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A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping



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ABSTRACT

Voyage optimization is a practice to select the optimum route for the ship operators to increase energy efficiency and reduce Green House Gas emission in the shipping industry. An accurate prediction of ship operational performance is the prerequisite to achieve these targets. In this paper, a modified Kwon's method was developed to predict the added resistance caused by wave and wind for a specific ship type, and an easy-to-use semi-empirical ship operational performance prediction model is proposed. It can accurately predict the ship's operational performance for a specific commercial ship under different drafts, at varying speeds and in varying encounter angles, and then enables the user to investigate the relation between fuel consumption and the various sea states and directions that the ship may encounter during her voyage. Based on the results from the operational performance prediction model and real time climatological information, different options for the ship's navigation course can be evaluated according to a number of objectives, including: maximizing safety and minimizing fuel consumption and voyage time. By incorporating this into a decision support tool, the ship's crew are able to make an informed decision about what is the best course to navigate.

In this study the Energy Efficiency of Operation (EEO) is defined as an indicator to illustrate the ratio of main engine fuel consumption per unit of transport work. Two case studies are carried out to perform the prediction of ship operational performance for Suezmax and Aframax Oil Tankers, and the results indicate that the semi-empirical ship operational performance prediction model provides extremely quick calculation with very reasonable accuracy, particularly considering the uncertainties related to the parameters of interest for the case study data. Within the case studies, the additional fuel consumption caused by the combined hull and propeller fouling and engine degradation is included in the model as a time-dependent correction factor. The factor may assist the ship owner/operator to determine the hull coating selection, and/or the dry-docking and main engine maintenance strategy.

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1. Introduction

Energy efficient shipping is a prerequisite for the reduction of the Green House Gas (GHG) emissions to the levels anticipated within the next decades. The continuous growth of the world population and the increase number of developing countries led to the increasing dependence of the world economy on the international trade. For 2007, it was estimated that shipping emits 1046 million tonnes of CO₂ from exhaust emissions, accounting for 3.3% of the global CO₂ emission during that year. CO₂ emission from International shipping alone were estimated to account 2.7% of the global CO₂ emission in 2007, and the carbon dioxide emissions from international shipping was projected to triple by the year

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2050 (IMO, 2009). These findings alerted the International Maritime Organization (IMO) and led to the introduction of the first maritime energy efficiency regulations that entered into force on the 1st of January 2013 (IMO, 2011). The aim of the regulations is to reduce carbon emissions by decreasing the amount of fuel consumed. This can be achieved by optimizing the ship's design, deploying new energy efficient technologies, or by improving the ship's operation. The regulations require both new and existing ship above 400 GT to have a ship specific Ship Energy Efficiency Management Plan, SEEMP (IMO, 2012).

An additional drive towards a more energy efficient shipping is the requirement to remain competitive within a fierce market. Although marine engines used for commercial shipping use the cheapest type of 'bunker fuel', the cost of IFO 180 has risen sharply with other petroleum products, increasing from \$170/t in 2002, and from \$230/t in 2005, to nearly \$700/t in July 2014 (Bunker Index, 2014). With such high fuel prices, the bunker costs could account for 50–60% of a ship's total operating costs (Wang and Teo,

2013). The rising fuel price has supported the increasing need for energy efficiency to survive in highly competitive and capacity oversupplied shipping market.

It is important to realize that an optimum route cannot only be evaluated in terms of fuel consumption. Normally, the voyage optimization has multiple, often conflicting, objectives, such as: minimizing costs regardless of arrival time; punctual time of arrival; safety; and passenger comfort. In most cases, improving one objective may reduce efficiency of another. Each attribute therefore requires a weighting of importance. For example, some shipping companies' business models prioritise on-time arrival and shorter transit times over reduced fuel consumption. For other companies, providing a 'green service' has a higher priority.

Most existing techniques and software solutions for voyage optimization extract the ship's operational performance from a database build on results from similar ships (in terms of type and size). However, the performance of each specific ship in various voyage conditions (speed, fouling and propulsion system degradation, and draft) may be quite different, especially under severe weather conditions. This highlights the need for real-time, flexible ship-specific modeling in order to provide increased accuracy of ship operational performance prediction for voyage optimization. Another common disadvantage of many existing voyage optimization software solutions is that they only present to the ship's master the recommended route. The users of the software cannot test their intended route and compare its performance to the software recommended route. As a result, captains may develop mistrust to the recommended route and proceed according to their own judgement.

Voyage optimization software can be evaluated according to:

- Technical status – the accuracy and practicability of ship operational performance prediction.
- User acceptance – the user friendliness.
- Economic performance – the evaluation of fuel saving based on voyage optimization.

These three evaluation principles are also the objectives of the research presented. This paper focuses on the development of an accurate and practical ship operational performance prediction model that can be used to select the optimum routes for minimum fuel consumption, taking into consideration average ship speed, encountering sea states and voyage time.

The ship operational performance model presented in this paper is developed by the modifying Kwon's method (Kwon, 2008) using a case study of ship's operational data (i.e. ship's noon reports) and sea trial data. The Kwon's method (Kwon, 2008) is an empirical method for the prediction of added resistance due to sea state and wave directions. The case study of ship's operational data is taken as the reference for the modified Kwon's method. This modified model can predict the ship's operational performance for a given wave and weather condition at different speeds, drafts and wave encounter angle in a semi-empirical way.

A decision support tool has been developed to select the optimum course according to the users' preference. The users can influence the selection of the optimized route by providing different weightings to the optimization objectives (see optimum route a–e listed in Fig. 10).

Besides the development of the ship operational performance prediction and the optimum routes selection, a time-dependent fuel consumption increase rate after ship dry-docking has been identified, which may be helpful in monitoring ship fouling and engine degradation condition. The identified fuel consumption rate of increase will further assist shipping companies with planning dry-docking and engine maintenance scheduling.

2. State of the art

2.1. Semi-empirical approaches for predicting the added resistance

The prediction of ship total resistance in waves (R_T) can typically be performed in two steps (ITTC, 2011):

- Prediction of still water resistance, R_{SW} , at speeds of interest.
- Prediction of added resistance in waves, R_{AW} , at the same speeds.

The prediction of ship total resistance in waves is obtained by summing the above mentioned predicted values:

$$R_T = R_{SW} + R_{AW} \quad (1)$$

several methods are available to determine the still water resistance of ships. In the presented analysis the Holtrop and Mennen method (Holtrop and Mennen, 1982) has been used.

The increase in resistance caused by waves, greater than the still water condition, can also be calculated using several methods, including Strip Method, Radiated Energy Method, Rankine Panel Method, Cartesian Grid Method, CFD Method, Experiment Method, Empirical Method, and Semi-empirical Method. In the following section, some of the semi-empirical methods for added resistance prediction are reviewed.

2.1.1. The approximated – Salvesen method

The Salvesen method (Salvesen, 1978) provides a basic formula for the added resistance calculation.

$$R_{AW} = -\frac{i}{2}k \cos \beta \sum_{j=3,5} \xi_j \{F_j^{i*} + \hat{F}_j^D\} + R_7 \quad (2)$$

where \hat{F}_j^{i*} , is the complex conjugate of the Froude-Krilov part of the exciting force and moment, and \hat{F}_j^D is very similar to the diffraction part of the existing force F_j^D , k is the wave number, β is wave heading direction, and ξ_j is the motion calculated by the strip theory. R_7 is given by

$$R_7 = -\frac{1}{2} \xi_1^2 k \frac{\omega^2}{\omega_e} \cos \beta \int_L e^{-2kds} (b_{33} + b_{22} \sin^2 \beta) dx \quad (3)$$

Where, ξ_j is the incident wave amplitude, b_{33} and b_{22} are the sectional heave and sway damping coefficient, d is the sectional draft and s is the sectional-area coefficient. Details of formula 2 and 3 are presented in Salvesen (1978).

The Salvesen method is able to provide accurate results for the longer waves regions ($L/\lambda < 1.5$). Therefore, to extend its use for short wave length regions a correction is added to the original Salvesen method to produce the approximated – Salvesen method (Matulja et al., 2011). The correction contains an approximated formula proposed by Faltinsen et al. (1980):

$$R_{AW} = \frac{1}{2} \rho g \left(1 + \frac{2\omega U}{g}\right) \int_{L1} \sin^2 \nu n_1 dl \quad (4)$$

where, $L1$ is non shadow zone of the water plane area, U is ship speed, ω is Encounter frequency, n_1 is X component of the inward normal n to the water line, and ν is the angle between the tangent to the water line and the x axis.

The final step of the approximated – Salvesen method is:

$$R = a \quad \text{for } L/\lambda \leq 1 \quad (5)$$

$$R = a + b \quad \text{for } 1 < L/\lambda \leq 2 \quad (6)$$

$$R = b \quad \text{for } L/\lambda > 2 \quad (7)$$

where,

$$a = -\frac{i}{2}k \cos \beta \sum_{j=3,5} \xi_i \{F_j^* + F_j^D\} \quad (8)$$

$$b = \frac{1}{2}\rho g \left(1 + \frac{2\omega U}{g}\right) \int_{L1} \sin^2 v n_1 dl \quad (9)$$

However, formula 8 is only valid in wave heading direction $\beta \approx 180^\circ$ if the speed U is high, and for $\beta \approx 90^\circ$ if the speed U is low. The full range of heading directions experienced by a ship in practice are therefore not accounted for with this method. This is a disadvantage for accurate ship performance prediction. Furthermore, the definition of the term ‘short waves region’ is loosely defined as it is related to the ship length, further increasing the uncertainty in the added resistance prediction.

In an overall view of the approximated – Salvesen method, the Faltinsen’s approximated formula was used to evaluate wave reflection added resistance and then the Salvesen’s results were combined with the wave reflection added resistance in a semi-empirical way.

2.1.2. Fuji-Takahashi method

The Fuji-Takahashi method (Fuji and Takahashi, 1975) is a semi-empirical method considering the drift force acting on an upright barrel and then correcting these forces with a coefficient for ship shape & speed. The drift force is calculated using the following equation:

$$D = \frac{1}{2}\rho g \xi_a^2 \int_{-B/2}^{B/2} \sin^2 \beta dy \quad (10)$$

where, ξ_a is the amplitude of the incident waves, ρ is sea water density, g is gravitational acceleration, β is an inclination angle for x -axis on the hull, B is ship breadth.

The added resistance generated by the reflected wave R_{AW} is calculated by:

$$R_{AW} = \alpha_1(1 + \alpha_2)\frac{1}{2}\rho g \xi_a^2 \int_{-B/2}^{B/2} \sin^2 \beta dy \quad (11)$$

$$\alpha_1 = \frac{\pi^2 I_1(kd)^2}{\pi^2 I_1(kd)^2 + K_1(kd)^2} \quad (12)$$

$$\alpha_2 = 5\sqrt{F_n} \quad (13)$$

where, α_1 , α_2 , d , and k denote coefficients for the draft effect, ship speed effect, draft, wave number, and F_n is Froude number.

The semi-empirical formula of Fuji-Takahashi is a widely used to predict ship added resistance, but the added resistance due to reflected waves acting on the bulbous-bow is not included. This may lead to significant error in predicting the added resistance as bow flare above the water surface may change the reflected wave properties, along with the presence of the bulbous bow under water.

2.1.3. Kuroda-Tsujimoto-Fujiwara-Ohmatsu-Takagi method

Based on the investigation of Fuji and Takahashi’s (1975) semi-empirical method, Kuroda et al. (2008) proposed an improved expression for the added resistance due to wave reflection (R_{AW}). The formula is as follows:

$$R_{AW} = \frac{1}{2}\rho g \xi_a^2 \alpha_d(1 + \alpha_U)BB_f(\chi) \quad (14)$$

where, α_d is effect of draft and frequency, $1 + \alpha_U$ is effect of advance speed, B_f is bluntness coefficient, and χ indicates ship heading direction.

Kuroda et al. modified the terms for added resistance due to wave reflection by taking into account the effect of draft, wave encounter frequency and speed of advance. The oblique waves were also applied on the method. Kuroda-Tsujimoto-Fujiwara-Ohmatsu-Takagi method requires tank testing in short waves and therefore the effect of hull form above water line is captured in the added resistance calculation. However, the added resistance due to reflected waves acting on bulbous-bow is still not included.

2.1.4. A simplified method to calculate added resistance based on Gerritsma and Beukelman’s method

Gerritsma and Beukelman’s method (Gerritsma and Beukelman, 1972) considers radiated energy to calculate added resistance.

The added resistance is calculated with the following expression:

$$R_{AW} = \frac{-k \cos \beta^2}{2\omega_e} \int_0^L b' |V_{z_b}|^2 \phi x_b \quad (15)$$

where, k is wave number, β is heading angle, ω_e is frequency of encounter, L is ship’s water line length, $|V_{z_b}|$ is the amplitude of the velocity of water relative to the strip, b' is the sectional damping coefficient for speed, x_b is x coordinate on the ship.

The Gerritsma and Beukelman’s method (Gerritsma and Beukelman, 1972) is one of the most widely used added resistance modeling methods that utilize Strip Theory, and it provides an accurate added resistance prediction across the different ship types. However, for added resistance calculation, calculating ship motions by strip theory is complex and might be unnecessary in some applications. To address this issue a further simplified method developed by Alexandersson (2009) was proposed for the added resistance calculation. The simplified method uses the Gerritsma and Beukelman’s method, applying to a large series of case studies to determine the added resistance, then using linear regression, a series of simplified formulas to determine the added resistance are derived. This simplified method is therefore a semi-empirical method as it uses the results from the Gerritsma and Beukelman’s analytical method (Gerritsma and Beukelman, 1972) and combines it with regression techniques.

Although the semi-empirical method simplifies the more complicated strip theory calculations whilst still providing relatively stable predictions for added resistance, the limitations of the method still exist, such as the prediction accuracy decreases in bow/beam/following waves and high frequency waves; trim of the ship is not included.

2.1.5. Summary of semi-empirical methods to predict added resistance

In an overview of the existing semi-empirical methods for added resistance prediction, they either combine empirical methods with analytical results, or update existing empirical method with analytical method, in a semi-empirical way. The common disadvantage for these methods is that they are not able to predict the added resistance accurately with different encounter angle. The short or long wave length is also a critical parameter for selecting the right formulas. The semi-empirical methods, which involve tank tests, may sharply increase the modeling cost as it may take much longer time for added resistance estimation.

2.2. Voyage optimization in routing service

Extensive surveys of research on ship routing and scheduling have been carried out about every 10 years (Ronen, 1983, 1993; Christiansen et al., 2004, 2013). Fagerholt et al. (2010) proposed mathematical models to optimize speed on a ship route. However, the fuel consumption was approximated by a cubic function,

which is not accurate enough for voyage optimization. Padhy et al. (2008) predicted the speed loss due to weather condition using sea-keeping computing tools. The pre-computed Response Amplitude Operator (RAO) was employed in Dijkstra's algorithm to obtain optimum route in a given sea-state. Hinnenthal and Clauss (2010) utilized strip-theory and wave spectra to generate RAO, and predicted the added resistance through a statistical evaluation method for voyage optimization. Avgouleas (2008) estimated mean added resistance in waves with the aid of SWAN1, which is an advanced frequency domain CFD code using Rankine Panel Methods. Then the Iterative Dynamic Programming algorithm was employed to achieve voyage optimization. The ship's response based routing and high fidelity computational hydrodynamic performance based routing require huge amount of computations, long simulation time and the up-to-date ship conditions are not involved. It seems to be immature for accurate and efficient voyage optimization. Larsson and Simonsen (2014), and Shao (2013) adopted Kwon's method (Kwon, 2008) to predict added resistance for weather routing. However, Kwon's method is a generic approach for large number of commercial ship types. Therefore, regarding the limited accuracy of added resistance and ship operational performance modeling for specific commercial ship, the accuracy of voyage optimization can be further increased.

The ship routing service can generally be categorized into ashore based routing services, on-board based routing services and the combination of ashore and on-board routing services. Table 1 provides an overview of available ship routing service.

3. Data description

Ships have to collect operational data on a daily basis, known as ship logs and ship reports (often referred to as noon reports as they are typically recorded every 24 h at noon). The type of data fields that are included in the ship reports cover: date/time of the report, ship position, and estimated time of arrival, arrival/departure port, observed distance, achieved speed, mean draft, Beaufort Number, wind direction, and total main engine fuel consumption

per day. There is no standard for the recording of operational parameters within the ship reports and therefore the content tends to differ between companies compared to the parameters mentioned above. These parameters contain a vast amount of uncertainty. This uncertainty originates from the methods used to obtain their measurement, the type of measurement, human error and the assumptions made during analysis. Some of the uncertainties related to the parameters of interest for the case study data are discussed here:

- **Achieved speed:** the achieved speed is calculated by dividing the observed distance recorded by the report duration. The speed is therefore given as an average value for the whole report duration. It does not take into account the speed profile which, due to the approximately cubic relationship between ship speed and power, could have a significant influence over the fuel consumed during the reporting period. The achieved speed is also the speed over ground and therefore, the effects of currents and tides are not taken into account. To improve the accuracy of performance prediction, the speed through water should be obtained.
- **Beaufort Number (BN):** the Beaufort measurement itself contains uncertainty as one number is used to represent a range of wave heights and sea conditions. More accurate added resistance performance prediction methods depend on the wave height as an input along with the type of sea spectrum (including surface waves and developed seas). Additional uncertainty is created with the measurement of Beaufort Number being made via judgement of the sea conditions typically out of the window on the bridge by the officer on watch. Not only is this measurement subjective as it is a judgement, it is also observed from some distance away from the sea surface. There is also ambiguity as to whether the Beaufort Number recorded is representative of the conditions at the observation point, or an average of the conditions observed over the report duration.
- **Wind direction:** recording of the wind direction is typically aided by the use of an anemometer. Obstructing super

Table 1
Exemplary compilation of routing service or decision support systems (Hinnenthal and Clauss, 2010).

Service provider	Installed Location	Service/System	Weather forecast	Route planning	Route optimization	Ship monitoring	Data recording
Aerospace and Marine International (USA)	ashore	Weather 3000, internet service, maps displaying fleet and weather information	X				X
Weather Routing Inc. (USA)	ashore	routing advice and Dolphin navigation program combined with a web-based interactive site	X	X			
Finish Meteorological Institute (Finland)	ashore	weather and routing advice for the Baltic sea	X	X			
Fleetweather (USA)	ashore	Meteorological consultancy	X	X			X
Metworks Ltd. (UK)	ashore	meteorological consultancy	X	X			
Applied Weather Technology (USA)	on-board	BonVoyage System	X	X			
Euronav (UK)	on-board	seaPro, software or fully integrated bridge system	X	X			X
Germanischer Lloyd, Amarcon B.V. (Germany, Netherlands)	on-board	SRAS – Shipboard Routing Assistance System	X	X		X	
Transas (UK)	on-board	ship guard SSAS, software or integrated to bridge system	X	X		X	X
Norwegian met office, C-Map (Norway, Italy)	on-board	C-STAR	X	X			
US Navy (USA)	on-board	STARS	X	X	X	X	
Meteo Consult (Netherlands)	on-board	SPOS - Ship Performance Optimization System	X	X	X	X	
Oceanweather INC., Ocean Systems INC. (USA)	on-board	VOSS – Vessel Optimization and Safety System	X	X	X	X	
Weather News International, Oceanwaves (USA, Japan)	ashore & on-board	voyage planning system VPS and ORION, routing and optimization software	X	X	X		
Swedish Met and Hydrology Institute (Sweden)	ashore & on-board	Seaware Routing, Seaware Routing Plus and Seaware EnRoute Live	X	X		X	
Deutscher Wetterdienst (Germany)	ashore & on-board	MetMaster, MetFerry, routing system, advice on demand	X	X	X		

structure in different wind directions is known to produce inaccuracies in the measurement, along with variations in wind strength at different heights. Uncertainty due to averaged measurements also applies in the same way as for Beaufort Number. Furthermore, the wind direction is assumed to be the same as the wave direction, which may be true in most instances of surface waves, but it could also be very different for swell direction. To improve sea and wind condition measurements the wave, swell and wind direction and strength or height, should be recorded.

- Ship heading direction: the angle between the direction of ship bow and the North Pole. The angle is measured clockwise from north, in degrees from 0° to 359°.
- Encounter angle: derived from wind direction, which is relative to the ship. It is also known as the weather direction, as presented in Fig. 1.
- Main engine fuel consumption: fuel flow meters improve the accuracy of fuel consumption measurements if they are calibrated and working correctly. However, in most cases the main engine fuel oil consumption is recorded by tank sounding. Not only could the measurement contains a vast amount of inaccuracy, but there is room for error in the tank sounding calculations and the recorded value is susceptible to transcription error and intentional alteration for various reasons.

Despite all of the uncertainties described, the parameters in the ship reports provide an insight into the operating conditions of the ship in sailing and thus provide a value to performance prediction modeling.

4. Model description

The method for a new semi-empirical approach proposed within this paper that can be used for modeling ship operational performance is introduced in this section. A modified Kwon's method is developed to enhance the accuracy of added resistance prediction. This method is based on Kwon (2008) added resistance modeling method but is updated to take into account ship specific characteristics by utilizing the analysis of collected operational data. The first step of the semi-empirical method is the estimation of the still water resistance. This is followed by the prediction of added resistance due to wind and wave conditions.

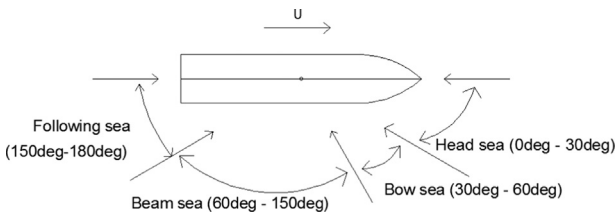


Fig. 1. Encounter angle.

Table 2
Direction reduction coefficient C_β due to weather direction.

Weather direction	Encounter angle (deg)	Direction reduction coefficient C_β
Head sea (irregular wave) and wind	0–30	$2C_\beta = 2$
Bow sea (irregular wave) and wind	30–60	$2C_\beta = 1.7 - 0.03((BN - 4)^2)$
Beam sea (irregular wave) and wind	60–150	$2C_\beta = 0.9 - 0.06((BN - 6)^2)$
Following sea (irregular wave) and wind	150–180	$2C_\beta = 0.4 - 0.03((BN - 8)^2)$

4.1. Still water resistance modeling

The well-known Holtrop and Mennen's Method (Holtrop and Mennen, 1982) is used to estimate the still water resistance of the ship. This method is widely used to calculate the total still water resistance of a ship with a good accuracy for a wide range of ship types, sizes, hull forms and for a range of Froude numbers.

4.2. Added resistance modeling

Kwon (2008) added resistance model is an approximate method for predicting speed loss of a displacement type ship due to added resistance in weather conditions (irregular waves and wind). The advantage of this method is that it is easy and practical to use.

The weather effect, presented as speed loss, compares the speed of the ship in varying actual sea conditions to the ship's expected speed in still water conditions. It is expressed in the following way using Kwon's method for modeling added resistance (Kwon, 2008):

$$\frac{\Delta V}{V_1} 100\% = C_\beta C_U C_{Form} \quad (17)$$

$$V_2 = V_1 - \left(\frac{\Delta V}{V_1} 100\% \right) \frac{1}{100\%} V_1 = V_1 - (C_\beta C_U C_{Form}) \frac{1}{100\%} V_1 \quad (18)$$

where,

V_1 : Design (nominal) operating ship speed in still water conditions (no wind, no waves), given in m/s.

V_2 : Actual ship speed in the selected weather (wind and irregular waves) conditions, given in m/s.

$\Delta V = V_1 - V_2$ Absolute speed loss, given in m/s.

C_β : Direction reduction coefficient, dependent on the weather direction angle (with respect to the ship's bow) and the Beaufort Number (BN), as shown in Table 2.

C_U : Speed reduction coefficient, dependent on the ship's block coefficient C_B . The loading condition and the Froude Number (F_n), as shown in Table 3.

C_{form} : Ship form coefficient (C_{form}), as shown in Table 4.

Table 3
Speed reduction coefficient C_U due to Block coefficient C_b .

Block coefficient C_b	Ship loading conditions	Speed reduction coefficient C_U
0.55	normal	$1.7 - 1.4Fn - 7.4F_n^2$
0.6	normal	$2.2 - 2.5Fn - 9.7F_n^2$
0.65	normal	$2.6 - 3.7Fn - 11.6F_n^2$
0.7	normal	$3.1 - 5.3Fn - 12.4F_n^2$
0.75	loaded or normal	$2.4 - 10.6Fn - 9.5F_n^2$
0.8	loaded or normal	$2.6 - 13.1Fn - 15.1F_n^2$
0.85	loaded or normal	$3.1 - 18.7Fn + 28.0F_n^2$
0.75	ballast	$2.6 - 12.5Fn - 13.5F_n^2$
0.8	ballast	$3.0 - 16.3Fn - 21.6F_n^2$
0.85	ballast	$3.4 - 20.9Fn + 31.8F_n^2$

Table 4
Ship form coefficient C_{form} due to ship categories and loading condition.

Type of (displacement) ship	Ship form coefficient
All ships(except container ships) in loaded loading condition	$0.5BN + BN^{6.5}/(2.7 \times \Delta^{2/3})$
All ships(except container ships) in ballast loading condition	$0.7BN + BN^{6.5}/(2.7 \times \Delta^{2/3})$
Container ships in normal loading conditions	$0.7BN + BN^{6.5}/(22 \times \Delta^{2/3})$

The Kwon's method (Kwon, 2008) provides a general introduction to the calculation of ship speed loss in different weather and sea conditions based on the ship's hull form, encounter angle and sea state. However, the method is not able to provide a very accurate prediction of added resistance for each specific ship. Therefore, the modified Kwon's added resistance modeling method developed and presented in this paper includes unique direction reduction coefficients, speed reduction coefficients and ship form coefficients for specific ship type and size. These coefficients are determined from the analysis of the recorded ship operational data. The case studies in Section 6 will be used to verify that the modified Kwon's method is a practical way to provide increased accuracy for the prediction of a specific ship's fuel consumption at varying speeds, encounter angles, drafts and sea states.

4.3. Ship operational performance modeling

Since the ship still water resistance has been predicted utilizing Holtrop and Mennen's Method (Holtrop and Mennen, 1982), the relation between vessel speed (U), total still water resistance (R_{total}), and the required effective power (P_E) can be extracted.

$$P_E = R_{total} * U \quad (19)$$

As the added resistance has been modeled by utilizing the modified Kwon's method, the speed loss under varying drafts, Beaufort Number (BN) and encounter angles has been modeled for specific commercial ship. The corresponding original still water speed (V_{cosw}) can be calculated by combining the actual ship speed (V_{actual}) in a seaway and speed loss (V_{loss}) due to added resistance.

$$V_{cosw} = V_{actual} + V_{loss} \quad (20)$$

Thus, under specific BN and ship heading direction, there is a corresponding original still water speed (V_{cosw}) for an actual ship speed (V_{actual}). Based on formula 19, for each still water speed, there is a corresponding required effective power. The relationship between actual ship speed (V_{actual}) and required effective power (P_E) can be extracted.

From effective power the required brake power (P_B) of main engine can then be determined as:

$$P_B = \frac{P_E}{\eta_T} \quad (21)$$

where η_T is the total power transmission efficiency (from brake power of main engine to effective power):

$$\eta_T = \eta_H * \eta_O * \eta_R * \eta_S \quad (22)$$

where, η_H is the hull efficiency; η_O is the open water efficiency; η_R is the relative rotative efficiency; η_S is the shaft efficiency.

The four efficiencies above can be generally estimated through empirical formulae. However, from the point of view of accurate operational performance prediction for specific commercial ship, the utilization of Speed-Power Curve in the sea trial documents can be used to extract total power transmission efficiency. When sea trial documents are available, for each specified speed, the total power transmission efficiency can be calculated using the Holtrop and

Mennen's method (Holtrop and Mennen, 1982) to determine the effective power and the Speed-Power Curve from sea trial documents to read the corresponding brake power of main engine. Since the total power transmission efficiency has been determined, the relationship between actual ship speed and required engine power under varying sea states is generated.

For each specific ship, the corresponding main engine performance documents contain the expected fuel consumption based on ISO reference conditions, which illustrate the Specific Fuel Oil Consumption (SFOC) with corresponding engine load, engine power and engine speed. The ship main engine Fuel Consumption Rate (FCR) can be determined as:

$$FCR = P_B * SFOC \quad (23)$$

Finally, the ship main engine fuel consumption rate under varying speeds, sea states, drafts, and ship heading directions can be predicted.

4.4. Weather and sea state modeling

To use the performance prediction model described as part of a voyage optimization model, a source of weather and sea state forecasting needs to be identified as an input. A 'GRIB2' ocean weather forecast file from the National Oceanic and Atmospheric Administration (NOAA) (2015) is used for this purpose. The decoding program has been written in house to read and output the global ocean weather forecast, as presented in Fig. 2. The information contained in the file includes significant wave height, swell, wind speed, and directions.

A flow diagram of the semi-empirical method proposed in this paper to predict the ship operational performance is shown in Fig. 3. The dashed boxes on the left indicate the inputs for this proposed model, and the modeling steps are shown in the solid boxes. The relationship flow between the inputs and modeling steps has been illustrated with arrows.

5. Voyage optimization

In this section, the development of grids system and utilization of the proposed performance prediction model in selecting the optimum route are illustrated. At this stage, the optimum route is defined as the one with minimum fuel consumption regarding given average ship speed, encountering sea states and voyage time.

5.1. Setting up grids

A grid system is able to clearly present the potential routes on ship navigation charts. At present, the grid system was plotted on world map, which is developed using the Google maps API (Google maps API, 2015). From start point to destination point, each possible route is equally divided into $n+1$ legs by n stages; the nodes in one stage are equally distributed with unique longitude. On each stage, the distance between the adjacent nodes is Δx , as presented in Fig. 4. The number of the stages and the quantity of nodes in each stage are determined with specific voyage area, total distance of route and the availability of computing capacity. Since

the grids system for specific voyage has been set up, and the departure time and ship speeds during each stage are decided by users, the weather information for the corresponding time at which the ship is expected in that area will be downloaded into each node by the in house program. Thus the information at each node includes its location (latitude and longitude) and the weather and sea forecast information. The combination of sea direction and ship heading direction at two consecutive nodes determines the encounter angle.

5.2. Route selection

As mentioned in Section 1, the user's preferences are incorporated into the development of the decision support system by using a process of weighting the attributes that are most important to them (e.g. passage time, fuel consumption). Commonly, the route with minimum fuel consumption is very popular in route selection. Based on the grids system, a ship performance model developed in house is able to predict the total main engine fuel consumption of each potential route. The outputs of this model also include the estimated time of arrival (ETA), sea state, encounter angle, and average speed. At this stage, the development of automatic optimization implements in progress. Depending on the preferences/priorities of shipmasters, such as lowest BN, shortest ETA, encounter angle with most head sea and bow sea, or the combination of these objectives with different weightings, we are able to manually select the route with minimum fuel consumption

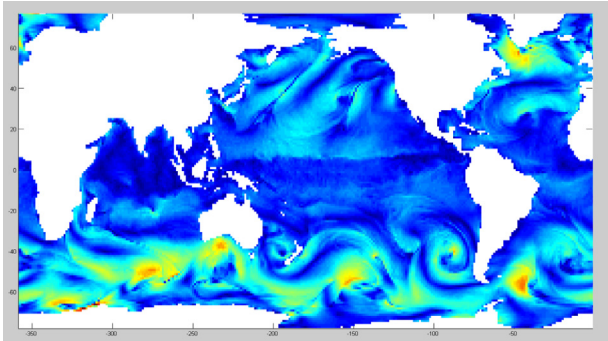


Fig. 2. Screenshot from decode program, graph of global ocean weather forecast.

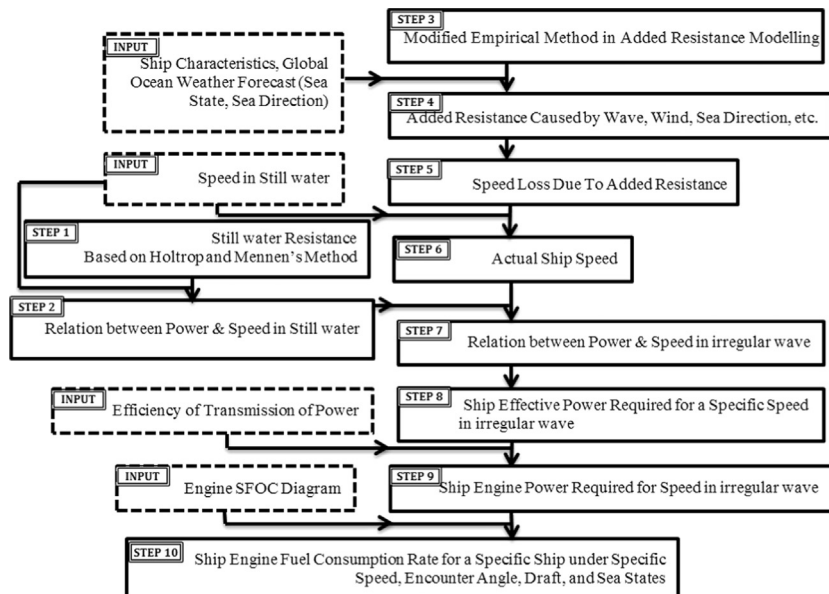


Fig. 3. Analysis diagram of the proposed semi-empirical ship operational performance prediction model.

considering weather and sea conditions. One case study of the optimum route selection has been carried out, and the results are presented in Fig. 10. Based on the grids system presented in Fig. 4, a simulation of the ship performance has been carried out. The simulation was run on a typical desktop PC with a 3.4 GHz Intel i7 CPU in serial model. With 36 nodes and 30625 potential routes, and the simulation time was around 1.5 h.

6. Results and discussion

6.1. Case studies of semi-empirical ship operational performance model

In this study, the 'Energy Efficiency of Operation' (EEO) is defined as the indicator used to illustrate the main engine fuel consumption efficiency and the ship's operational performance.

$$EEO = \frac{FC}{m_{\text{cargo}} \times D} \quad (24)$$

where, FC is the main engine fuel consumption (tonnes), m_{cargo} is cargo carried (tonnes), and D is the distance in nautical miles corresponding to the cargo carried or work done.

An advantage of using the EEO as an indicator is that it contains many of the same elements and could be easily converted to the Energy Efficiency Operational Index (EEOI), which is recommended within the Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2012).

The basic expression for EEOI for a voyage is defined as:

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{\text{cargo}} \times D} \quad (25)$$

Where, j is the fuel type, FC_j is the mass of consumed fuel j at one voyage, and C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j .

In order to verify the accuracy of the semi-empirical ship operational performance model, the predicted EEO based on the modified Kwon's method and the recorded EEO using recorded operational data from noon reports were compared in the following two case studies. The predicted EEO and the recorded EEO were compared under same conditions, such as Beaufort Number, speed and encounter angle.

6.1.1. Case study 1 – ‘Suezmax oil tanker A’

A comparison between the predicted EEO (using the modified Kwon’s method) and recorded EEO (using data from the noon reports) for the ‘Suezmax oil tanker A’ is shown in Fig. 5.

The average difference between the predicted EEO and recorded EEO of ‘Suezmax oil tanker A’ by using the developed method is 5.12% compared to the average difference of 14.7% using the original Kwon’s method. Under each sea state (sorted by Beaufort number), the predicted EEO and recorded EEO for each weather direction are compared: a good agreement between predicted and recorded value can be observed as shown in Fig. 6 using BN=3 as an example.

6.1.2. Case study 2 – ‘Aframax oil tanker B’

The comparison between the predicted EEO and recorded EEO for the ‘Aframax oil tanker B’ is shown in Fig. 7.

The average difference between predicted EEO and recorded EEO of ‘Aframax oil’ tanker by using the developed method is 7.15% compared to the average difference of 21.6% using the original Kwon’s method. Under each sea state (sorted by Beaufort number), the predicted EEO and recorded EEO for each wind direction are compared. A good agreement between predicted and recorded value can be observed as shown in Fig. 8 using BN=4 as an example.

6.2. Fouling effect and engine degradation

Through the comparison between the predicted EEO and recorded EEO in case study 1 and case study 2, it has been verified

that the proposed semi-empirical ship operational performance model provides very reasonable prediction results. However, two factors that are not taken into account within the semi-empirical ship operational performance model are ship hull and propeller fouling effect and main engine degradation conditions. These factors are likely to be a source of error causing the predicted fuel consumption rate using the semi-empirical method to be lower than the rate of fuel consumption recorded in the noon reports. This error in prediction can be taken as the percentage increase in fuel consumption due to hull and propeller fouling and engine degradation, which are known to increase over time between maintenance periods. For the case study of Suezmax oil tanker A and Aframax oil tanker B, the errors are presented in Fig. 9.

The trendline A and trendline B indicate that there is a time-dependent factor that increases the total recorded fuel consumption and thus decrease the energy efficiency of the ships. This time-dependent factor can predominantly be assumed to be due to the effect of hull and propeller fouling together with engine degradation. As shown in Fig. 9, the coefficient of determination of trendline A is 0.984, and that of trendline B is 0.9961, both trendline A and B follow very similar trends and increase rates. This illustrates a common rate of the increase in fuel consumption rate caused by hull and propeller fouling and engine degradation. Currently, due to the lack of ship dry-docking reports and main engine maintenance reports, we cannot separate the time-dependent fuel consumption increase rate due to hull and propeller fouling and engine degradation separately. However, the identification of this time-dependent increase in fuel consumption rate can help us to provide up-to-date information about the

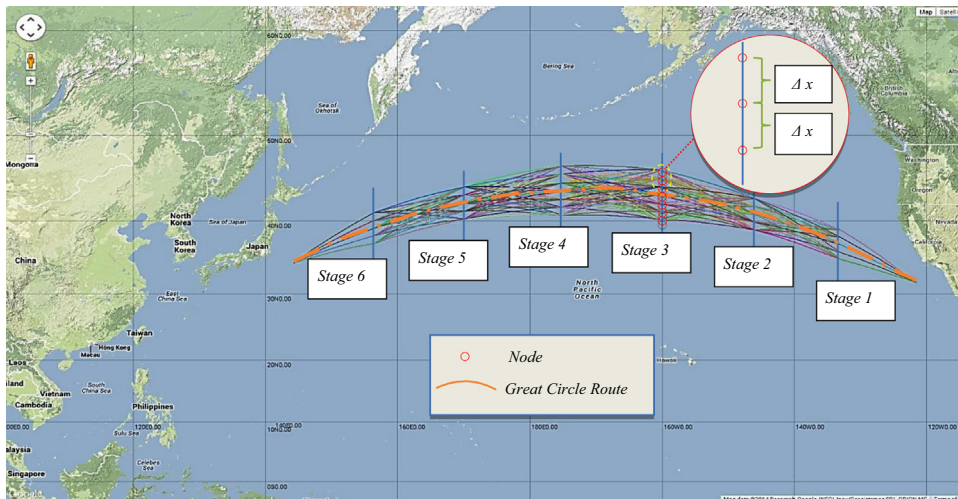


Fig. 4. Grids example for the route between Los Angeles Offshore and Chiba, Japan.

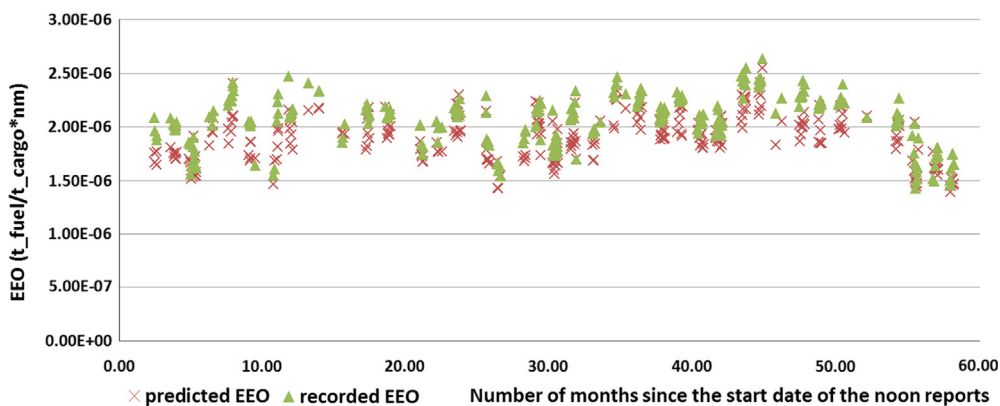


Fig. 5. Comparison between predicted EEO and recorded EEO of ‘Suezmax oil tanker A’.

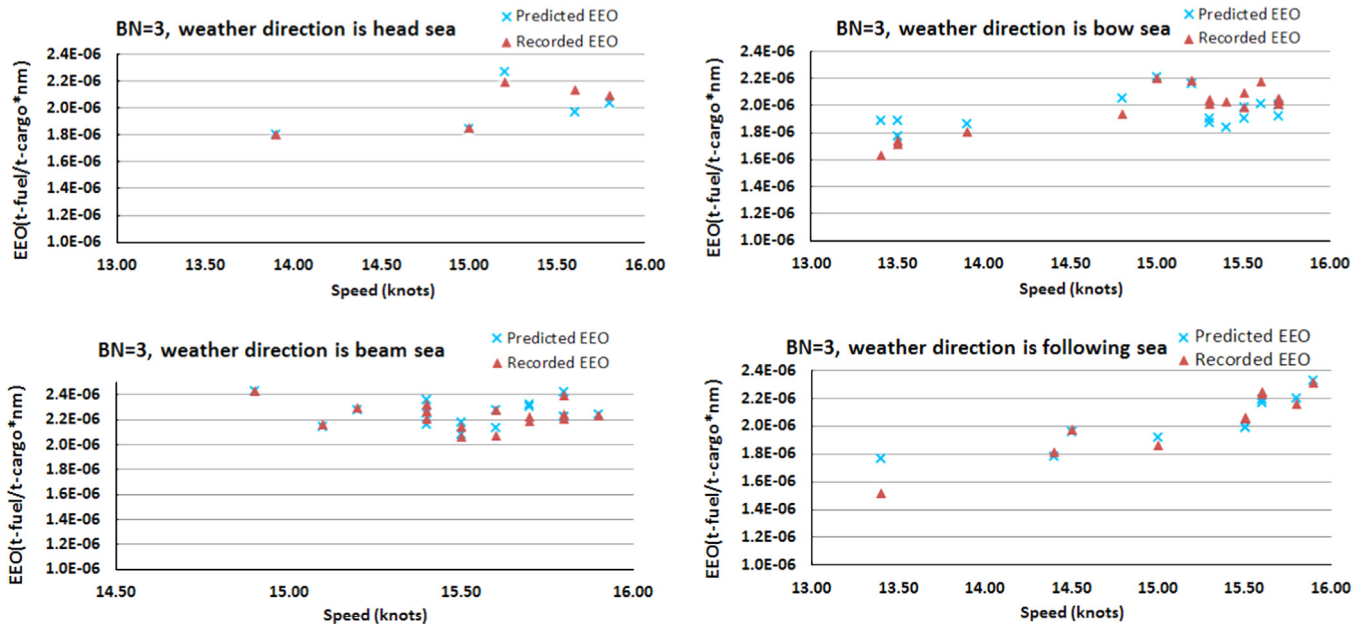


Fig. 6. Comparison between predicted EEO and recorded EEO of 'Suezmax oil tanker A' with each weather direction under the BN=3.

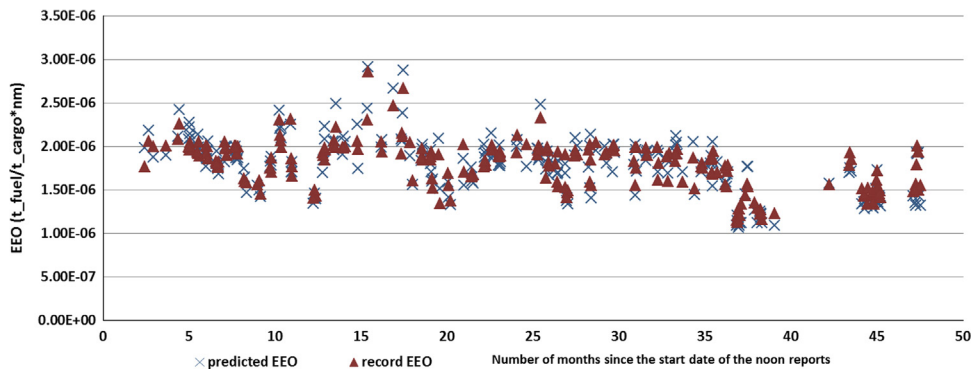


Fig. 7. Comparison between predicted EEO and recorded EEO of 'Aframax oil tanker B'.

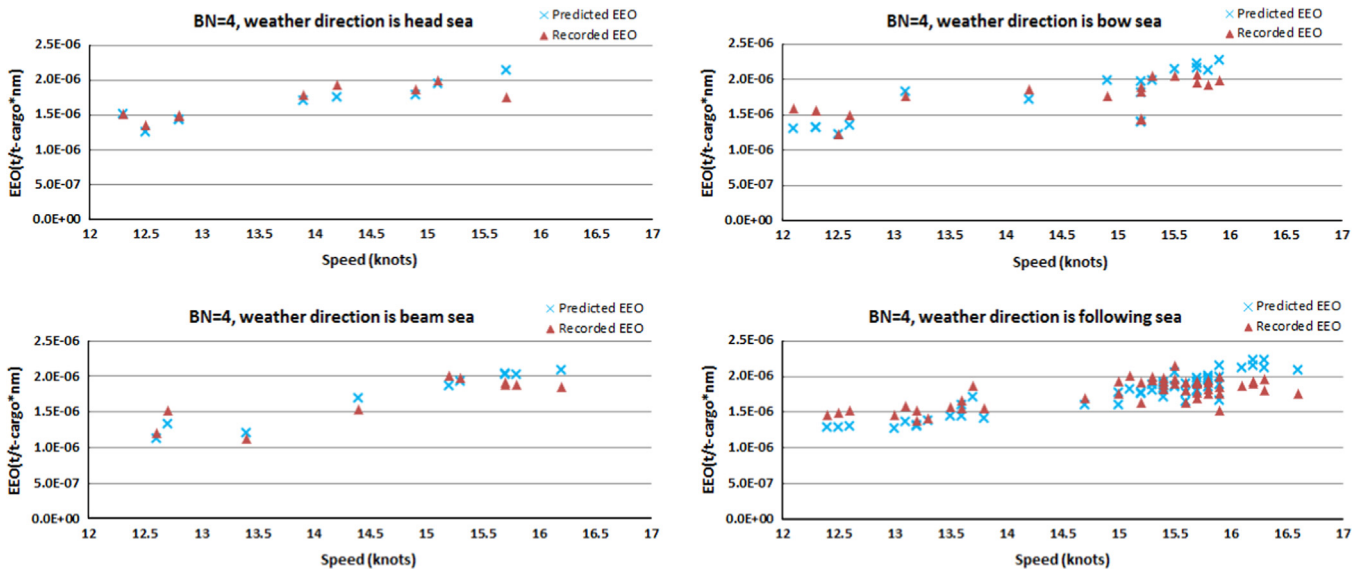


Fig. 8. Comparison between predicted EEO and recorded EEO of 'Aframax oil tanker B' with each weather direction under the BN=4.

combined influence on ship performance. The engine data on engine degradation is extremely difficult to obtain and therefore it is a very challenging task to separate the engine degradation and ship fouling and remains a future task to develop a separate modeling.

6.3. Case study of routes selection

With a given departure date and time, draft, fixed average speed, specific ship noon reports and sea trial data, the recommended route with minimum fuel consumption can be identified to the shipmaster as follows (Fig. 10):

- Route a – the blue route is the route with lowest Beaufort Number (low risk to damage the ship and/or its deck cargo; high comfort to passengers) and low fuel consumption.
- Route b – the green route is the Great-Circle Route – with shortest distance between two ports on earth as well as the route with shortest time.
- Route c – the violet route is the route with most head sea and bow sea.
- Route d – the brown route is the route with lowest fuel consumption regardless of voyage time.
- Route e – the red route is the frequently used route as recorded in noon report.

The ship operational performances of these five selected routes have been compared, as shown in Table 5 by using the developed model. The encountered Beaufort Number (BN) and Heading Direction of each route have been listed. The fuel consumption of the selected optimum routes can achieve 10% less than the recorded route. As the average voyage speed is fixed, the voyage durations of the selected optimum routes are very close, but much less than the recorded route.

7. Conclusion

As the SEEMP is mandatory since 1st January 2013 for all ships engaged in international trade while at the same time there is fierce competition in shipping market, it is almost a necessity to improve the existing solutions and approaches for voyage optimization.

In this paper, a modified Kwon's method has been developed to estimate the ship's added resistance considering the specific ship type. Based on the modified Kwon's method, as well as ship noon reports and sea trial data, a semi-empirical ship operational performance prediction model has been developed to provide accurate ship operational performance prediction under varying drafts, speeds, encounter angles, sea states, fouling effect and engine degradation conditions for each specific ship. Through the

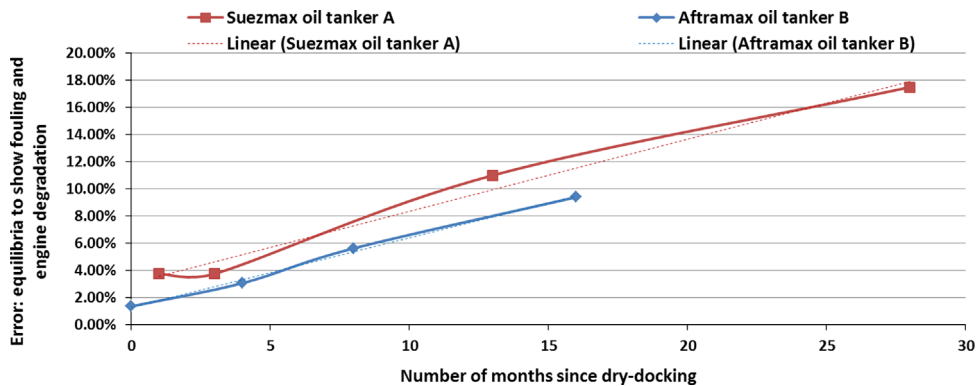


Fig. 9. Error between predicted total fuel consumption of each voyage and recorded one since dry-docking for both Suezmax oil tanker A and Aframax oil tanker B.

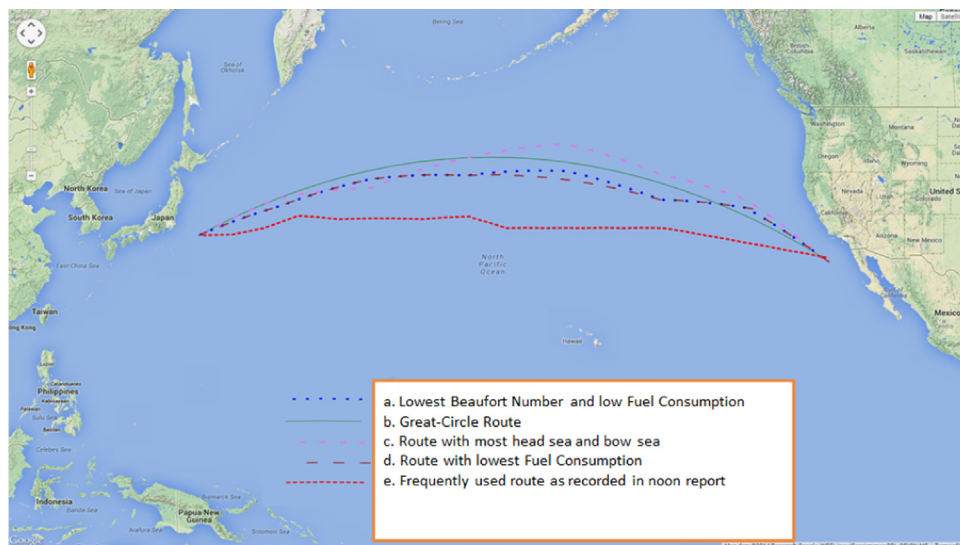


Fig. 10. Optimum route selection based on shipmasters' preference.

Table 5
Comparison of ship operational performance between the selected optimum routes and recorded route.

The encountered Beaufort Number (BN), Heading Direction with given departure date & time, loading condition and fixed average speed	Route a		Route b		Route c		Route d		Route e	
	BN	Direction	BN	Direction	BN	Direction	BN	Direction	BN	Direction
	5	Bow	5	Bow	5	Head	5	Bow	5	Bow
	5	Beam	5	Beam	5	Bow	5	Beam	7	Bow
	3	Bow	4	Bow	5	Bow	3	Bow	6	Head
	3	Beam	3	Beam	4	Beam	3	Beam	5	Head
	3	Beam	4	Beam	4	Beam	3	Beam	5	Head
	3	Beam	3	Beam	4	Bow	3	Beam	5	Head
	1	Head	1	Head	2	Head	1	Head	2	Bow
Voyage Duration (h)	367.7		366.1		368.5		367.3		392	
Main Engine Fuel Consumption (t)	555.5		558.3		580.4		554.9		623.5	
% of Fuel saving compared to Route e	10.90		10.46		6.91		11.01		0	

two case studies of Suezmax oil tanker A and Aframax oil tanker B, it has been verified that the proposed semi-empirical model is very fast and very reliable on ship operational performance prediction, and may also be used to examine the fouling effect of hull and propeller, and engine degradation trends. Together with a grids system and real-time climatological information, the ships' various courses can be evaluated according to a number of objectives including maximization of safety, minimization of fuel consumption and voyage time. Finally, by utilizing a decision support tool, the shipmasters as well as shore based route planners may now select the optimum voyage route with minimum fuel consumption considering weather and sea conditions.

8. Future work

Since the weather is stochastic, the ship performance simulation needs to be repeated with the weather forecast update frequency, which is normally 4 times a day. As the actual voyage course may not follow the suggested route absolutely, and the latest updated weather forecast may not exactly follow previous forecast, minor changes of the suggested route are expected. However, for a long distance voyage, due to the big uncertainties of long-term weather forecast, bigger changes may be expected by comparing the actual voyage route after arrival with the suggested route before departure.

It would be interesting to examine the applicability of the semi-empirical ship operational performance prediction model to other ship sizes and ship types. Therefore, more case studies will be carried out. Following the development of the ship added resistance model, the next step would be the development of a self-refined ship performance database. The database would be able to store the fuel consumption rate under each sea state, speed, encounter angle, draft and ship conditions (fouling conditions of hull and propeller, and main engine degradation conditions). The feedback from shipmasters would also be recorded to update the ship operational performance records. Using the self-refined ship performance database, the users will be able to extract relevant ship operational performance for a given sea state, speed, draft, encounter angle and ship conditions. With the minimum inputs, the improved accuracy in performance prediction will increase the benefits to be gained from using such systems for energy efficient solutions.

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