Case study: Wind-assisted ship propulsion performance prediction, routing, and economic modelling

van der Kolk, Nico; Bordogna, Giovanni; Mason, J.C.; Desprairies, P.; Vrijdag, Arthur

Publication date
2019

Document Version
Final published version

Published in
Proceedings of the International Conference Power & Propulsion Alternatives for Ships

CASE STUDY: WIND-ASSISTED SHIP PROPULSION PERFORMANCE PREDICTION, ROUTING, AND ECONOMIC MODELLING

N J van der Kolk, Delft University of Technology, NL
G Bordogna, Delft University of Technology, NL
J C Mason, The University of Manchester, UK
P Desprairies, Bienfair Inc.
A Vrijdag, Delft University of Technology, NL

SUMMARY

In this paper, a vessel model for the performance of wind-assisted ships is combined with a routing tool to assess the fuel savings available from the installation of both one and two Flettner rotors when travelling along a Great Circle Route path. This is combined with an economic analysis to assess commercial viability for these hybrid concepts. The case study is performed in collaboration with DAMEN shipyards, who have provided a design for a wind-assist concept to sail in the Baltic Sea, that, since January 2015, is an Emission Control Area where a sulphur limit content of 0.1 % is enforced on the ship fuels. Results for this case study are presented in terms of fuel savings and payback period analysis, where the reference case is an identical ship sailing without wind propulsors. For the 5,150 dwt general cargo vessel travelling at a speed of 10 knots, average fuel savings of 2.99% were obtained in the Baltic Sea for the single Flettner scenario, and 6.11% for the double Flettner scenario. A discussion of key engineering and design constraints for these ships is included.

NOMENCLATURE

AWS	Apparent wind speed - ship frame (kts)
CLR	Center of lateral resistance (m)
EEDI	Energy Efficiency Design Index
k	Flettner rotor spin ratio (-)
FC	Fuel consumption (kg/hr)
SFC	Specific fuel consumption (kg/kWh)
TWA	True wind angle - ship frame (deg)
TWD	True wind direction - global frame (deg)
TWS	True wind speed - global frame (kts)
ECA	Emission Control Area
HFO	Heavy Fuel Oil
WASP	Wind-assisted ship propulsion

1. INTRODUCTION

Around 90% of world trade is carried by the global shipping industry, accounting for nearly 3% of anthropogenic carbon dioxide emissions (Smith et al., 2015). (Nelissen et al., 2016) reports that greenhouse gas emissions due to seaborn transport are expected to increase by 50-250% by 2050. Furthermore, Heavy Fuel Oil (HFO), which contains high sulphur content, is still commonly used by the global fleet. This causes the shipping industry to be responsible for around 13% and 15% of the global SOx and NOx emissions due to human activities respectively (Smith et al., 2015). Because of this, the maritime industry is currently under pressure to mitigate its negative impact on the environment and on human health and this is sought by issuing ever stricter emission regulations.

As stated in (Argyros, 2015), wind assistance has the potential to deliver double-digit fuel savings and, according to the same study, it is one of the few technologies for which a substantial cut in fuel consumption is achievable in the short-term. Similar studies performed by (Naaijen et al., 2010), (Traut et al., 2014) Eggers, 2016), (Fujiwara et al 2005), also demonstrate the emission reduction potential of wind assist technology. Given that (Traut et al., 2018) demonstrate that full decarbonisation is necessary by close to the middle of the century for the shipping industry to stay in-line with the Paris agreement, the implementation of short-term emission reduction measures is of vital important to curb cumulative emissions. Wind propulsion is also one of a limited number of suitable mitigation options that provide a reduction in both carbon dioxide and other pollutants, such as SOx and NOx (Bows-Larkin et al., 2014). Its implementation could help to avoid a potential lock-in of infrastructure that solely focuses on current sulphur regulations, such as with Liquefied Natural Gas.

In this paper, a modelling for the performance of wind-assisted ships is combined with a routing tool for voyage optimisation and an economic analysis to assess commercial viability. The case study is performed on two Baltic Sea routes, a North-South route between Lulea and Gdańsk, and an East-West route between St. Petersburg and Stockholm. The study is conducted with the support of DAMEN shipyards, which has provided vessel details for the Combi Freighter 5000, a coaster. The economic analysis is presented in terms of a payback period analysis.

This paper presents the work of contributors across several disciplines. An outline is provided to orient the reader: The paper begins with a review of operational, regulatory and market drivers for the greening of sea shipping. Next, the details of the present case study are provided, including the statistics for wind conditions for each route and the wind propulsor investment. The methodology section first described the approach whereby

the analysis efforts of each contributor are combined, followed by a (necessarily brief) description of the individual models. The results are presented in three parts: First, the vessel modelling is reviewed with attention placed on key engineering and design constraints for wind-assist ships, followed by a discussion of the weather routing results, and the payback period analysis for both cases. Finally, a description of the ongoing work of each contributor is included in the conclusion.

2. STRONG DRIVERS TAKE SEA SUPPLY CHAINS TOWARD GREENER FUTURES

While volatile fuel costs and constraining environmental regulations push sea freight operators toward low carbon operational business models, growing retail consumer awareness toward current environmental challenges also push carrier operators toward a cleaner supply chain, whereby a greener shipping fleet can deliver a higher value to their client. In this economical discussion, we enumerate three significant drivers that will prompt sea freight operators to shift toward a greener shipping industry.

2.1 OPERATIONAL DRIVERS

Fuel costs represented 40% of the sea freight industries overall operational costs in 2010 (Samitas, 2010). This figure has increased up to 50-60% in 2018 (Stratiotis, 2018) due to the recent steep increase in fuel prices and also because of the increasing use of alternative fuels. As an example, the upcoming introduction of the 2020 Sulfur Cap, with its expansion of Emission Control Areas to a global scope, will result in the increased investment in expensive alternative fuels such as LNG by sea freight operators, with an estimated impact of $50,000 a day for a 20,000 TEU ship (Stratiotis, 2018).

Increasing fuel prices is also accompanied with an increase in market volatility. 2018 saw the CBOE Crude Oil Volatility Index peaking to a 10-years high, resulting in fuel prices that had not been as volatile since the 2008 financial crisis. As a consequence, the sea freight industry has been using financial instruments, such as swap or futures in order to hedge from volatile bulk prices, implying a premium equally as expensive than the chosen hedging level (Samitas, 2010).

2.2 REGULATORY DRIVERS

The International Maritime Organisation (IMO) acknowledges that energy efficiency measures are largely underutilised and that market drivers alone are insufficient to bring about the required technical and operational measures (2nd IMO report 2009, Acciaro et al, 2011). The IMO estimates that unrealised portential for efficiency savings in the maritime sector lies between 25% and 75% for CO2 emissions. The shipping industry, relatively unregulated when compared to other elements of the global economy, is now subject to two IMO policies for ships: the Energy Efficiency Design Index (EEDI), imposing increasingly ambitious targets for new-build ships, and the Ship Energy Efficiency Management Plan (SEEMP), intended to improve the operational efficiency of all ships. The EEDI targets are to increase from 10% (present) to 30% in 2025.

It has been shown that projected growth for the maritime shipping sector is such that even a full implementation of presently available technology, under existing policy measures, would be insufficient to curb the contribution of the sector to the sum of anthropogenic CO2 emissions (Bazari, 2011). It is for example unlikely that the targets of the European Commission (40-50% reduction by 2050) will be reached, as demonstrated by (Faber et al., 2009) and (Acciaro et al, 2011). It has also been reported that the EEDI is not adequately incentivising the adoption of all innovative measures with the potential for significant savings (IMO 2015)

2.3 MARKET DRIVERS

Wind-assist commercial shipping also represents a market opportunity, potentially increasing the perceived value of the shipped products. Indeed, a Nielsen survey reported a growing demand for greater sustainability from end-consumers, with 66% of global consumers willing to pay more for sustainable brands in 2015 (up 55% from 2014), although this result needs to be tempered considering the fact that only small-sized niche markets actually do buy sustainable products (Littler, 2011). Since WASP technology makes supply chains greener, it can consequently be highly valued to supply these niche markets.

Beside, wind-assist commercial shipping can also be used toward stronger and wider marketing strategies. Green chains favour chain transparency and vice-versa (Mol, 2015), with transparency increasing the brand trust and eventually strengthening some aspects of the consumer-brand relationship such as loyalty (Kang, 2013). But there is even more potential to that. Indeed, transparency enables Business-to-Consumer companies to collect, index and retrieve supply chain information in the form of stories (Woodside et al., 2008), implementing storytelling as an efficient marketing strategy (Pulizzi, 2012). Quoting Michael Margolis in 2014, “people don’t buy a product, service, or idea; they buy the story that’s attached to it.” Wind-assist commercial shipping can provide additional marketing substance to sea freight operators’ clients, bringing novel value, and the possibility to sell the shipped products at a higher price to the final consumer.

In Summary:

- Increasing fuel costs is expected to incite sea freight operators to implement low-consumption changes.

- Based on the growing understanding that present regulatory measures are insufficient, a more stringent regulatory climate is expected.
- Sustainable supply chain brings additional value to final consumers, and raises the possibility of increasing the perceived value of the shipped good.
- To be watched: OPEC strategy to lower fuel price, deregulation moves.

3. CASE STUDY

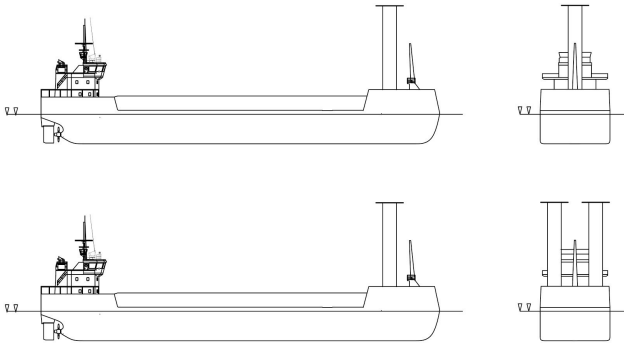

Figure 1: CF5000 with one (top) & two (bottom) Flettner rotors

3.1 THE SHIP

The ship considered in the present case study is a general cargo coaster, the Combi Freighter 5000, whose specifications were given by DAMEN shipyards. The ship has the following characteristics: LOA= 86.82 [m], Beam= 15.20 [m], Draft= 6.35 [m], Displacement= 6682 [t] and Deadweight= 5150 [t].

3.2 WIND PROPULSION SYSTEMS

Two different solutions were considered, a single Flettner case with one Flettner rotor and a double Flettner case with with two Flettner rotors (see Figure 1).

Specification	Value	Units
Diameter	3	[m]
Span	18	[m]
Weight (including foundation)	29	[ton]
Buying cost	300k	[euros]
Installation cost	50k	[euros]
Maintenance cost	7k	[euros/year]
Lifetime	25+	[years]

Table 1: Details of the Flettner rotors used in the case study

The wind-propulsion system used to retrofit the analysed vessel is the Flettner rotor. In particular, a small size Flettner rotor, as offered by the company NORSEPOWER, was chosen. The details of the selected system are given in Table 1.

3.3 BALTIC SEA ROUTE

Figure 2: Map of the Baltic Sea. (Google Maps, 2019)

The ship will be operating in the Baltic Sea region. The route has been simplified to two legs, an East-West route between St. Petersburg and Stockholm, and a North-South route between Lulea and Gdansk (see Figure 2).

Route	Point 1	Point 2	Distance
Lulea-Gdansk	21.75E, 65.25N	18.75E, 54.75N	1179km
St Petersburg-Stockholm	29.25E, 60N	18.75E, 59.25N	596km

Table 2: Details of the routes selected for analysis in the Baltic Sea region.

The details of the routes, including the latitude and longitude point of each destination, and the total distance between the routes can be seen in Table 2

Information about the True Wind Speed (TWS) and True Wind Direction (TWD) was collected along both routes using ERA-Interim weather data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), and this has been presented as a wind rose plot for each leg (Figures 3 and 4). Wind rose plots are polar plots displaying both wind speed and direction. The radial direction represents the TWD and the colours represent the TWS. A TWD of 90 degrees represents a wind blowing from west to east, or a westerly wind. The wind speed is binned according to wind strength. The thickness of each colour indicates the frequency that the wind speed occurs.

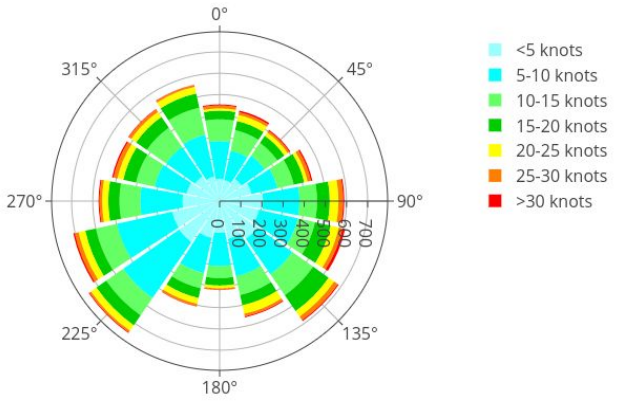

Figure 3: Wind rose plot for the route between Lulea and Gdansk.

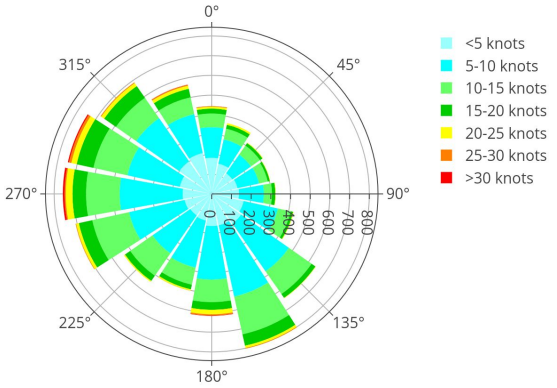

Figure 4: Wind rose plot for the route between St. Petersburg and Stockholm.

From the wind rose plots, it can be seen that the wind conditions for both routes are light and variable. The TWS experienced on the North-South route between Lulea and Gdansk is mainly between 0 and 15 knots. The dominant wind direction on the route is 225 degrees (a north-easterly wind), with a secondary peak at 135 degrees (a north-westerly wind). Along the East-West route between St. Petersburg and Stockholm, the dominant wind direction is easterly, with a secondary peak for north-westerly wind. The maximum TWS for both routes is over 30 knots, but this occurs only a small proportion of the time. In particular, for the East-West route between St. Petersburg and Stockholm, this occurs less than 0.3% of the time.

4. METHODOLOGY

4.1 VESSEL MODEL

To arrive at the achievable fuel savings of the considered wind-assisted ship sailing along a desired route, it is first necessary to study its performance in terms of aerodynamics, hydrodynamics and total fuel efficiency. Key components of the vessel model are indicated in Figure 5.

The use of wind propulsion systems to transform wind energy into forward thrust may be used in two ways:

- Increase the speed of the ship while maintaining the same engine output the ship would have without wind-assisted propulsion
- Reduce the use of the main engine while maintaining the same service speed the ship would have without wind-assisted propulsion

The latter solution is generally considered the most interesting from an operational perspective, and is adopted for the vessel modelling presented here.

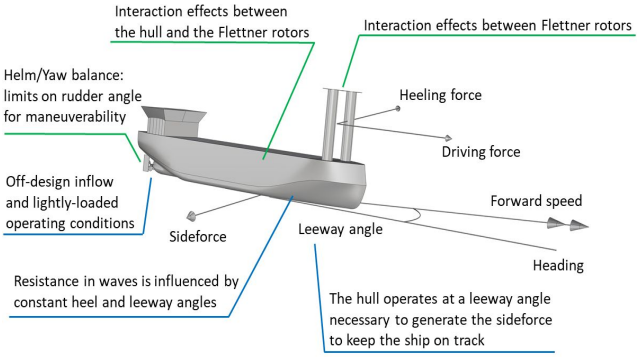

Figure 5: Key components of the vessel model.

The desired wind-generated thrust also introduces undesired aerodynamic forces that need to be balanced by corresponding hydrodynamic reactions. For a chosen vessel service speed, the equilibrium between the aerodynamic and hydrodynamic forces and moments is found with the use of an optimisation routine that selects an equilibrium with the minimum required propeller thrust. The system is solved in four degrees of freedom: surge, sway, roll and yaw. The propeller thrust that the ship must generate to achieve an equilibrium is calculated as the sum of all components in surge:

T(1-t) = Wind assist thrust -
Calm water resistance -
Added resistance in waves -
Rudder induced resistance -
Hull induced resistance -
Hull windage

The results of this procedure are then passed to the fuel consumption model. In fact, as hybrid vessels, the performance of a wind-assist design will depend on the contribution of the wind-propulsion system alongside the efficiency of the main engine, where (in general) an off-design operating point will be detrimental for the specific fuel consumption. Finally, the power required to rotate the Flettner rotors is taken into account as an added load for the ship electric grid.

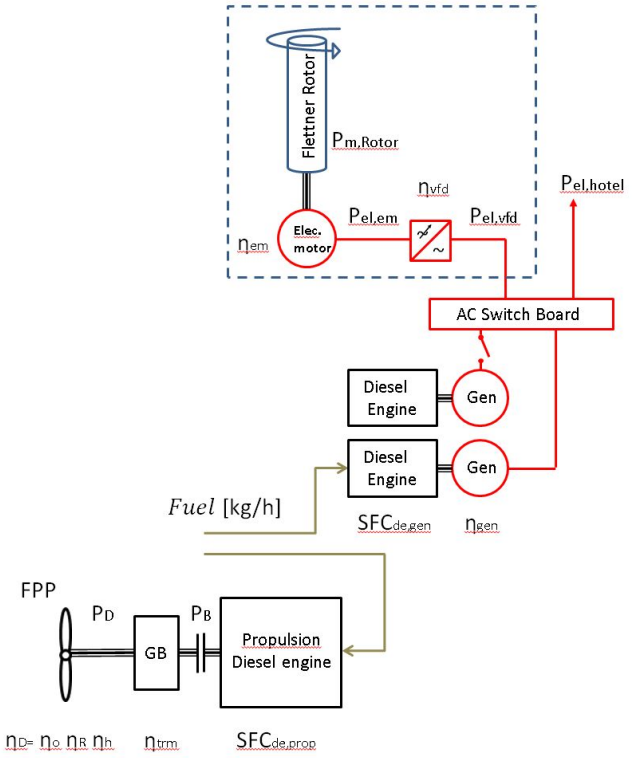

Figure 6: Schematic of the main propulsor and ship electric grid.

The power and propulsion system that is considered in this paper is visualised in Figure 6. It shows a fixed pitch propeller, driven by a main propulsion diesel engine, which delivers brake power P_B. The fuel in [kg/h] required to deliver this brake power depends on the operating point of the engine in terms of P_B and $SFC_{de,prop}$. The top right part of Figure 6, shows the electrical (AC) grid of the vessel. It shows two installed gensets, of which one is online. The online genset feeds the switchboard, from which the electrical consumers are fed. In this case we focus on one particular consumer: the Flettner rotor, which is driven by an electrical motor, which in turn in fed via a variable frequency drive to allow for control of the Flettner rotor rotation speed. Since this drive system requires power it should be taken into account when estimating the potential of the total WASP system to reduce overall fuel consumption.

The solution of the process here described, that is the fuel consumption in [kg/hr], needs to be determined for all combinations of true wind angles and true wind speeds that the ship might encounter en route. This is the backbone idea behind the vessel modeling.

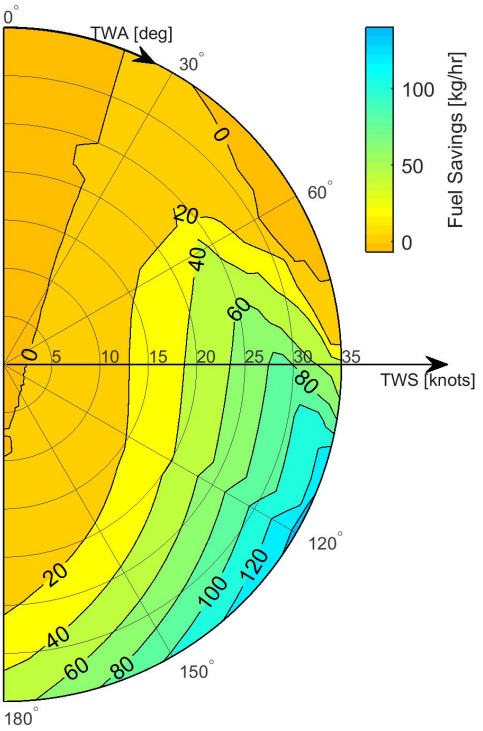

Figure 7: Fuel savings polar for single Flettner case

Results for vessel modelling are typically presented in a polar plot, in which variables describing vessel performance are plotted for wind speeds and wind directions. The axes are defined relative to the ship heading: the ship is sailing directly into the wind at TWA = 0 deg, and with wind astern for TWA=180 deg. In the polar diagram presented in Figure 7, the fuel savings were computed by taking the difference between the Single Flettner case and the reference case.

In the remainder of this section, a description of the modeling for each aspect of the vessel modelling is provided. Given the scope of work presented, the level of detail is necessarily brief. References are provided to relevant technical publications.

4.1 a) Aerodynamics

From an aerodynamic perspective, to achieve a reliable performance prediction, it is necessary to consider the selected wind-propulsion system in its real sailing conditions. This means that scale effects, interaction effects occurring between the several wind propulsors installed on the ship's deck, as well as the interaction effects occurring between the propulsors and the ship itself, need to be taken into account. The aerodynamic interaction effects entail a change in wind speed and wind angle of incidence that will generate a change in the lift and drag forces generated by all the wind propulsors employed and, for these reasons, cannot be neglected.

In this work, the Flettner rotor is the wind-propulsion system chosen to be installed on the analysed vessel. The Flettner rotor is a cylinder spun by an

electric engine and it generates a lift force due to the Magnus effect. Nowadays, Flettner rotors are becoming increasingly popular as, in change of a minimal absorbed power, they generate a significant amount of thrust with a reduced "sail" area.

The aerodynamic data used in the current study are the results of dedicated experiments carried out at Politecnico di Milano wind tunnel. In particular, two separate series of tests on Flettner rotors were conducted. The first test series dealt with a large-scale rotating cylinder, in which the objective was to measure the aerodynamic forces for different Reynolds numbers in order to study possible scale effects (Bordogna et al., 2018). The highest Reynolds number reached was $Re=10^6$, that is roughly between one and four times lower the actual Reynolds numbers experienced by a full-scale Flettner rotor in typical sailing conditions. The CL and CD data relative to the results obtained at $Re=10^6$ were used throughout this work as baseline.

The second series of tests dealt with two smaller Flettner rotors, set at several different combinations of distances and angles with respect to the incoming wind. These experiments aimed at measuring the effects of the aerodynamic interaction on the lift and drag forces generated by each Flettner rotor. The results of such experiments were used in the current work to modify the lift and drag obtained in the first test series, given the relative distance, position and spinning velocity of each installed Flettner rotor.

Lastly, the effects of the interaction between the ship's hull and the Flettner rotors, and the windage of the ship were calculated according to (Walree, 1988) and (Fujiwara et al., 2005) respectively.

4.1 b) Hydromechanics

Fitting a commercial vessel with an auxiliary wind propulsor will introduce a set of forces and moments besides the desired aerodynamic thrust. The ship will adopt a steady heel and leeway angle -- the sailing condition -- to arrive at an equilibrium for each operating condition. The leeway angle is the angle-of-attack for the hull, necessary to generate a hydrodynamic sideforce in opposition to transverse component of the aerodynamic force. Further, the distribution of the hydrodynamic sideforce along the hull will result in a net yawing moment. At last, the vertical separation between the sideforce components will create a heeling moment.

The performance of a wind-assist concept will depend on the contribution of the wind propulsor to the required thrust, alongside the efficiency of the sailing ship. The underwater ship of a conventional freighter is ill-suited for efficient sideforce production, and significant induced resistance is to be expected. Of course, the introduction of a sail-plan will only benefit the vessel if the net thrust gained outweighs any loss in efficiency or increase in resistance. The course-keeping ability of a ship represents a key modeling and design challenge for wind-assist vessels. A conventional cargo vessel hull—with an undersized rudder as the only appendage—is essentially unfit for sailing. Such a hull will operate with greater leeway angles, and with 'weather helm' as a consequence of this inefficient side-force generation. The rudder can be used to oppose this destabilising moment, with an associated resistance penalty. Most of all, the vessel must be able to maneuver. This is a fundamental operational constraint that must be present in any vessel modeling. The sailing efficiency and course-keeping are determined with a Reynolds-Averaged Navier Stokes computational fluid dynamics (RANS-CFD) tool. The simulation methodology for analysis of wind assisted ships has been validated in (van der Kolk et. al. 2019) and (van der Kolk et. al. 2019).

Hydromechanics for the reference cases (ship operation without wind assistance) follows standard industry practice. The ship resistance curve is determined with the RANS-CFD simulation tool. The contribution of the added resistance in waves is determined with the method of Gerristma-Beukelman (Gerritsma & Beukelman 1972) using sectional hydrodynamic loading. Under the present analysis, it is assumed that the sea state is coupled to the wind direction and strength. The sea state is defined with a Pierson-Moskowitz spectrum for fully developed seas. The spectrum is scaled according to the Beaufort scale for significant wave height, where a maximum value for the wind speed is prescribed (20 m/s) to avoid unrealistic fully developed storm sea.

4.1 c) Fuel consumption model

To make a fair comparison of total fuel consumption between the baseline ship and the WASP designs (schematically visualised in Figure 6), the following approach was taken: First of all, a realistic baseline propulsion system design was made, resulting in a maximum ship speed of 11 knots at maximum engine speed and 85% MCR For both ships a fixed pitch propeller was assumed. Subsequently, for both ships, for a fixed ship speed of 10 kts (adopted for the remainder of the analysis), the required propeller thrust for each combination of true wind speed and direction was determined, taking into account the contribution from resistance penalties incurred as a result of the sailing operating condition of the ship.

For each combination of wind speed and angle, the required propeller speed and power is determined, using a Wageningen B propeller open water diagram, assuming that the increased drift angle of the WASP ship does not influence the propeller behaviour significantly via the disturbed wakefield. Based on these results, in combination with a gearbox reduction ratio and transmission losses, the engine operating point per condition is determined, including a "flag" in case the required engine operating point is impossible because it lies outside the engine operating envelope, which can for instance happens in case of strong headwinds. A parametric model of specific fuel consumption (SFC in

kg/kWh) of the propulsion diesel engine (Shi, 2010) is incorporated from which, for each operating condition (given required engine speed and brake engine power), a fuel consumption in kg/h, required for propulsion can be calculated.

For the WASP case, the power required to spin the Flettner rotor, has to be taken into account, since this results in additional electrical load, and therefore into additional fuel consumption. The efficiency train from required mechanical Flettner rotor power to generator fuel consumption contains an electric motor, a variable frequency drive, and a generator set, as shown in Figure 6. Note that the SFC behaviour of the genset is not modelled in detail as is done for the propulsion diesel engine: instead a constant SFC is taken which is typically higher than the SFC of the larger, slower running propulsion diesel engine.

4.2 WEATHER ROUTING

Using the fuel consumption model discussed above, it is possible to obtain the fuel consumption of the vessel, in kg of fuel per hour, for a given wind direction and speed. These results are then passed to the routing algorithm.

The weather routing module is broken down into two components: a Great Circle Route (GCR) simulation and a voyage optimisation simulation. This allows a relatively fast GCR simulation to be performed independently of the computationally intensive voyage optimisation simulation.

The GCR is composed using equations developed in a planar coordinate system by (Chen et al., 2015). This allows the latitude and longitude of multiple waypoints on the GCR to be calculated. These waypoints were obtained for the outward and return routes between Lulea-Gdansk and St Petersburg-Stockholm. For each route, the GCR was split into six waypoints, corresponding to five stages. At each waypoint, the wind speed and direction is found using ERA-Interim data from ECMWF with 0.75X0.75 degrees spatial resolution. From this, the angle between the wind and the vessel heading is found. These values are used in conjunction with the fuel consumption modelling, to calculate the fuel consumed between adjacent waypoints. Subsequently, the fuel consumed on the entire route can be found.

The GCR routing methodology presented here assumes that the vessel perfectly follows the GCR, requiring a constant bearing change. In reality, this may not be possible, and the vessel may approximate the GCR by following several rhumb lines (lines of constant bearing). This would produce a discrepancy in the wind direction experienced by the vessel. However, due to the small distances considered in this study, these discrepancies would be minimal and the GCR routing will provide a good approximation.

Voyage optimisation incorporates the weather conditions experienced by the vessel on the route to reduce the total fuel consumed on the voyage. This involves altering the route of the vessel, away from the GCR, to search for advantageous weather conditions. Dijkstra's optimisation algorithm (Dijkstra, 1959) is commonly implemented to minimise the fuel consumption along the route, and the algorithm is a grid-based algorithm. An associated cost of travelling between adjacent grid waypoints is set according to the fuel consumed when traveling between the two points. Based on these associated costs, the optimisation algorithm searches all possible pathways along the grid and determines a route with minimal fuel consumption.

This study solely focuses on simulations of the wind-assisted vessel on the GCR, with voyage optimisation subject to future research. The outward and return journeys of both routes were simulated for the 5,150 DWT general cargo vessel travelling at a speed of 10 knots. The routes were simulated for the vessel with no wind propulsion installed, for the vessel with one Flettner rotor installed and for the vessel with two Flettner rotors installed. Subsequently, the fuel consumption savings from the addition of both one and two rotors was found relative to the vessel with no wind propulsion.

4.3 ECONOMIC ANALYSIS

In order to assess the economic viability of the wind-assist technology in a commercial perspective, the payback period of the project (whose duration is assumed to be the average lifetime of maritime equipments) needs to be assessed assuming a 300 months-period. To do so, the costs over time induced by the WASP project are compared with the costs over time for the reference case.

The payback period is defined through two main cost functions:

- Investment[€] : overall investments needed to buy and install WASP equipment.
- Savings(t)[€/t] : The changes in overall cash flow savings resulting from the installation of the WASP technology, calculated on a monthly basis.

The Savings function is defined as the difference between the total operational costs under a WASP installation scenario and the total operational costs without WASP installation scenario, all other things being equal. After breaking down the operational costs into several sub-cost functions, it is also possible to write down the Savings function as the sum of all these sub-cost function between the two scenarios :

$$\begin{aligned}\text{Savings}(t)[€/t] = {} & \Delta\text{fuel cost}(t) + \\ & \Delta\text{maintenance}(t) + \\ & \Delta\text{revenue}(t) + \\ & \Delta\text{insurance}(t) + \\ & \Delta\text{administration}(t) + \\ & \Delta\text{payroll}(t)\end{aligned}$$

4.3 a) Fuel Savings: Δfuel cost(t)

The change in operating costs due to fuel consumption (WASP technology vs Business as Usual) is the result of the vessel and routing modelling detailed above. The result is a statistical average for fuel savings per month. An operating profile (days at sea per month) of 0.72 is assumed. Finally, p[€/ton] is defined as the price for fuel. For operation in the Baltic Sea region, a designated Emission Control Area, the ship is obliged to purchase 0.1% sulphur grade fuel. The fuel price is a key driver for the economic model and the sensitivity to the value is studied. The fuel cost function now reads:

Δfuel cost(p,t) = p[€/ton] * fuel savings [ton] *
Operating profile [-]

4.3 b) Added maintenance costs: Δ_maintenance(t)

According to NORSEPOWER, the installation of wind-assist technology implies maintenance costs amounting to 2% of the initial investment costs annually. Therefore, the maintenance cost function is as follows:

Δmaintenance(t) = - 2% * Investment * t /12

4.3 c) Revenue variation: Δrevenue(t)

The added weight of the Flettner rotor installation will reduce cargo deadweight by up to 0.9%. Insufficient information was available to compute the impact of this variation in the cost, but in light of the magnitude, it is assumed that this variation is negligible. Similarly, we will not mention the handling costs variation in harbours coming from the deadweight variation.

4.3 d) Insurance and administration costs variation

It is assumed that insurances and administration costs do not vary.

4.3 e) Payroll costs variation

According to NORSEPOWER, there is no need to hire additional crew, meaning that there is no payroll cost variation.

Finally, the sum of all variations considered is written as:

Savings(p,t)[€/t] =Δfuel cost(p,t) + Δmaintenance(t)

The payback period is found by determining the number of months, t, for which the savings function equals the initial investment:

0 = - Investment[€] + Savings(t,p)[€/t]

5. RESULTS & DISCUSSION

5.1 VESSEL MODEL

Before considering the results in terms of fuels savings, it is of interest analysing the polar diagrams of some parameters that are important for the sailing behaviour of the vessel. Significant effects are highlighted for each component of the vessel model.

5.1.a) Aerodynamics

From an aerodynamic perspective, it is interesting to compare the spin ratios of the Flettner rotors (that is the ratio between the tangential velocity of the rotor and the incoming wind speed) to understand the effects of the Flettner rotor aerodynamic interaction on the results.

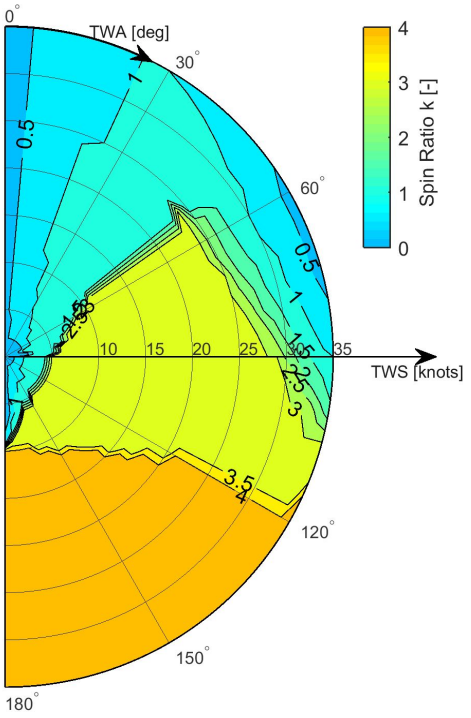

Figure 8: One-Flettner rotor case: spin ratio

The spin ratio, in fact, has a direct influence on the amount of aerodynamic force generated. In Figure 8 the spin ratio for the one-rotor case is depicted, whereas the spin ratio for the two-rotor case is given in Figure 9. In the latter case, the polars are reported both for the port side and the starboard side rotor. Looking at the spin ratio polars, it can be noticed that the two configurations show some similarities but also several differences.

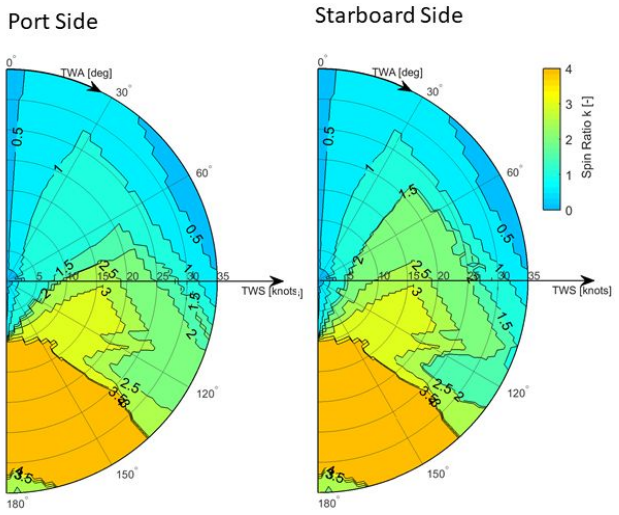

Figure 9: Two-Flettner rotor case: spin ratios

Both designs adopt a low spin ratio when sailing upwind and a larger spin ratio when the wind comes from astern. This is because when sailing at small TWAs is more beneficial to have a high lift/drag ratio, and this occurs at low spin ratios (k≈1). Conversely, at large TWAs, the forward thrust is generated both by the lift and the drag forces. High values of lift and drag occur at large spin ratios. It should be noticed that a plateau for both the lift and the drag force is found at k=4, meaning that a further increase of the spin ratio would only produce a detrimental rise of the power consumption of the Flettner rotors.

Regarding the differences encountered in the two designs, for wind angles 60°<TWA<150°, there is a marked difference between the spin ratios of the one- rotor and the two-rotor design. In this range of wind conditions, in fact, the two Flettner rotors strongly interact with each other, generating (generally) detrimental variations of the incoming flow angles. To compensate for these effects, and to generate an optimum overall thrust, the spin ratios of the port side and starboard side Flettner rotor differ from each other and are (generally) lower with respect to the single-rotor case. The trade-off is that a lower spin ratio means a lower thrust but also less detrimental interaction effects. It should be kept in mind that, in case no aerodynamic interaction effects were modelled, the polars of the port side and starboard side rotor would be the same as the polar of the single-rotor case, meaning that the aerodynamic thrust would have been overestimated.

On the other hand, for wind angles 30°<TWA<60°, the differences in spin ratios between the single and the double rotor design, is caused by an imposed limit on the rudder angle in order to maintain sufficient maneuverability. In this condition, both Flettner rotors of the two-rotor design have to depower (adopt a lower spin ratio) to keep the balance of the ship within the imposed limit for the rudder angle.

5.1 b) Hydromechanics

A survey of the hydromechanic response of the system reveals one key effect: the yaw-balance for the ship. The flow mechanisms responsible for sideforce generation have a destabilising effect on the course keeping ability of the ship. This effect severely limits the operating points of the wind-assist vessel. It is a key design concern.

The physical mechanism responsible for the strong destabilising yawing moment is referred to as the Munk moment. The Munk moment is (in principle) a pure couple that arises as a body encounters an oblique flow. Whereas the yawing moment will develop rapidly, the sideforce production for the hull of a commercial ship is heavily dependant on the higher-order component that is characteristic for low-aspect-ratio lift. The hydromechanic vessel response in the yaw equation is defined by the center of lateral resistance (CLR), a quantity that expresses the distribution of the hydrodynamic sideforce, including the Munk moment. For sailing yachts, these phenomena are experienced as weather helm, a steady rudder angle required to keep a course.

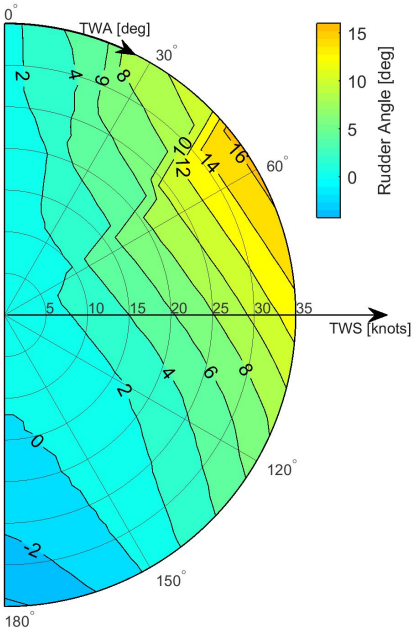

Figure 10: Rudder angle for single-rotor case (no limit imposed)

Commercial ship types, operating without a keel or other specialised appendages designed to mitigate this effect, are essentially unfit to sail. The rudder angle for the single-rotor case is presented in Figure 10 to underscore this point. For upwind sailing conditions at 60° TWA, the necessary rudder angle increases to as much as 16°. The maneuverability of the vessel is clearly impacted for this relatively modest implementation of WASP technology. A limit for the rudder angle has been set to 10°, afterwhich the Flettner rotors will need to depower. This effect is visible in Figures 8 for the single rotor case, where the

contour corresponding to 10° rudder coincides with a reduction in spin ratio. Similarly, the rotors in the Two-Flettner case are never fully engaged for upwind courses, as seen in Figure 9. The effect of this depowering is seen in the required propeller thrust as well (Figure 11). For reference, the heel is less than four degrees for the single Flettner and double Flettner cases.

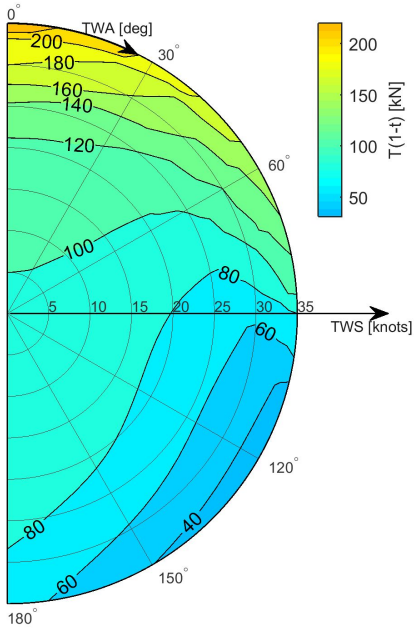

Figure 11: Required propeller thrust

5.1 c) Fuel Consumption Model

Based on the aerodynamic and hydrodynamic force calculation, for each true wind speed and angle, the required propeller force to sail 10 kts can be calculated, both for the reference case and for the WASP case(s). Figure 11 shows this force for the single rotor case. Note that the chosen spin ratio of the Flettner rotor and the restriction on rudder angles has an effect.

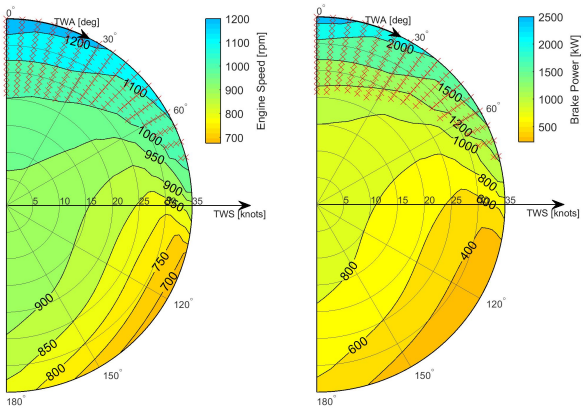

Figure 12 Main engine speed (left) and brake power (right)

Subsequently the propeller speed, engine speed (Figure 12(left)) and brake engine power (Figure 12(right)) that are required to deliver this force can be calculated, based on the open water diagram and the fixed gearbox reduction ratio. However, the propulsion diesel engine can not deliver all combinations of engine speed and power: only combinations that lie inside the engine envelope are possible. Combinations that are not allowed are visualised in Figure 12 by the red x-markers.

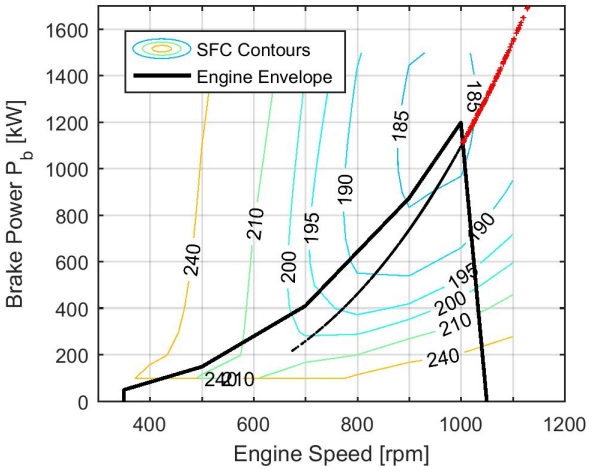

Figure 13 Main engine speed envelope and SFC curves

Their locations can be cross-verified with the engine envelope as shown in Figure 13. These operating conditions correspond to a ship speed reduction due to strong headwinds/seas, which is currently not captured in the routing model. However, for these cases, the reference ship and the wind-assist concepts will be similarly hindered (i.e. the fuel savings will be zero).

Subsequently, for all wind speed and angle combinations, the SFC of the main engine can be determined. To make a fair comparison, additional fuel consumption of the generator due to the power required to spin the Flettner rotor has been calculated and added to the fuel consumption of the main engine. The result of this vessel modeling is expressed as fuel savings compared to the reference case, and has been presented at the beginning of Section 4 (Figure 7). This polar diagram is passed to the routing model.

5.2 WEATHER ROUTING

The Baltic Sea routes were simulated for four departure times per day for the whole year of 2015. The four departure times selected were 00:00:00, 06:00:00, 12:00:00 and 18:00:00, using the weather data obtained from ECMWF. The simulations were performed for the vessel without a Flettner rotor installed, with one Flettner rotor installed and with two Flettner rotors installed.

5.2 a) Lulea - Gdansk

	Lulea - Gdansk		Gdansk - Lulea	
	Fuel savings (%)	Fuel savings (kg)	Fuel savings (%)	Fuel savings (kg)
One rotor	3.67%	373	3.46%	353
Two rotors	7.49%	755	6.96%	703

Table 3: Average fuel savings provided by the installation of a single Flettner and double Flettners per trip, for the outward and return route between Lulea and Gdansk.

The average yearly total fuel savings, in both percentage and kilograms, was calculated for both the Single Flettner and the double Flettner scenarios, using data from the 1,460 simulated voyages from each route. This was done for the outward journey between Lulea and Gdansk, as well as for the return journey from Gdansk to Lulea. The results can be seen in Table 3. Simulations of the Single Flettner scenario produced average fuel savings of 3.67% and 3.46%, whereas simulations of the double Flettners scenario produced average fuel savings of 7.49% and 6.96%. For both journeys, the average fuel savings produced by double Flettners were around double the fuel savings produced by one. Both the outward and the return journey also produced very similar fuel savings when averaged throughout the full year for both the Single Flettner and the double Flettner case.

5.2 b) St Petersburg - Stockholm

	St Petersburg - Stockholm		Stockholm - St Petersburg	
	Fuel savings (%)	Fuel savings (kg)	Fuel savings (%)	Fuel savings (kg)
One rotor	2.78%	141	2.05%	105
Two rotors	6.20%	313	3.79%	194

Table 4: Average fuel savings provided by the installation of a single Flettner and double Flettners per trip for the outward and return route between St Petersburg and Stockholm.

The fuel savings calculations were repeated for the voyage simulations between St Petersburg and Stockholm. The results can be seen in Table 4. Simulations of the Single Flettner scenario produced average fuel savings of 2.78% and 2.05%, whereas the double Flettner scenario produced average fuel savings of 6.20% and 3.79%. Again, the simulation of an additional rotor produced average fuel savings of around double. The journey between St Petersburg and Stockholm also showed higher average fuel savings than the return journey, for both the Single Flettner and the double Flettner case.

The results show that the average fuel savings for the route between Lulea and Gdansk (North-South) are larger than for the route between St Petersburg and Stockholm (East-West), pointing towards the existence of more advantageous weather conditions for wind-assisted vessels along this route. Referring back to the wind rose plots (Figure 3 and Figure 4) in Section 3.3, this result is expected, due to the higher frequency on strong winds on the route between Lulea and Gdansk. The route between Lulea and Gdansk also experiences greater savings than the return route between Gdansk and Lulea. This is again expected, due to the slight presence of a dominant wind from the north easterly and north westerly direction, which is a beneficial wind angle to produce fuel savings from the rotors on the Lulea to Gdansk journey. Similarly, the route between St Petersburg and Stockholm experiences greater savings than the return route between Stockholm and St Petersburg. This is once again expected due to the presence of a dominant easterly wind direction, providing tailwind for the first route and headwind for the second.

These results demonstrates that variations in fuel savings occur between different routes in the Baltic Sea region. However, the N-S and the E-W routes are two contrasting routes in this area, and voyages between ports along similar directions (such as Lulea-Gdansk and Helsinki-Gdansk, which both traverse a N-S direction), may produce similar results. The results also demonstrate that fuel savings correspond well with the wind rose plots for each specific route.

Values for average fuel consumption savings agree with the range of values produced by previous studies on Flettner rotors. However, this range is large, due to the variety of factors that have been shown to affect fuel savings produced by wind-assistance, such as vessel size, vessel speed, route, time period analysed, as well as others. Therefore, care must be taken when making comparisons between specific studies. The closest comparison is discussed by Traut et al. (2014), who analyse the average fuel savings for a 5,500 DWT general cargo vessel, travelling at 8.8 knots from Varberg to Gillingham for the year 2011. (Traut et al., 2014) demonstrate 21% savings for a single Flettner rotor. This value is significantly greater than the fuel savings produced in this study, potentially demonstrating that beneficial weather conditions are experienced on the route between Varberg and Gillingham or showing the significance of the larger Flettner rotor dimensions incorporated in the study by (Traut et al., 2014).

5.2 c) Single Flettner vs. double Flettners

	All Baltic voyages		
	Average fuel saving	90th percentile fuel saving	Maximum fuel saving
One rotor	2.99%	8.22%	34.2%
Two rotors	6.11%	17.8%	89.6%

Table 5: Average fuel savings, 90th percentile fuels savings and maximum fuel savings for both one and two rotors for all combined routes on the Baltic Sea.

The fuel savings from all four journeys were combined to assess the performance of the technology

throughout the Baltic Sea for both the Single Flettner and the double Flettner scenarios. From this, the average fuel saving, 90th percentile fuel saving and maximum fuel saving was calculated for the Baltic Sea. These results can be seen in Table 5 and the distribution of values can be seen in Figure 14 for the double Flettner case. The Single Flettner case shows a similar distribution of results. The average fuel saving for the Single Flettner case and the double Flettner case was 2.99% and 6.11% respectively, with the double Flettner again roughly providing double the fuel savings throughout a full year.

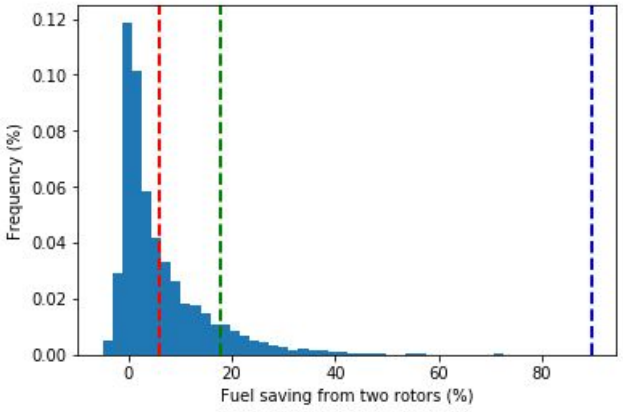

Figure 14: Histogram showing the frequency of fuel savings (in % of fuel saved) from double Flettners for all combined routes on the Baltic Sea. The average (red), 90th percentile (green) and maximum (blue) of the distribution are shown.

The maximum fuel saving, however, shows a marked difference to this pattern, with the double Flettner providing a maximum fuel saving of 89.6%, compared to 34.2% for the Single Flettner case. These two maximum fuel savings were experienced on exactly the same simulation date and route, which saw both very large wind speeds and beneficial wind directions.

It can also be seen from the distribution of fuel savings in Figure 14, that a small proportion of the fuel savings are negative. For these cases, the vessel with rotors installed is consuming more fuel than if there were no rotors installed at all. This is expected, due to the added resistance of the rotors in unfavourable weather conditions.

5.2 d) Monthly variation

Monthly-averaged fuel savings were calculated for all four combined routes, to assess the monthly variation in fuel savings throughout the full year of 2015. The results from the double Flettner case can be seen in Figure 15. Average fuel savings for each month vary, with values ranging between a minimum of 2.06% in June to a maximum of 9.61% in December. The monthly variation in average fuel savings for the Single Flettner scenario is not presented here, but shows a similar distribution of results.

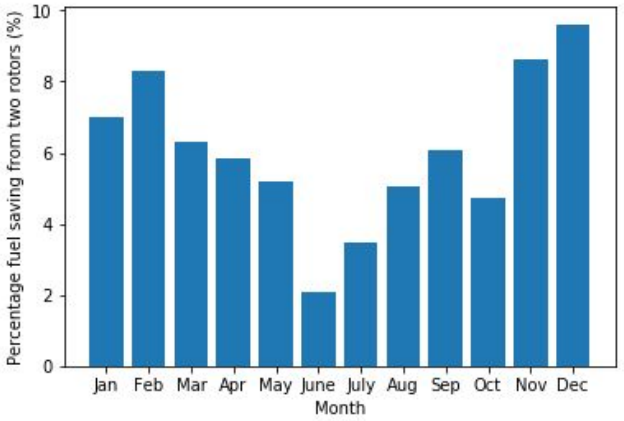

Figure 15: Monthly-averaged fuel savings (in % of fuel saved) obtained from double Flettners for all combined routes on the Baltic Sea.

The results shown in Figure 15 show greater fuel savings in the late autumn and winter months, when winds are stronger, with lower fuel savings in the summer months, especially June and July. However, as these simulations have been conducted for one year only, these conclusions are not statistically valid, and further work is necessary to confirm a relationship between fuel savings and months in the Baltic Sea. However, these initial findings agree with seasonal variations found in other papers for wind-assisted vessels (Smith et al. (2013)).

5.3 ECONOMIC EVALUATION

The price 520€ is highlighted with black dots since this is the current BW0.1S price in Rotterdam. (590USD with 1.14 USD/€ as of 18/01/2019). The variation in price over the last three months was between 500€ and 650€.

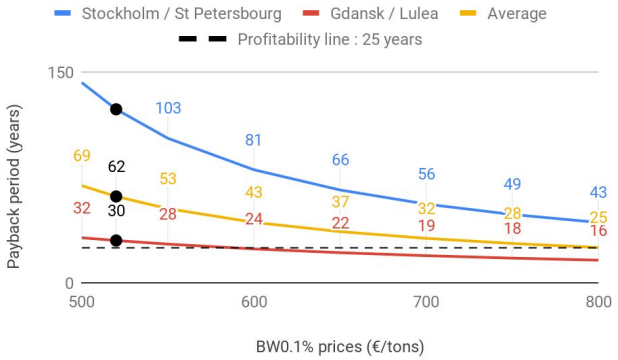

Figure 16: Payback period in Baltic sea under the Single Flettner scenario

The payback period for both cases is presented in Figure 16 and Figure 17 above, with results displayed for Stockholm - St. Petersburg, for Gdansk - Lulea, and as an average for all simulations (indicative for operation in the Baltic region). The installation of WASP technology on a ship operating in the Baltic region will become profitable

(meaning with a payback period of less than the assumed 300 months/ 25 years) once the BW0.1S price rises above 800 € / tons for both the Single and Double Flettner scenarios.

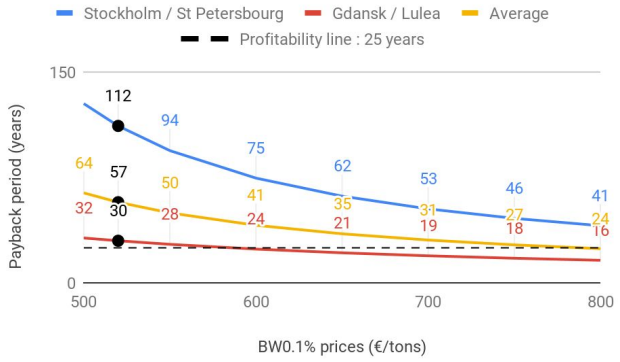

Figure 17: Payback period in Baltic sea under the Double Flettner scenario

The discrepancy in fuel savings between the two routes that was observed in Section 5.2 is evident in the economic performance. A ship operating on the Gdansk - Lulea route becomes profitable when BW0.1S price reaches 586 € / tons, which is within the range of fuel price fluctuations in recent months. The poor savings obtained on the Stockholm - St. Petersburg have a direct consequence for the payback period, which is nearly double the average.

In the definition of the savings function several assumptions were made due to the absence of available information. An assumption was to neglect the 0.9% reduction in deadweight due to the weight of the rotor and rotor foundation,. The change in deadweight may be compensated by the reduced bunkering requirement of wind-assist vessels, where especially for longer voyages, the weight of fuel savings may exceed the rotor weight. As a final observation, the reduced bunkering requirement may lead to financial benefits resulting from a reduced hedging activity against fuel price variations. Further analysis is needed here.

6. CONCLUSIONS

The performance of a wind-assist concept, a 5,150 DWT general cargo vessel, with both one and two Flettner rotors has been assessed using a comprehensive vessel model and routing algorithm on four routes on the Baltic Sea. The average fuel savings for the installation of a Single Flettner is 2.99% and the average fuel savings for the Double Flettner case is 6.11%.

6.1 VESSEL MODELLING

The vessel modelling presented here is the combination of three main modules representing the work of individual authors in each discipline: in aerodynamics, hydromechanics and marine engineering. The description of the vessel modelling has been necessarily brief due to the scope of work presented. A number of design and engineering effects have been highlighted.

From an aerodynamic perspective, the most remarkable result is that the aerodynamic interaction effects occurring between the two installed Flettner rotors decrease the amount of wind-generated thrust that would help reduce the fuel consumption of the ship.

The course-keeping ability of the ship is severely compromised by a destabilizing yaw moment. It is possible to compensate with the rudder to some extent, however the maneuverability of the ship will eventually impacted. In absence of classification society guidelines, a limit of 10 degrees was adopted in the present modelling. This limit for rudder angles is effectively a limit on the aerodynamic thrust, as can be observed in Figure 11. In fact, for the double Flettner case the vessel is obliged to depower both rotors on upwind courses (see Figure 9, for $30°<TWA<60°$), indicating that the ship is overcanvased. The yaw balance of the ship severely limits the operating points for double rotor case. This is a key design concern.

Finally, the engine selection for wind assist cases must be made with care considering the variation of operating point within (or without) the engine envelope, as shown in Figure 13. For a main propulsor arrangement with a fixed pitch propeller, as considered in the present case, a wide envelope is desirable.

6.2 WEATHER ROUTING

The study shows that there is a clear variation in average fuel savings depending on the route traversed in the Baltic Sea, with the highest savings obtained for the route between Lulea and Gdansk. A wide range of savings is also seen for each particular route, with the double Flettner case providing fuel savings as high as 89.6% for one specific simulated voyage, with particularly advantageous weather conditions seen on that date. Initial calculations also demonstrate a variation in fuel savings depending on the month travelled in, with more savings obtained between November and February due to the stronger wind conditions experienced in these months, but further work is needed to confirm the statistical validity of these results. This study, therefore, demonstrates that the fuel savings obtained from a Flettner rotor vary between different routes, and also on the same route over time in the Baltic Sea, which is seen as one of the key challenges to wind-assisted vessels (Nelissen et al., 2016, Rehmatulla et al., 2017).

6.3 ECONOMIC ASSESSMENT

The direct fuel cost savings for operation across the whole Baltic region, with light and variable wind conditions, are not currently sufficient to justify the installation of the Flettner rotors on a 5,150 DWT general cargo vessel operating at 10 knots, when solely incorporating an

operational perspective. Under the current BW0.1S prices, the payback period for a ship operating throughout the Baltic region is 57 years for the double Flettner case and 62 years for the single Flettner case, which is significantly more than the expected 25 year-lifetime of the Flettner rotors. However, breaking the assessment of the technology down into individual routes provides a different perspective. If the vessel were restricted to a North-South route (avoiding the Eastern Baltic), then the investment becomes profitable when BW0.1S price reaches 586 € / ton. This is within the range of fuel oil fuel price fluctuations in recent months. Key variables will also have an impact on these results, such as vessel size, speed and Flettner rotor dimensions.

It is important to note that the inclusion of both regulatory- and market-based drivers will also be key factors when considering the suitability of Flettner rotors. For example, the investment in Flettner rotors will prove increasingly beneficial by the favorable impact that installed wind assist technologies have on the vessel EEDI. Wind-assist technologies can contribute to the EEDI rating of the new-build vessel under the category "Innovative energy efficiency technologies", described in the annex of (IMO, 2013). A discussion of the impact of wind assist available effective power on the EEDI calculation will be included in the next presentation of this model. From a market-based perspective, wind-assist trade can be seen as a promising option for investment in the near term, as the push for transparency in shipping broadens to include more types of supply chains.

Future work on wind-assisted vessels in areas of sea with weather conditions similar to those in the Baltic should focus on the incorporation of technologies and practices that enhance the fuel savings of the vessel. For example, combining the technology with route optimisation could increase the profitability of the vessel, by improving the wind conditions experienced on the route to further increase fuel savings. Speed optimisation could also be employed to produce similar results.

Finally, it being understood that the performance of wind assist depends on favorable prevailing winds along the chosen route, the next presentation of this modeling will include results for a deep-water freighter on a trans-Atlantic route, where the vessel will enjoy favorable prevailing winds. From an operational perspective, this has the potential of increasing fuel savings resulting in a much improved payback period.

6.4 ONGOING WORK

The aerodynamic model that is currently under development will allow to quickly assess several different positions of the Flettner rotors on the ship's deck in order to find the most favourable ones for the specific case analyzed.

The management of flow separation along the bilges of the hull promises to mitigate the strong 'destabilising' yaw moment that is a consequence of lateral force production by commercial vessel hulls. The sailing performance of commercial hull-types fitted with diverse appendage configurations was investigated in a recent towing tank experiment and will be presented in an upcoming publication.

The next iteration of the engine modeling will include an approach for controllable pitch propellers, a propeller type that is designed to accommodate variable operating points and thought to be well suited to wind assist vessels. Finally, the vessel modelling is to be rebuilt to accommodate ship speed as a variable, enabling more elaborate route optimisation.

Future routing work will involve the incorporation of route optimisation and speed optimisation, where it will be possible for the vessel to deviate from the GCR to look for advantageous weather conditions to further reduce fuel consumption. This, along with the inclusion of varying forecasted weather forecast data for weather conditions over time, will be developed into the model for future studies.

Finally, direct contact with the client will allow for a more nuanced economic assessment. In particular, detailed information is needed about the operating profile, the consequences of financial hedging strategies for fuel price, and finally, possible marketing strategies of the client with respect to green supply chains.

6.5 COLLABORATION IN FUTURE WORK

Wind-assisted ship propulsion is a dedicated research theme at the Ship Hydromechanics section of Delft University of Technology. This research program is conducted in close cooperation with partners across the Dutch maritime sector. Relevant research topics encompass a wide range of disciplines, extending beyond physical modelling to include logistics and economics. The further development of this promising technology, and its eventual implementation, will be made possible by these academic, research and industry partners working in concert. The Ship Hydromechanics section is actively pursuing further collaboration in the form of shared publications and shared applications for national and international funding instruments.

7. ACKNOWLEDGEMENTS

The Authors would like to thank Jochem de Jong and Willem Kroon at DAMEN Shipyards, and Tuomas Riski of Norsepower for their assistance with this work.

Part of this research is funded by The Engineering and Physical Sciences Research Council (EPSRC). Additionally, the Authors would like to thank John Broderick, Alice Larkin and Paul Gilbert for their PhD supervision and stimulating discussions on this work. The Authors would also like to thank the Vaderland Fonds and the Bijlboegfonds for their support.

8. REFERENCES

ACCIARO, M, HOFFMAN, P.N., EIDE, M.S. (2013) *The energy efficiency gamp in maritime transport.* Journal of Shipping Ocean Eng. 3(10):1-10, 2013.

BARAI, Z., LONGVA, T. (2011). Estimated CO2 Emissions Reduction From Introduction of Mandatory Technical and Operational Energy Efficiency Measures for Ships. IMO MEPC 63/INF 2, 2011.

BORDOGNA, G., MUGGIASCA, S., GIAPPINO, S., BELLOLI., M., KEUNING, J.A., HUIJSMANS, R.H.M., VAN 'T VEER, R. (2018) *Experiments on a Flettner rotor at high Reynolds numbers.* Manuscript submitted for publication

BOWS-LARKIN, A., MANDER, S., GILBERT, P., TRAUT, M., WALSH, C. and ANDERSON, K. (2014) *High Seas, High Stakes.* High Seas Final Report. Tyndall Centre for Climate Change Research

BUHAUG, Ø., CORBETT, J.J., ENDRESEN, Ø., EYRING, V., FABER, J., HANAYAMA, S., LEE, D.S., LEE, D., LINDSTAD, H., MARKOWSKA, A.Z., MJELDE, A., NELISSEN, D., NILSEN, J., PÅLSSON, C., WINEBRAKE, J.J., WU, W. and YOSHIDA, K. *Second IMO GHG Study* (2009), International Maritime Organization (IMO) London, UK, April 2009

CHEN, C., HSIEH, T., HSU, T. (2015) *A novel approach to solve the great circle track based on rotation transformation.* Journal of Marine Science and Technology. 23 13-20 DOI 10.6119/JMST-013-1212-1

DIJKSTRA, E. (1959) *A note on two problems in connection with graphs.* Numerische Mathematik, 1(1) 269-271 DOI 10.1007/bf01386390

EGGERS, R. (2016) *Operational Performance of Wind Assisted Ships,"* 10th Symposium on High- Performance Marine Vehicles (HIPER), Cortona, Italy, 2016.

FABER, J., MARKOWSKA, A., NELISSEN, D., DAVIDSON, M.,EYRING, V., CIONNI, I., ET AL (2009) *Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport*, CE Delft. 2009.

FUJIWARA, T., HEARN, G., KITAMURA, F., UENO, M.,MINAMI,Y. (2005). *Stead sailing performance of a hybrid-sail assisted bulk carrier*. Journal of Marine Science and Technology, pp. 131-146, 2005.

FUJIWARA, T., UENO, M. and IKEDA, Y. (2005) *A new estimation method of wind forces and moments acting on ships on the basis of physical component models.* Journal JASNOE, Vol. 2

GERRITSMA, J., BEUKELMAN, W. (1972) *"Analysis of the Resistance Increase in Waves of a Fast Cargo Ship".* International Shipbuilding Progress Vol. 19 Issue 217.

GOOGLE MAPS. (2019) *Google Maps.* [online] Available at: https://www.google.com/maps/d/embed?mid=15uIgdviES-EURVyK11fkCThF8hwG1-ac

IMO, 2015 *EEDI Database – Review of Status of Technological Development – Note by the Secretariat*. IMO MEPC 68/INF.13, 2015.

KANG, J. and HUSTVEDT, G. (2014) *Building Trust Between Consumers and Corporations: The Role of Consumer Perceptions of Transparency and Social Responsibility.* Journal of Business Ethics 125 (2):1-13, 2014.

LITTLER, J. *"What's wrong with ethical consumption?"* In: Lewis, T and Potter, E (Eds.), Ethical Consumption: A Critical Introduction. (pp. 27-39). Routledge. (2011).

MATSUMOTO, N., INOUE, M., SUDO, M. (1982). *2nd International Conference on Stability of Ships and Ocean Vehicles,* STAB '82, Tokyo, pp 451–464

MOL, A., (2013) *Transparency and value chain sustainability.* Journal of Cleaner Production. 107. Nov. 12 2013

NAAIJEN, P., SHI, W. and KHERIAN, J. (2010) *Assessing the fuel savings by using auxiliary wind propulsion from traction kites.* RINA, Royal Institution of Naval Architects - Ship Design and Operation for Environmental Sustainability - Papers. 27-37.

NELISSEN, D., TRAUT, M., KÖHLER, J., MAO, W., FABER, J., and AHDOUR, S., (2016) *Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships.* DOI 10.2834/68747

NIELSON SURVEY www.nielsen.com, Oct 10, 2015

PULIZZI, J. (2012) *The Rise of Storytelling as the New Marketing.* Publishing Research Quarterly 28(2), 2012

REHMATULLA, N., PARKER, S., SMITH, T. and STULGIS, V. (2017) *Wind technologies: Opportunities and barriers to a low carbon shipping industry.* Marine Policy 75 217-226, DOI 10.1016/j.marpol.2015.12.021

SAMITAS, A. and TSAKALOS, I. (2010) *International Journal of Financial Markets and Derivatives.* Vol. 1, issue 2, 196-212, 2010

SHIP & BUNKER. (2019 *Ship & Bunker* [online] Available at: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#ULSFO

SMITH, T, NEWTON, P, WINN, G, GRECH LA ROSA, A. (2013) *"Analysis techniques for evaluating the fuel savings associated with wind assistance.* Low Carbon Shipping Conference, London 2013.

STRATIOTIS, E. (2015) *Fuel costs in ocean shipping.* http://www.morethanshipping.com, (Accessed 22nd January 2018)

TRAUT, M., GILBERT, P., WALSH, C., BOWS, A., FILIPPONE, A., STANSBY, P. and WOOD, R. (2014) *Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes.* Applied Energy, 113 362-372, DOI 10.1016/j.apenergy.2013.07.026

TRAUT, M., LARKIN, A., ANDERSON, K., MCGLADE, C., SHARMINA, M. and SMITH, T. (2018) *CO2 abatement goals for international shipping.* Climate Policy 0(0) 1-10 DOI 10.1080/14693062.2018.1461059

VAN DER KOLK, N.J., AKKERMAN, I., KEUNING, J.A., HUIJSMANS, R.H.M. (2019) *"Part 1: Experimental Validation of a RANS-CFD Methodology for the Hydrodynamics of Wind-Assisted Ships Operating at Leeway Angles"* (2019) Ocean Engineering. Accepted for publication.

VAN DER KOLK, N.J., AKKERMAN, I., KEUNING, J.A., HUIJSMANS, R.H.M. (2019) *"Part 2: Simulation Methodology and Numerical Uncertainty for RANS-CFD for the Hydrodynamics of Wind-Assisted Ships Operating at Leeway Angles".* (2019) Manuscript submitted for publication

VAN WALREE, F. and WILLEMSEN, E. (1988) *Wind loads on offshore structures.* BOSS-88 Conference, Trondheim 1988

WEI, S., GRIMMELIUS, H.T. and STAPERSMA, D. (2010) *Analysis of ship propulsion system behaviour and the impact on fuel consumption*. International Shipbuilding Progress 57 (2010) 35–64 35, DOI 10.3233/ISP-2010-0062

WOODSIDE, A.G., SOOD, S. and MILLER, K. (2008) *When consumers and brands talk: Storytelling theory and research in psychology and marketing.* Wiley Periodicals, 2008