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Report.

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Speed trial and route analysis of m/v Tharsis with wings

WASP Wind Assisted Ship Propulsion

Interreg North Sea Region WASP European Regional Development Fund

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Speed trial and route analysis of m/v Tharsis with wings

A speed trial was performed with m/v Tharsis in May 2022. The purpose of the test was to verify the power saving of the wings. This report describes the tests conditions, measurements, analysis, and results. The trial test result is extrapolated to annual fuel reduction using voyage analysis and statistical weather distribution.

The work is a part of the Interreg North Sea Region project WASP - Wind Assisted Ship Propulsion.

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Summary and recommendations

A speed trial was performed on m/v Tharsis in May 2022 with the purpose of verifying the power saving of the wings.

At true wind speed 8 m/s and ship's speed 8 knots, the wings give a net power saving for apparent wind angles larger than around 20 degrees and the saving reaches up to 7% at the most favourable wind angle.

The speed trial result is scaled up to give a prediction of the in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction on typical routes is between 2.5% corresponding to a power saving of 26 kW.

The mayor uncertainties of the trial result include the wind speed, ship speed and power measurements. The measured ship speed differences were on the limit for what can be recorded with significance using the speed log. <u>Therefore, the result should be interpreted large uncertainty margins.</u>

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Figure 3	Route analysis results

Symbols and abbreviations

ξ_p	Load variation factor, for power correction according to ITTC (2017)	-
AWS	Apparent wind speed	m/s
AWA	Apparent wind angle	deg
AWS_x	Apparent wind speed in ship longitudinal direction	m/s
AP	Aft perpendicular	
A_T	Transversal wind area	m^2
A_W	Total projected wing area	m^2
B	Beam of hull	m
BL	Baseline	
CL	Center line	
FP	Fore perpendicular	
FS	Full scale	
GWA	Global wind angle	deg
H	Wings height	m
IMO	International Maritime Organization	
ITTC	International Towing Tank Conference	
T	Draught	m
T_F	Draught at fore perpendicular	m
TWA	True wind angle	deg
TWS	True wind speed	m/s
V	Volume displacement	M3
V_s	Ship speed	knots
SOG	Speed over ground	knots
COG	Course over ground	deg
STW	Speed through water	knots

1 Introduction

Ship owner Tharsis installed the wind assistance solution from Econowind on m/v Tharsis in 2022. On May 26, 2022, a speed trial was performed with the purpose of evaluating the performance of the wings.

The Trial Team present onboard included Ship Master Jan Albert de Vries, Maxime Broer, engineer at Econowind, and Sofia Werner, SSPA Sweden AB. The trial was planned and conducted by the Trial Team in cooperation.

The speed trial result is scaled up to a predicted annual fuel reduction using a route analysis and statistical weather data. All data processing, analysis and route evaluation is carried out independently by SSPA.

This work is a part of Work Package 5 in the Interreg North Sea Region project WASP. The scope of Work Package 5 is to demonstrate the performance of Wind Propulsion Technologies on five vessels.

Figure A. m/v Tharsis (84.45m x 11.4m) with two wings from Econowind. Sea trial on May 26, 2022

2 Speed trial data

2.1 Conventions and definitions

The following coordinate systems are used in this report:

- Used when referring to locations or distances on the ship:
  - Body-fixed, Cartesian, right-handed system "XYZ" with the origin in intersection of AP, CL and BL.
  - X-axis positive forward
  - Y-axis positive to port
  - Z-axis positive upwards

The following definitions of directions and angles are used in this report.

- Global wind angle (GWA): defined in the geographical system
  - GWA=0° means wind coming from north
- True wind angle (TWA): the angle between the wind direction and the course of the ship
  - TWA=0° means head wind
  - TWA=90° means beam wind (starboard side)

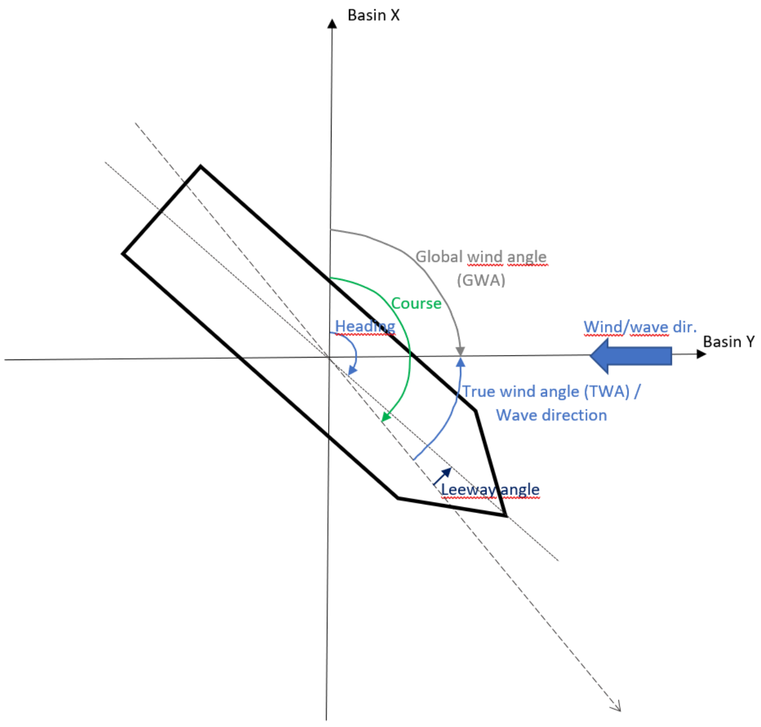

Figure B Definitions of directions and angles

2.2 Ship

The general cargo vessel m/v Tharsis (IMO 9649196) operates mainly in the North Sea region.

The ship data used for the sea trial analysis is listed in Table 1. The ship has two fixed pitch propellers. The ship loading condition during trial is given in Table 2.

Table 1. Ship data

Name	Symbol	Magnitude	Comment
Length over all	Loa	84.45 m	
Beam over all	B	11.4 m	
Load variation factor for power	ξ_p	-0.15	Based on SSPA experience
Hight of anemometer	h	8.2 m	from waterline at trial
Transversal wind area	A_T	83.5 m^2	

Table 2. Ship loading condition during trial

Name	Symbol	Magnitude	Comment
Draft forward	Tf	3.8 m	
Draft aft	Ta	3.8 m	

2.3 Wind propulsion system

The ship is equipped with two wings from Econowind with dimensions according to Table 3. The wings are fitted with flat racks and tiltable sideways over the hatch covers. Rotation angles and flap angles are set automatically based on the apparent wind measured in the mast.

Table 3 Wind propulsion system particulars

Name	Magnitude	Comment
Span	8 m	
Chord	3.27 m	
Thickness	0.4 m	
Area	52.32 m^2	Projected, both wings
Position wing 1	44 m	From AP
Position wing 2	63	From AP

Figure C. Econowind wing system for Tharsis

2.4 Trial location and environmental conditions

The trial was conducted in the English Channel. Waves were moderate as the tests were carried out in shelter from the cost. Water depth was 26m. Weather conditions are stated in Table 4. Environmental conditions registered onboard are given in Table 5.

Table 4. Observed weather.

Wind	WSW	5-8 m/s	https://catalogue.marine.copernicus.eu/)
Waves	W	0.8 m	Observed onboard

Table 5. Environmental conditions, registered onboard

Name	Symbol	Magnitude	Comment
Temperature sea water	t_{sw}	11^o	
Density sea water	ρ_{sw}	1000 kg/m^3	Assumed
Temperature air	t_a	11^o	
Air pressure	p	1013 mbar	Was not measured
Density air	ρ_a	1.24 kg/m^3	Derived from temperature

2.5 Data acquisition

All recorded data is listed in Appendix 1, Figure 1. Data acquisition was performed using the systems given in Table 6.

The power consumption from these passive wings is neglectable.

Table 6. Data acquisition sources

Variable	Instrument	Recording system	Frequency
Main engine	Electric engine output	Ship's data log	1 min running average
SOG, COG	GPS	Ship's data log	1 min running average
STW	Doppler log	Manually	1 min running average
Relative wind at mast top	Ships Anemometer	Ship's data log	1 min running average

2.6 Trial procedure

The trial was conducted according to the principles in ISO 15016/ITTC 7.5-04-01-01.1, with some deviations.

The trial program included 16 single runs according to Table 7. Each run was about 10 minutes long. Constant heading was kept during the runs using the ships autopilot.

The following sequence was followed for each heading:

1) Wings were folded down on the deck
2) Steady heading and speed were checked with external GPS by plotting over time.
3) Measurements conducted for 10 minutes
4) While keeping heading, rpm and pitch constant, wings were raised and set in operation mode.
5) Steady heading and speed were checked with external GPS by plotting over time.
6) Measurements conducted for 10 minutes

For some headings, the order was opposite (wings first, without wings second). Additionally, two runs were conducted without the wings straight into and following the wind. All runs were performed at a constant shaft rate and propeller pitch. The tracks are shown in Figure D, where the circles mark the start of a run.

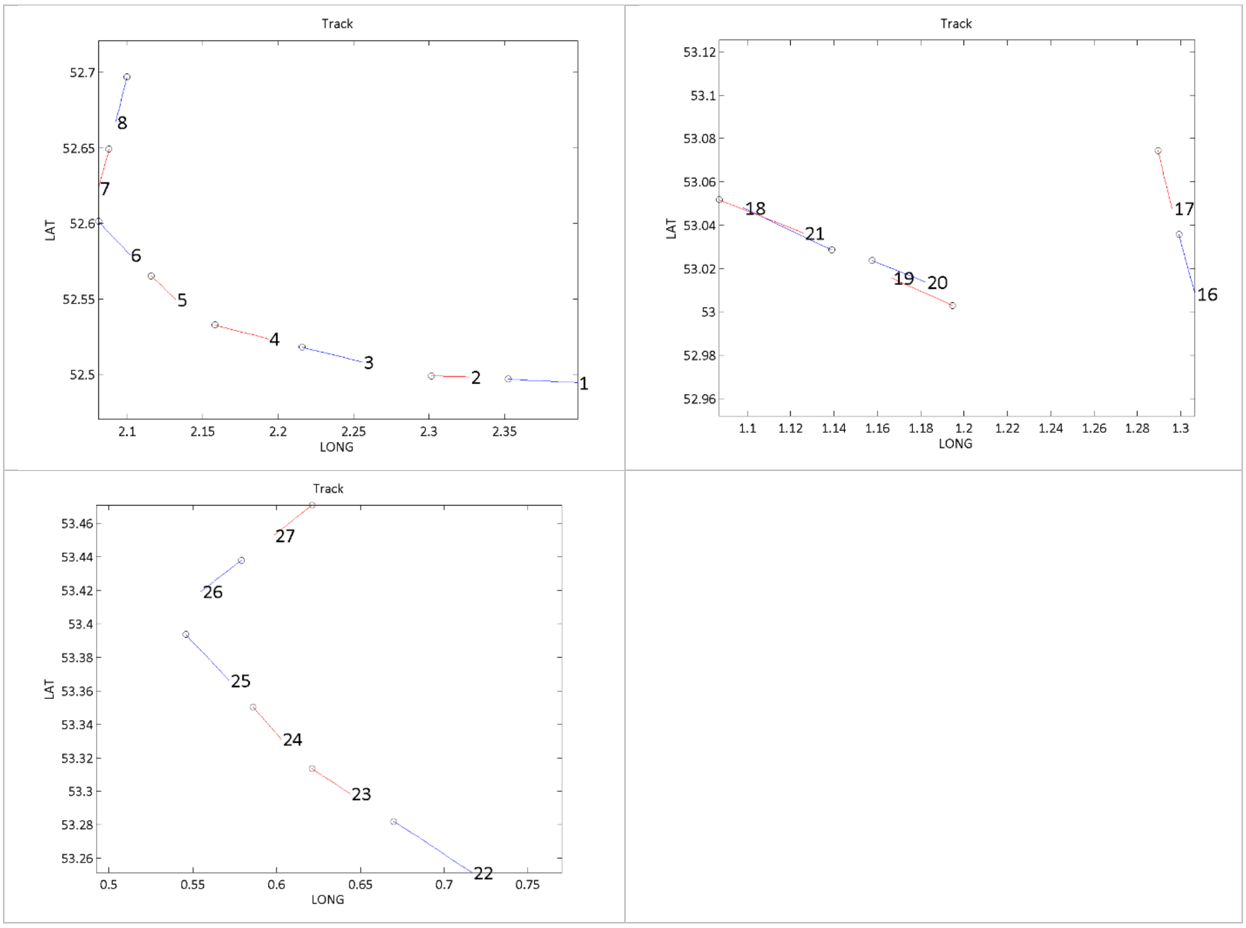

Figure D. Tracks of trial runs. Black dots mark the start of each run. Red=with wings, blue=without wings

Table 7. Trial program

Run	Wings up	Comment
1	up	
2	down	
3	up	
4	down	
5	down	
6	up	
7	down	
8	up	
9	down	speedtest
10	down	speedtest
11	down	speedtest
12	down	speedtest

Run	Wings up	Comment
16	up	
17	down	
18	up	
19	down	
20	up	
21	down	
22	up	
23	down	
24	down	
25	up	
26	up	
27	down	

3 Trial analysis and results

3.1 Current

In standard speed trial analysis, the ship's speed over ground (SOG) is measured with the GPS and corrected to speed through water (STW) using the double runs. The GPS is generally regarded as far more accurate than the speed log. However, this procedure is not possible to follow for WASP sea trials. Therefore, the analysis is based on the difference in speed measured with the log.

3.2 Wind

The true wind during the trial shown in Figure E and Figure F is derived from the apparent wind measured with the ship's anemometer and the ship's speed. The wind was not completely constant during the trial. This could potentially disturb the trial evaluation process, when runs with and without wings are compared. To minimise the disturbance this may have on the comparison, the ship's wind resistance is subtracted from each individual run, according to the ISO 15016 procedure.

According to ISO 15016, the measured wind should be averages between two runs in opposite directions, to reduce the disturbance of the ship's superstructure on the anemometer. In this trial, the runs were however not conducted as reciprocal double-runs and therefore this procedure cannot be followed.

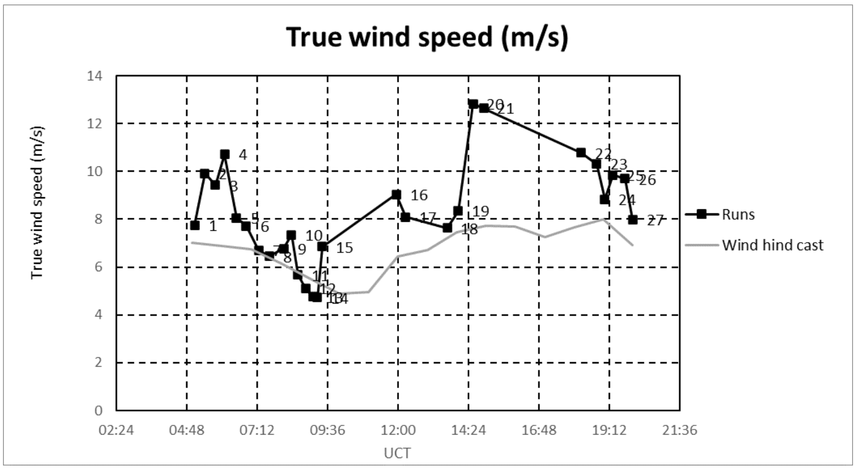

Figure E. True wind speed, at height of anemometer

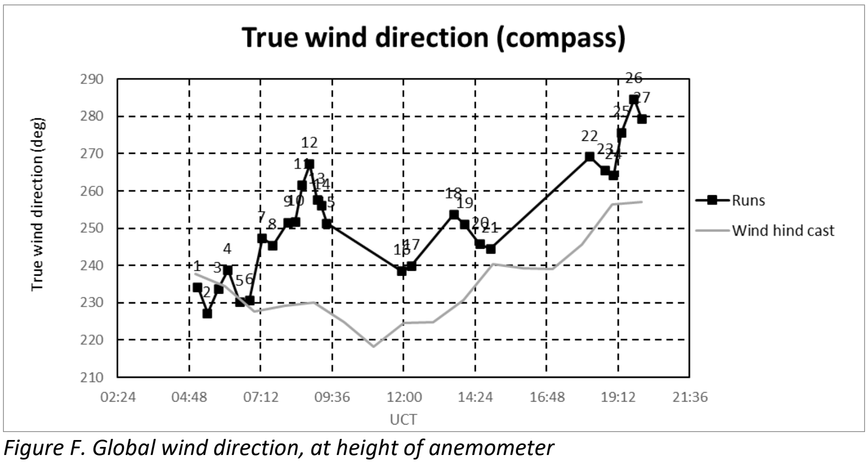

Figure F. Global wind direction, at height of anemometer

3.3 Water temperature, displacement and superstructure resistance

The measured power for each single run is corrected for the wind resistance of the superstructure based on ISO/ITTC standard procedure. The wind resistance coefficient is from SSPA's database.

Correction for water temperature and a correction of displacement to baseline displacement are done according to the procedures.

3.4 Power correction

The correction of propulsive efficiency due to the added resistance corrections is derived using the Direct Power Method according to the ISO standard using the assumed load variation factor stated in Table 1. (See the ISO 15016 standard for a detailed description of the Direct Power Method.)

The corrected power is listed in Appendix 1, Figure 2.

3.5 Baseline

There were no model test curves available for the ship. Instead, the baseline curve was derived by a series of runs at different power settings, Figure G.

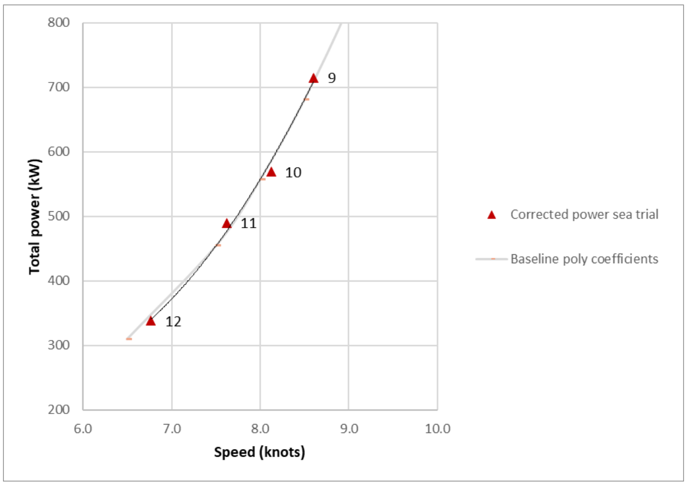

Figure G. Power at sea trial – speed test without wings. Power corrected according to ISO 15016.

3.6 Wing evaluation

The principle of the wing evaluation is to compare single runs *with and without* wings at the *same wind angle*. Table 8 give a comparison of the speed and corrected power between the runs with and without wings. At all measured wind angles except for one, the speed increases when the wings are employed. Normally, an increased speed due to additional wind thrust gives a slightly reduction of power due to higher efficiency when the propeller is off-loaded. However, this is not observed in all runs. This could be due to measurement uncertainty of the power. In the following wing performance analysis, the speed difference is the dominating factor and the possible errors in the power measurement has less influence, but it adds to the uncertainty of the results.

Th numbers in Table 8 are the direct results from the trial, but they are hard to interpret. In Chapter 4, the result is normalised to give representative power savings for a given speed.

Table 8 Speed and corrected power from speed trial.

	TWA	AWA	AWA180	∆ STW	∆ Ps
				knots	%
Run 1&2	7.7	333.4	26.6	0.21	0.0%
Run 3&4	9.4	318.4	41.6	0.12	0.0%
Run 6&5	7.7	290.3	69.7	0.15	-0.2%
Run 8&7	6.4	279.1	80.9	0.31	-0.2%
Run 16&17	9.0	271.7	88.3	0.06	0.0%
Run 18&19	7.6	91.4	91.4	0.00	-0.1%
Run 20&21	12.8	315.0	45.0	0.37	1.2%
Run 22&23	10.8	324.2	35.8	0.14	0.0%
Run 25&24	9.8	319.3	40.7	-0.34	-0.1%
Run 26&27	9.7	272.1	87.9	0.20	-0.5%

4 Wing performance analysis

The result of the trial presented in the previous chapter showed that the wings are able to increase the speed. In this chapter, the trial result is normalised such that a power reduction for a given ship speed can be presented. Two alternative normalisation methods are used.

4.1 Normalisation Method 1

To derive the power difference at a nominal speed V_{ref}, the corrected trial power is interpolated to V_{ref}, using the shape of the ship's baseline curve. (The baseline curve was derived in Section 3.5). This is done by fitting a 3rd order polynomial to the baseline curve and shift it vertically, as Figure H indicates.

The derived power difference is corrected to a nominal wind speed using:

$$\Delta P_{TWS_{ref}} = \Delta P \cdot \frac{{TWS_{ref}}^2}{TWS^2} \cdot \frac{\rho_{a\ ref}}{\rho_{a\ trial}} \tag{4}$$

where TWS_{ref} is the reference wind speed and TWS is the true wind speed during the sea trial, at the same height. The wind variation over height is computed according to ISO 15016 using exponent 1/7. $\rho_{a\ ref} = 1.24\ \mathrm{kg/m3}$. TWS_{ref} is set to 8 m/s since it is close to the averaged wind speed during the trial.

The resulting power savings are given in Table 9.

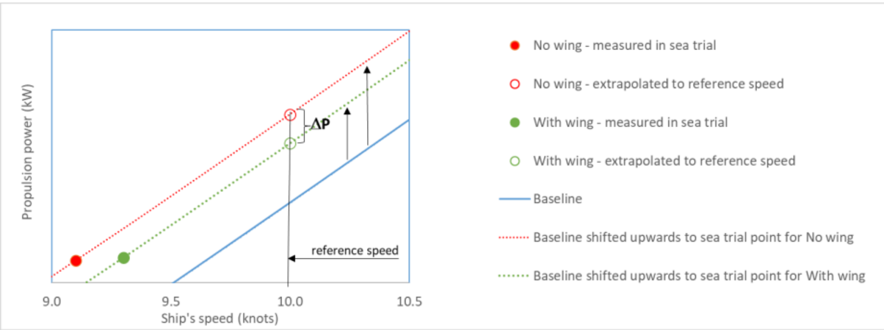

Figure H. Example of how speed trial result is extrapolated to nominal speed using the shape of the Baseline curve.

Table 9. Method 1: Power reduction derived from speed trial and normalized to reference ship's speed 8 knots. "Gross" means without considering power consumption from wings.

	Trial wind condition at anemometer				Ship's speed 8 knots		
Run	**AWA**	**AWS**	**TWA**	**TWS**	**ΔPd Gross** trial wind condition	**AWA for TWS=8m/s**	**ΔPd Gross** TWS=8m/s
	deg	**m/s**	**deg**	**m/s**	**kW**		**kW**
2 & 1	333.4	11.3	319	7.7	41	26	41
4 & 3	318.4	12.1	301	9.4	19	39	13
5 & 6	290.3	8.1	261	7.7	33	68	33
7 & 8	279.1	5.5	237	6.4	82	89	118
17 & 16	271.7	8.4	248	9.0	9	79	7
19 & 18	91.4	6.2	126	7.6	1	91	1
21 & 20	315.0	15.4	302	12.8	76	38	28
23 & 22	324.2	13.7	312	10.8	33	31	17
24 & 25	319.3	12.4	305	9.8	-52	36	-32
27 & 26	272.1	8.9	247	9.7	47	78	30

4.2 Normalisation Method 2

In Method 1, the translation of a speed increase to a power decrease is done by shifting the power curves. This does not fully account for the changed propulsive efficiency when the propeller is unloaded due to the wind propulsion. A second simplification in Method 1 is that the changed apparent wind due to a changed ship speed is accounted for. In order to include these effects, a second normalisation method is introduced. It makes use of a 1DOF speed-power prediction program, which can model the relation between speed, power and the change in propeller efficiency due to changed speed or propeller load. The propeller characteristics of Wagening C 4.40 is used to model the propeller. The process follows the present steps:

1. Ensure that the output of the speed-power prediction program is equal to the Baseline curve (the ship's calm water speed-power curve at the actual loading condition, without wings)

2. Use the speed-power program to find the additional force in the longitudinal direction that matches the change in speed AND corrected power between two runs *with* and *without* wings. That force was the wings thrust, *T* in the run with wings.

3. The thrust coefficient is derived by

$$C_t = \frac{T}{\frac{1}{2}\rho_a \cdot A_W \cdot AWS^2} \tag{5}$$

   with AWS measured at the trial and translated to mid-hight of the wings and using 1/7 power law.

4. Ct is regressed against AWA by adapting a theoretical Ct curve of a generic wing derived by CFD. (See further section 5.1.2) (Figure I).

5. For the nominal condition (ship's speed 8 knots, TWS_{10m}=8m/s, air temperature 15 deg), the apparent wind is computed for a range of wind directions, and the wings thrust *T* is computed using the C_t-polynomial.

6. The speed power prediction program is executed both with and without the wings thrust (entered as a reduction of resistance) and at the nominal speed. The difference in the resulting power is denoted Gross Power Saving. This represents the hydrodynamic power saving.

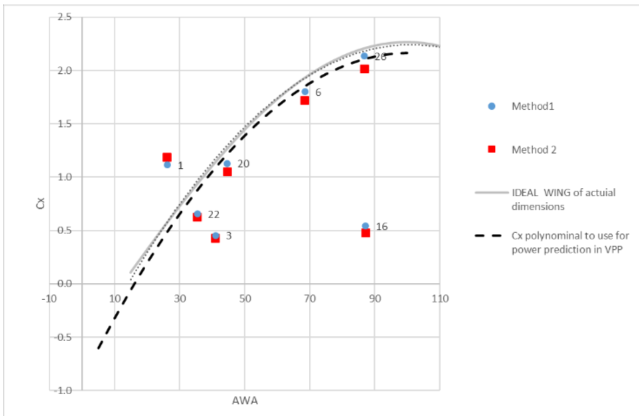

Figure I. Thrust force coefficient derived indirectly from sea trial. Regression found by adapting the Ct curve of a generic wing forces from SSPA database.

4.3 Results

The resulting gross saving (power saving without considering the wings power consumption) from Method 1 and Method 2 are compared in Figure J.

The derived net power saving at the nominal condition is given in Figure K. At true wind speed 8 m/s and ship's speed 8 knots, the wings give a net power saving for apparent wind angles larger than ~20 degrees and it reaches up to 7% saving at the most favourable angle. There appears to be a difference in performance between starboard and port tack. Considering that the wings are placed in the ship's port side, it is possible that one tack is favourable over the other. However, the observed differences could well be due to measurements uncertainty and it cannot be concluded that the observed difference is due to a real difference in performance.

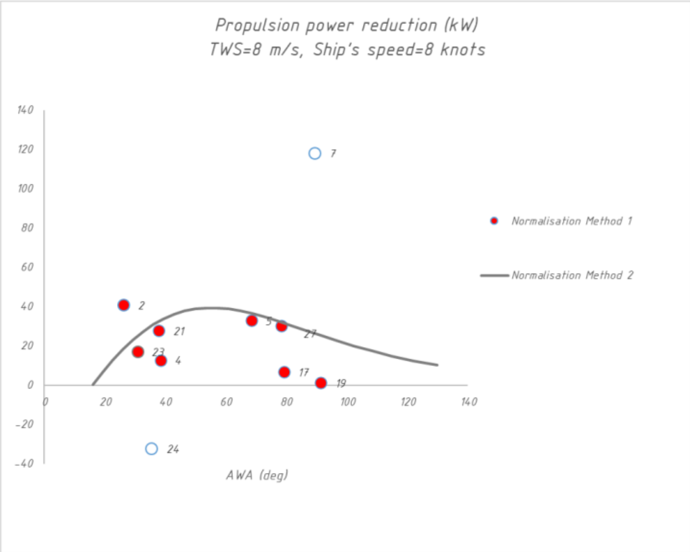

Figure J. Power savings derived with normalization method 1 and 2 at nominal conditions. Reference wind speed 8m/s at 10m above sea.

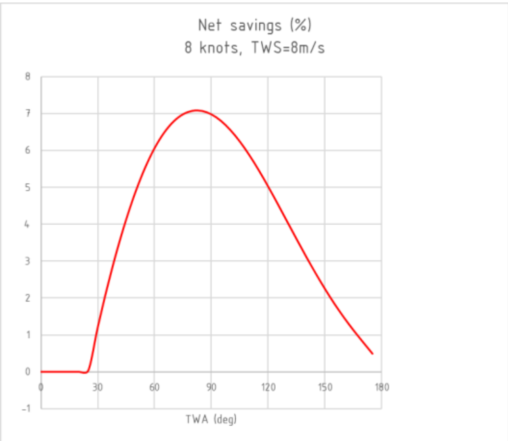

Figure K Power savings derived with normalization method 2 at nominal conditions.

5 In-service fuel saving

The following sections describe the methodology applied to estimate the power saving due to the wings for the given routes.

In short, the procedure is outlined as follows:

- Calibrate digital models of the ship, propeller and wings against sea trial.
- Predict the required power to reach the intended speed for a matrix of environmental conditions, using an in-house Velocity Power Prediction (VPP) program. The VPP model is presented in section 5.1.
- Assembly statistics of the environmental conditions that the vessel will encounter along the route over time.
- Perform route simulations using Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement.

5.1 Power prediction

5.1.1 Ship and propeller models

For each unique environmental condition encountered by the vessel it is necessary to predict the power requirement to reach the intended speed. A quasi-static force equilibrium is found at the intended speed, at which the propulsive and rudder forces are in equilibrium with hydrodynamic and aerodynamic forces. This equilibrium equation is set up in 4 DOF (Degrees of Freedom) including surge, sway, roll and yaw as follows:

$$[Fx, Fy, Mx, Mz] = f(n, \delta, \varphi, \psi)$$

Where $[Fx, Fy, Mx, Mz]$ are total force and moment residuals on the vessel in surge, sway, roll, and yaw respectively, n is the propeller rpm, δ is the rudder angle, φ is the heel angle and ψ is the leeway angle. The problem is a multi-dimensional root-finding problem and is solved iteratively, ultimately finding the required input parameters to generate a zero vector as output.

The function f consists of a set of force calculation routines, each one responsible for calculating a subset of the total force acting on the vessel given the current input parameters. The following force calculation routines has been used in this report:

- **Calm water resistance**

The speed-power curve in the actual service condition was first derived as described in Section 3.5 Resistance curves were derived using the propulsive efficiency η_D from the model test of similar ships.

- **Added resistance in waves**

Spectral superposition of R_{AW} (found from model tests in regular waves from SSPA database) and wave spectrum (ITTC) to find mean added resistance in an irregular sea state.

- **Manoeuvring and rudder forces**

Manoeuvring forces based on bis system model in Norrbin (1970). The forces on the hull and rudder due to drift and rudder angles are introduced in the ship simulation tool in terms of manoeuvring coefficients. The manoeuvring coefficients used is extracted from SSPAs database of manoeuvring model tests.

- **Propulsive forces**

The propulsive factors are taken from the model test of similar ships from SSPA's database. The propeller is modelled as a Wagening C 4.40 with constant pitch 0.95. This simplification is assumed not to have any impact on the result, since the propeller model only needs to predict the slope of the propeller efficiency correctly. The chosen propeller model is supposed to represent the actual propeller well in this respect.

The propulsive set-up is checked by comparing the predicted power and shaft rate with the sea trial base line runs.

- **Superstructure aerodynamic forces**
  The wind resistance coefficient is from SSPA's database.

- **Wind propulsor model**

A quasi-static force model of a generic wing sail is used for the route simulations in this report

- Apparent wind is calculated, including effects from the Atmospheric Boundary Layer (ABL) in accordance with ITTC recommended profile (ITTC 1984).

- Wind propulsor force coefficients are derived as detailed in Section 5.1.2.

- Force contribution in vessel coordinate system is calculated based on apparent wind, aerodynamic coefficients and geometry.

5.1.2 Wing model

The wings model is derived with the following process:

A generic wing is modelled by RANS CFD simulations with the wing standing on a symmetry plane, i.e without any ship hull. The interaction effect between the two wings is modelled using a lifting line based code (Malmek 2020). The ideal wings model is calibrated to the measured speed trial results, which accounts for the interaction between the ship hull and the wings.

The same correction is applied to the side force, assuming that the ideal wings Cl/Cd is preserved. This is an assumption, but since side forces is not measured at the speed trial, it is the best possible assumption. However, the magnitude of the side force has only a marginal effect on the power gain for the current case.

The wings are assumed to be lowered and stored on deck when they do not provide a net saving.

5.1.3 Power saving

The speed power predictions are executed both with and without the wings thrust at the nominal speed. The difference in the resulting power is denoted Gross Power Saving.

5.2 Route analysis method

The route simulation tool uses a Monte Carlo technique over combinations of environmental conditions along the route to estimate statistical properties of route energy requirement. The method is described in by Olsson et.al (Olsson 2020).

The methodology entails the following limitations and assumptions:

- No route optimisation with respect to weather or current.
- The wings will be in use whenever wind condition allows.
- When wings are used, main engine power will be reduced to keep the prescribed ship speed.
- The main engine is assumed to always deliver enough power and torque to reach the intended speed, i.e. no involuntary speed reductions.
- Voluntary speed reductions are not accounted for.

The routes are divided into legs, as shown in Figure L. For each leg on the route, a discrete joint weather distribution (True wind speeds and True wind angles) is derived from wind statistics obtained from the ERA5 reanalysis dataset available in the Copernicus Climate Data Store (https://cds.climate.copernicus.eu). Each leg is treated independently, and leg-wise distributions are assumed to be uncorrelated.

5.2.1 Operational conditions for route simulation

The route analysis is carried out for the following conditions:

- Ship's speed 8 knots
- Laden draught: 3.8 m e.k.
- Density air 1.24 kg/m^3
- SFOC=200 g/kWh independent on engine load

Two routes are analysed. Route 2 is a generic setting based on the EEDI weather matrix (IMO 2021), considering the complete weather matrix (not excluding the 50% worst conditions). The wind statistics for the route is presented in Figure M.

Table 10. Routes for analysis

Route 1	Goole-Rotterdam	Rotterdam - Goole
Route 2	EEDI weather	EEDI weather

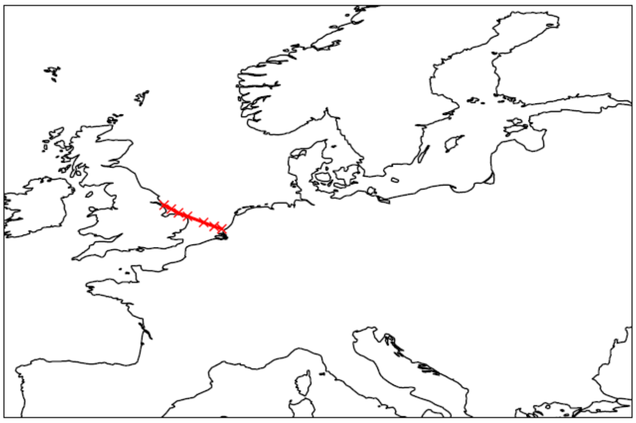

Figure L. Route

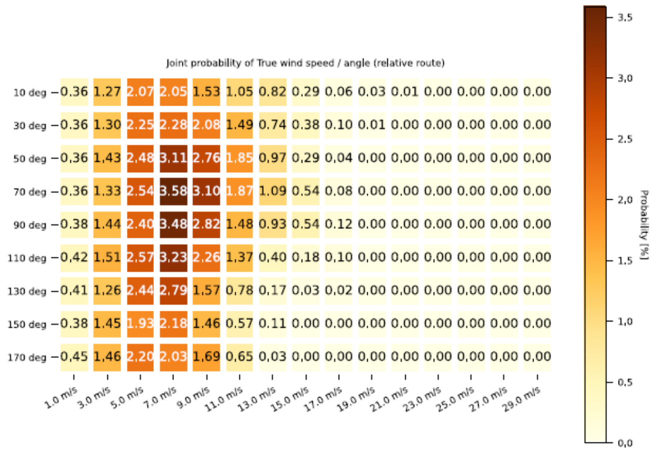

Figure M The probability of true wind speed at the route.

5.3 Results

5.3.1 Power saving at all wind conditions

The power prediction model is used to derive the power saving at all wind conditions, as presented in Figure N.

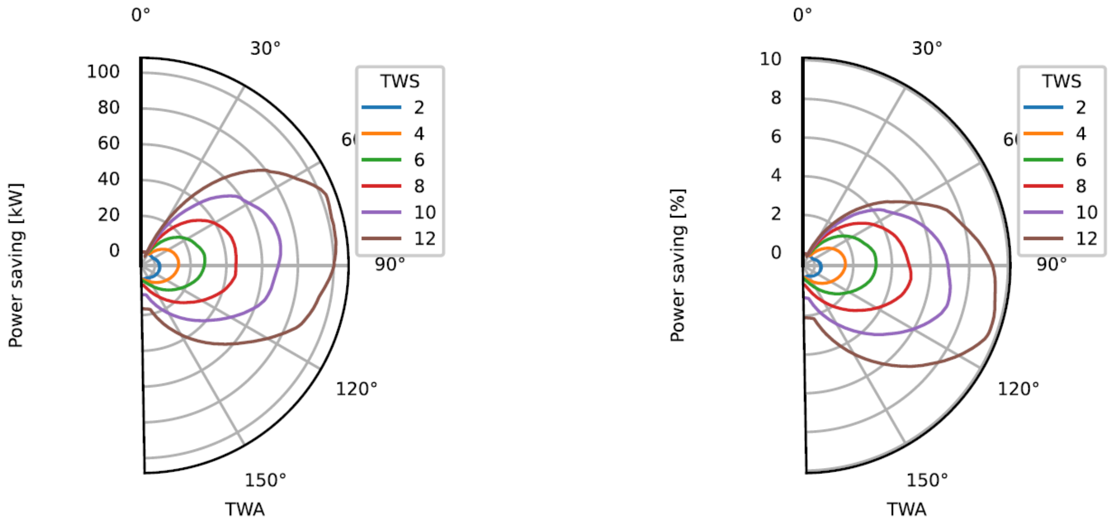

Figure N. Net power saving at various wind speeds.

5.3.2 Power saving on the route

The average power and fuel savings are given in Table 11 and Figure O. This represents the average value of letting the ship sail the route 100 000 times in randomly chosen weather conditions based on weather statistics from the full year of 2019. Some days the weather will be favourable with large power savings, some days it will be adverse. The probability distribution curves are shown in Appendix 1.

The expected fuel savings per year can then be calculated based on the expected number of the various trips.

Table 11 Average power and fuel saving predicted for routes

	Route	power saving (%)	power saving (kW)	energy saving (MWh/trip)	fuel saving (ton/trip)	fuel saving (kg/nm)
1	Goole Rotterdam	2.7	26.2	0.5	0.09	0.58
	Rotterdam Goole	2.5	25.6	0.5	0.09	0.57
6	EEDI weather		16.3			

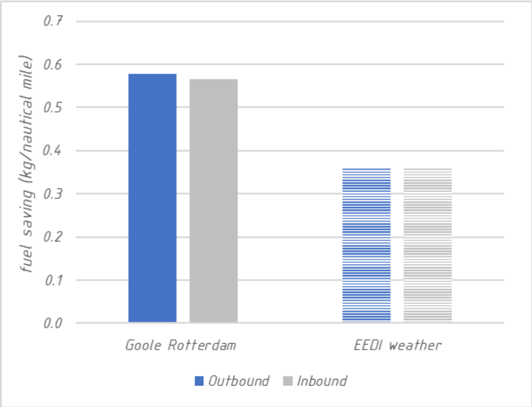

Figure O. Average power saving per route

6 Conclusions

6.1 Result

A speed trial was performed on m/v Tharsis in May 2022 with the purpose of verifying the power saving of the wings.

At true wind speed 8 m/s and ship's speed 8 knots, the wings give a net power saving for apparent wind angles larger than around 20 degrees and the saving reaches up to 7% at the most favourable wind angle.

The speed trial result is scaled up to give a prediction of the in-service fuel reduction using a ship simulation model correlated to the actual speed trial measurements, a voyage prediction tool and statistical weather distribution.

It is estimated that the power reduction on typical routes is between 2.5% corresponding to a power saving of 26 kW.

The mayor uncertainties of the trial result include the speed and power measurements. The disturbance of hull to the wind measurement onboard the vessel may disturb the relation between the trial result, which is based on the on-board measurements, and the route analysis that scale up the result to yearly fuel savings, which is based on the natural undisturbed wind on the ocean.

The mayor uncertainties of the trial result include the wind speed, ship speed and power measurements. The measured ship speed differences were on the limit for what can be recorded with significance using the speed log. Therefore, the result should be interpreted large uncertainty margins.

6.2 Recommendations

It is recommended to log the wind speed on the route, the ship's fuel consumption and operability of the wings for at least one year to complement this study.

7 References

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			from datalog 1 min averaged data						Calculated		
Run	**Wings**	**Comment**	**STW (knots)**	**SOG (knots)**	**Power (kW)**	**COG**	**AWA**	**AWS**	**TWS**	**TWA**	**TWD**
1	up	strange results	8.18	7.90	539	275	333	11	8	319	234
2	down	strange results	7.96	7.78	539	273	327	13	10	314	227
3	up		8.13	7.34	539	292	318	12	9	301	234
4	down		8.01	7.38	539	293	320	14	11	306	239
5	down		7.80	6.68	540	328	290	9	8	263	230
6	up		7.95	6.98	539	330	290	8	8	261	231
7	down	probably incorrect!	8.22	7.33	539	9	277	6	7	238	247
8	up	probably incorrect!	8.53	7.68	538	8	279	5	6	237	245
9	down		8.60	8.49	743	299	331	10	7	313	252
10	down		8.12	8.22	596	301	328	11	7	311	252
11	down		7.62	7.98	509	302	336	9	6	320	262
12	down		6.77	7.45	353	306	337	8	5	321	267
16	up	strange results	7.13	7.74	330	351	272	8	9	248	239
17	down	strange results	7.07	7.48	330	352	275	8	8	248	240
18	up	strange results	8.34	8.72	556	128	91	6	8	126	254
19	down	strange results	8.34	8.83	556	127	93	7	8	124	251
20	up		8.08	7.42	633	304	315	15	13	302	246
21	down		7.72	6.96	625	303	314	15	13	301	244
22	up		7.67	8.00	488	317	324	14	11	312	269
23	down		7.53	8.34	488	318	321	13	10	308	265
24	down	probably incorrect!	7.77	8.98	488	332	312	11	9	292	264
25	up	probably incorrect!	7.44	8.80	487	331	319	12	10	305	276
26	up		8.09	9.48	484	38	272	9	10	247	285
27	down		7.89	9.37	487	37	273	7	8	243	279

0 degrees = head wind
positive = from starboard

Ship particulars		Propulsion particulars	
Length L_{PP} [m]	84.45		
Length L_{WL} [m]	84.45		
Beam B [m]	11.40		
Cb [-]	0.89		
C_p [-]	1.00	C_n [-]	1.000
ESD	no	MCR [kW]	1200

Loading condition	Baseline	Sea trial	Warnings
Displacement [metric tonnes]	3347	3350	
Draft at aft perpendicular (T_A) [m]	3.80	3.80	
Draft at forward perpendicular (T_F) [m]	3.80	3.80	
Transverse projected area‡ (A_T) [m²]	93	93	

Nomenclature of environmental parameters					
GWA	Global wind angle	$H_{W1/3}$	Significant height of local wind driven waves	h	Water depth
AWA	Aparent wind angle	θ_{WT}	True wave direction	ρ_{air}	Density of air
AWS	Aparent wind speed	θ_{SR}	Relative swell direction	ν_{water}	Kinematic viscosity of sea water
TWS	True wind speed	θ_{ST}	True swell direction	ρ_{water}	Density of sea water
TWA	True wind angle	$H_{S1/3}$	Significant height of local swell	T_{water}	Water temperature
T_{Wm}	Mean wave period	T_{Sm}	Swell period	T_{air}	Air temperature
		θ_{WR}	Relative wave direction		
Remarks: Relative directions are defined from bow, positive to s.b. All wave and wind directions are defined as the direction the waves or wind come from. 0º=from the bow.					

Environment			
Air temperature [deg C]	11.0	Water temperature [deg C]	11
Air density [kg/m³]	1.243	Water density [kg/m³]	1026
Water depth [m]	36		

Appendix: 1

Figure: 2b

Onboard measurements					
Run		Heading [deg]	V_S (STW) [knots]		P_d [kW]
1		275	8.19		534
3		292	8.13		534
6		330	7.95		533
8		8	8.53		533
16		351	7.13		327
18		128	8.34		550
20		304	8.09		626
22		317	7.67		483
25		331	7.44		482
26		38	8.09		480
2		273	7.96		534
4		293	8.01		534
5		328	7.80		534
7		9	8.12		533
17		352	7.07		327
19		127	8.34		550
21		303	7.72		619
23		318	7.53		483
24		332	7.77		483
27		37	8.08		482

Wind at the height of anemomenter					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	TWD [deg]
1	11.28	-27	7.74	-41	234
3	12.14	-42	9.42	-59	234
6	8.12	-70	7.72	-99	231
8	5.47	-81	6.45	-123	245
16	8.38	-88	9.04	-112	239
18	6.21	91	7.64	126	254
20	15.42	-45	12.82	-58	246
22	13.73	-36	10.78	-48	269
25	12.43	-41	9.84	-55	276
26	8.91	-88	9.69	-113	285
2	13.10	-33	9.91	-46	227
4	13.56	-40	10.72	-54	239
5	8.53	-70	8.06	-97	230
7	5.74	-83	6.67	-121	248
17	7.54	-85	8.08	-112	240
19	6.94	93	8.35	124	251
21	15.10	-46	12.65	-59	244
23	13.06	-39	10.31	-52	265
24	10.99	-48	8.83	-68	264
27	7.10	-87	8.04	-118	279

Wind at reference height					
Run no.	AWS [m/s]	AWA [deg]	TWS [m/s]	TWA [deg]	GWA [deg]
1	11.49	-27	7.96	-41	234
3	12.40	-42	9.70	-59	234
6	8.31	-70	7.94	-99	231
8	5.61	-82	6.63	-123	245
16	8.62	-89	9.30	-112	239
18	6.40	92	7.85	126	254
20	15.78	-45	13.19	-58	246
22	14.03	-36	11.09	-48	269
25	12.70	-41	10.13	-55	276
26	9.16	-89	9.97	-113	285
2	13.38	-33	10.20	-46	227
4	13.86	-40	11.03	-54	239
5	8.74	-70	8.29	-97	230
7	5.89	-84	6.86	-121	248
17	7.74	-86	8.32	-112	240
19	7.14	94	8.59	124	251
21	15.45	-46	13.01	-59	244
23	13.35	-39	10.61	-52	265
24	11.23	-48	9.08	-68	264
27	7.30	-88	8.27	-118	279

Corrections						
Run no.	Wind [kN]	Waves [kN]	Depth [knots]	Temp/Dens [kN]	Idling WPU [kN]	
1	3.6	0.0	0.00	0.0	0.0	
3	3.6	0.0	0.00	0.0	0.0	
6	-0.3	0.0	0.00	0.0	0.0	
8	-0.7	0.0	0.00	0.0	0.0	
16	-0.5	0.0	0.00	0.0	0.0	
18	-0.6	0.0	0.00	0.0	0.0	
20	5.5	0.0	0.00	0.0	0.0	
22	5.4	0.0	0.00	0.0	0.0	
25	4.0	0.0	0.00	0.0	0.0	
26	-0.6	0.0	0.00	0.0	0.0	
2	5.0	0.0	0.00	0.0	0.0	
4	5.0	0.0	0.00	0.0	0.0	
5	-0.3	0.0	0.00	0.0	0.0	
7	-0.6	0.0	0.00	0.0	0.0	
17	-0.5	0.0	0.00	0.0	0.0	
19	-0.7	0.0	0.00	0.0	0.0	
21	5.2	0.0	0.00	0.0	0.0	
23	4.7	0.0	0.00	0.0	0.0	
24	2.2	0.0	0.00	0.0	0.0	
27	-0.6	0.0	0.00	0.0	0.0	

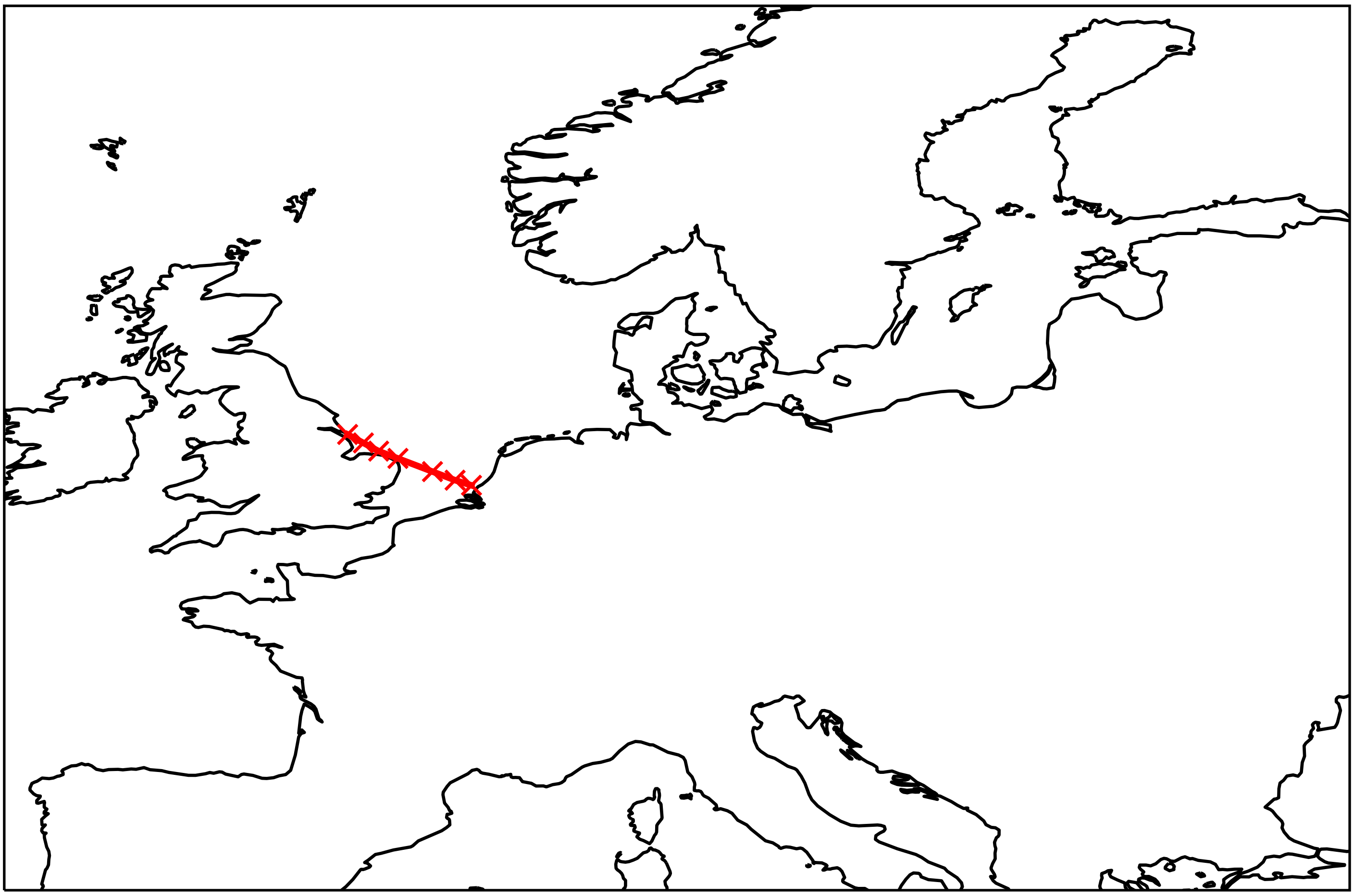
Corrections in percent of total resistance							
Run no.	Wind [%]	Waves [%]	Depth [%]	Temp/dens [%]	Idling WPU [%]	Displ. [%]	Eff. [%]
1	4.3	0.0	0.0	0.0	0.0	0.0	0.5
3	4.3	0.0	0.0	0.0	0.0	0.0	0.5
6	-0.4	0.0	0.0	0.0	0.0	0.0	0.5
8	-0.8	0.0	0.0	0.0	0.0	0.0	0.5
16	-0.8	0.0	0.0	0.0	0.0	0.0	0.5
18	-0.7	0.0	0.0	0.0	0.0	0.0	0.5
20	5.5	0.0	0.0	0.0	0.0	0.0	0.5
22	7.1	0.0	0.0	0.0	0.0	0.0	0.5
25	5.1	0.0	0.0	0.0	0.0	0.0	0.5
26	-0.7	0.0	0.0	0.0	0.0	0.0	0.5
2	5.9	0.0	0.0	0.0	0.0	0.0	0.5
4	5.9	0.0	0.0	0.0	0.0	0.0	0.5
5	-0.3	0.0	0.0	0.0	0.0	0.0	0.5
7	-0.7	0.0	0.0	0.0	0.0	0.0	0.5
17	-0.8	0.0	0.0	0.0	0.0	0.0	0.5
19	-0.7	0.0	0.0	0.0	0.0	0.0	0.5
21	5.0	0.0	0.0	0.0	0.0	0.0	0.5
23	5.9	0.0	0.0	0.0	0.0	0.0	0.5
24	2.8	0.0	0.0	0.0	0.0	0.0	0.5
27	-0.7	0.0	0.0	0.0	0.0	0.0	0.5

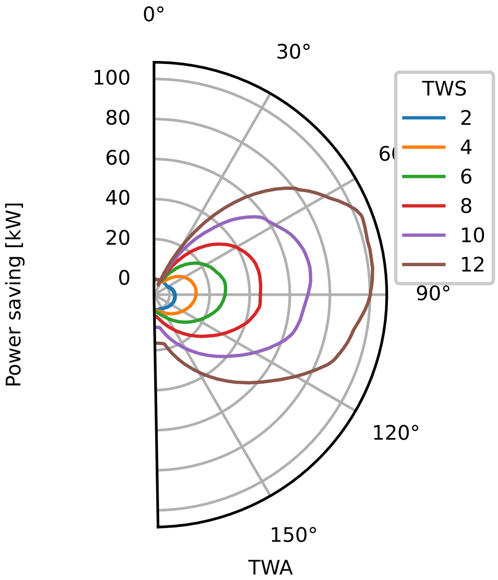
Corrected power		
Run no.	Pdt (ST) [kW]	
1	509	
3	509	
6	536	
8	537	
16	330	
18	554	
20	589	
22	447	
25	455	
26	483	
2	500	
4	500	
5	536	
7	538	
17	330	
19	555	
21	585	
23	452	
24	468	
27	486	

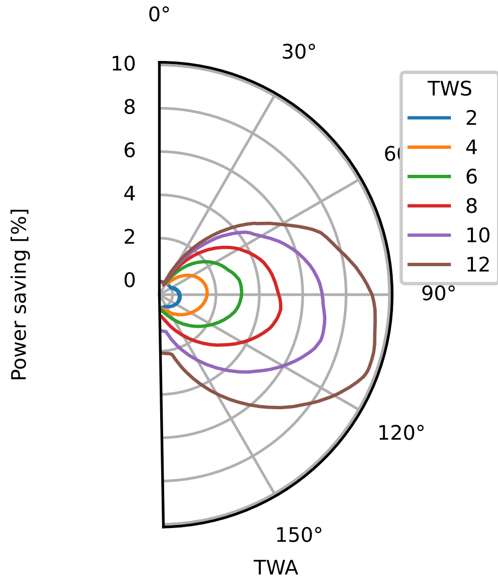
Route analysis report: WPS evaluation

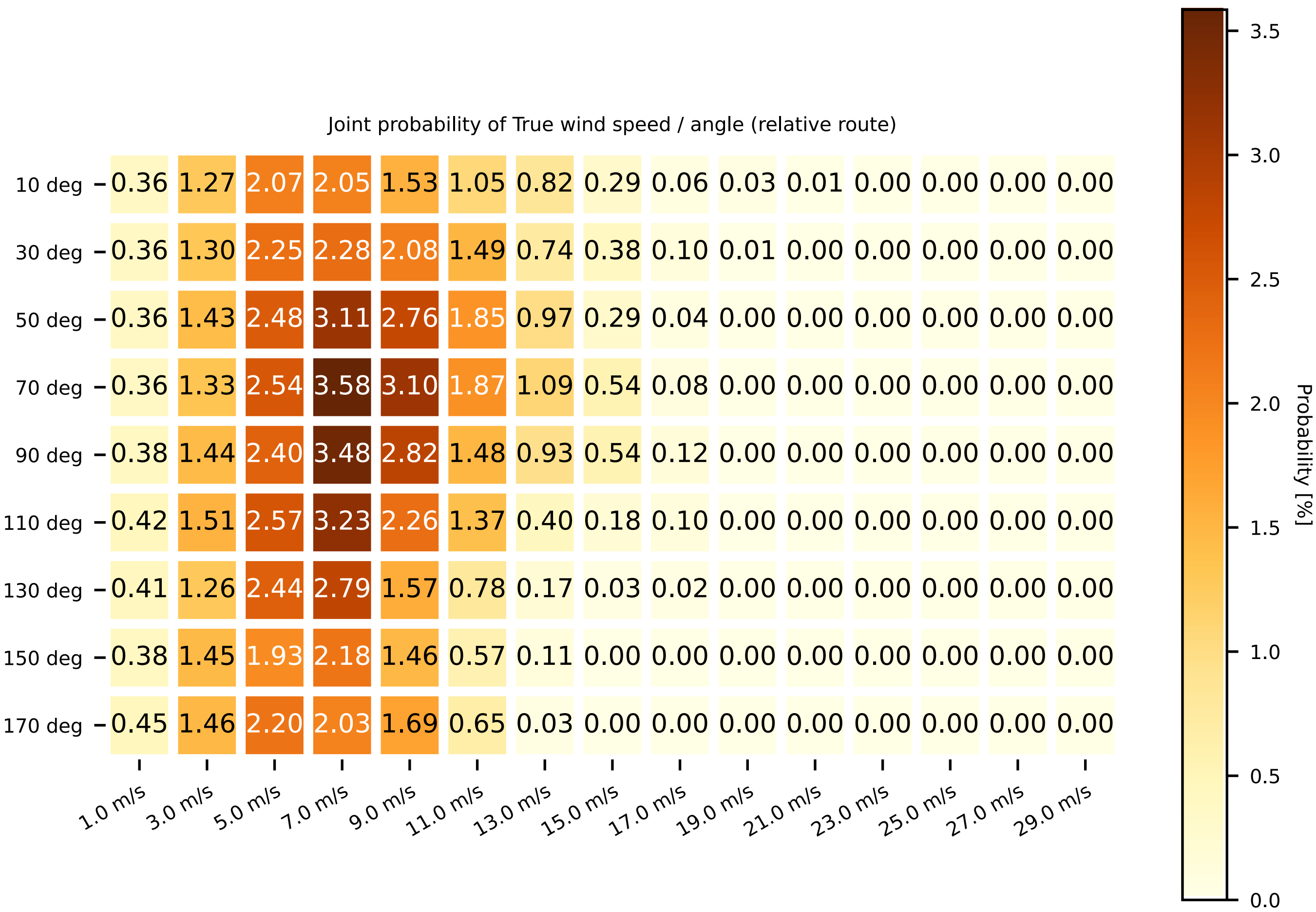
Results for a route analysis for ship: Tharsis (laden) on route: Goole - Rotterdam (inbound) with total distance: 162.8 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	25.58	-3.40	67.14
Energy saving on route (MWh)	0.46	-0.06	1.21
Energy saving on route (%)	2.5	-0.3	6.2

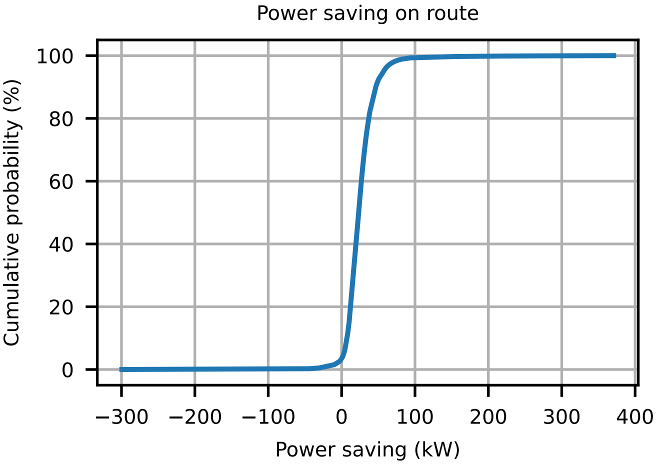


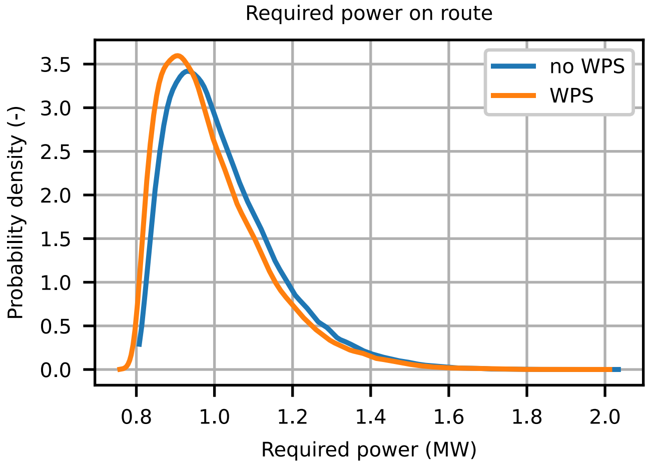






	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	0.36	1.27	2.07	2.05	1.53	1.05	0.82	0.29	0.06	0.03	0.01	0.00	0.00	0.00	0.00
30 deg	0.36	1.30	2.25	2.28	2.08	1.49	0.74	0.38	0.10	0.01	0.00	0.00	0.00	0.00	0.00
50 deg	0.36	1.43	2.48	3.11	2.76	1.85	0.97	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00
70 deg	0.36	1.33	2.54	3.58	3.10	1.87	1.09	0.54	0.08	0.00	0.00	0.00	0.00	0.00	0.00
90 deg	0.38	1.44	2.40	3.48	2.82	1.48	0.93	0.54	0.12	0.00	0.00	0.00	0.00	0.00	0.00
110 deg	0.42	1.51	2.57	3.23	2.26	1.37	0.40	0.18	0.10	0.00	0.00	0.00	0.00	0.00	0.00
130 deg	0.41	1.26	2.44	2.79	1.57	0.78	0.17	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	0.38	1.45	1.93	2.18	1.46	0.57	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
170 deg	0.45	1.46	2.20	2.03	1.69	0.65	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

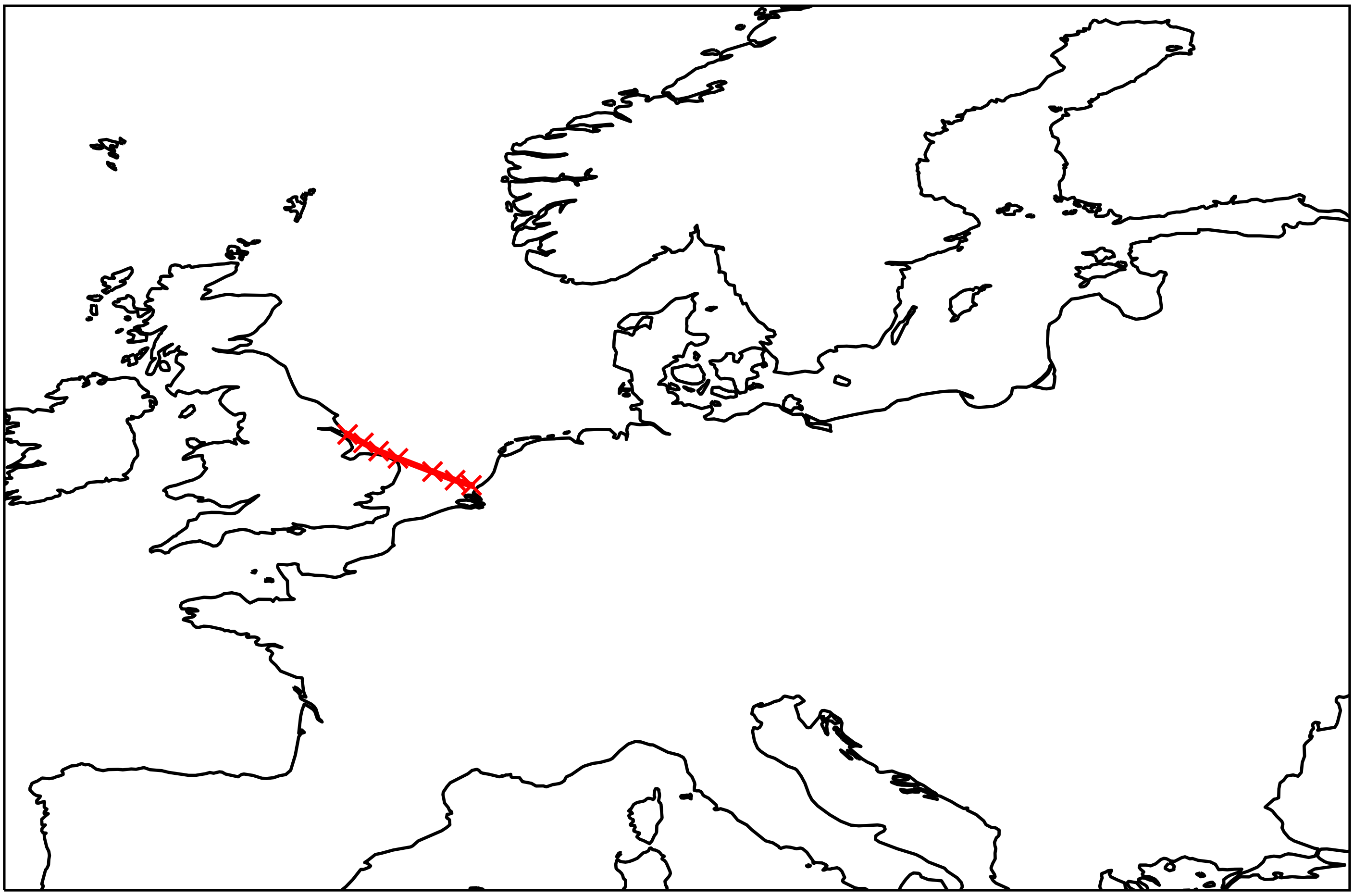

Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−300
−200
−100
0
100
200
300
400
Power saving (kW)

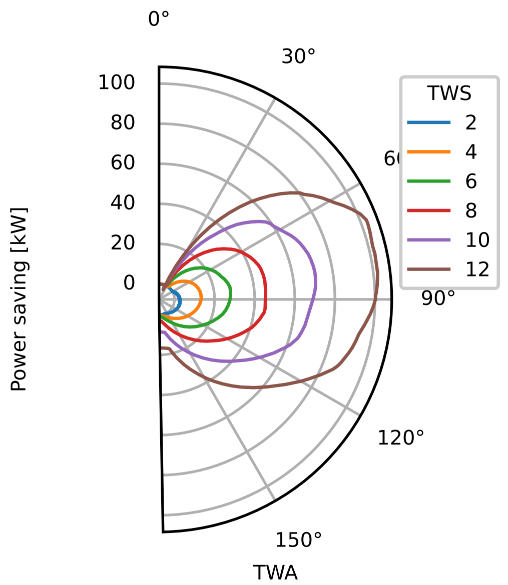

Required power on route
Probability density (-)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Required power (MW)
no WPS
WPS

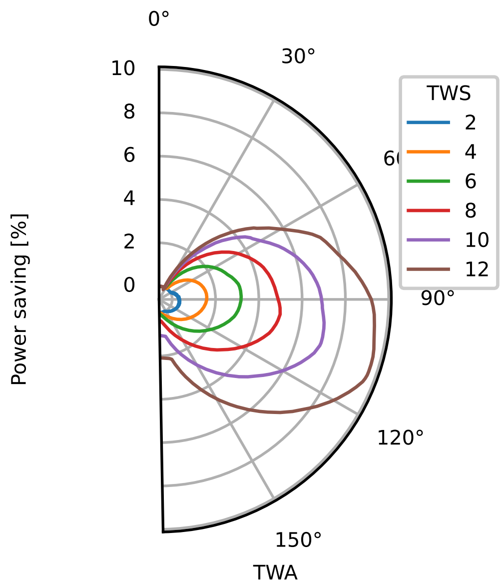
Route analysis report: WPS evaluation

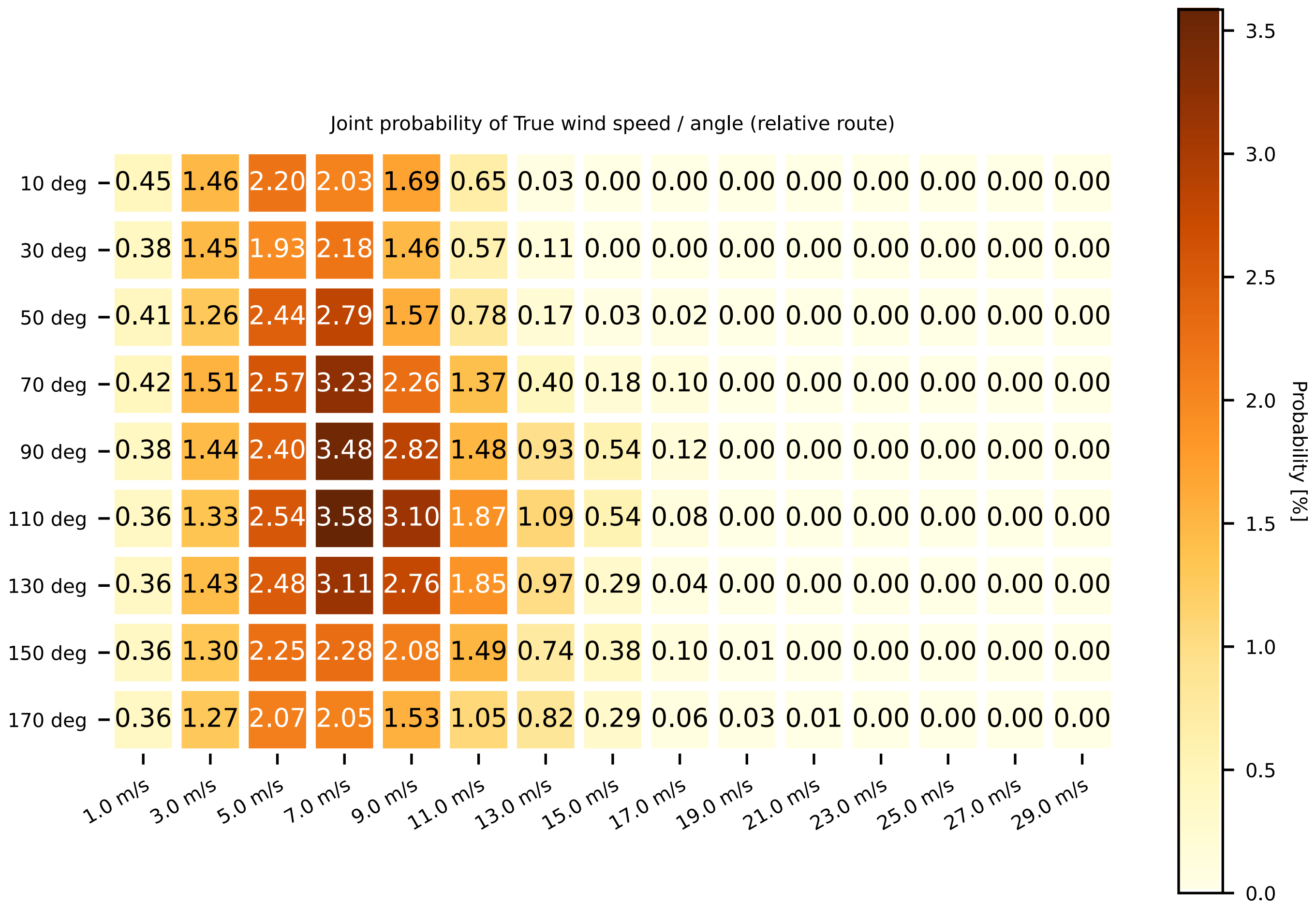
Results for a route analysis for ship: Tharsis (laden) on route: Goole - Rotterdam (outbound) with total distance: 162.8 nm

	Average	Min (2.5%)	Max (97.5%)
Power saving (kW)	26.19	-22.77	128.07
Energy saving on route (MWh)	0.47	-0.41	2.32
Energy saving on route (%)	2.7	-2.2	12.3

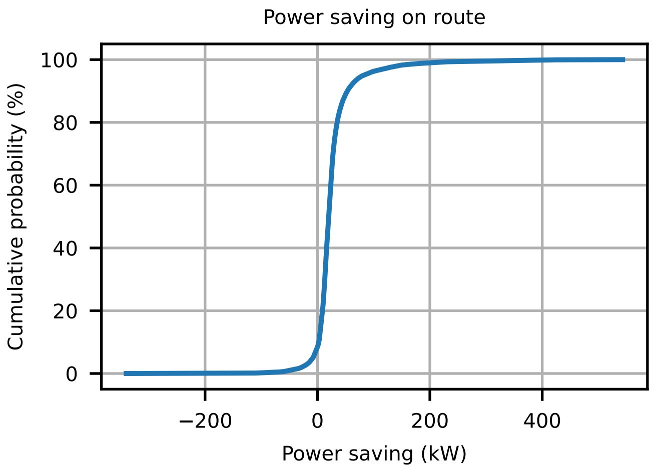


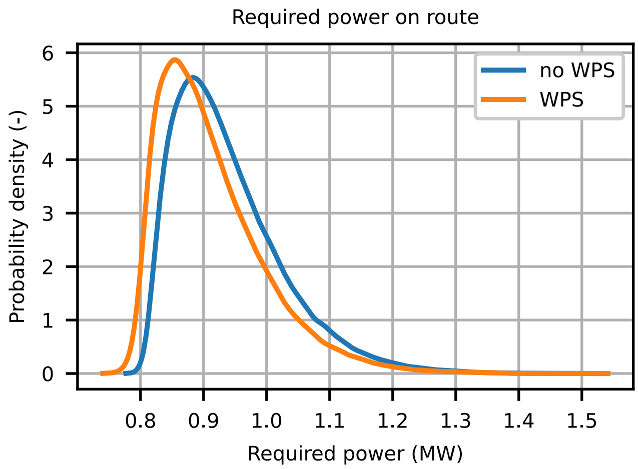






	1.0 m/s	3.0 m/s	5.0 m/s	7.0 m/s	9.0 m/s	11.0 m/s	13.0 m/s	15.0 m/s	17.0 m/s	19.0 m/s	21.0 m/s	23.0 m/s	25.0 m/s	27.0 m/s	29.0 m/s
10 deg	0.45	1.46	2.20	2.03	1.69	0.65	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30 deg	0.38	1.45	1.93	2.18	1.46	0.57	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50 deg	0.41	1.26	2.44	2.79	1.57	0.78	0.17	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00
70 deg	0.42	1.51	2.57	3.23	2.26	1.37	0.40	0.18	0.10	0.00	0.00	0.00	0.00	0.00	0.00
90 deg	0.38	1.44	2.40	3.48	2.82	1.48	0.93	0.54	0.12	0.00	0.00	0.00	0.00	0.00	0.00
110 deg	0.36	1.33	2.54	3.58	3.10	1.87	1.09	0.54	0.08	0.00	0.00	0.00	0.00	0.00	0.00
130 deg	0.36	1.43	2.48	3.11	2.76	1.85	0.97	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00
150 deg	0.36	1.30	2.25	2.28	2.08	1.49	0.74	0.38	0.10	0.01	0.00	0.00	0.00	0.00	0.00
170 deg	0.36	1.27	2.07	2.05	1.53	1.05	0.82	0.29	0.06	0.03	0.01	0.00	0.00	0.00	0.00


Power saving on route
Cumulative probability (%)
100
80
60
40
20
0
−200
0
200
400
Power saving (kW)


Required power on route
Probability density (-)
6
5
4
3
2
1
0
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Required power (MW)
no WPS
WPS