Estimation of fuel consumption using discrete-event simulation - a validation study

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ABSTRACT: In this paper, we investigate the validity of quasi-static discrete-event simulation for estimation of fuel consumption and assessment of energy effective ship designs. Stricter emission regulations for ships and developments in computer science have sparked an interest in virtual testing and simulation approaches to enhance our understanding of vessel performance early in the design process. Our methodology uses discrete-event simulation and historical weather data to replicate the operational conditions, and quasi-static calculations to estimate wave and wind added resistance on the ship hull. The validity of this approach is tested in a case study using full-scale measurements from a deep-sea vessel. Results show that we are able to recreate the voyage in a manner that show several similarities to the case vessel measurements. Speed policies that better replicate real operation and fuel curves that take the engine state into account is recommended in order to improve fuel consumption estimates.

1 INTRODUCTION

Fuel efficiency of ships has become increasingly important in recent years due to higher fuel costs and stricter emission regulations. This has sparked an interest in the industry and academia towards establishing new and improved design methodologies to enhance the designer's understanding of design performance. Required power and fuel consumption is commonly estimated using static numerical and empirical tools in the early design stage. The impact of weather is approximated using a sea margin, relying on experience and statistics. Virtual testing and benchmarking schemes has been developed in recent years for marine applications, enabling the designer to factor in the characteristics of the area of operation. The IDEAS project worked on developing a simulation-based benchmarking tool for evaluation of ship designs (Fathi et al. 2013). VISTA (virtual sea trial) was developed for assessing operability of complex marine operations during design (Erikstad et al. 2015). ViProMa (virtual prototyping of maritime systems and operations) presents an open virtual prototyping tool based on distributed co-simulation (Skjong et al. 2017).

The majority of Norwegian ship builders and design companies has for many years had vessels for the offshore oil and gas industry as their core activity and source of income. Due to the rapid drop in oil price in 2014, the demand for such vessels plummeted, resulting in near empty order books and challenging financial times. Many of the companies that experienced this downturn looked to new industries and segments for projects. Cruise/expedition vessels, fishing/aquaculture vessels, ferries and offshore wind support vessels are some of the segments now replacing offshore oil and gas vessels in Norwegian ship yards. This poses challenges for designers, evolving and adapting to a new set of requirements and considerations to assess during design and engineering. In this context, a methodology for rapid testing and exploration of design performance is advantageous due to the often limited knowledge base applicable across vessel type.

Ship owners and operators focus on the operation and economy of vessels. Their studies often require a more detailed operational scenario, specifying a vessel schedule for cargo pick-ups and drop-offs as part of a logistics system. Facilitating detailed descriptions of such scenarios results in a flexible platform capable of providing knowledge also during a vessels lifetime.

In this paper, we investigate the validity of quasi-static discrete-event simulation models for estimation of required propulsion power and fuel consumption.

A case study is presented where we attempt to replicate the voyage of a ship in transit between China and the United States, using the simulation based GYMIR workbench (see chapter 3 for further description) developed in the research project SFI Smart Maritime (SFI Smart Maritime 2015). The case vessel is a general cargo carrier outfitted with an onboard performance monitoring system. Logged data from the voyage is used for comparison towards the simulation results. Discrete-event simulation and hindcast weather data is applied to replicate the vessel sailing conditions along the route. Quasi-static calculations are applied to estimate the required propulsion power and fuel consumption, taking calm water and added resistance due to wind and waves into account. Our focus is to compare and evaluate the simulation-based results towards the performance monitoring system measurements, emphasizing challenges and potential sources of error in view of the uncovered differences.

2 CASE VESSEL DATA

2.1 *Vessel particulars*

The particulars for the case ship studied in this paper are given in table 1.

Table 1. Case vessel particulars

Length Meters	Beam Meters	Draft Meters	Gross tons Tons
204	32.3	13	37 000

2.2 *Data acquisition*

The vessel is outfitted with a real-time monitoring system which stores operational data with a sampling period of 15 minutes. A list of the applied parameters are given in table 2.

Table 2. List of parameters applied in case study and respective measuring techniques.

Parameter	Measuring technique
Shaft torque, RPM and power	Optical sensors
Fuel consumption	Fuel line flowmeter
Speed through water	Doppler sonar
Speed over ground	GPS
Position	GPS
Wind	Anemometer

2.3 *Route*

The vessel route is from Qingdao to Seattle, covering a distance of 4,514 nautical miles over the North Pacific. The voyage was conducted during fall of 2016. The route is simulated as three successive legs as shown in table 3.

Vessel speed is varied between routes in order to minimize the spatial distance between the real and simulated vessel in time. Loading condition is kept constant for all legs according to the case vessel.

Figure 1. Vessel route map.

Table 3. Route legs and key information

Leg	Speed Knots	Duration Hours	Distance Nautical miles	Draft Meters	Trim Meters
1	15.8	72.4	1144.1	8.5	0.7
2	15.5	133.6	2071.1	8.5	0.7
3	16.0	80.8	1292.2	8.5	0.7

3 METHODOLOGY

3.1 *Simulation workbench*

GYMIR applies discrete-event simulation to replicate the vessel voyage. Methodology flowchart is shown in figure 2. The simulation is set to follow the vessel route as shown in figure 1, updating weather condition according to the current position and time.

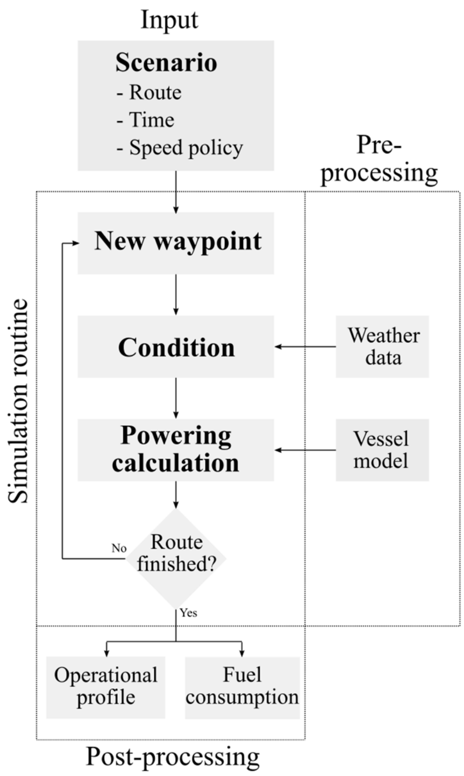

Figure 2. Methodology flow chart.

A speed policy must be set in order to determine the simulator actions towards maintaining speed in weather. For this study, a constant speed policy was applied. In this setting the powering calculation function determines the propulsion power required to maintain the specified speed in the current weather condition. A new event is triggered either by an update in position, defined by the route waypoints, or an update in weather condition between two successive waypoints.

3.2 *Quasi-static estimates*

The discrete event simulation in GYMIR is using static calculations of speed and power for each event. The average added resistance is calculated for the given speed and sea state, and the power required to reach the specified speed with the increased resistance is calculated by interpolation of calm water propulsion characteristics. The increase of added resistance is found by using quadratic added resistance transfer functions computed by the pressure integration method of Faltinsen (Faltinsen et al. 1980) and extended Gerritsma & Beukelman (Loukakis & Sclavounos 1978), implemented in the linear frequency-domain strip-theory seakeeping program ShipX Veres.

3.2.1 *Resistance*

The total vessel resistance, R_T, in our model consists of the calm water resistance R_{T0} and added resistance due to waves R_{AW} and wind R_{AA}.

$$R_T = R_{T0} + R_{AW} + R_{AA} \tag{1}$$

The calm water resistance term is weather independent, defined only by loading condition and vessel speed through water. The added resistance terms are highly influenced by weather conditions and relative direction.

3.2.2 *Calm water resistance*

Calm water resistance curves are taken from towing test results of the vessel hull. Admiralty coefficient C_{adx}, based on the towing power P_E, is applied to account for differences in loading condition.

$$C_{adx} = \frac{\nabla^{\frac{2}{3}} \cdot V_s^3}{P_E} = \frac{\nabla^{\frac{2}{3}} \cdot V_s^2}{R_t} \tag{2}$$

The resistance curve is calibrated using the case vessel measurements by comparing the power requirement in a series of calm sea states.

3.2.3 *Added resistance due to waves*

Added resistance due to waves is caused by two separate physical phenomena; wave reflection and vessel motion induced wave generation. Two approaches are applied for calculation of short-term added resistance coefficients due to waves. The Gerritsma & Beukelman method is derived from radiated energy consideration and strip-theory (ST) approximation for head seas. Loukakis and Sclavounos generalized this approach to cover oblique waves. The second approach is the pressure integration method (PI) where the pressure is integrated along the intersection between the ship hull and water surface and over the average position of the wetted ship hull. Both methods are combined with the asymptotic formula for low wavelengths to account for wave reflection.

3.2.4 *Added resistance due to wind*

Vessel area above water is approximated using general arrangements drawings. The influence of cargo cranes is neglected. Drag coefficients for the specific vessel type is applied using the ShipX database, based on (Brix 1993).

3.3 *Propulsion*

The vessel is a single screw vessel outfitted with a Mewis duct. Open water and propulsion test reports for the case vessel are used for propulsion power calculations.

3.4 *Weather data*

Hindcast data from the recently released ECMWF ERA5 catalogue is used to replicate the environmental conditions. It combines models and observations which allow high temporal and spatial resolution.

3.5 *Fuel consumption*

The last step in the presented methodology is estimation of fuel consumption. This is done using shop test results from the main engine onboard the vessel.

4 SOURCES OF ERROR

Each step in the simulation process, i.e. from the occurrence of weather to calculation of fuel consumption, is a potential source of error and deviations from the measured data. These errors are caused by physical phenomena not taken into account in the simulation, or models that are not able to capture and sufficiently describe the system state and underlying factors. This section provides an overview of the most prominent sources of error and their influence on fuel consumption estimates.

4.1 *Hydrodynamics*

Replicating vessel performance in a sea way presents great modelling challenges. For propulsion system fuel consumption, our main concern is related to the resistance and propulsion efficiency.

4.1.1 *Added resistance*

Added resistance of ships in a seaway is notoriously difficult to estimate due to the complex interaction process between the waves and the ship hull. The two applied methods, strip-theory and pressure integration, have limited accuracy in certain scenarios due to their underlying assumptions. Strip-theory is known to give conservative estimates of added resistance (Fathi & Hoff 2017), implying a conservative estimate of required power. Coefficients for following and stern quartering seas are found to be considerably larger for strip-theory than the equivalent pressure integration coefficients for the case study vessel. The pressure integration approach requires an accurate description of the flow surrounding the hull. Added resistance coefficients are calculated using 15-degree increments for relative wave heading, interpolating for intermediate headings during simulation.

4.1.2 *Propulsion coefficients*

As a ship advances through waves, the wake field is influenced by the motion of the hull and the incident wave induced particle velocity. Significant changes in propulsion performance can therefore be expected (Taskar et al. 2016). These effects are not captured by the presented methodology due to the assumption of steady-state propeller inflow conditions for a given ship speed described by the calm water test results.

4.1.3 *Steering losses*

Manoeuvring causes an increase of resistance due to rudder drag and hull angle of attack relative to the direction of travel. The hydrodynamic model applied in the simulation does not account for these effects, and the contribution to required power is hard to estimate, as there are no information regarding rudder use and relative angle of attack in the monitoring data. The monitoring system does however specify the vessel state/mode, allowing us to disregard periods where the vessel is in manoeuvring mode close to port.

4.2 *Weather data*

Even though the hindcast database relies on state of the art meteorological services, we can not say with certainty that the weather events occurring in the simulation coincide perfectly with the real voyage weather. In addition, the six-hour time resolution of the weather data can cause significant errors if conditions are rapidly changing in time and space. Figure 3d shows a comparison of relative wind speed calculated from hindcast data and measured data from the vessel.

4.3 *Vessel and machinery condition*

Vessel and machinery condition will certainly affect vessel performance. Marine growth, roughness and substrate fouling on the hull can cause a significant increase in resistance. Propeller fouling causes an increase in required power due to reduced efficiency. Machinery maintenance affect the fuel consumption and required power. As mentioned in section 3.2.1, the calm water resistance curve is calibrated using the measured propulsion power. Hence, the error in power estimation due to hull condition is minimized.

4.4 *Quasi-static estimation*

Quasi-static estimation of added resistance due to waves assumes a characteristic steady-state value to be present for the duration of the sea state. Added resistance is in reality a dynamic process, with significant transient loading in most commonly observed sea states. However, for the applied propulsion power, which is of more interest here, we do not expect the same rapid variation since the captain usually do not vary engine power settings between individual resistance peaks.

5 RESULTS

Simulation results and performance monitoring data are compared in figure 3-5. A comparison of the simulation and real voyage is presented in table 4.

Table 4. Voyage comparison

	Duration	Average speed	Distance	Consumption
	Hours	Knots	Nautical miles	%Case vessel total
Vessel	286.8	15.73	4514	100
GYMIR	287.0	15.71	4510	PI: 88.4 ST: 86.7

Vertical lines are used in figure 3d to indicate updates in weather data, occurring at six-hour intervals in the hindcast data applied in the simulation. Between these lines the simulation routine updates weather as a consequence of changes in vessel position, disregarding temporal changes. This causes a saw tooth-pattern clearly visible in most simulation variables. The most prominent cases occurs between time instant 100-130 and 230-280. In the first period, the simulated vessel is approaching an area with harsh weather, as seen in figure 2. The harsh weather is moving in the same direction as the vessel but remains fixed for six hours in the simulation. This

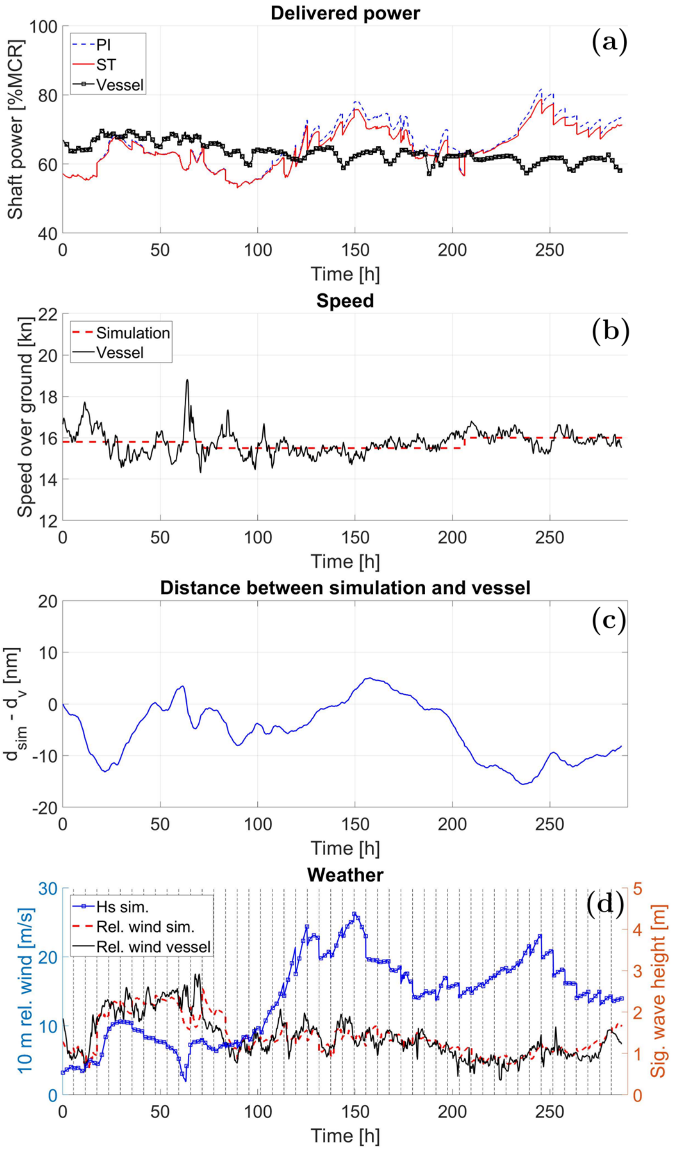

Figure 3. (a): Time series of propulsion power for case vessel and simulation for pressure integration (PI) and strip-theory (ST) calculations of wave added resistance. (b): Speed over ground for case vessel and simulation. (c): Distance between simulation and real vessel position. (d): Relative wind speed measured onboard case vessel. Significant wave height and relative wind speed from hindcast data applied in simulation.

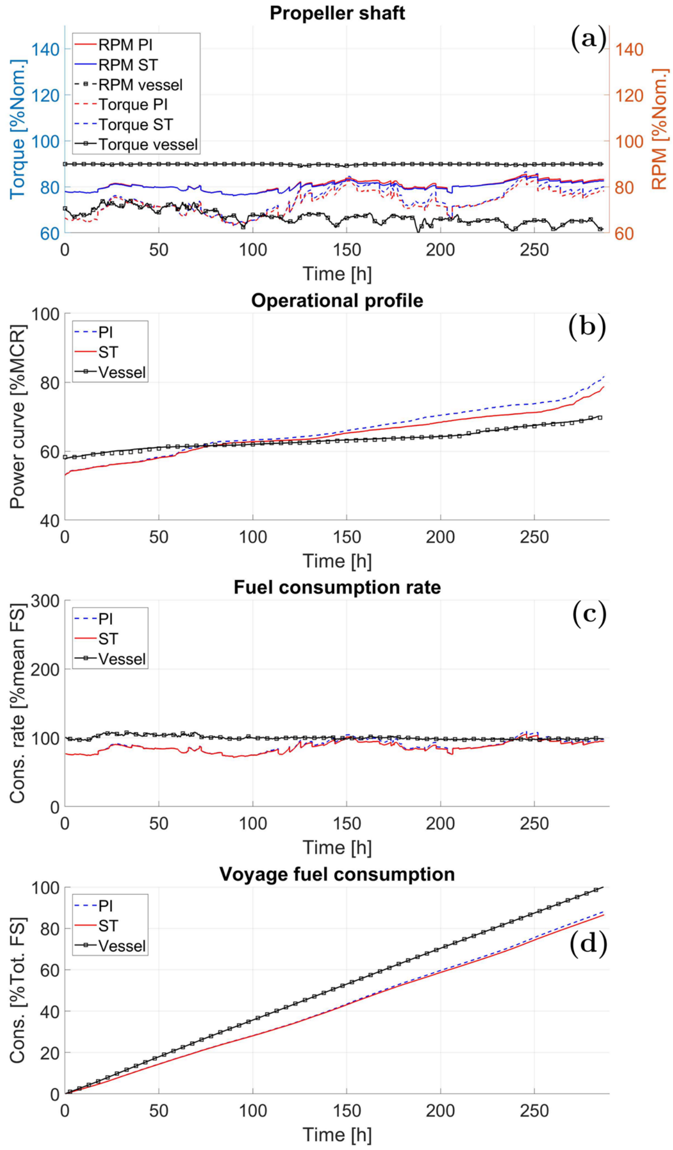

Figure 4. (a): Time series of propeller shaft characteristics from case vessel and simulation. (b): Operational profile taken as the sorted power output in figure 3(a). (c): Fuel consumption rate normalized using the mean consumption rate of the case vessel measurements. (d): Total fuel consumption normalized using the total voyage consumption for the case vessel. Each plot show results for pressure integration (PI) and strip-theory (ST) calculations of wave added resistance.

causes a steep increase in significant wave height as the vessel moves between updates in weather, and a sudden drop once the weather and storm location is updated. Between time instants 230-280, a storm is passing in front of the vessel at an angle relative to the direction of travel. We observe the same pattern here since the vessel sails for six hours into the storm between each weather update. As the weather is updated, the significant wave height is reduced as the storm moves further away to the side of the vessel.

The simulation propeller shaft torque and rpm characteristics differs from that measured onboard the case vessel, as seen in figure 4a. Lower and frequently varying RPM is applied in the simulation, as apposed to the measurements where the RPM is kept seemingly constant at 90% nominal rating. The case vessel has for the majority of the time a lower torque and a higher RPM than the simulation, indicating a lighter propeller load.

A clear difference between the simulation and real operational profile is that the simulator applies a wider range of power, both higher and lower than the case vessel. The logged data indicate a control setting of constant RPM for the real vessel while constant speed is used in the simulation. Higher rating occurs since the simulator opts for an increase in power rather than accepting a speed loss in harsh weather. Lower rating occurs in the calm waters at the start of the route, where the case vessel measurements show an increase in speed and the simulator holds a constant speed of 15.8 knots.

The fuel consumption results indicate that the use of the engine shop test curve in the simulations is too optimistic, as shown in figure 4c and 4d. Even for the high engine loads towards the end of the route, the simulation results indicate only a marginally higher fuel consumption than the case vessel measurements.

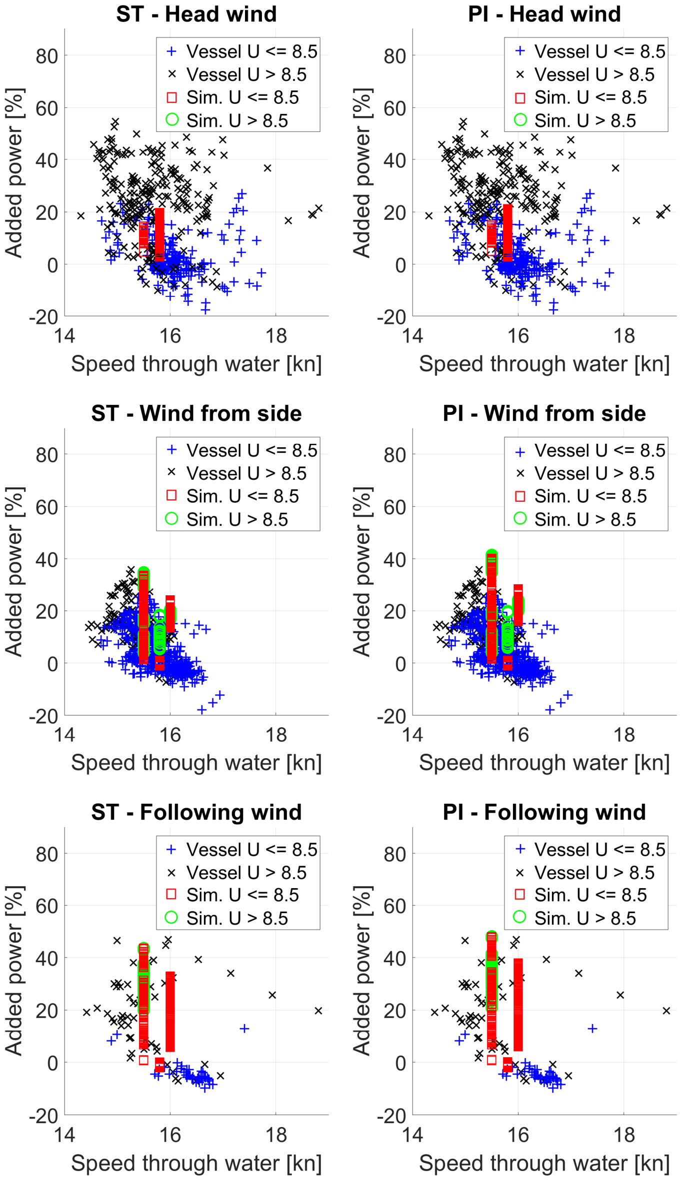

Figure 5. Added power relative to the calm water estimates from the vessel model sorted according to relative wind direction and wave added resistance calculation method. Results using strip theory (ST) in the left column and pressure integration (PI) in the right column. Each plot show cases for relative wind speed U above and below 8.5 m/s.

Overall, the fuel consumption in the simulation is approximately 12 % lower than the measured data.

Figure 5 show the added power relative to calm water power calculated using the steps outlined in section 3.2.1 and 3.3. The results are sorted in terms of relative wind direction due to the lack of information regarding wave condition in the case vessel monitoring system. The results indicate a reasonable level of agreement between simulation and case vessel. Pressure integration gives a higher power requirement than strip theory, shown in figure 3a to be most prominent for harsh sea states. The case vessel data have higher counts of negative added power than the simulation results for higher speeds. Since the resistance curve was calibrated such that the calm water power in the vessel model coincide with the case vessel power at approximately 16 knots, this indicate that the model is conservative in its prediction of power requirement at higher speeds.

6 DISCUSSION

Attempting to replicate the case vessel voyage, using what must be described as low-fidelity models, is clearly ambitious. Vessels moving in a seaway are subject to hydrodynamic effects notoriously difficult to estimate, affecting both resistance and propulsion characteristics. However, even though our models are built on significant simplifications, we do observe several similarities between the simulation results and measured data.

First of all, to have a basis for comparison, it is imperative to have similar weather conditions in our simulation as for the case vessel. Since the onboard performance measurement system is limited to wind measurements, we are limited to comparison between relative wind speed time series for verification. Figure 3d indicate that the wind measured on the vessel deck and the combination of historical data and calculation of relative wind speed are closely matched. We do however observe a distinct saw-tooth pattern in our weather time series as a consequence of the six-hour time discretization, which makes us question the validity of the intermediate results. These patterns are most prominent where the weather changes rapidly in time and space, i.e. along storm edges. For this reason, we recommend careful use of weather data with poor time resolution, especially in combination with scenarios where the probability of storms is high.

The quality of the simulation result is heavily dependent on the vessel model. In this case study, we have applied experimental data for both the resistance and propulsion characteristics. It can therefore be argued that this model has the best possible foundation for estimation of required power. This was done to factor out the differences in calm water, allowing us to test the quality of the added power estimates due to weather. The added power is applied to maintain speed when resistance is increased due to wind and waves. When comparing the operational profiles in figure 4b, it is apparent that the range of applied power is significantly wider than the case vessel measurements. This is partly due to the assumed constant speed policy applied in the simulation. The propulsion machinery onboard vessels are not regulated according to a set speed, but rather constant RPM. This causes an involuntary speed loss in the presence of harsh weather, but limits engine wear and fuel consumption. For instances of harsh weather in the historical weather data, we also observe a reduction in measured case vessel power, suggesting a voluntary speed loss. Both voluntary and involuntary speed loss are disregarded in the presented simulation routine, causing higher maximum power in the operational profile from the simulation.

The added resistance estimates are based on pre-processed coefficients calculated in ShipX using pressure integration and the Gerritsma & Beukelman method. These methods are known to overestimate the added resistance and resulting increase in required power. Our comparison with the case vessel measurements is based on calculation of added power relative to the calm water power estimates of the vessel model. Figure 5 indicate that the added power applied in the simulation is comparable to the measured data. However, our application of calm water propulsion characteristics is likely to reduce the required propulsion power relative to that of the real vessel. In addition, our simulation routine does not factor in the influence of current, affecting speed trough water. The difference between strip theory and pressure integration for the added resistance due to waves is most prominent in the rougher sea states. For the calm sea states early in the simulation, the difference in resulting propulsion power is found to be negligible. In more rough sea states the pressure integration method result in higher estimates.

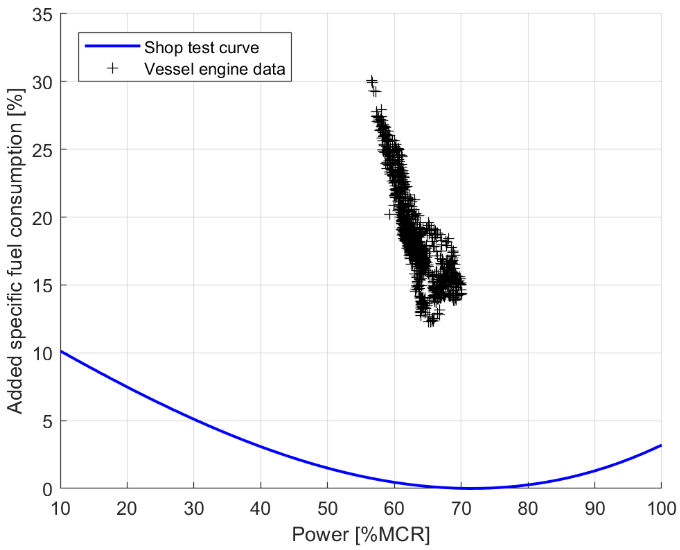

Figure 6. Added specific fuel consumption for shop test curve and case vessel measurements normalized using shop test curve minima.

Our fuel consumption estimates are found to be highly optimistic. Even though the simulator opts for an increase in power when subjected to harsh weather conditions rather than accepting a speed loss, the resulting estimated fuel consumption is lower than the case vessel measurements. Figure 6 shows the difference in added consumption between the measured data and the shop test fuel curve used in simulation. The shop test fuel curve is created based on tests performed in an engine laboratory, where the engine loads are reasonably static and the inlet and surrounding air temperatures are lower than for operating conditions. In addition, we lack information regarding engine service and maintenance history. The explanation for the pattern in figure 6 may therefore be the exposure to dynamic engine loads, higher air temperatures and reduced performance due to engine condition.

Overall, the most prominent causes of differences in required power and fuel consumption is the speed policy and fuel consumption curve. It is clear that further description of the weather-speed relationship must be included to get simulation behaviour more similar to realistic operations. As an alternative, requiring constant RPM seems to be an option according to the case vessel measurements presented here. Furthermore, especially with regards to long-term simulations, models that describe hull degradation and operational machinery performance should be included to achieve more realistic fuel consumption and emission estimates.

Further research, with a larger test program of routes, seasons, loading conditions and ship types, is needed to conclude on the validity of the methodology. The focus in this paper has been on the power requirements related to propulsion for a general cargo carrier, with emphasis on the impact of wind and waves. For more complex ship types, such as cruise vessels, the power requirement and fuel consumption must be evaluated while considering hotel and equipment power loads.

7 CONCLUSION

In this paper we have investigated the validity of quasi-static discrete-event estimation of operational profile and fuel consumption in early design. A case study was performed where we replicated the voyage of a general cargo carrier across the North Pacific. Our results indicate that even though the applied hydrodynamic models and quasi-static calculations are based on significant simplifications, the methodology provides knowledge regarding the vessel's performance in realistic operating conditions. Recommended improvements include vessel speed-policy, hull degradation and fuel curves that take the operational engine performance into account. However, further research including more routes, ship types and seasons are required to provide a general conclusion.

8 ACKNOWLEDGEMENT

The authors are grateful for the financial support from the Research Council of Norway through the Centre for Research based Innovation (SFI) Smart Maritime project number 237917. In addition, we are thankful for the comments our anonymous reviewers provided towards improving this article.

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