	0.45	-
Identified Pitch ratio ([100%)	P/D	1.16	-
Propeller speed	n	148	RPM

Figure 23 shows the propeller characteristic curves for two different pitch ratio of 87% and 97%. As seen from figures, the vessel propeller characteristics especially the torque coefficients and open-water efficiency follow the assigned model.

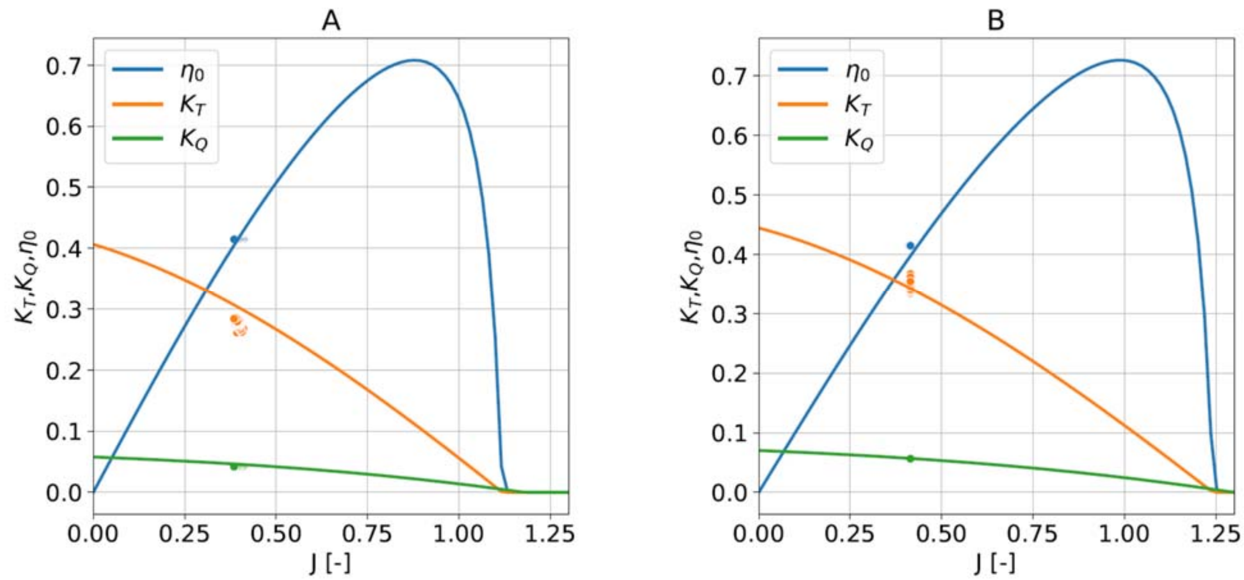

Figure 23. Propeller characteristics in A) pitch ratio of 87% and B) 97%.

Figure 24 depicts the generated thrust from two suction sail units once the vessel is moving northwards and its speed is 10 knots and the true wind speed at 10 m above sea level is 10 m/s. It is assumed an optimal angle of attack of 25 deg. for the foils. It is also assumed that the fans provides abundant suctions during their operations to have the optimal lift coefficients.

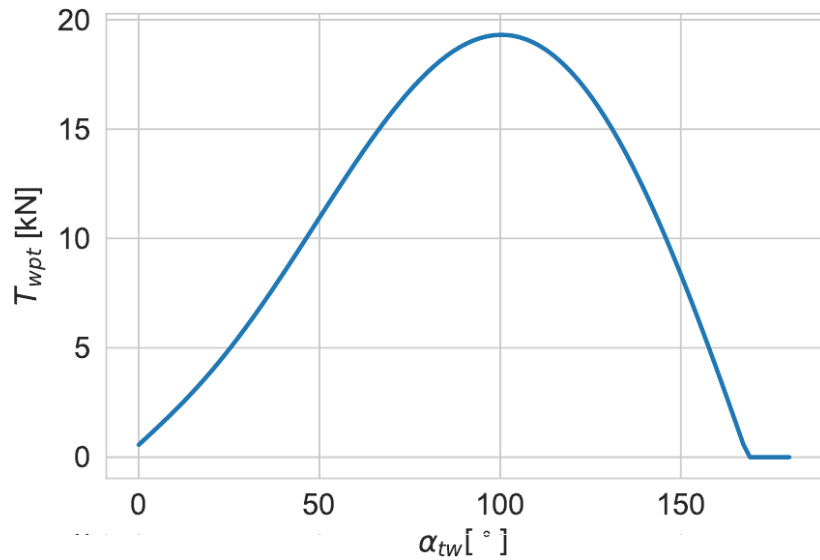

Figure 24. The generated thrust from two suction sail units assuming a fixed ship speed of 10 knots and a fixed true wind speed of 10 m/s with varying the true wind angle from 0 to 180 deg.

As seen from the figure, an optimal force generation is occurred at apparent angle of 100 deg.

Figure 25 shows the Frisian Sea vessel engine SFOC scattered plot versus the corresponding power load. To avoid the effects of ambient weather conditions on engine performance, only SFOC logged data in calm and moderate are collected and a 2nd order polynomial is fitted to the data. As seen from figure, engine has its optimal thermal efficiency with minimum SFOC at around its 1000 kW load. The SFOC would be much higher in part loads.

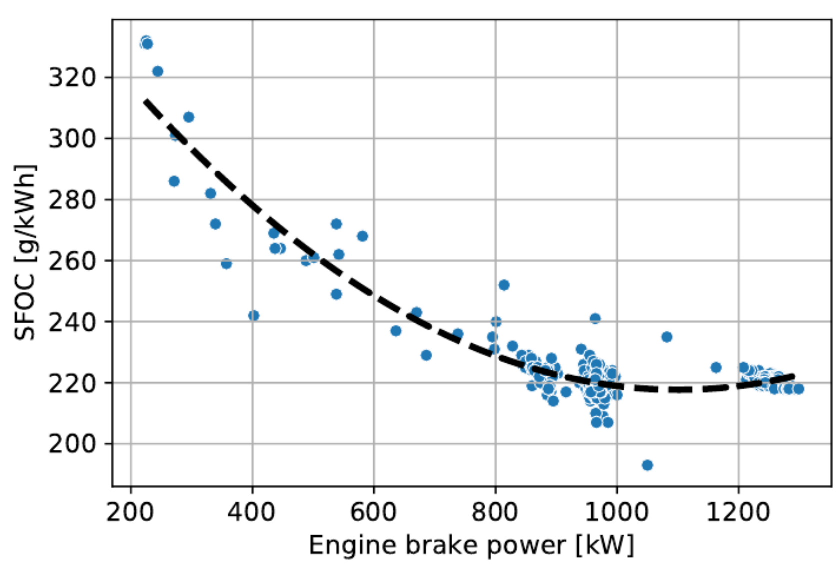

Figure 25. The engine SFOC scattered data and corresponding 2nd order polynomial fitting.

Table 4 shows the results of our digital twin model for power and SOG compared with the corresponding measurements. As seen from the table the power difference is below 3% and the SOG difference is below 9%. Considering the uncertainty of power and SOG measurements (which is 1% for power and 0.5 knots for SOG), we can confirm that our digital twin is validated with the trial data. The gross propulsion power from WPT is computed considering the thrust force from suction sail, the vessel speed and total propulsion efficiency. The lift coefficient $C_L = 6$ is identified from suction sail of the technology provider data and used for the suction sails' power generation calculations.

Table 4. Analysis of trial data in which the vessel WPT were active

Run	Propulsion Power measurement (kW)	Propulsion Power from Digital Twin [kW]	diff [%]	SOG measured (knots)	SOG from digital twin [C_L=6] [knot]	Diff [%]	Gross Pwpt from Digital Twin [C_L=6] [kW]
2	850.3	858.0	0.90	9.66	9.67	0.10	82
7	888.0	903.0	1.69	10.17	9.95	2.16	27
8	897.0	914.0	1.90	9.9	9.45	4.55	74
11	885.0	865	2.26	9.3	9.32	0.22	106
12	932.0	913.0	2.04	9.65	8.81	8.70	110
15	950.5	972.0	2.26	9.45	8.93	5.50	88

Figure 26 depicts the wind rose plot with normed displayed in percent for the entire sailing positions of the vessel from July 2021 and July 2022 and when the suction sails were active. The dominant winds have speeds below 10 m/s. From this figure, one can conclude that the vessel were mainly sailed in following sea (true wind angle less than 90 degree with respect to the bow).

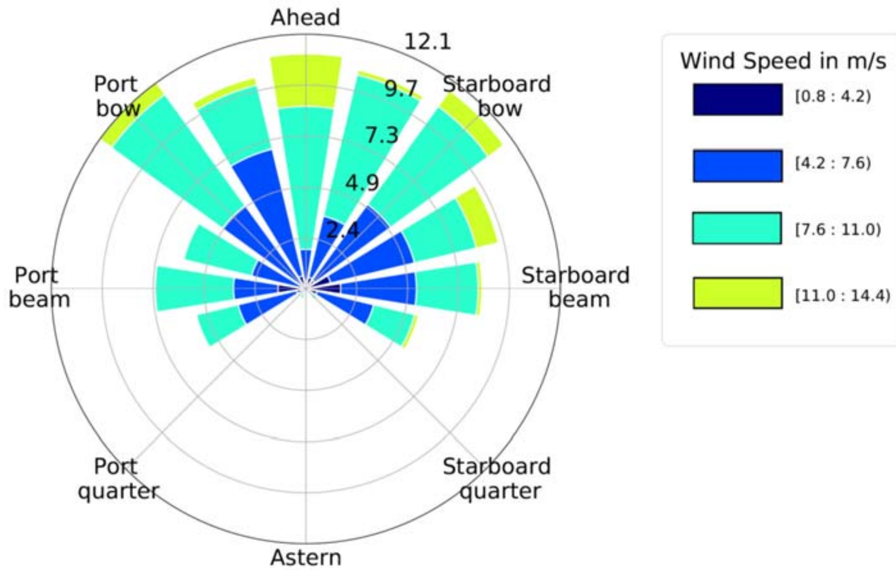

Figure 26. Polar histogram plot of true wind speed and direction relative to the ship bow.

From the logged data, it can be found that the suction sail units have been utilized only 15% of the entire voyage times. It can be seen from logged data during suction sail operations that the added wind thrust was mainly used to increase the vessel speed to reach the destination faster. From a fuel economy viewpoint, however, the added thrust could be used in depowering the engine and keeping the ship speed to its nominal speed and letting the vessel drive with added wind thrust.

Figure 27 depicts the estimated engine power saved because of suction sails operation. The logged data from Eefting system at the time of suction sail operations are used to calculate the net saved power. First the captured thrust forces from units are estimated and then based on the ship speed measurements the equivariant saved effective power from suction sail units are calculated and finally by considering the efficiency of energy conversions from water to the engine output, one can estimate the gross engine power saved because of the suction sail units. Finally the net captured power is estimated by subtracting the aspiration power demand of suction sails from the gross saved engine power. The average value of the net saved engine power is around 64 kW. The accumulative saved power can be calculated by integrating the saved engine power because of suction sail units over the time intervals of sailing with suction sails. It is estimated that around 53.84 MWh of engine power is saved because of WPT in the whole sailing time intervals of 841.5 h with suction sail units.

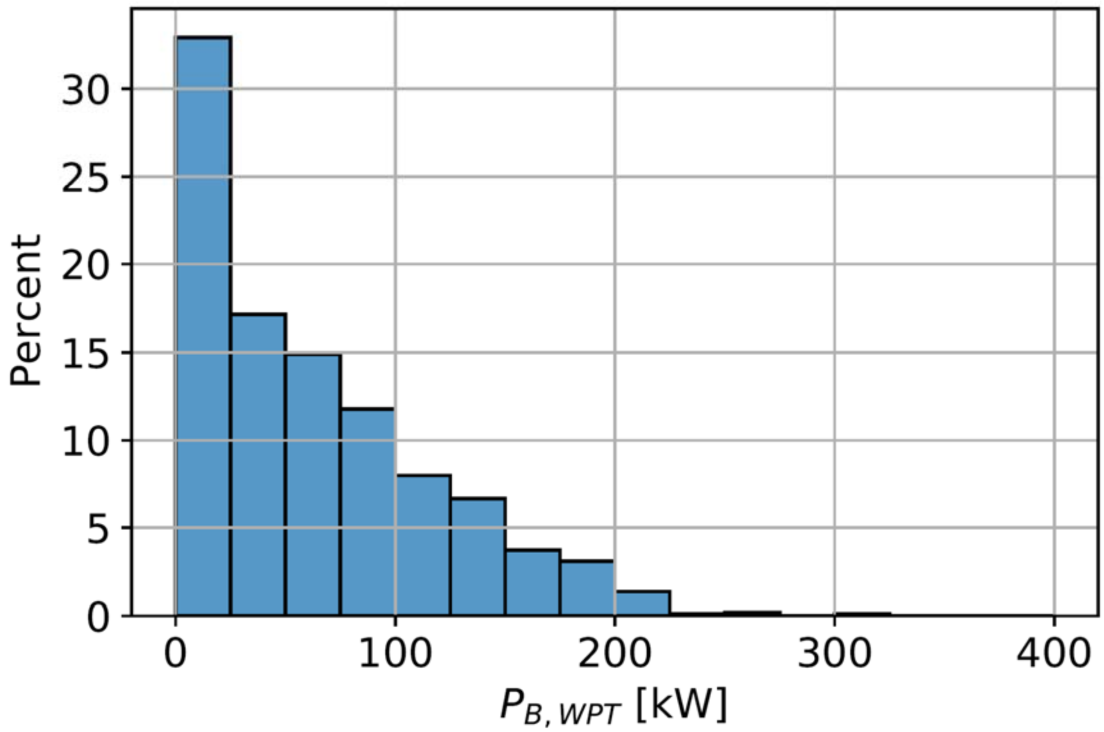

Figure 27. The histogram of the equivalent engine power generated from the two suction sail units considering the wind and vessel conditions of Figure 26.

The cumulative fuel saved during WPTs operation between July 2021 to July 2022 is estimated to be 11.8 tons of marine gas oil (MGO). Considering the value of cumulative MGO fuel use of 219 tons for the entire period of WPTs in operation, the percentage of WPTs fuel saving in their operational periods is 5.4% of the total burned MGO. Using a 3.2 kg CO_2 generated/kg fuel burned ratio, this represents 37.8 tons of CO_2 abated as a result of WPT usage. Considering the total travel distance with active suction sail, it is estimated that around 1.34 kg MGO per nautical mile has been saved due to suction sails. This is equivalent of reducing 4.31 tons of CO_2 emission per nautical mile. Table 5 below summarizes the results of savings due to WPT when the suction sails were active.

Table 5. The estimated savings due to WPT for Frisian Sea vessel when the WPTs were active

Fuel saving [ton]	CO_2 reduction [ton]	Percentage of fuel saving [%]
11.8	37.8	5.4

Based on the developed digital twin, we conducted a simulation between two ports and compared the results of the digital twin with the logged data. The route is between Sillamae port in Estonia and Szczecin in Poland. Figure 28 below shows the vessel route.

Figure 28. The vessel sailing route started in March 10, 2022.

Based on realistic weather data from CDS, we run the simulation tool. Here, the input to the model is extracted from logged propeller pitch. The vessel was in full load condition. The simulation results from our model has been compared with the logged data. Figure 29 shows the scatter plot of vessel SOG logged by Eefting data logger versus our simulation results.

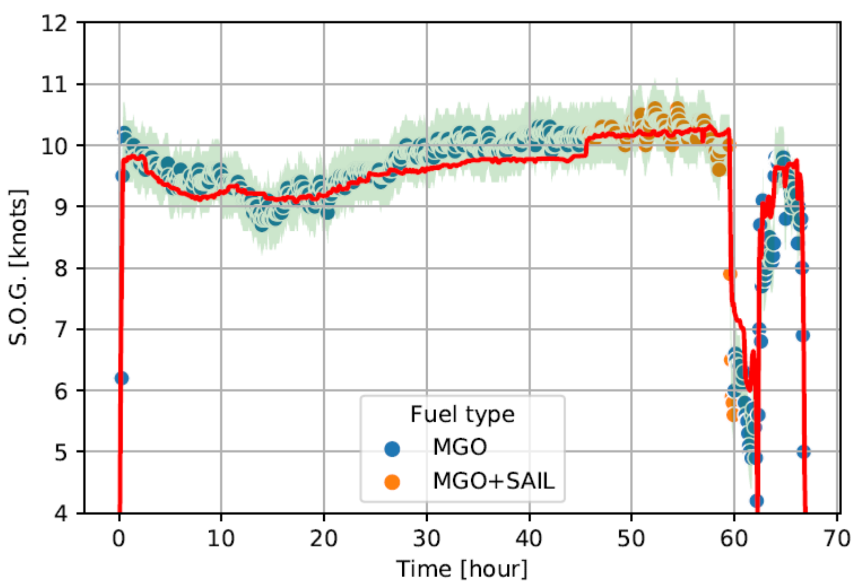

Figure 29. The vessel SOG scatter plot vs. the simulation results of our digital twin model in red lines, the SOG sensor uncertainty area is overlaid on the simulation results.

The mean absolute error of SOG between our simulation results and logged data is 0.29 knots which is lower than SOG sensor uncertainty of 0.5 knots. The fuel oil consumption (FOC) prediction by our digital twin is shown in the Figure 30 and compared with logged data.

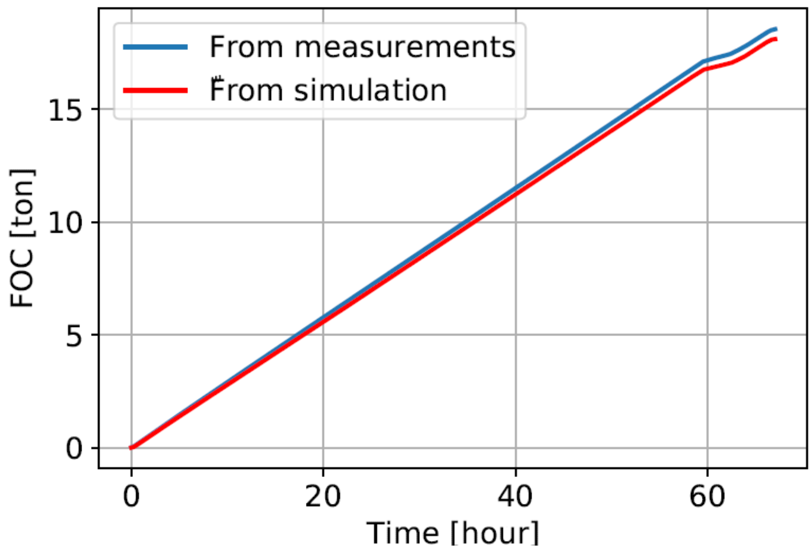

Figure 30. The vessel FOC from digital twin compared with the Eefting logged data.

Finally, the histogram of the generated power by two suction sail units is shown in Figure 31.

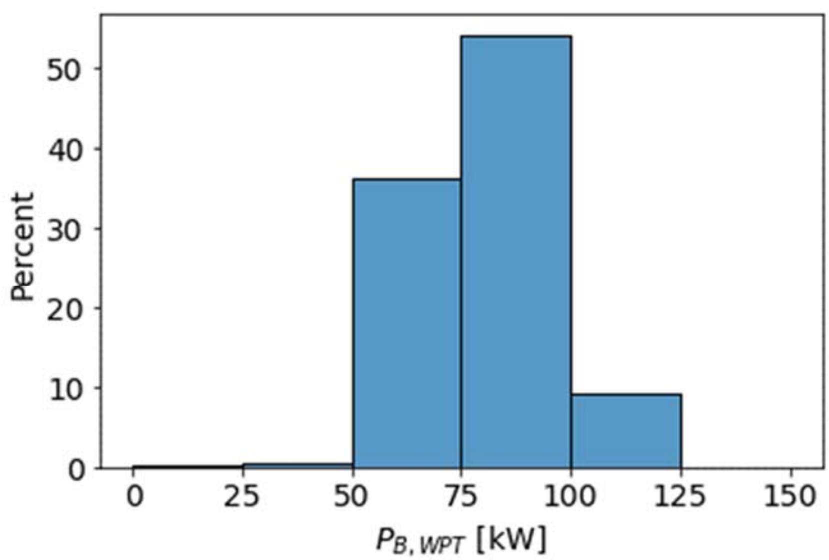

Figure 31. Suction sails generated power as a percent of total voyage time.

Note that the estimated generated WPT power is based on the thrust coefficients identified from technology provider data and we can see that for this specific route using these coefficients with high values (C_L = 6), we see least difference between SOG of our digital twin and sensor measurements when the vessel is benefiting from sail and MGO. The simulations with different lift coefficients have been conducted and the results for SOG and fuel rate with different lift coefficients are compared with the corresponding logged data on board the vessel. In Figure 32 we see that with active suction sails with higher lift coefficients a better match with SOG scatter plot exists. The simulation results for fuel rate have less differences in different simulations as the propeller pitch in both simulations are the same and thus the propeller propulsion powers and the fuel consumptions in both simulations have a low discrepancy.

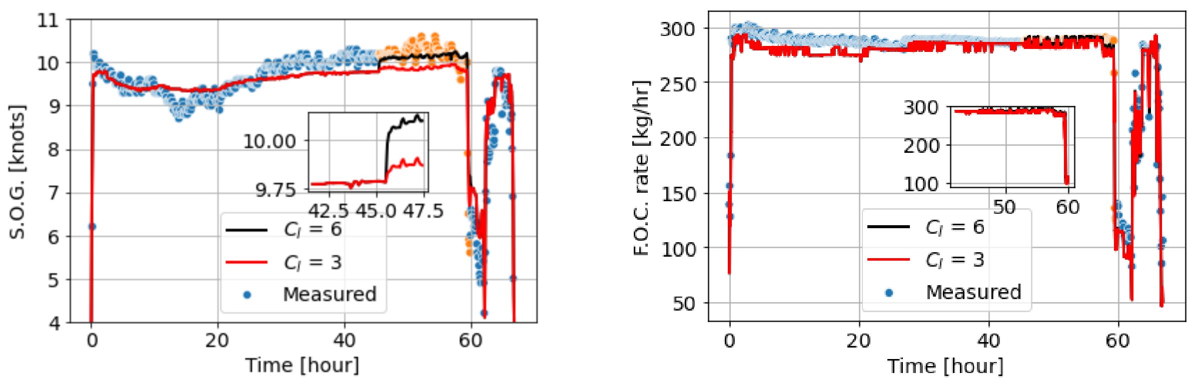

Figure 32. The vessel SOG and FOC scatter plot vs. the simulation results of our digital twin model with different lift coefficients.

Table 6 compares the traveled distance by SOG measurements and by our digital twin based on different lift coefficients. As seen from the table in case of $C_L = 6$ there a better match between our results and the measurements. This again suggests that the $C_L = 6$ is closer to the suction sails' performance for the route.

Table 6. The traveled distance once WPT were active (between 45h35 min and of travel 54h55min)

	Based on integration of SOG measurements once WPT is active	Based on $C_L = 3$	Based on $C_L = 6$
Traveled distance [nautical mile]	144.93	140.44	144.38

Tharsis Sea-River Shipping – M/V Tharsis

The Tharsis is a 2300 DWT, multi-purpose low draft coaster powered by three diesel-electric Volvo Penta D13 MG sets, each rated to 400 kW. It benefits from a power management system developed by D&A Electric to decrease fuel consumption of the diesel electric generators substantially. In the Tharsis vessel, the diesel engines are completely decoupled from the propeller. The ship service speed is 9.3 knots and two fixed pitch propellers are connected to AC motors with an output power of 375 kW each, operating at a constant speed of 1800 RPM (as the generator sets provide the frequency stability for the ship's AC grid). A gearbox with a ratio of 4.92 couples the AC drive output to the propeller shaft. Based on the power requirement from the propulsion system and other auxiliary loads, generator sets can activated or deactivated on-demand, but the total power is always equally shared between active generator sets. Table 7 shows the main parameters of the vessel in the light load condition.

Table 7. Tharsis vessel main parameters when lightly loaded

Parameter	Symbol	Value	Unit
Length between perpendiculars	L_{pp}	84.50	m
Breadth on water line	B	11.40	m
Mean draft	T	3.70	m
Displacement mass	Δ	3350	tons

In order to characterize the multi-element wing sail units thrust force generations, we used the data of the trials conducted and reported by SSPA. Figure 33 shows scatter plot of the trial data of gensets power against the speed through water for the cases where the wing sail units are down and up and for each run group with and without WPT. As seen from Figure 33, in most cases the added wind propulsion thrust was simply used to speed up the vessel while the gensets' brake power was kept fixed. Thus, the we have to estimate the saved propulsion power through an estimation of how would be the power output of the gensets if there were no WPT for the same ship speed and apparent wind speed when they were up.

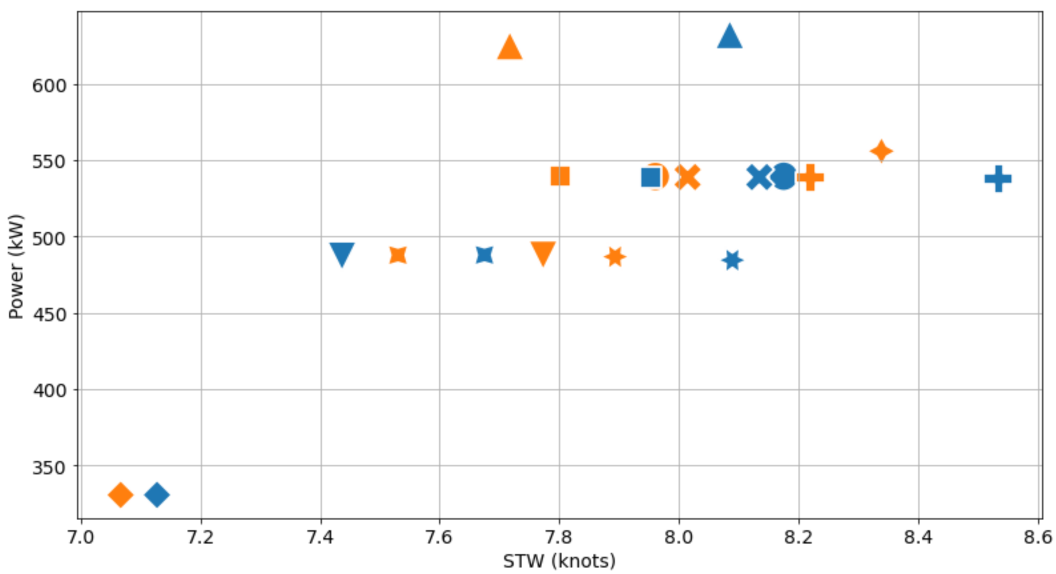

Figure 33. The different runs of Tharsis vessel with wingsails up and down: the orange ones are with wingsails down and the blue ones corresponds to the runs with wingsail up.

We found the following relationship between the propulsion power of the vessel as a function of the ship speed through water and apparent wind speed when the WPT is down. In fact, for each vessel speed through water and apparent wind speed an exponential function were used to relate the propulsion power to the two parameters.

$$P = 17.594e^{0.4166V_{stw}}e^{0.016(V_{aws}-7.25)}$$

It was found that the accuracy of the predicted power in the above equation is above 97%. With this accuracy, we can estimate the needed power for the same situations of when the WPT are working and estimate the corresponding power needed in case where no WPT are available.

Table 8 and Figure 34 show the equivalent genset's power generated by WPT for different trials which occurred in different speed through water (STW), V_{stw}, apparent wind speeds (AWS), V_{aws}, and apparent wind speed directions, AWA.

Table 8. The estimated power difference made by WPT for Tharsis vessel for different STW and AWS and AWA

STW (knots)	Vaws [m/s]	AWA [deg]	ΔP [kW]
8.18	11.28	27	33
8.13	12.14	42	15
8.08	15.42	45	77
7.13	8.38	88	13
7.67	13.73	36	33
8.09	8.91	88	57

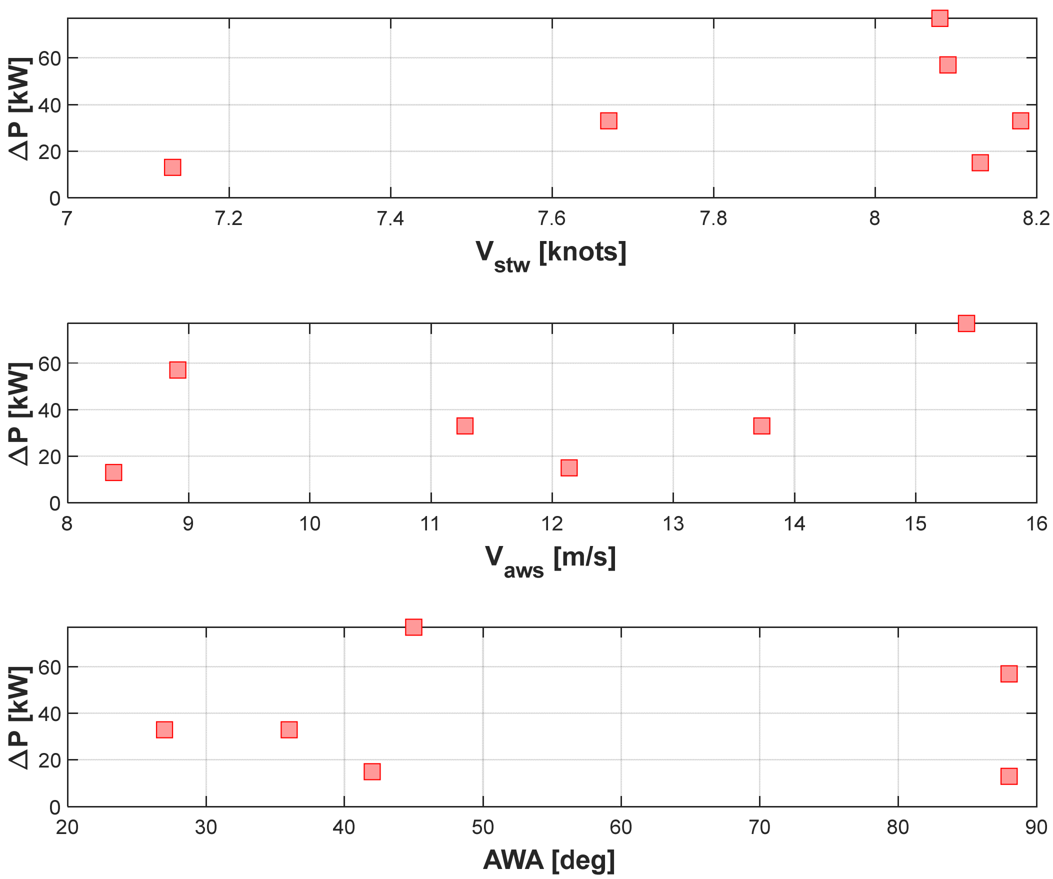

Figure 34. Visualization of the equivalent Tharsis gensets' power generated by WPT for different ship speed and apparent wind conditions.

Finally, we can calculate the multi-element wingsail thrust coeffiecients through the estimated added power. Assuming a fixed total propulsion effieciency, η_D, of 0.54 from SSPA reported data on Tharsis vessel, the thrust coeffiecients can be calculated according to Equation 1 [3].

$$C_t = \frac{\Delta P \eta_D}{0.5\rho A_s {V_{aws}}^2 V_s (1 - \frac{P_w}{P_0}\xi)} \quad (1)$$

with ρ as air density, A_s, as the total sail projected area to the wind, V_s, as the ship speed, P_w is the vessel engine power when WPT is available and P_0 is the engine power without WPT. Figure 35 shows the scatter plot of the calculated thrust coefficient as a function of AWA together with a curve fitted to the thrust coefficients. The following regression analysis was done in order to find the appropriate lift and drag coefficients fitted to the thrust coefficients data according to the Equation 2. The identificed values of lift and drag coefficients are 2.43 and 0.63 respectively.

$$C_t = C_l \sin(\mathrm{AWA}) - C_d \cos(\mathrm{AWA}) \quad (2)$$

The above formula will be used to estimate the saved power in a route.

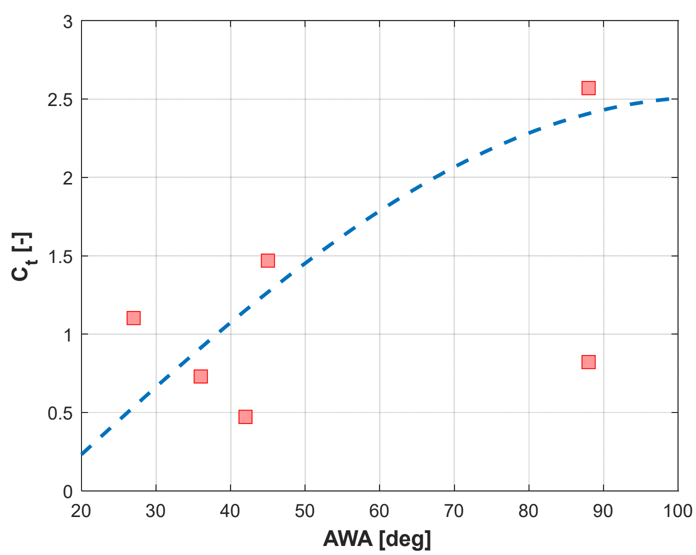

Figure 35. The scatter plot of the estimated thrust coefficients vs. AWA and curve fitting to the values.

Figure 36 shows the histogram of the true wind speed at 10 m above sea level for the locations of the vessel in North sea for the year of 2021. Assuming that the vessel sails from its route between Rotterdam and Humber, the plot shows that the dominant wind in north sea are towards the northeast direction.

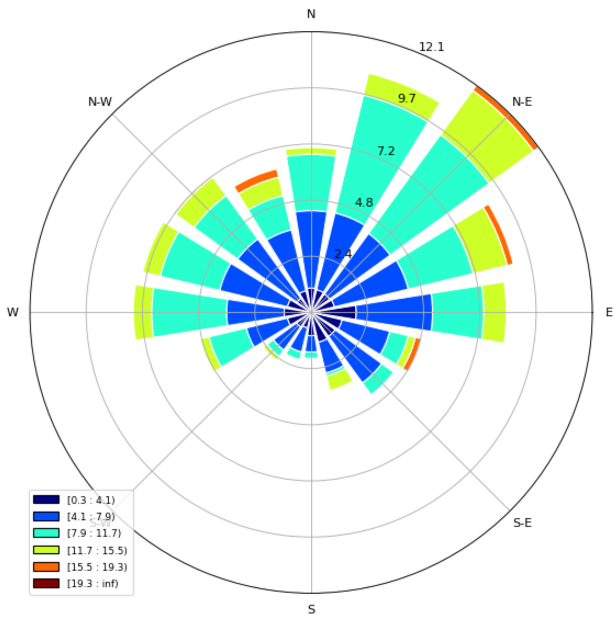

Figure 36. Rose plot for wind speed and direction 10 m above sea level for North Sea in 2021- The ERA5 data from Copernicus has been used.

Assuming that the vessel sailing in north sea on a route following rhumb line with COG of 60 degree relate to the north counter clockwise, the following formula is used to calculate the potential of WPT in generating equivalent gensets power.

$$\Delta P = 0.5\rho A_s {V_{aws}}^2 V_s (1 - \frac{P_w}{P_0}\xi) C_t / \eta_D \qquad (3)$$

Here, it is assumed a total propulsion efficiency of 0.54. From the data of true wind speed and direction, we can estimate the apparent wind speed and direction and the thrust coefficient. Once those calculations are completed, the generated power can be subsequently calculated.

Figure 37 shows the histogram of the potential power saving from WPT. The average WPT power generation is around 35 kW. Note that in reality, the generated power is mainly used only to speed up the vessel. A better way to benefit from WPT would be to depower the gensets according to the amount of power generated from WPT and keep the vessel speed fixed.

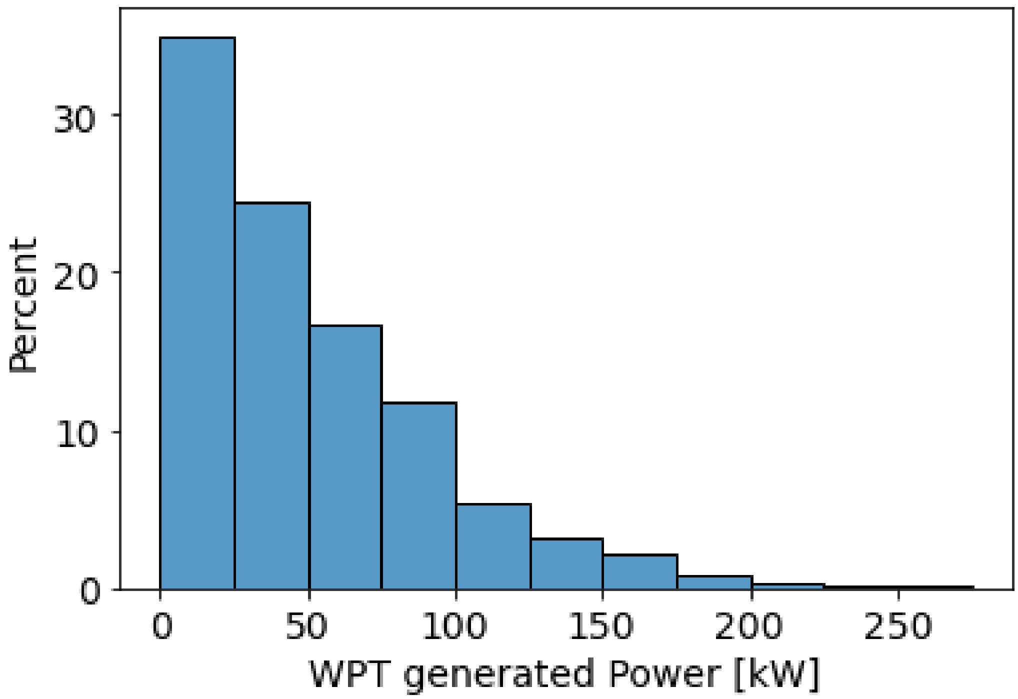

Figure 37. The histogram of the equivalent engine power generated from the two wingsail units considering the wind speed and direction in North Sea from Figure 36.

Considering the vessel speed and the apparent wind speed histogram for route sailing with the speed of 9 knots, a power range of 550 to 776 kW is needed for vessel to maintain the speed as shown in Figure 38.

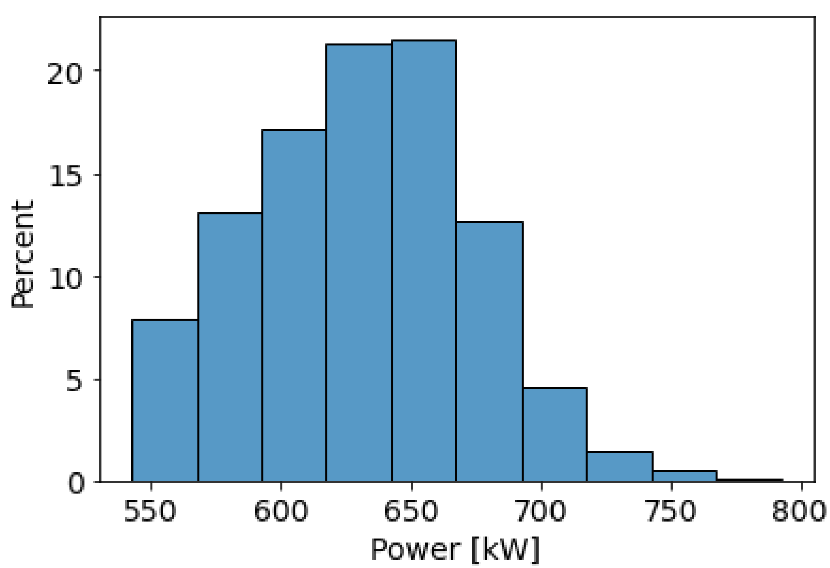

Figure 38. The histogram of the propulsion power to sail the vessel in the route.

Figure 39 shows the fuel consumption of each Volvo penta genset used in Tharsis vessel. As seen from the plot, for a power setting 360 kW and 1800 RPM, a linear relationship holds between the fuel consumption and power. Considering this relationship, the ship fuel consumption mass can be calculated with the assumption of the density of ship fuel of 840 kg/m^3. Further, assuming a CO_2/fuel ratio of 3.2 allows the accompanying CO_2 reduction to be computed.

Considering the time commuting between Rotterdam to Humber with the vessel speed of 9 knots is about 20 hours, the average total genset power consumed is around 12.6 MWh. Assuming that the WPT is used for 80% of the travel time and a fixed wind profile for the whole 20 hours of the travel, the accumulative potential power saving of WPT varies between 0 to 4.4 MWh averaged at 798 kWh. The fuel consumption along the route varies between 2.28 to 3.26 tons (with an average of at 2.64 tons) depends on weather conditions. Based on the aforementioned assumptions, the fuel consumption saving along the route varies between 0 to 0.85 tons with an average of 0.167 tons. The total CO_2 emission range for the route is (7.29, 10.44) tons averaged at 8.46 tons while the total CO_2 emission saving is between 0 to 2.72 tons of CO_2 averaged at 0.53 tons. The average fuel consumption and CO_2 emission reduction percentage is 6 %.

Assuming that the vessel commute 15 times in a month in the route, this would end up to an average fuel consumption of 476.4 tons of fuel (or 1524.5 tons of CO_2 emission) while the average WPT fuel saving is 30.2 tons (or 96.6 tons of CO_2 emission). This is equivalent to an average saving of around 6% tons of fuel saving and CO_2 emission per year.

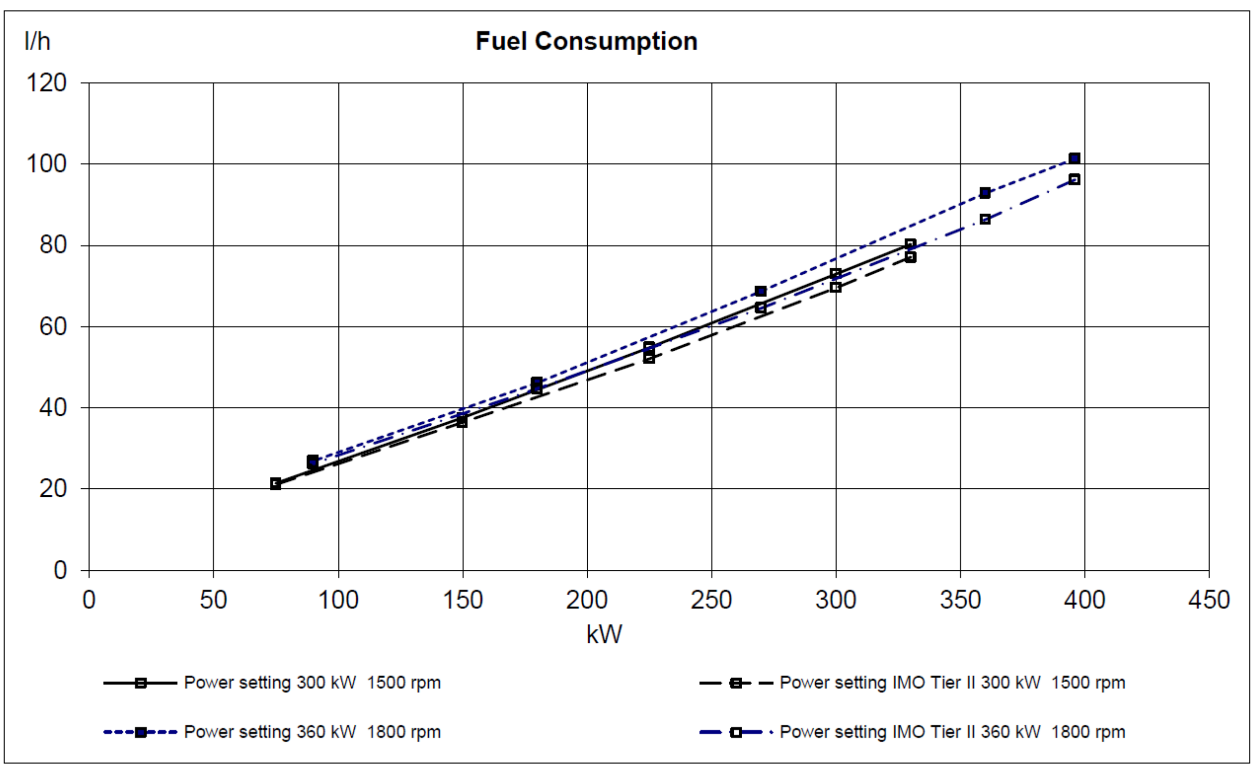

Figure 39. Fuel rate consumption of VOLVO Penta genset model used in Tharsis vessel.

Table 9 summarizes the results of potenial savings due to WPT for Tharsis vessel.

Table 9. The estimated savings due to WPT for Tharsis *vessel*

Annual fuel saving [ton]	Annual CO_2 reduction [ton]	Percentage of fuel saving [%]
30.2	96.6	6

Digital Twins References

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Discussion of uncertainties and discrepancies between sea trial and numerical results

Despite a combination of both experimental measurements at sea and high-fidelity numerical tools, assigning a single value to WPT-derived fuel savings is not a trivial task due to the presence of uncertainties in both the models and the experiments. In this section, we discuss a number of the ramifications of these uncertainties, and the reasons for which discrepancies exist between the sea trials and simulation outputs. Some of these issues were posed in previous sections, but they are compiled here for each vessel in a similar manner. It should be noted that due to inconsistent experimental results for the Ankie sea trials (i.e. RE40201042-04-00-A Speed trial of Ankie), those measurements are not included in this discussion. It must also be emphasized that the previous fuel savings results given as percentages only consider nominal sailing operation and not time spent at low or zero speeds (e.g. low-speed maneuvering or loading/unloading in ports) where there is no savings provided by the WPTs. In that case, the overall fuel savings from wind capture as a percentage of total fuel consumption would decrease due to the inclusion of vessel operations where wind assistance is not possible.

In the following four figures, the differences between WPT equivalent brake engine power determined from the sea trials and those calculated by the numerical tools are compared. In these figures, the solid black line represents a perfect, 1:1 correlation between the sea trials and the numerical simulations. This set of figures also investigates the fidelity of a simple, 1 DOF model (only considering forces along the longitudinal axis of the vessel) against a 4 DOF tool such as ShipCLEAN.

Figure 40 and Figure 41 show that in certain conditions, the simple 1 DOF model can accurately capture the wind power capture from the WPTs (a closer match between the ideal, solid black line and the 1DOF simulation results). However, note the significant discrepancies between experiments and simulations at the conditions experienced by the M/V Annika Braren in Figure 41, which are as high as ~175%.

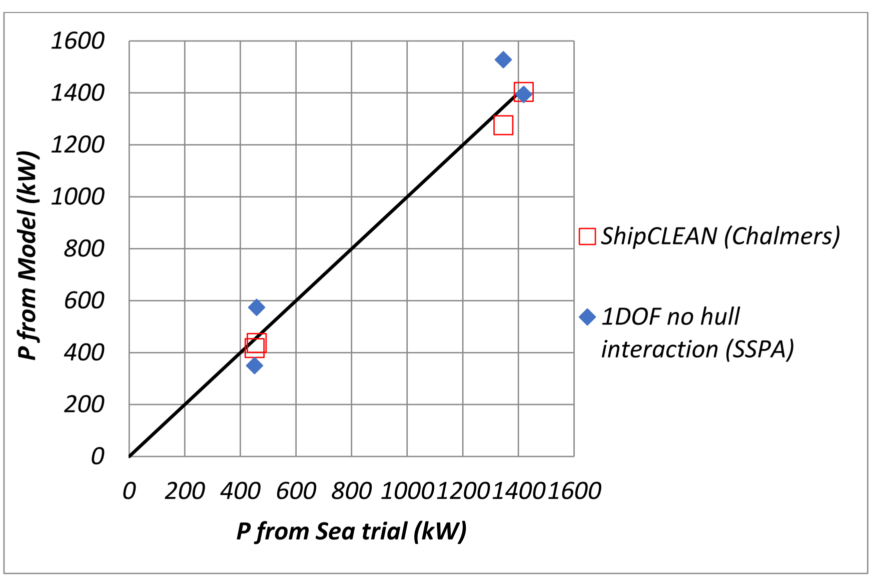

Figure 40. M/V Copenhagen sea trial results against ShipCLEAN predictions of engine power

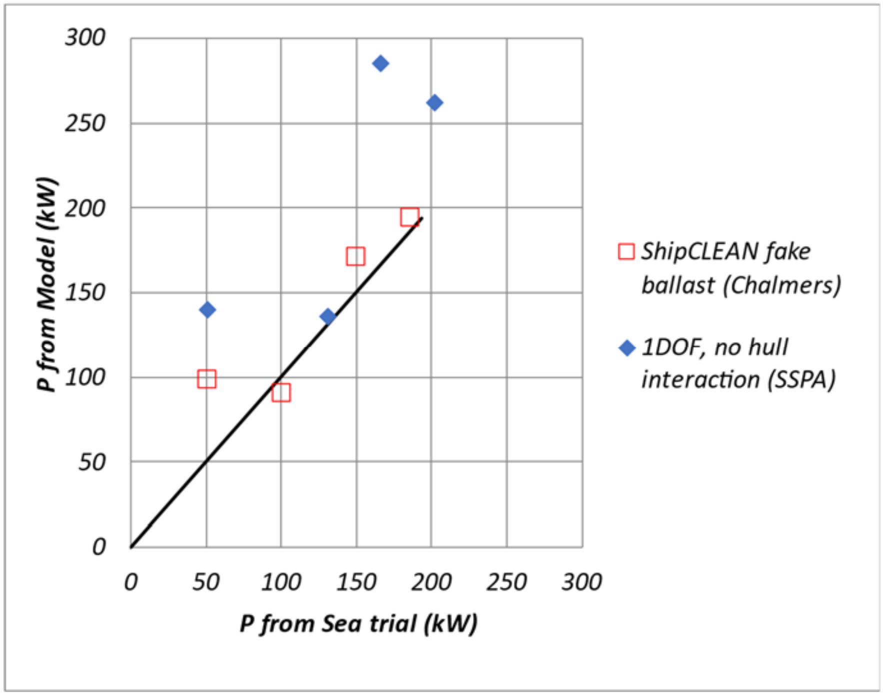

Figure 41. M/V Annika Braren sea trial results against ShipCLEAN predictions of engine power

In general, it is expected that an accurate prediction of wind-assisted vessel performance over a range of wind speed and direction will require a characterization of side forces created by the presence of a WPT or WPTs. This necessitates at least a 4 DOF approach to produce a model with high enough fidelity over all the conditions that would be encountered on a route. Despite the increased degrees of freedom, such a model remains computationally inexpensive, and therefore can be used for optimization studies.

The large differences between the Frisian Sea digital twin and the sea trials in Figure 42 (when C_L = 6 in the simulations) highlights the importance of an accurate assessment of the WPT performance, which can be described largely through the coefficient of lift or C_L. As previously mentioned, data from the technology provider indicated a C_L of approximately 6, which was applied to most of the simulations, and the sea trials determined a maximum C_L of ~2.5. Because the power generated by the WPTs will scale linearly with C_L, the discrepancy accounts almost entirely for the differences seen in the figure. Applying the same C_L to the simulations as found in the sea trials leads to similar results. This is highlighted by the blue diamonds in Figure 42 lying much closer to the ideal curve (solid black line) as opposed to the open red squares (C_L = 6). While long-term data seemed to indicate a higher coefficient of lift was valid (likely a value between 2.5 and 6), it is possible that the suction sails may not have provided the same performance during the sea trials, which chronologically occurred before long-term tests. This is an ongoing investigation for future work that will focus on force sensor analysis of the suction sails, as it is difficult to explain this discrepancy at this point without further data. In the case of the Tharsis vessel wingsails, there was less uncertainty in terms of WPT performance (though a roughly ~20% difference between simulation and sea trial in one of the cases shown in Figure 43).

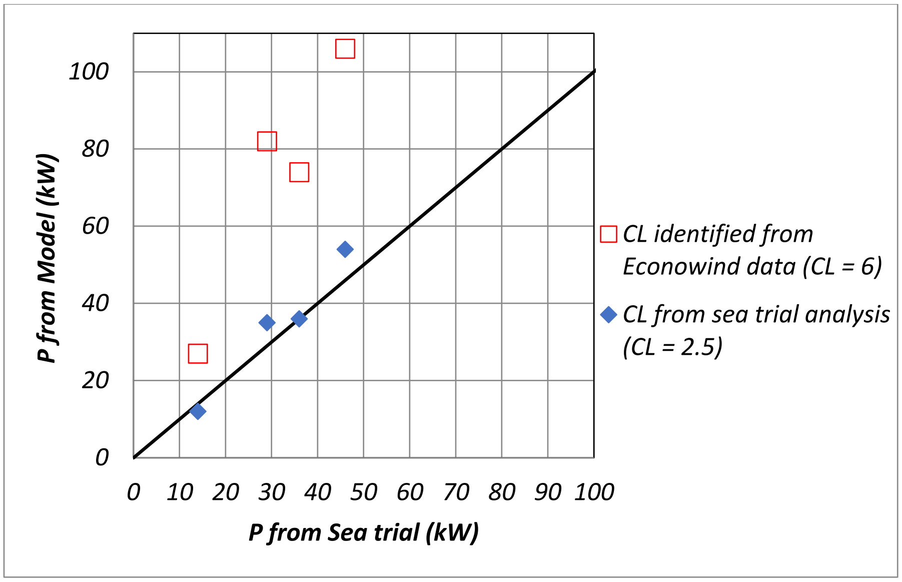

Figure 42. M/V Frisian Sea sea trial results against digital twin predictions of engine power

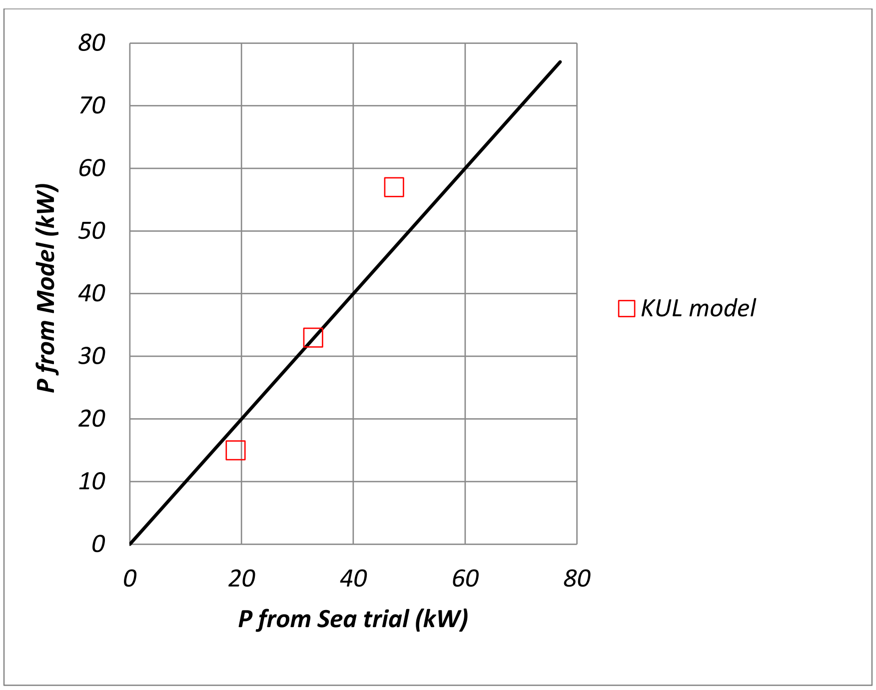

Figure 43. M/V Tharsis sea trial results against digital twin predictions of engine power

While some questions about WPT performance may persist, it is clear that the numerical tools have the capability to capture the fundamental dynamics of a wind assisted vessel, and therefore are able to provide high fidelity assessments of expected fuel savings and emissions reductions. Of course, these models will only be as accurate as their input, and they will typically rely on weather models and wind data from online repositories for long-term savings predictions, as there are often no historical wind measurements available for the vessel positions. Table 10 highlights the differences between wind measurements taken on board the Frisian Sea during the sea trials against online wind data available from Copernicus.

Table 10. Measured wind data during sea trial for the M/V Frisian Sea versus Copernicus weather

TWS [sea trial] [m/s]	TWS [CDS] [m/s]	TWS diff. [%]	TWA [sea trial] [°]	TWA [CDS] [°]	TWA diff. [%}
6.3	9.15	45.2	265.6	240	-9.6
7.7	9.53	23.8	255.3	236	-7.6
7.2	9.53	32.4	261.0	237	-9.2
9.8	9.34	-4.7	237.5	246.0	3.6
7.3	9.34	27.9	241.6	246.0	1.8
6.9	9.65	39.9	237.7	239.0	0.5
7.6	8.82	16.1	237.0	255.0	7.6
8.0	8.86	10.8	258.0	257.13	-0.3
7.8	8.86	13.6	247.4	257.0	3.9
7.8	7.34	-5.9	250.1	255.0	2.0
8.0	7.38	-7.8	263.5	258.0	-2.1
8.6	7.04	-18.1	257.5	258.0	0.2
9.7	7.04	-27.4	262.5	258.0	-1.7
9.3	7.39	-20.5	264.5	245	-7.4
9.3	7.39	-20.5	256.1	245	-4.3

In many cases, the online wind data (particularly the true wind speed) is drastically dissimilar (by as much as ~50%) to the measured wind. Interestingly, there are times where the online weather database overpredicts and others where it underpredicts the measured wind conditions. As the number of operating conditions in a dataset increases (i.e. a longer voyage), the more opportunity there is for such over- and underpredictions to cancel out as a quantity is integrated over the dataset, such as fuel savings. This would suggest that while the source of wind data will have a significant impact on estimated WPT performance at a single condition, that effect should be more negligible for the characterization of performance or savings over a longer voyage or a number of long routes throughout a year. On this basis, it would be expected that the Scandlines M/V Copenhagen ferry, which operates over a relatively short (~2 hours), fixed route between Gedser, Denmark and Rostock, Germany, will have more likelihood for discrepancies between the predictions of fuel savings (using a weather model in the ShipCLEAN tool) and the realized savings at sea. However, a rigorous confirmation of these ideas is left to a future publication once more data is collected.