Reduced environmental impact of marine transport through speed reduction and wind assisted propulsion

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ABSTRACT

To achieve IMO's goal of a 50% reduction of GHG emission by 2050 (compared to the 2008 levels), shipping must not only work towards an optimization of each ship and its components but aim for an optimization of the complete marine transport system, including fleet planning, harbour logistics, route planning, speed profiles, weather routing and ship design. ShipCLEAN, a newly developed model, introduces a coupling of a marine transport economics model to a sophisticated ship energy systems model – it provides a leap towards a holistic optimization of marine transport systems. This paper presents how the model is applied to propose a reduction in fuel consumption and environmental impact by speed reduction of a container ship on a Pacific Ocean trade and the implementation of wind assisted propulsion on a MR Tanker on a North Atlantic trade. The main conclusions show that an increase of the fuel price, for example by applying a bunker levy, will lead to considerable, economically motivated speed reductions in liner traffic. The case study sowed possible yearly fuel savings of almost 21 300 t if the fuel price would be increased from 300 to 1000 USD/t. Accordingly, higher fuel prices can motivate the installation of wind assisted propulsion, which potentially saves up to 500 t of fuel per year for the investigated MR Tanker on a transatlantic route.

1. Introduction

Shipping today accounts for 90% of all freight transport. Forecasts of the world's transportation needs in 2050 show that it will double the current level. At the same time, shipping must become more energy-efficient and before 2050 reduce its contribution to emission of greenhouse gases to 50% of the level in 2008 (IMO, 2018). A first, and crucial step towards reducing the fuel consumption of ships is to be able to accurately predict the consumption of existing ships as well as the positive impact on reduction of fuel consumption due to (i) operational or retrofitting measures and (ii) design changes. To achieve this, each part and the interaction of all parts in a ship's energy system must be understood. A schematic of the complexity of a ship's energy system and the interaction of all parts as well as the environmental influences is shown in Fig. 1. In this study a novel model, "ShipCLEAN", a coupled model including ship performance prediction and maritime transport logistics, is introduced and applied to two case studies. The main objectives of the study are to demonstrate how the ShipCLEAN model can be used to minimise the fuel consumption without compromising with the logistics planning, and to demonstrate how the implementation of energy saving measures can be economically motivated. Two case studies are presented. Firstly, in an example of a container carrier on a Pacific Ocean route, it is shown how higher fuel prices will economically motivate lower ships speeds and hence lower fuel consumption. Secondly, in an example

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| Nomenclature		P_D	Power delivered, [kW]
		Q	Capacity, [t, TEU]
B	Breadth, [m]	R	Freight rate, [USD/t, USD/TEU]
C	Total costs, [USD]	T	Draft, [m]
DOF	Degrees of freedom, [–]	TWA	True wind angle, [deg]
FC	Fuel consumption, [t, t/day]	TWS	True wind speed, [m/s, kn]
Fn	Froude number, [–]	u	Load factor, [–]
H_s	Significant wave height, [m]	u_A	Wind speed (with boundary layer effects)
I	Income, [USD]	v_W	Free wind speed, [m/s]
k	Shape parameter (Weibull distribution), [–]	X	Other operation costs (OPEX), [USD/day]
L_{oa}	Length over all, [m]	λ	Scale parameter (Weibull distribution), [–]
L_{pp}	Length between perpendiculars, [m]	μ	Mean value, [–]
p	Fuel price, [USD/t]	σ	Standard deviation, [–]
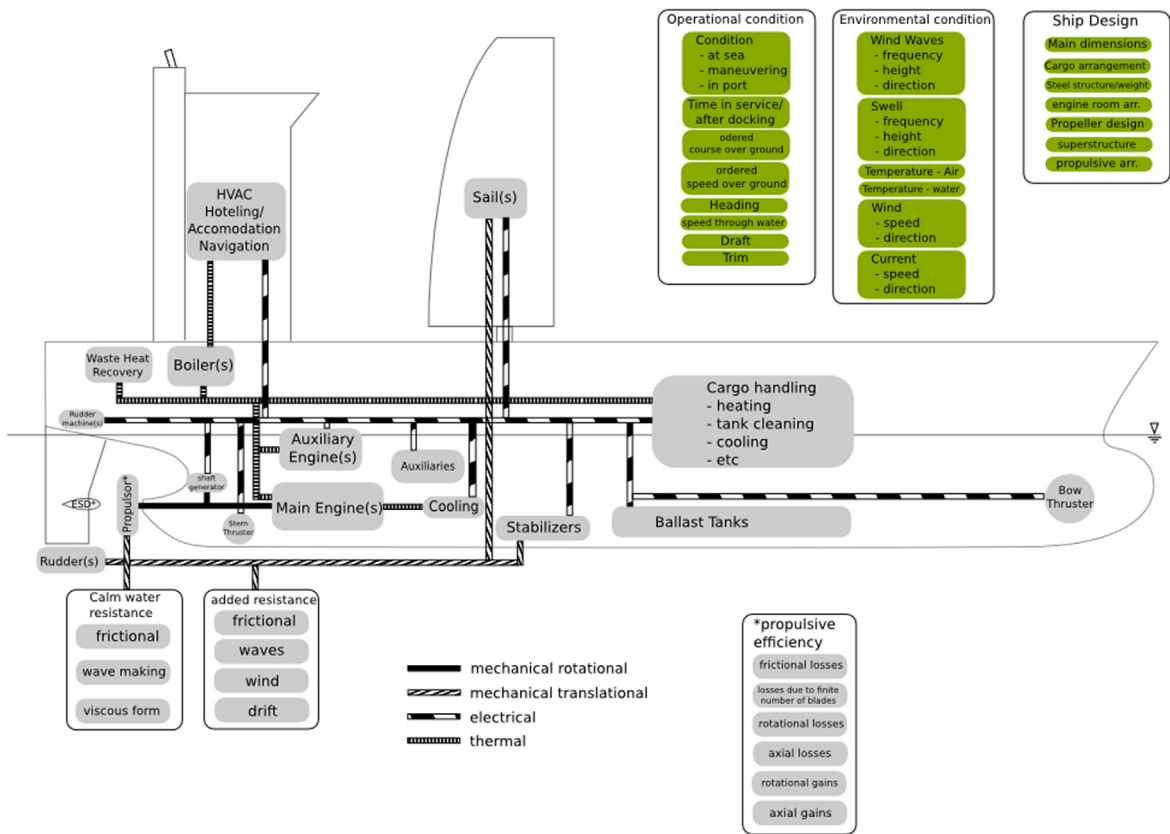
Fig. 1. Overview of system components and connections within the ship's energy system model presented in (Tillig et al., 2017; Tillig and Ringsberg, 2019).

with a MR Tanker on an Atlantic Ocean route, it is studied how the installation of wind assisted propulsion can be economically motivated and considerably lower the fuel consumption. Apart from the results showing how higher fuel prices motivate lower ship speeds and investments in alternative propulsion, this study introduces a novel approach to evaluate the fuel saving potentials by performing Monte Carlo simulations using statistical weather conditions, resulting in an accurate long-term prediction, including the expected variation of the fuel savings.

In recent years numerous models to predict the fuel consumption of ships in realistic operational have been developed. These models can be divided into two groups, (i) white box models which physically model the ship's energy system (see e.g. Calleya, 2014; Lu et al., 2015; Tillig et al., 2017; Tillig and Ringsberg, 2019; Mermeris et al., 2011), and (ii) data-driven or machine learning models which are trained by full scale measurement data (see e.g. Aldous, 2015; Bialystocki and Konovessis, 2016). The latter group is made possible by the mandatory data collection for estimation of the EEOI (IMO, 2018). After a learning period, data driven models can accurately predict the behaviour and fuel consumption of existing ships (Aldous, 2015). They can be very useful for routing and

voyage planning purposes (Bialystocki and Konovessis, 2016; Wang, 2018) as well as for strategic maintenance such as hull and propeller cleaning (Vinther Hansen, 2011). While the above-mentioned measures are crucial to maximize the fuel efficiency of existing ships, shipping will not achieve the IMO goals while limiting itself to optimizing the maintenance and operation of existing ships. To cut the emissions of shipping by the targeted 50%, drastic measures must be taken in the design, operation and propulsion of ships. For this purpose, a ship energy systems model must be capable of predicting the performance of generic ships prior to the actual design phase or retrofitting of existing ships with alternative propulsions systems. This is a task that can only be achieved with white box models.

A wide range of white box models is presented in the literature, but most of them focus on special parts of ships. As an example, in (Mermeris et al., 2011) the focus is on modelling the hotel and auxiliary loads and their dynamic behaviour on the environmental conditions while the propulsive power is modelled either with time consuming CFD computations or by a single empirical method without control of uncertainties. In (Calleya, 2014) the whole energy system of ships is modelled; however, the model is based on some example ships and only small changes to the ships can be applied. Other models are presented that focus on mimicking one ship, so called virtual twins (van Os, 2018). Virtual twins are set up to predict the performance and aging of ships with very high accuracy. However, none of the above-mentioned models can predict the fuel consumption of a generic ship, with very limited input data (main dimensions) with a short lead time, i.e. without the use of model tests or CFD computations. Further on, most performance prediction models only consider 1 degree of freedom (1 DOF), the resistance and thrust (surge). Nevertheless, recently approaches towards 4 DOF models were presented in (van der Kolk et al., January 2019; Viola et al., 2015) for wind-assisted propelled ships. These studies show that 4 DOF models are crucial to accurately predict the savings from wind-assisted propulsion. However, both models lack the ability to accurately predict the fuel consumption of generic ships. Further on the model in (Viola et al., 2015) relies on CFD computations to estimate the sail forces, which results in long lead times and special knowledge to use the model.

To fill the gap of a fast and easy to use model that can accurately predict the fuel consumption of ships with and without wind-assisted propulsion, while requiring only the main dimensions as input data, the authors of this study developed the generic ship energy systems model (Tillig et al., 2017; Tillig and Ringsberg, 2019). The focus in the development of the model was the generic applicability but also the reduction of uncertainties by combining several empirical methods with numerical hull and propeller series (Tillig et al., 2018).

In parallel to the development of performance prediction models, economic models to balance a ship's or a fleet's economic performance and environmental impact through speed optimization are developed (Psaraftis, 2019). However, such models rely on very simplistic formulations of the fuel consumption. In this study a unique approach towards coupling a fast and generic ship performance model (Tillig et al., 2017; Tillig and Ringsberg, 2019) with an economic model (Psaraftis, 2019) is presented. The resulting model, "ShipCLEAN" provides the opportunity to perform optimisations of both, a ship's or fleet's logistics and the ship design including wind assisted propulsion.

This article is divided into three main parts. In Section 2, the ShipCLEAN model is introduced and a validation using full-scale and model-scale measurements is presented. Section 3 discusses the representation and modelling of environmental conditions (wind, current, waves and water temperature) in ShipCLEAN. The results from several realistic case studies are presented in Section 4 including a discussion of sources of uncertainties in the simulations. The conclusions of this study are presented in Section 5.
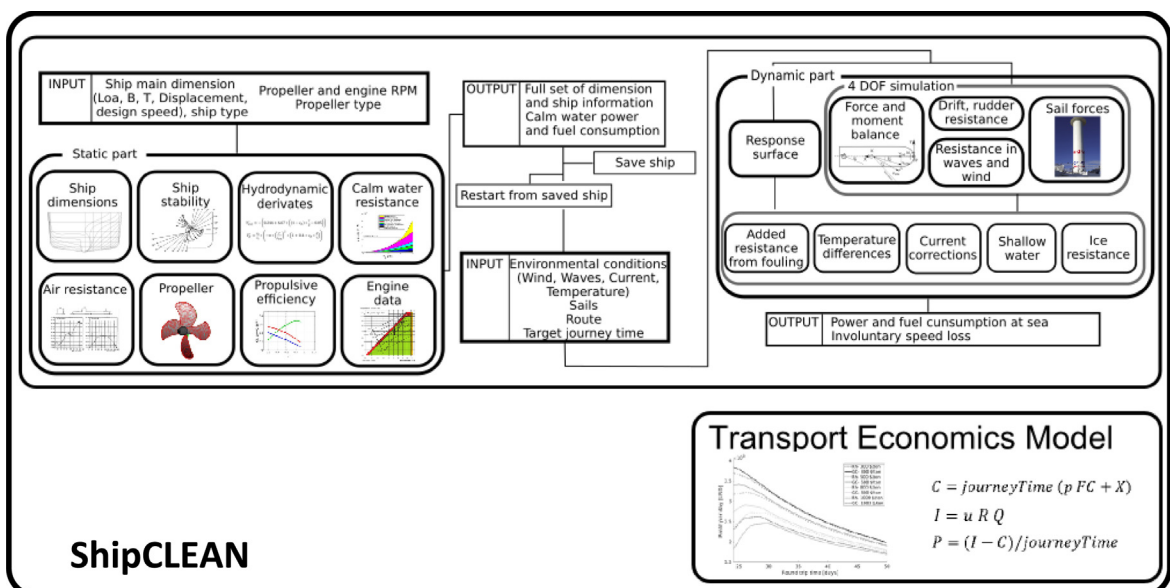

Fig. 2. A schematic overview of the ShipCLEAN model.

2. Model description

The ShipCLEAN model is an integration of two main simulation models, a generic ship energy systems model to predict the fuel consumption under operational conditions with very limited required input of the ship's characteristics, and a transport economics model used to estimate costs and income of the journey. An overview of the complete model is given in Fig. 2. Even though the models do not have optimization routines included, the component-based design provides the opportunity for component or system optimization, as it is done for the journey time in the container vessel case study.

The unique combination of a generic operational power prediction and an economic model provides the possibility to investigate alternatives in transport logistics, fleet sizes, ship dimensions and ship propulsion concepts at a very early stage of a project, i.e. as soon as the transport task is known. It can be used to project newbuilding, analyse a retrofitting, and for decision making when existing ships are to be used on a new trade. Thus, the model is targeted at designer/project teams interested in new buildings and new trades, and ship operators that want to improve the utilization of their ships.

2.1. Generic ship energy systems model

The generic ship energy systems model aims to provide reliable fuel consumption prediction for conventional ships at sea with very limited required input parameters and including wind assisted propulsion. The model is a pure white box model implemented using Matlab (Mathworks, 2019), where each component of the ship's energy system is represented by a function. An overview of the model is shown in Fig. 2. The model can be divided into two main parts: (i) a static part for calm water power prediction based on empirical methods and standard propeller and hull series as well as the estimation of all required ship dimensions and properties using empirical formulas, and (ii) a dynamic, 4 DOF, part for the analysis of the required power under realistic operational conditions, including effects from wind, waves, current, temperature differences, fouling, shallow water and wind-assisted propulsion (if applied).

The static part is described in detail in (Tillig et al., 2017), with the expected accuracy discussed in (Tillig et al., 2018). The calm water resistance prediction is based on two empirical methods for the residual resistance coefficient at design speed (Tillig et al., 2017): a numerical standard hull series for the wetted surface and generic curves of the residual resistance coefficient over the ship's speeds. The latter are different for each ship type and capture the bulb effect of ships with large bulbous bows, e.g. container ships. Additionally, a correction of the wetted surface and the residual resistance coefficient due to off-design loading conditions is applied. This correction is based on the numerical standard hull series for the wetted surface as well as the Hollenbach empirical method (Hollenbach, 1998) and model test results for the residual resistance coefficient. The propulsive coefficients are based on empirical methods for the wake and hull efficiency as well as a numerical standard propeller series for the open water efficiency (Tillig et al., 2017).

In (Tillig and Ringsberg, 2019) the dynamic part is presented in detail; it includes added resistance from waves, wind and fouling (Tillig et al., 2017; Tillig and Ringsberg, 2019; Tillig et al., 2018) as well as a correction of the ship speed, true wind angle and true wind speed due to ocean currents. The added resistance in waves is based on two empirical methods (Tillig and Ringsberg, 2019; Tillig et al., 2018) and the wind resistance is estimated using the wind resistance coefficients presented in (Blendermann, 1994). It is shown in (Tillig and Ringsberg, 2019; Viola et al., 2015) that it is crucial to include the added resistance due to both the drift and the rudder angle in the analysis of wind-assisted ships. This is also especially important for ships with high windage area, such as PCTC or container ships. Thus, a 4 DOF analysis is necessary for those ships. During a 4 DOF analysis, the equilibrium of all forces and moments considering surge, drift, yaw, and heel is found. Additionally, the rudder angle is used as a variable to compensate yaw moments in the system. This results in a more accurate prediction of the power consumption since all external forces and moments (e.g. from the sails) are considered and compensated for by applying drift and rudder angle. For a wind assisted ship, there are scenarios when the side force and yaw moment from the sails cannot be compensated by the rudder and by drift of the hull, or the resulting added resistance from drift is larger than the thrust force of the sails. In those cases, the sails are "reefed" which for a Flettner rotor, for example, implies that its rpm is reduced. ShipCLEAN iteratively reefs the sails creating the largest yaw moment or side force, dependent on which one causes the problem, to find the condition with the optimal thrust force from the sails.

A 4 DOF simulation takes about 8 s per waypoint on an 8 core 3.2 GHz desktop computer. Since large number of waypoints must be computed during route optimizations or statistical analyses, as done in this study, this computation time per waypoint quickly leads to impractical simulation times. Thus, an interpolation routine and predefined computations have been developed. A grid of combinations of wind speed, wind angle, wave height and wave angles are pre-computed using the 4 DOF method; this is used to build up a gridded interpolator available in the Matlab software (Mathworks, 2019). In the current study, the grid was further simplified since the wave height and angle were assumed to be directly coupled to the wind speed and angle. A grid of 18 wind speeds and 18 wind angles is used in the study, for which the computation time was around 2 h.

In the case studies in Section 4, Monte Carlo simulations with statistical weather are performed to evaluate the long-term performance of a container ship and a tanker with Flettner rotors. The interpolation routine in these Monte Carlo simulations could not be timed individually, but a simulation of all 700 000 points of the 10 000 runs for the Pacific Ocean route took about 60 s. During numerical tests, the difference between the direct simulation (8 s per waypoint) and interpolated propulsion power (60 s Monte Carlo simulations) was less than 0.1%.

2.2. Transport economics

The transport economics part of ShipCLEAN has been developed by the Technical University of Denmark and it is described in detail in (Psaraftis, 2019). It is based on a cost-income analysis of marine transport. The costs can be divided into fuel costs and miscellaneous other operating costs (OPEX, X [USD/day]). The fuel costs are naturally coupled to the fuel consumption (FC, [t/day]) and the fuel price (p, [USD/t]), while the other costs are proportional to the journey time. Total costs (C, [USD]) are estimated by:

$$C = journeyTime(pFC + X) \qquad (1)$$

The income (I, [USD]) is related to the load factor, u, i.e. the percentage of the cargo capacity used, the capacity, Q, and the freight rate, R, and can be estimated by:

$$I = uRQ \qquad (2)$$

The result of the model is a per day profit (P):

$$P = (I - C)/journeyTime \qquad (3)$$

This per day profit can be used to optimize the ship speed, route, or utilization of the ship.

2.3. Validation of the power prediction

In (Viola et al., 2015) the expected uncertainties in the prediction of the power and fuel consumption of generic ships using "ShipCLEAN" are identified and quantified. Results in (Viola et al., 2015) show that the power at sea and in calm water is expected to be within 10% of the power measured in model tests. Thus, a deviation of 10% is defined as allowable for this validation study. Model test results are available for both case study ships introduced in Section 4. A comparison of the predicted propulsion power (P_D) from ShipCLEAN and from model tests is shown in Fig. 3, with the design speeds marked with a dot. Input data to the prediction using ShipCLEAN was limited to the information given in Table 1 (Container ship) and Table 2 (MR Tanker).

In Fig. 3, the predicted propulsive power from ShipCLEAN is within 4% of the power predicted from model test results. At design speed the difference is only 2% for both case study ships. Keeping in mind the limited input data to the model this is a very good results which far exceeds the expected accuracy from the analysis in (Tillig et al., 2018).

For both ships the difference between the ShipCLEAN and the model test power prediction is changing over the speed. This effect is caused by the difficulties of predicting the shape of the residual resistance curve over the speed. Especially for ships with large bulbs, e.g. the Container ship, there will be a bulb effect, i.e. an area with larger residual resistance at low speeds. In Fig. 3 it is shown that the bulb effect is predicted by ShipCLEAN at a higher speed than it appears to be in model tests. This will influence the speed optimization in Section 4, i.e. the resulting speed might be slightly different if the model tests results are used instead of the ShipCLEAN prediction.

To validate the predicted power at sea, i.e. considering wind and waves, it is referred to the validation of the methods used, see (Tillig et al., 2018) for a detailed analysis. Additionally, full scale measurements of the ship speed, the true wind angle, the true wind speed, draft and trim and the main engine power are available for the Container ship for a full year of service on the studied route. Measurements were taken once every hour. The loading and weather conditions varied from a draft of 8.3 m (i.e. ballast draft) through 14.7 m (i.e. scantling draft) a trim between -3.2 m (to the stern) through 0.2 m, a ship speed from 5 to 22.5 kn and a true wind speed between 1.6 and 48.12 kn. Comparing the measured and predicted power reveals an average difference of 6.3% for the full year, with the ShipCLEAN model overpredicting the required power. The differences between measured and predicted power for this validation case are up to 30% at some measurement points. This difference occurs mainly since (i) the wave heights are not measured, but only predicted using Eq. (6) and, (ii) the accelerations are not measured; thus, the ship might accelerate or decelerate
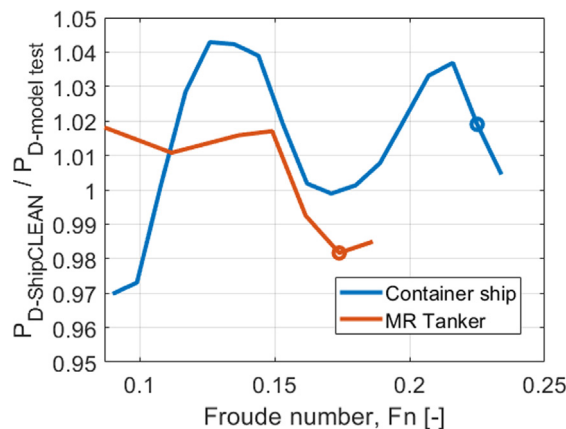

Fig. 3. Comparison of the delivered power from prediction using ShipCLEAN and from model test.

Table 1
Particulars of the case study container ship.

L_{oa}	350 m
B	45.6 m
T	13 m
Displacement (design)	128 000 t
Design speed	25 kn
Propeller rpm at design speed	105 min^{-1}

Table 2
Particulars of the case study MR Tanker.

L_{oa}	183 m
B	32.2 m
T	11 m
Displacement (design)	50 600 t
Design speed	15 kn
Propeller rpm at design speed	130 min^{-1}

at the time of the measurement.

The sail module of ShipCLEAN has been verified by comparison of simulated fuel savings to full scale-measurements from a cruise ferry with a single 4 × 24 m Flettner rotor. Three parties were involved in this project, two of which analysed the measured data, and one, the authors of this study, used the measured wind speed and wind angle to predict the power and fuel savings from the rotor sail using the ShipCLEAN model (Norsepower, 2019). The difference between the measured fuel savings and the fuel savings predicted by ShipCLEAN are found to be as low as 1.7% (Norsepower, 2019), showing that the model can simulate sail-assisted propelled ships in realistic weather.

With the results from the validation and verification, it can be concluded that the ShipCLEAN model can accurately predict the required power of the case study vessels as well as the fuel savings from wind-assisted propulsion.

3. Environmental conditions and route definition

In ShipCLEAN, a function to produce waypoints along the great circle route using a start and an end point, is included. Weather in terms of mean values or distributions is included, based on historical data and estimation formulas. The available weather data can also be used on any other route, defined by waypoints given as longitude and latitude coordinates.

3.1. Wind

In ShipCLEAN, historical wind data is available in a grid of 2.5 by 2.5 degrees covering the whole world and it is based on the reanalysis for the years 2002 to 2012 as presented in (Onogi et al., 2007) and available as GRIB files on (N. C. f. A. Research, 2018). For the case studies presented in Section 4, Monte Carlo simulations are performed. The wind speed is assumed to follow a Weibull distribution with the probability density function according to Eq. (4).

$$f(x) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}$$

(4)

The shape parameter k and the scale parameter λ are found iteratively to match the mean and standard deviation values from the historical wind data for each waypoint. The wind direction (wind angle) is assumed to follow a normal distribution with the probability density function as shown in Eq. (5).

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

(5)

A distribution for the wind speed and the wind direction is fitted for each waypoint and each time of the year that is studied, i.e. January, August and the yearly average. With about 250 waypoints and three different weather scenarios, more than 750 different distributions for the wind speed and direction were used in the study.

Due to limitations in the underlying methods (especially the added wave resistance) of the model, and since the model is built to be used for the estimation of energy efficiency, the wind speed is limited to a maximum of 33 knots (kn), i.e. Beaufort 7. Usually, weather routing software (and the crews on board) would avoid areas with higher wind speed. The ship is assumed symmetrical; thus, the true wind angle (TWA) is limited to be between 0 and 180 degrees, values outside this ranged are recomputed using symmetry conditions.

3.2. Waves

The wave heights are estimated using the wind speed and the formulas for fetch limited (6) and for fully developed (7) wind seas, as shown below and presented in (Coastal Engineering Research Center, 1984).

$$H_S = 0.01616 U_A \sqrt{fetch} \tag{6}$$

$$H_S = \frac{0.2433}{9.81} U_A^2 \tag{7}$$

$$U_A = 0.71 v_W^{1.23} \tag{8}$$

where U_A is the wind speed, corrected for the boundary layer effects, and v_W is the free wind speed.

Commonly Beaufort 7 (around 30 kn wind speed) winds are associated with up to 6 m waves (Sea state 6), while a fully developed wave system would have a significant wave height of above 10 m. This difference is due to the fact that the areas of high winds, i.e. low-pressure systems, are smaller than the fetch necessary to create a fully developed wave system. An analysis of the equations (4) and (5) gives a fetch of about 260 nautical miles (nm) to create 6 m waves with 33 kn of wind, which is thus set as a maximum fetch in the study. The ITTC spectrum (ITTC, 2014) is used to define the spectrum of the wave heights and wave angles around the above discussed mean values.

3.3. Other factors

Ocean currents, without tides, are included in the model based on a global forecast valid for 2018-12-01, provided on (Sailweatheronline, 2018). These ocean currents are not prone to quick changes due to e.g. changing weather. It is thus assumed that a single forecast gives reasonable data for the study.

For the ocean passages in the current study, shallow water effects will not be noticeable. Thus, the water depth is set to a constant 2000 m, which will eliminate any effects from shallow water. Biofouling on the hull is simulated by an increased frictional resistance in the container ship study. The hull of the tanker is assumed to be clean.

Sea surface temperature data is available from (Eumetsat, 2018). This data is based on satellite imaging and shows considerable scatter in areas with high cloud coverage. The data was reduced to a mean value temperature over the latitude. In that way, the influence of colder water further towards the poles is captured, but local influences are neglected. Two dataset files are used and interpolated in between, one for August and one for January. In addition, the water density is modelled as a function of the water temperature, and effects from differences in salinity are neglected.
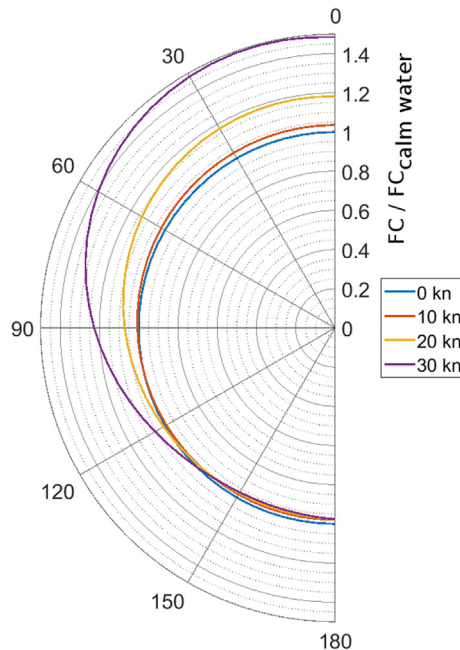

Fig. 4. Polar plot of the relative fuel consumption per hour (FC/FC$_{calm\ water}$) at ship speed 20 kn and various wind speeds with corresponding wave heights.

4. Results and discussion

Two case studies are presented, one container liner shipping case on the Pacific Ocean and one tanker with Flettner rotors on the North Atlantic. While the container ship is one of the reference vessels in the ShipCLEAN project, with detailed data available, a tanker is selected since it provides open deck space for installing Flettner rotors and the low operational speeds of tankers are beneficial for the wind assistant propulsion.

Both case studies use weather statistics, as presented in Section 3, in Monte Carlo simulations. In total, 10 000 random wind speeds and wind directions were used, both being treated as independent random variables. At each waypoint the fuel consumption is evaluated using the 4 DOF model. The result of the Monte Carlo simulations are distributions of the expected total fuel consumption for the journey according to the distribution of the wind speeds and directions. To avoid unrealistic quick changes in the weather and to match the accuracy of the weather statistics, the waypoints along the routes were spaced with 100 nm in between.

4.1. Speed optimization for container liner shipping

A large container ship, with the particulars as shown in Table 1, traveling on a Pacific Ocean liner service is considered as the example for a speed optimization using ShipCLEAN. The liner route consists out of numerous harbours on each side of the Pacific Ocean. In this study, however, only the transpacific leg between Shanghai (China) and Manzanillo (Mexico) is considered. The economic load factor is assumed to be 0.75, while the displacement is kept at 95% of the design displacement. The freight rate is defined to be 1500 USD/TEU and OPEX is defined to 15 000 USD/day.

A polar plot of the fuel consumption per hour related to the calm water fuel consumption per hour

($FC/FC_{calm\ water}$) in 10, 20 and 30 kn of wind speed with corresponding waves is presented in Fig. 4. Compared to the calm water case, the fuel consumption increases at 10 kn wind speed with a maximum of about 5%, while for 30 kn wind speed the fuel consumption is increased by up to 50%. Further, it can be seen that the increase in fuel consumption is almost constant between 0- and 30-degrees TWA and that the reduction in fuel consumption in following wind and seas is marginally. On the studied routes, the wind speeds are mainly around 10 kn with a maximum of around 20 kn.

In a first analysis, the great circle and the rhumbline routes are compared in terms of fuel consumption. Both routes are shown in Fig. 5. While the great circle route represents the shortest possible route for the crossing (6950 nm each way), it goes through more northern latitudes, resulting in potentially harsher weather. The rhumbline route represents the route with a constant bearing which is longer (7270 nm each way), but it goes through areas with more moderate weather. Additionally, a combined option is studied, where the ship travels on the rhumbline route on the westbound journey and on the great circle route on the eastbound journey. The mean wind speed (here, TWS) and wind angle (here, TWA) as well as the standard deviation for the yearly average on both routes (westbound journey) are presented in Figs. 6 and 7.

To clarify the seasonal differences on the route, histograms of the experienced wind speeds and wind angles (westbound journey) are shown for all 10 000 runs of the routes in Fig. 8 for the rhumbline and in Fig. 9 for the great circle route.

It can be concluded from the Figs. 6–9 that the TWA on the rhumbline route is more stable than on the great circle route, especially during August. This can be explained by the fact that the rhumbline route is within the trade wind region for most of the time. On the great circle route, the wind direction is more evenly distributed with slightly more westerly winds (head wind on the westbound journey), while easterly winds dominate on the rhumbline route during August. During January the wind direction is almost evenly distributed on the rhumbline route. Wind speeds are lower in August than in January on the great circle route, and almost the same over the year on the rhumbline route. From Figs. 8 and 9 it can also be seen that the combined route option will be the most favourable in terms of wind direction.

The comparison of the fuel consumption on the three route options is carried out with a round trip time of 30 days (excluding harbour times), which results in an average speed of 19.2 kn for the great circle route and 20.2 kn for the rhumbline route. The ship

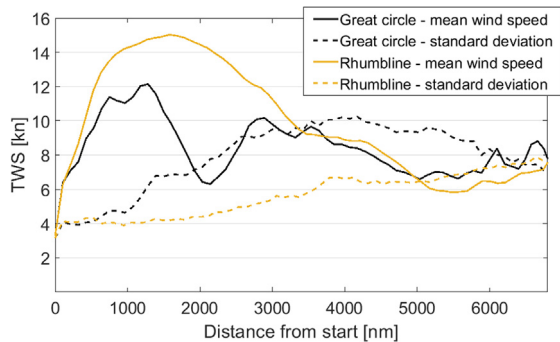**Fig. 5.** Great circle (solid) and rhumbline (dashed) route for the Pacific Ocean crossing.

Fig. 6. The TWS with standard deviation for the rhumbline and the great circle route; yearly average, westbound.
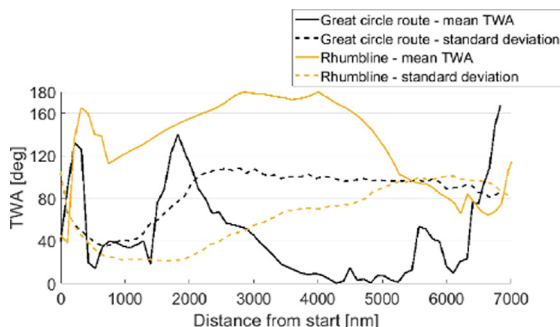

Fig. 7. The TWA with standard deviation for the rhumbline and the great circle route; yearly average, westbound.
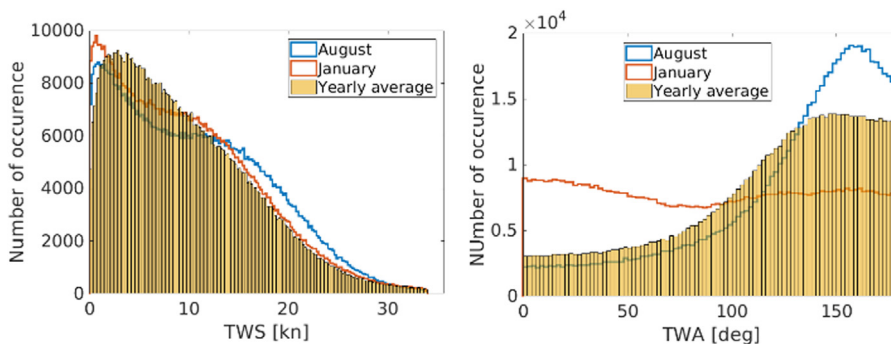

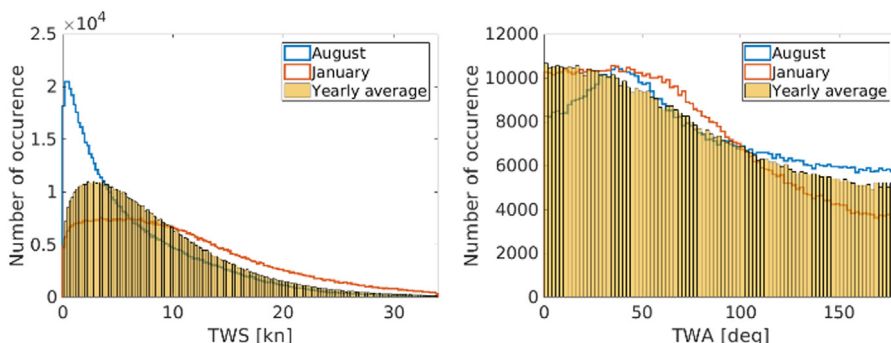**Fig. 8.** Histogram of experienced TWS and TWA on the rhumbline route, westbound.

Fig. 9. Histogram of experienced TWS and TWA on the great circle route, westbound.
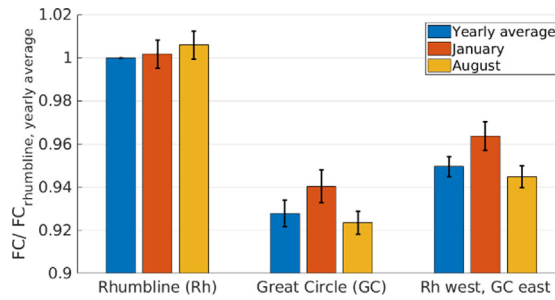
Fig. 10. Comparison of the fuel consumption on different routes for the container trade.

did not experience any involuntary speed loss at this target speed for any of the routes. Fig. 10 presents the results of this comparison for the yearly average, for the January and August weathers. It can be concluded from the results that the great circle route is the most favourable route option, with a fuel consumption that is 7% lower than the fuel consumption on the rhumbline route, for the yearly average weather.

The fuel consumption on the combined route is 2% higher than the fuel consumption on the great circle route. These differences are due to the difference in route length, which results in higher ship speeds and higher fuel consumption per nautical mile. The variation of the fuel consumption depending on the season was shown to be 2% for the great circle route, with standard deviations for each season of about 1%. Seasonal dependence and standard variations are much smaller (less than 0.5%) on the rhumbline route, due to the more stable trade wind conditions.

To maximize profits on the trade, the journey time (i.e. the average ship speed) must be carefully chosen to avoid high fuel costs due to high ship speeds or high capital costs due to long journey times.

The speed optimization for the trade is allowing for round trip times between 24 and 50 days (excluding harbour times). It is based on the results from Monte Carlo simulations with 10 000 runs. The average speed is assumed to be identical for the eastbound and the westbound trips, with the weather represented by the yearly average for the route. In this study, the fuel price can vary as 300, 500, 800 and 1000 USD/t. In Fig. 11 the resulting optimal ship speed and round trip times are shown as function of the fuel price. The profits per day are shown in Fig. 12. Fig. 11 also presents results for the optimal speed and round-trip time for the ship with biofouling on the hull. For this analysis the frictional coefficient is increased by 30% which corresponds to biofouling with some barnacles according to (SSPA, 2019).

The optimal speed clearly depends on the fuel price, while the ship speed is approaching the maximum allowed for the study for the lowest fuel price of 300 USD/t. The speed is reduced to 20.5 kn for the highest investigated fuel price of 1000 USD/t. Biofouling on the hull reduces the optimal speed due to higher fuel consumption. Reducing the average speed from 24 kn to 20.5 kn will save 1934 t (36%) of heavy fuel oil per round trip, which is equivalent to 6015 t of CO_2. This corresponds to a saving of 101 t fuel oil (313 t of CO_2) per day at sea. Since the ship operates in liner traffic, a high utilization rate can be assumed. With a utilization of 85%, the yearly savings would sum up to 21 274 t of heavy fuel oil, corresponding to 66 162 t of CO_2.

The optimal ship speed is similar for both routes except for the case with the fuel price 300 USD/t, where the round-trip time is similar, i.e. the shortest allowed round trip time. This results in longer journey times on the rhumbline route. It must further be mentioned that the optimal speeds where identical for all 10 000 investigated runs of the Monte Carlo investigation, i.e. the optimal speed is not changing with the changing weather on the routes. Correspondingly, the standard deviation of the per day profits were very low, 0.03–0.05% for 300 USD/t through 0.12–0.23% for a fuel price of 1000 USD/t. The difference in profit between the journeys with maximum and minimum profit (with the same ship speed) was found to be 2.5%.

Fig. 12 shows that the profits per day over the journey time have flat maxima, indicating that it is possible to vary the ship speed without losing a lot of profit. For the case with 1000 USD/t fuel price the difference of the profit per day is only 1.2% for round trip
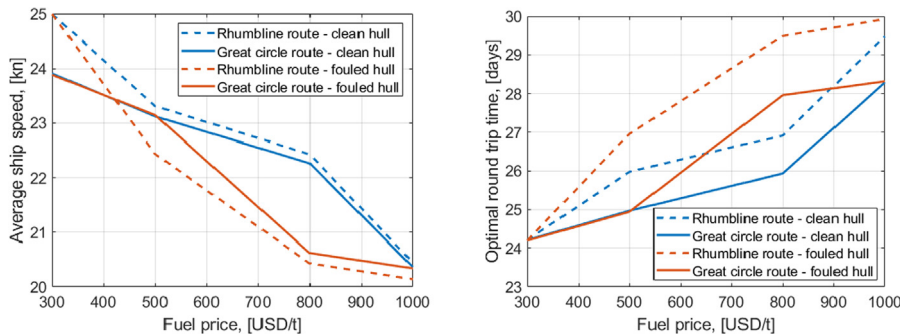

Fig. 11. Optimal round-trip time and ship speed for the rhumbline route and the great circle route, depending on the fuel price and hull fouling condition.
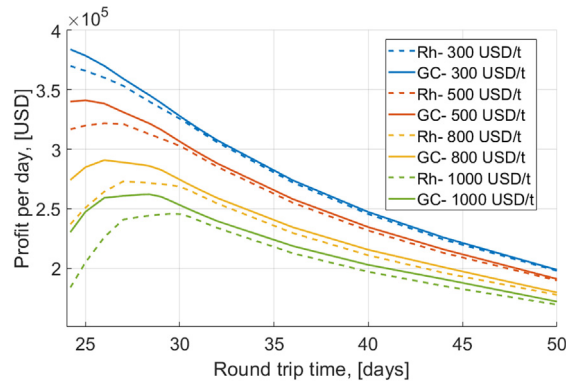
Fig. 12. Mean values of the profits per day on the rhumbline (Rh) and great circle (GC) route for different fuel prices.

times between 26 and 29 days. It can also be seen that the decrease in profit is much steeper with decreased journey times (higher ship speeds) than for longer journey times (lower ship speed). This indicates that ship operators could further reduce the ship speed to save more fuel, without losing significantly on the profit. The results show the effect of fuel prices and possible bunker levies on the optimal ship speed and consequently on the fuel consumption and CO_2 emissions of the ship. The results show that the choice of route has a significant impact on the fuel consumption and achievable profits. It is also shown that the influence of varying weather on the fuel consumption is smaller than the influence from increased ship speeds due to longer routes.

4.2. Variation of the size of Flettner rotors on a MR Tanker

A MR Tanker with particulars shown in Table 2 is equipped with 1, 2, 4 and 6 Flettner rotors of three different sizes, all with an aspect ratio (height to diameter) of 6. The different combinations and sail areas are shown in Table 3. A sketch of possible Flettner rotor arrangements is presented in Fig. 13. It must be noted that interaction effects between the rotors are not included in the current version of the ShipCLEAN model.

The fuel saving potential of the Flettner rotors is shown in the polar plots in Fig. 14. The plots are created for 20 kn TWS, with corresponding wave heights and a ship speed of 12 kn. It is shown, that the setup with 6 rotors of 5 × 30 m can give a fuel saving of up to 85% in ideal conditions. In general, one can see for each of the sail configurations that the losses in headwind are much smaller than the gains in all other wind directions. In Fig. 14 it is shown that the shape of the polar plots varies for the different sail arrangements and sizes. For large sail areas, a gull wing shape of the fuel saving can be observed. The differences in the shape of the polar curves originate from the reefing (reduced rpm of the Flettner rotors) of the sails in some conditions. Thus, in headwind and downwind conditions, were the sails introduce large side forces, large sail areas are reefed and might thus not produce more thrust than arrangements with small sail set ups. However, at wind angles close to 90 degrees apparent wind angle, the sails can be operated at the maximal thrust point and the sail thrust increases linearly with the sail area. Thus, the polar curves are of similar shape for all arrangements in head and downwind but significantly differ at true wind angles around 120 degrees. The maximum experienced static heel angle in the presented condition of 20 kn true wind speed was 1.4 degrees.

The MR Tanker is studied on a triangle route on the North Atlantic with the following three legs: (i) Rotterdam (Netherlands) – New York (USA), (ii) New York (USA) – Houston (USA), and (iii) Houston – Rotterdam. The second leg is assumed to be on ballast draft and the two others are assumed to be fully loaded. A sketch of the route is presented in Fig. 15. The average speed is defined as 12 kn for each leg, which corresponds to moderate slow steaming for a MR Tanker. With a total route length 9961 nm the round-trip time is 34.6 days.

Table 3
Rotor combinations on the MR Tanker.

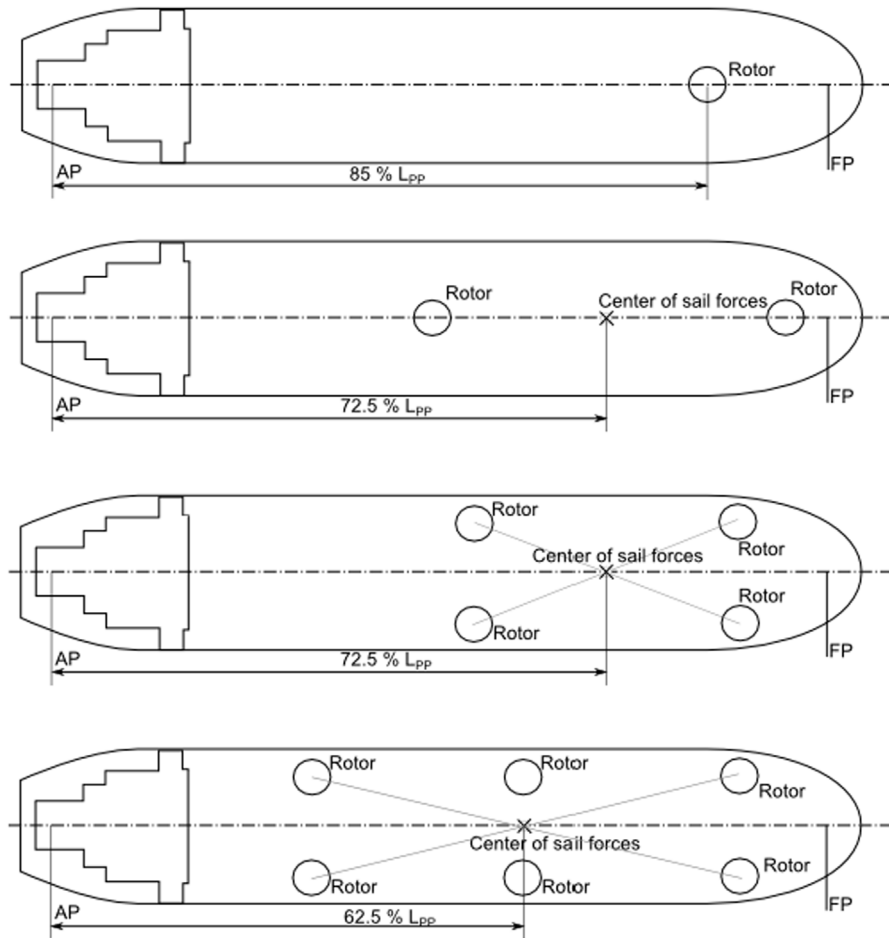| ID	Diameter [m]	Height [m]	No rotors	Sail area [m^2]
1	3	18	1	54
2	3	18	2	108
3	3	18	4	216
4	3	18	6	324
5	4	24	1	96
6	4	24	2	192
7	4	24	4	384
8	4	24	6	576
9	5	30	1	150
10	5	30	2	300
11	5	30	4	600
12	5	30	6	900

Fig. 13. Sketch of possible Flettner rotor arrangements.

The mean and standard deviation of the true wind angle (TWA) and true wind speed (TWS) along the route are shown in Fig. 16. The distribution of the wind angles and wind speeds for the complete journey and all runs in the Monte Carlo simulations is shown in Fig. 17.

Fig. 16 shows that the average weather on this route is very unsuitable for sail-assisted ships with the mean value of the TWA, the ship experiences head or stern winds during most parts of the journey, thus the sails are either creating drag or are not very effective.

As a first step the ship with the different Flettner rotor setups is analysed using the average weather. The results from this analysis are shown in Fig. 18. Due to the unfavourable mean TWA throughout most of the journey, the results show virtually no savings with the sails.

However, due to the statistical distributions of the TWA and TWS the ship will experience different weather during each voyage. During the Monte Carlo simulation not a single simulation of all the 10 000 runs showed losses due to the sails, while the maximum achieved fuel saving was 20% for the setup with 6 rotors 5 × 30 m. The results from the Monte Carlo simulations, mean relative fuel consumptions and standard deviations, are shown in Fig. 19.

The results show that savings of up to 71 t (12%) of heavy fuel oil and 221 t of CO_2 per round trip can be achieved with rotor sails on the tanker. This total saving corresponds to 2 t of fuel and 6 t of CO_2 per day. Naturally the achieved savings are larger with larger sail areas.

To judge the efficiency of the different sail setups, the savings could be related the costs of the sails by calculating the number of necessary round trips to reach the breakeven point, shown in Fig. 20.

According to Norsepower, installation costs of the Flettner rotors can be assumed to be 300 000 EUR (about 320 000 USD) per unit for the 3 × 18 m, 500 000 EUR (about 540 000 USD) per unit for the 4 × 24 m and 750 000 EUR (about 800 000 USD) per unit for the 5 × 30 m rotor. Yearly maintenance costs are assumed to be 2% of the installation costs. Fig. 20 presents the necessary number of round trips to reach breakeven for three different fuel prices. It must be noted that the payback time evaluation only includes the abovementioned installation and maintenance costs, but no other capital costs. The installations with one rotor are the most cost-efficient for each sail size. The reasons for this trend are like the reasons discussed earlier. Additionally, the cost model for the sail installation is on a per unit base. Thus, the costs increase linearly with the number of installed rotors, but the savings do not.
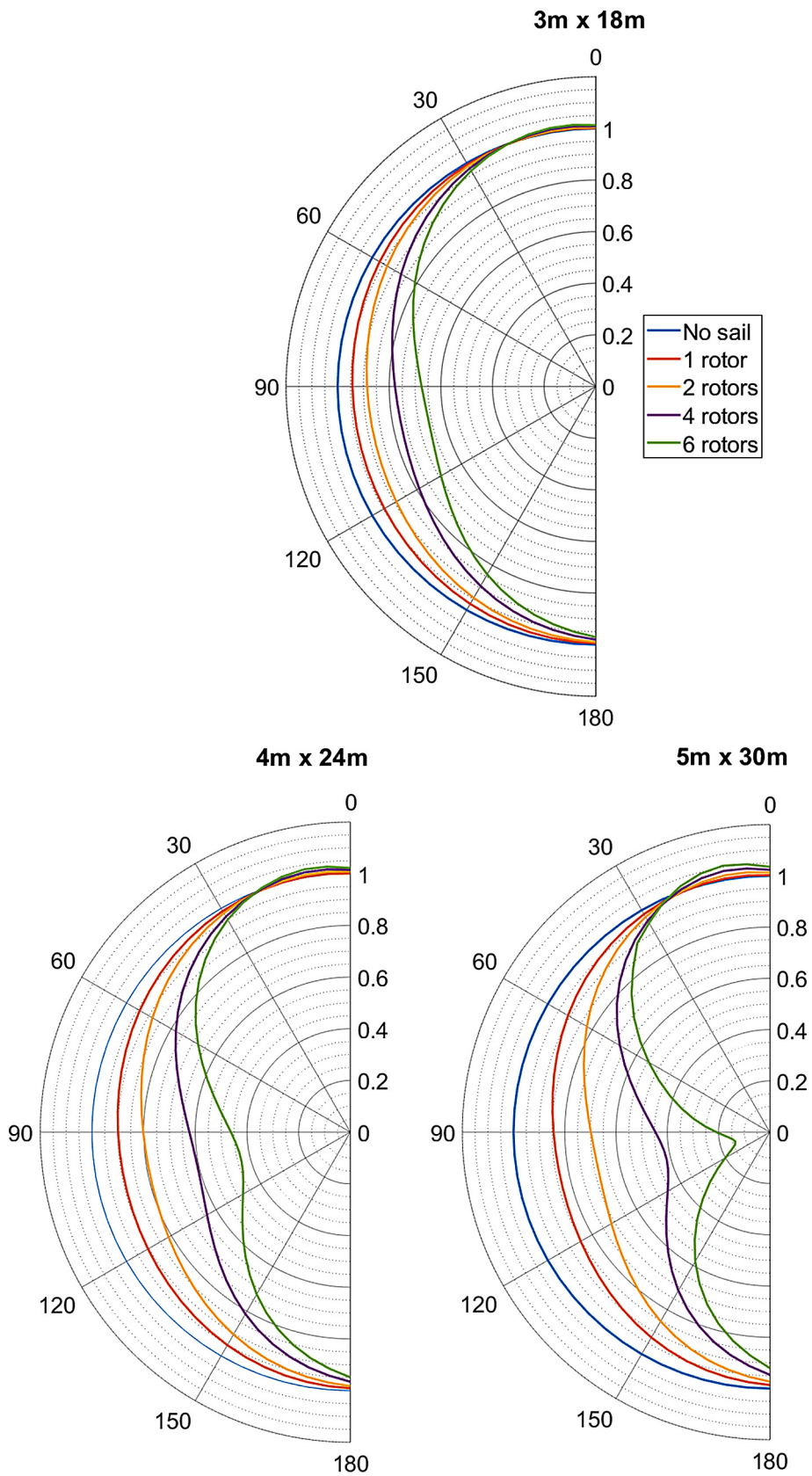
Fig. 14. Polar plots of relative fuel consumption per hour (FC/FC$_{\text{no sail}}$) for the different sail set-ups in 20 kn TWS and 12 kn ship speed.
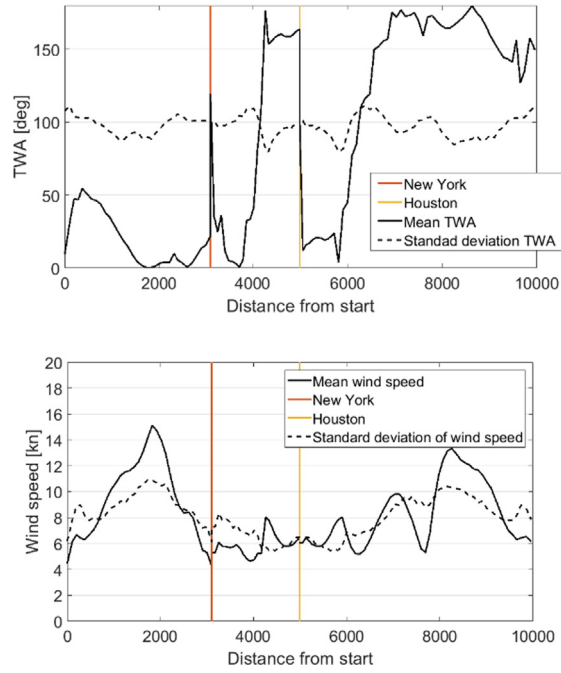
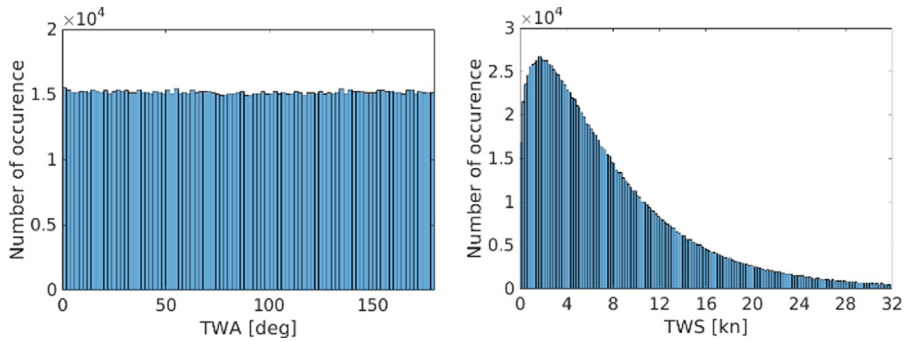**Fig. 15.** Sketch of the North Atlantic route for the MR Tanker.

Fig. 16. Mean values and standard of the TWA (top) and TWS (bottom) along the North Atlantic route. The red line marks New York, yellow line Houston.
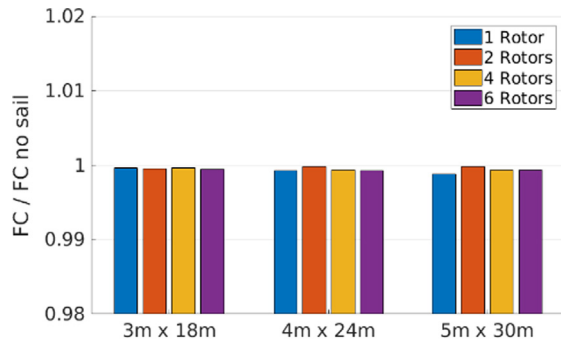

Fig. 17. Distribution of TWA and TWS for the complete route and all runs of the Monte Carlo simulations.

Assuming a utilization rate of about 65% (i.e. the time the ship spends actually traveling related to the time in harbour or on anchorage), the ship will perform 7 round trips per year. With today's fuel price of about 500 USD/t this means that the breakeven for the most efficient sail (Fig. 20: 1 rotor 4 × 24 m) is 16.7 years. For an assumed future fuel price of 1000 USD/t, this time is reduced to 8.4 years. For the installation with the highest savings (Fig. 20: 6 rotors 5 × 30 m) the breakeven time is 21.1 years for a fuel price of
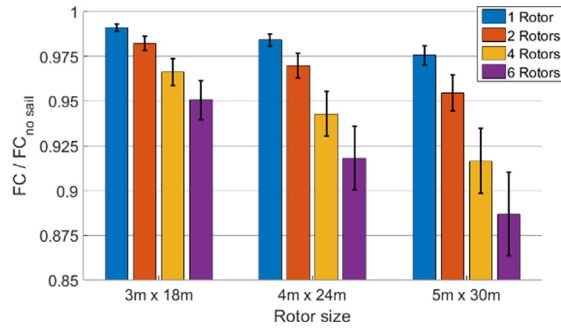
Fig. 18. Relative total fuel consumption (FC/FC$_{no\ sail}$) using the mean wind speed and direction along the route.
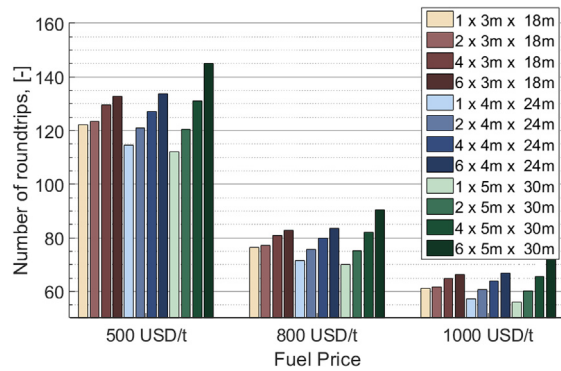

Fig. 19. Relative mean fuel consumption (FC/FC$_{no\ sail}$) and standard deviation from the Monte Carlo simulations.
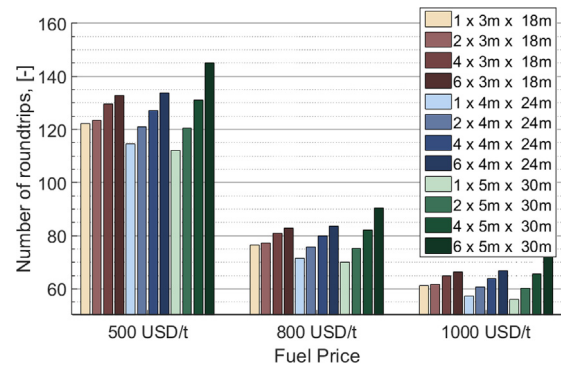

Fig. 20. Number of necessary round trips to reach breakeven of installation costs and savings, for three different fuel prices.

500 USD/t and 10.6 years for a fuel price of 1000 USD/t. With the utilization assumption, the fuel savings with 6 rotors 5 × 30 m will be 497 t per year, corresponding to about 1546 t of CO_2. The difference in payback time with different number of rotors is caused by the linear increase of the costs with the number of rotors while the savings cannot increase linearly due to regions of headwind and reefing of the sails.

The results show that fuel savings can be achieved with Flettner rotors as sails even on routes with average weather that seems unsuitable at the outset. However, with the current (2019) pricing of the Flettner rotor, the selected route and with the current (2019) fuel price, the breakeven for the investment costs of a large sail area (6 rotors, 5 × 30 m) is close to a tanker's expected maximum target service life. Increased fuel prices, either by market or by bunker levies, can highly increase the economical attractivity of rotor sails.

4.3. Uncertainties

Uncertainties in the presented case studies can be found in three main areas: (i) the power and fuel consumption prediction, (ii) the prediction of the economics, i.e. freight rate and utilisation, and (iii) the prediction of the encountered weather.

The first area, uncertainties in the power prediction using the ShipCLEAN model are addressed in (Tillig et al., 2018) and in

Section 2.3 and are found to be low, i.e. below 5%, for the case study vessels. However, it is shown in Section 2.3 that, for the Container ship, the difference between the predicted power from model tests and the predicted power from ShipCLEAN is not constant over the ship speed. This will cause the results from the speed optimization in Section 4.1 to be slightly different if performed with the power prediction from model tests instead of the predictions from ShipCLEAN. However, the methods and trends presented in Section 2.1 will be the same even if performed with the power prediction from model test, the only difference will be in the absolute value of the optimal ship speed. In Section 2.1 it is shown that the ShipCLEAN model can accurately predict the fuel savings from wind-assisted propulsion, especially since any uncertainties of the absolute fuel consumption will not affect the fuel savings because they are present for the wind-assisted and the conventional version of the ship. Some uncertainties can be introduced into the estimation of the payback time, since the absolute fuel consumption is necessary to compute the costs. In Section 2.3 it is, however, shown that the power predictions of ShipCLEAN and from the model tests are very close to each other, thus any uncertainties are expected to be low. To reduce uncertainties from the power prediction, one could use model test or CFD results in the power prediction, especially for the residual resistance.

For the second area of uncertainties, the prediction of economic factors, is can be seen from Eq. (2) that both the freight rate and the utilization rate are linear factors in the estimation of the income, and thus also for the profit. Thus a 10% difference of the utilization rate of the freight rate will cause a 10% difference in the profit. A higher profit will imply higher ship speeds. However, ship owners and operators do not reveal details about the achieved freight rates and utilization rates. Thus, the values used in this study are guesses based on the experiences from the authors. It is expected that the uncertainties introduced by the freight and utilization rate are high, in the range of about 10% of the estimated profit. However, the presented method can, without modification, be applied to a real case with detailed information about freight and utilization rates for each part of the journey, which will significantly reduce uncertainties from this area.

Another source of high uncertainty, especially for the case study of the wind-assisted Tanker, is area (iii), the prediction of the encountered weather. The sail forces are quadratically dependent on the wind speed. Thus, e.g., an increase of the wind speed from 12 to 16 kn will increase the forces from the rotors by about 40%. Even though the sails do not only create thrust but also a side force and thus induce an added resistance due to drifting of the hull, this relation of the force to the wind speed shows the importance of accurate weather prediction. Increasing the mean wind speed will highly affect the savings due to the relation discussed above. Additionally, as shown in Fig. 14, the fuel savings from wind-assisted propulsion are highly dependent on the wind angle. As an example, varying the true wind angle from 70 degrees to 90 degrees will increase the fuel savings from about 55% to 80% for the case of 6 of the largest (5×30 m) rotors, a true wind speed of 20 kn and a ship speed of 12 kn. Since the present study is based on global wind statistics, the uncertainties in the predicted wind speed and angle are expected to be considerable. However, the presented method can, without adjustments, be applied using measured wind data from onboard a ship traveling on the route in question, which will significantly reduce the uncertainties of this area.

5. Conclusions

The paper presented a simulation model called ShipCLEAN which can be used to minimise the fuel consumption of ships by modelling the ship performance and the transport economics. The main novelty with the ShipCLEAN model is that it is an integration of two main models, a generic ship energy systems model that predicts the fuel consumption under operational conditions considering the ship's characteristics, and a transport economics model that estimate costs and income of the journey. This unique combination provides the possibility to investigate alternatives in e.g. transport logistics, fleet sizes, ship dimensions, ship retrofitting, and ship propulsion concepts, as soon as the transport task is known or of it is subjected to change. In validation studies, the predicted power and predicted fuel savings due to wind-assisted propulsion from ShipCLEAN are found to be close to measurements in model and full scale.

Two case studies were presented. The first case study of a container liner shipping on the Pacific Ocean showed that for a yearly statistical weather the great circle route is always the most fuel-efficient route as compared with the rhumbline route or a route which is a combination of the two, see Section 4.1 for details. However, the transport economics calculation showed that the optimal profit per day calculation was strongly dependent on fuel price, fouling on the hull, optimal round-trip time, and ship speed. It was shown how increased fuel prices will lead to decreased ship speed and huge savings in terms of fuel consumption and CO_2 emissions.

In the second case study, wind assisted propulsion of a MR Tanker on the North Atlantic route was simulated and investigated in detail. The number of Flettner rotors and their sizes were compared in parametric studies with regards to e.g. optimal setup for maximum fuel savings and fuel cost reduction. The transport economics calculation showed that the fuel price had great impact on the breakeven between the investment in the Flettner rotor technology and the reduction in fuel costs that originate from higher energy efficiency from the wind assisted technology. The results show that for the case study tanker, an investment of Flettner rotors can be justified from an economic perspective. However, as for the container case, an increased fuel price will highly decrease the payback time of the installation of the Flettner rotors.

One important outcome from these case studies' results is that they prove that an increased fuel price, if necessary, artificially increased through a bunker levy, will lead to a decrease of the CO_2 emissions of ships by economically motivating ship operators to decrease the ship speed and invest in wind assisted propulsion. An alternative approach to increased fuel prices could be to require ships to use alternative fuels, which will not only increase the fuel price, and thus decrease the economically optimal speed as shown in this study, but potentially further reduce emissions. However, alternative fuels were not part of this study.

The analysis and discussion of uncertainties showed that the highest uncertainties in the prediction of the fuel savings and optimal speeds are caused by uncertainties in the prediction of the weather condition and the economic factors, i.e. the freight and utilization

rate.

With potential fuel savings of about 12% for the tanker and even less for the container ship, results of this study do still not fulfil the 2050 goal of 50% reduction of CO_2 emissions. To achieve this goal, more studies on alternative propulsion, routing and speed reduction must be carried out. However, it was shown in the polar diagrams of the wind assisted tanker, that sails could full propel a MR Tanker at 12 kn ship speed, if conditions are preferable, showing that wind assisted propulsion can be one solution to solve the problem of how to reduce the fuel consumption of ships.

Finally, the case studies show that the ShipCLEAN model enables to make realistic scenario-based analyses which account for market-driven requirements and expectations that create incitements to changing ship operation conditions and transportation logistics. It can be applied to simulate, assess and explore options for installation of new technology such as Flettner rotors that can reduce the fuel consumption, leading to less emissions and higher profit. For decision-makers, it is thus a useful tool for scenario-based simulations and assessment which contributes to more energy-efficient shipping taking us to the target before 2050 to reduce shipping's contribution to emission of greenhouse gases to 50% of the levels 2008.

CRediT authorship contribution statement

Fabian Tillig: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Jonas W. Ringsberg:** Conceptualization, Resources, Writing - review & editing, Writing - original draft, Supervision, Project administration, Funding acquisition. **Harilaos N. Psaraftis:** Writing - review & editing, Methodology. **Thalis Zis:** Writing - review & editing, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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