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CASE STUDY BASED INVESTIGATION ON IMPACT OF ADDED WAVE RESISTANCE MODELS ON VESSEL POWER CONSUMPTION AND ROUTING

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ABSTRACT

Shipping is an important factor for the climate crisis, since its exhaust gases account for over three percent of global greenhouse gas (GHG) emissions. This is reflected in the GHG Strategy of the International Maritime Organization (IMO), which requires the maritime industry to adopt measures to ensure an uptake of near-zero GHG solutions by 2030 and reach net zero GHG emissions by 2050. To achieve this goal, all available energy saving means, such as alternative fuels, novel propulsion systems, hull modifications, as well as operational measures, e.g. slow steaming, fleet management, just-in-time port calls and voyage optimization, need to be considered. With regard to the quantification of power demand and emissions, as well as utilization in voyage optimization tools, prediction models that can accurately quantify ship resistance and power consumption with minimal computational effort are essential. While robust, semi-empirical models for vessel calm water resistance are firmly established, added resistance in waves is often addressed via models of very low fidelity. Thus, this paper explores the impact of different added wave resistance models on the power consumption prediction and moreover their effect on the weather routing. For this purpose, multiple approaches for the calculation of added wave resistance and in turn power demand, such as simple one-equation models and semi-empirical models, which account for irregular 2D directional wave spectra, are compared. Utilizing a set of voyage calculations, the influence of the respective models on overall power consumption prediction and routing details is discussed. The results suggest that even simple models, as long as they account for the directionality of the waves, can yield satisfactory results.

Keywords: wave added resistance, empirical modelling, route optimization, A* Algorithm

1. INTRODUCTION

Climate change presents a well known threat to the security and prosperity, as well as economic and social development, of the world. A major driving factor is greenhouse gas (GHG) emission. Human activities, namely the burning of fossil fuels for electricity, heat and transportation, are largely responsible for the increase in GHG in the atmosphere over the last 150 years [1]. In response, the United Nations (UN) General Assembly has its firm intention to combat climate change and the associated changes in the environment within the framework of the Sustainable Development Goals [2]. Similar goals were adopted in the GHG Strategy of the International Maritime Organization (IMO), which will require the maritime industry to transition from fossil fuels towards zero-carbon alternatives within this century [3].

To achieve this ambitious goal, all available energy saving means, such as alternative fuels, novel propulsion systems, hull modifications, as well as operational measures, e.g. slow steaming, fleet management, just-in-time port calls and weather routing, need to be taken into account. In the near future, special attention will be given to operational measures, since these can be applied without integrating additional large-scale components in the ship. Effective implementation of operational measures is highly dependant on corresponding decision support systems, which in turn require fast and accurate simulation models to facilitate their effectiveness and functionality during day-to-day operations. The calculation of a vessel's power demand naturally depends on the ship resistance, which can be separated into contributions of calm water resistance, additional resistance due to interaction effects between hull and propulsor, as well as additional resistance due to environmental conditions, primarily waves and wind [4]. While Computational-Fluid-Dynamics (CFD) based approaches for all resistance components are available and yield highly accurate results [5], their usage in this context is often rendered infeasible due to the associated computational effort and requirements regarding input information. Consequently, vessel performance is usually assessed by means of empirical models and machine learning approaches [6–10]. While calm water resistance is usually calculated using firmly established methods, such as those from Holtrop & Mennen [11] or Guldhammer & Harvald [12], which usually yield error ranges below 15%, added resistance in waves is often addressed using highly simplified methods.

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In the most simple case, the added resistance is not directly calculated. Based on the sea-margin, the installed power of the vessel and a quadratic relationship between wave amplitude and additional power demand, the resulting power demand in seaway is calculated. It should be noted this a simplistic approach, in which the applicability to a wide range of vessels based on minimal input data is paramount. A slightly more sophisticated approach is given by the Townsin-Kwon formula, see e.g. [4], which calculates added wave resistance based on the vessel's calm water resistance, displacement, significant wave height, and a step-wise dependency on mean wave direction. IMO and International Towing Tank Conference (ITTC) recommend usage [13, 14] of the SNNM method [15], a semi-empirical method which takes into account multiple wave and vessel related parameters to provide a more adequate estimation of the added wave resistance in regular waves. Resistance in natural seaway is obtained utilizing the assumption that the wave field is composed of multiple regulars waves. Here, a spectral distribution is assumed for wave period and wave direction. Recently, the SNNM method has been improved by Kim et al. [16]. The improved method performs better at estimating added wave resistance at high wave heights, resonance frequencies and low speeds. Finally, potential theory based codes, see e.g. PDStrip [17], can be employed to efficiently calculate added resistance in waves.

Simulation tools enabling implementation of operational measures, such as just-in-time port calls and weather routing, need to integrate methods for vessel performance calculation with suitable approaches to optimize vessel speed and route. Multiple approaches, among them Dynamic Programming, the Dijkstra Algorithm, the A* Algorithm as well as genetic algorithms have successfully been applied for this purpose [18]. Naturally, time-resolved environmental conditions along the simulated routes need to be made available to the algorithms. A suitable source is given by European Union's climate data store [19].

In this work, ship wave resistance and in turn power demand of the well known KCS container ship were assessed and route optimization was performed by means of DLR's *Odyssa Framework*. Odyssa is a holistic framework for the design and investigation of future-oriented ships and ship operation, including modules to account for vessel performance, energy system, techno-economic evaluation, as well as operational measures to minimize fuel consumption, e.g. route optimization. The paper is aimed at providing a suitable tool to support investment decisions regarding novel energy systems and operation strategies by enabling accurate prediction of energy demand and comparison of energy saving measures. The method provided by Kim et al. [16], the Townsin-Kwon formula, as well as a simple relation between vessel speed, wave height and power were integrated and employed to assess vessel performance. Making use of the European Union's climate data store, the A* Algorithm was utilized to perform route optimization for the KCS vessel on the route from New York to Lisboa. The influence of the wave added resistance models on the routing algorithm was investigated. The results suggest that the method by Kim et al., provided an irregular seaway is assumed, as well as the Townsin-Kwon fomula yield results with moderate discrepancies while weather routing based on a simple power relation delivers large differences in route power consumption.

2. WAVE AND WIND ADDED RESISTANCE

The method presented by Kim et al. [16] obtains results for wave resistance by blending the SNNM method and a method from Lang & Mao [20]. For the blending, hyperbolic functions based on ship type, ship and wave length, as well as wave angle of attack are employed. Both sub-methods separate overall added wave resistance due to regular waves into contributions from wave reflection (diffraction) and ship motion (radiation), taking into account significant wave height, wave period, wave angle of attack, as well as several vessel related parameters, such as block coefficient and bow opening angle. A detailed description of the method is omitted here for the sake of brevity, but can be found in the respective original papers [15, 16, 20]. Added resistance in irregular waves is calculated based on the assumption that the irregular seaway is composed of a superposition of regular waves of different frequency and direction

$$R_{AW} = 2\int_{-pi/2}^{pi/2}\int_0^{\infty}\frac{R_{AW,reg}(\omega,\alpha,v_S)E(\omega,\alpha)}{\zeta^2}d\omega d\alpha, \quad (1)$$

with

$$E(\omega,\alpha) = S(\omega)D(\alpha). \quad (2)$$

In this case, v_S is the ship velocity and ω, α, as well as ζ refer to wave frequency, angle of attack and wave amplitude, while E is the directional wave spectrum, which is composed of the standard frequency spectrum S and the angular distribution function D. For the frequency spectrum, a JONSWAP spectrum, see e.g. [21], is utilized, while the angular distribution function is of the cosine-power type, see e.g. [13]. This way, wave peakedness as well as spreading factor of the natural seaway are taken into account. Here and in the following, calculations based on the Kim method and the assumption of irregular waves are denoted by "Kim, irreg", while calculations based on the Kim method and the assumption of regular waves are denoted by "Kim, reg".

Another relatively simple method to calculate added resistance in waves, here and in the following referred to by "Townsin-Kwon" is given by the Townsin-Kwon formula (see e.g. [4]):

$$R_{AW} = ((\frac{\Delta v_S}{v_S}+1)^2-1)R_{CW}, \quad (3)$$

and

$$100\frac{\Delta v_S}{v_S} = (0.7BN + \frac{BN^{6.5}}{22\nabla^{\frac{2}{3}}})\mu. \quad (4)$$

Here, R_{AW} and R_{CW} are added wave resistance and calm water resistance, while BN, ∇ and μ denote Beaufort number, ship displacement and weather reduction factor, respectively. The Beaufort number is calculated based on significant sea wave height via a simplified relation given by Jalkanen et al. [22], while the weather reduction factor is calculated based on the Beaufort number, see e.g. [4]. $\frac{\Delta v_S}{v_S}$ is the velocity loss due to presence of waves.

Wind resistance is calculated by means of the method proposed by Blendermann [23]. Since the KCS vessel design does not include the ship superstructure, suitable values for lateral and frontal areas from similar ships were utilized. The influence of wind on resistance, power demand and routing is not discussed.

3. POWER CALCULATION

The method employed for calculation of the vessel power demand depends on the modelling of environmental effects. In case any of the methods presented in Sect. 2 are utilized (methods "Kim, reg", "Kim, irreg", "Townsin-Kwon"), first the required thrust is calculated according to

$$T(1-t) = R_{CW} + R_{AW} + R_W. \tag{5}$$

Here, the calm water resistance R_{CW} is derived using the Holtrop & Mennen [11] method and R_W refers to wind resistance. For the thrust deduction factor t, a generic value of 0.1 is used. The rudder is not considered. The matching power demand is obtained based on experimentally measured open water results [24] for the KCS propeller provided by Schiffbau-Versuchsanstalt Potsdam (SVA). Based on the data, the characteristic curves of thrust coefficient, torque coefficient and efficiency are modelled as third-order polynomials. Given required thrust and propeller inflow speed, the equations are solved for their zero points to deliver the necessary rotational speed. The propeller inflow speed is obtained using a generic value of 0.15, as recommended in [4], for the wake fraction. Thus, the interplay of propeller and hull is assumed to be fixed and Eq. (5) can be solved as a simple balance equation instead of an equilibrium that depends on the operation state of the propeller. Based on the rotation rate of the propeller, the torque is calculated directly from the characteristic curves and the required power is then obtained via

$$P = 2\pi Q n. \tag{6}$$

Here, P refers to power demand, Q is required torque and n is rotation rate.

Another method of calculating the vessel power demand is to make use of simple relations between vessel speed, wave height and power demand. Results obtained with this method will be referred to by "Power Relation". The propulsive power associated with calm water resistance is estimated based on the propulsive power at the ship design speed, see

$$P_{CW} = \frac{P_{CW,v_D}}{v_D^3} v_S^3. \tag{7}$$

In this case, P_{CW,v_D} denotes the power required to operate the ship at design speed v_D in calm water conditions, calculated with Eq. 5 and Eq. 6. For practical purposes, this value would be taken as the motor power installed on the vessel. The propulsive power associated with wave resistance is obtained by

$$P_{AW} = \frac{0.15 P_{CW,v_D}}{\zeta_{max}^2} \zeta^2. \tag{8}$$

To calculate the wave related power component, a power share of 15% of the calm water propulsion power at design speed along with a maximum wave amplitude of $\zeta_{max} = 3m$ is assumed. Overall power is then simply calculated by

$$P = P_{CW} + P_{AW}. \tag{9}$$

It should be noted that this method for estimating power demand is highly simplified and is likely to deliver only a rough estimation of actual power demand. For both presented approaches to calculate the required power, considerations regarding the power supply system are neglected. This means efficiencies related to power supply, e.g. gear box efficiency, are not taken into account. The power supply system is assumed to be able to provide any requested power demand.

While it would be possible to integrate the power prediction directly into the routing algorithm, usage of a Ship Response Matrix (SRM) as an intermediary is favorable with regard to computational effort and re-usage of calculation results in multiple simulations. For all possible combinations of a given range of environmental parameters and ship speeds, the required power is calculated and the results are saved in the SRM. Provided the range of the input parameters for the SRM is resolved with suitable accuracy, results for arbitrary parameter values within the given range can then be obtained by means of interpolation.

4. ROUTING ALGORITHM

To obtain an optimized route, a variant of the A* Algorithm, which makes use of time dependent costs, is applied. The original A* Algorithm [25] can be understood as an extension of the Dijkstra Algorithm. Both are path-finding algorithms, which employ a probabilistic road-map approach. They rely on a map consisting of nodes, their connections, as well as a cost associated with traversing from a node along the respective connection to its neighbour. The objective of the algorithms is to find the cost-optimal path to travel from a given start node to an end node. At basic, the A* Algorithm manages two lists, an *open list* to keep nodes to be checked and a *closed list* to keep nodes that have been checked. Beginning with the start node, the neighbours of the currently investigated node are added to to the open list, provided they are not included in the closed list. At this point, the closed list only contains the start node. Investigating a node refers to the process of calculating the cost of each of its neighbours. For each neighbour, the cost is calculated by means of

$$F(c) = G(c) + H(c). \tag{10}$$

Here, c refers to the current (neighbour) node. G is the actual minimum cost for the path from the starting node to the current node, while H is a heuristic function that estimates the cost to reach the end node from the current node. In the simple case of finding a distance-wise optimal path, often the euclidean distance is chosen as the heuristic. Thus, F is the estimated total cost of the path from starting node to end node. Among the nodes in the open list, the node with the lowest estimated total cost belongs to the optimal path and is added to the closed list. The open list is cleared and then re-populated with the neighbours the just identified node before the algorithm enters the next iteration.

As long as the heuristic is *consistent*, the A* algorithm is guaranteed to find the globally optimal path for a given path map with fixed costs. A heuristic is consistent, if the estimated cost $F(c)$ from current node to end node are never overestimated and if the estimated costs $F(c)$ of a node c are never greater than the sum of the actual costs $G(c \longrightarrow s)$ to go from node c to successor node s and the estimated cost $F(s)$ of node s. However, this only holds true for maps with fixed costs. In case of route optimization for ships, since the weather conditions are dependent on the velocity of the ship and the chosen path, the costs are not fixed. In this case, the identified solution is only optimal in a truly heuristic sense. Additionally, route optimization requires the identified solutions to be constrained regarding travel time.

For the current work, energy consumption is utilized as the cost function. The heuristic function that estimates the cost to reach the end node from the current node c reads

$$H(c) = \frac{D_c}{v_D} P_{CW,D}. \tag{11}$$

Here, D_c is the distance from the current node to the end node within the path network, evaluated by means of a prior-run Dijkstra / A* Algorithm search for the shortest distance path, while v_D is the ship design speed and $P_{CW,D}$ is the corresponding vessel power demand in calm water conditions. The actual cost to reach a node c is given by

$$G(c) = \sum_{l=1}^{i} E_l + \sum_{j=1}^{k} \frac{d_j}{v_{i+1}} P_j \quad \text{for} \quad i \geq 1, \tag{12}$$

and

$$G(c) = \sum_{j=1}^{k} \frac{d_j}{v_{i+1}} P_j \quad \text{for} \quad i = 0. \tag{13}$$

Here, i denotes the number of connections between nodes in the closed list. Equation 13 refers to the very start of the algorithm, when only the start node is included in the closed list. When calculating the estimated cost of each neighbour (i.e. the current node) of an investigated node, the value of i does not change. l is an index denoting each of the connections to reach the investigated node. Index j denotes segments of length d_j of the connection from the investigated node to the current node. The segmentation is introduced to sample weather data at adequate time intervals instead of only at the investigated node. A sufficient number of segments k must be chosen to ensure that weather conditions do not change excessively. v_{i+1} is the velocity all segments are traversed with and P_j refers to the power in the respective connection segment, calculated according to the considerations in Sect. 3. E_l is the energy accumulated over all segments to traverse the respective node connection. Figure 1 illustrates these considerations. For all i connections the required

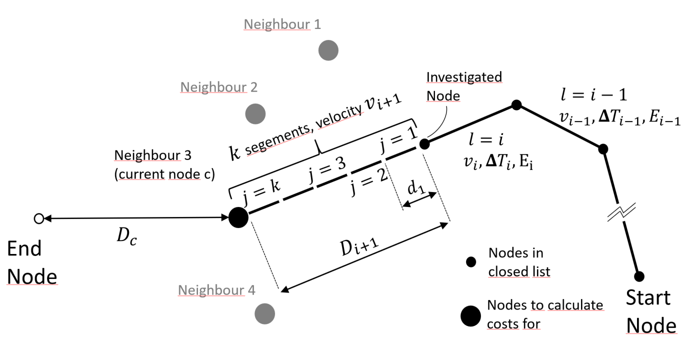

FIGURE 1: ROUTING ALGORITHM SCHEMATIC

energy has been calculated in previous steps and is thus known. For the connection between investigated node and current node, the environmental conditions at the respective segment, at the time the segment is reached, are considered. For the connection from investigated node to the current node, the velocity v_{i+1}, which, together with the weather conditions, will then dictate the power demand, needs to be decided. For all segments of a connection, the same velocity is used. To obtain this velocity, an additional equation, with a similar structure as Eq. (10) and Eq. (12), is introduced, see

$$\vec{T_{ETA}} = \sum_{l=1}^{i} \Delta T_l + \frac{D_{i+1}}{\vec{v_P}} + \frac{D_c}{\vec{v_P}}. \tag{14}$$

Here, ΔT_l is the respective time required to traverse the connections up to the investigated node, D_{i+1} is the distance between current node and the investigated node and D_c is still the distance from the current node to the end node within the path network. $\vec{v_P}$ is a vector of permissible ship velocities. Thus, $\vec{T_{ETA}}$ is a vector of estimated arrival times when travelling at the respective speeds given in $\vec{v_P}$. The lowest velocity in $\vec{v_P}$, which leads to an estimated arrival time within a given time limit, is chosen as the velocity v_{i+1} to traverse the current connection.

Consequently, the presented algorithm will identify the geographical path the vessel takes while the vessel speed is only constrained using the travel time. As the identification process depends only on the neighbours of each node and a heuristic function that neglects upcoming weather conditions, future events can not be accounted for.

TABLE 1: KCS VESSEL PARAMETERS

Parameter	Unit	Value
Design Speed	kn	24
Length between Perpendiculars	m	230
Beam	m	32.2
Draught	m	10.8
Displacement	m^3	52030

TABLE 2: ROUTE INFORMATION

Parameter	Value
Start Harbor	New York
End Harbor	Lisbon
Great Circle Distance	5409 km
Max. Travel Time (24 kn)	122 h
Max. Permissible Speed	28 kn

5. CASE DESCRIPTION

In the following, a case study is carried out using the example of the well known KCS container vessel. A summary of the main vessel parameters is given in Table 1. The vessel is assumed to traverse the Atlantic Ocean on a route from New York to Lisbon. Table 2 summarizes information on the route as well as boundary conditions for the routing algorithm. During routing, the maximum travel time is set at 122 hours to enforce an average speed of 24 knots. The maximum permissible speed is defined as 28 knots. For the routing, about 5000 nodes distributed throughout the Atlantic Ocean are utilized, see Fig. 2. With this node setup,

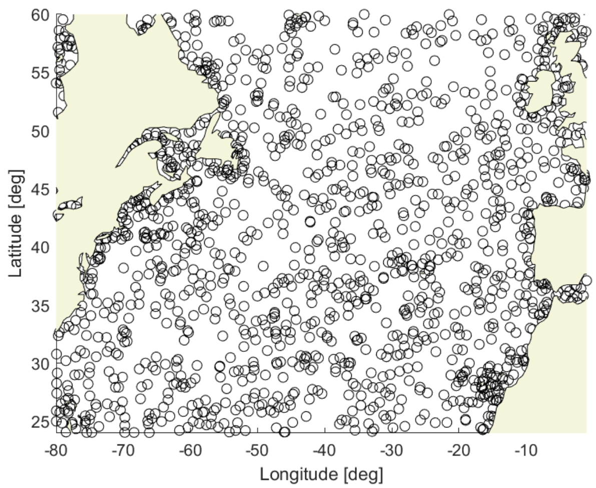

FIGURE 2: NODES CONSIDERED BY A* ALGORITHM

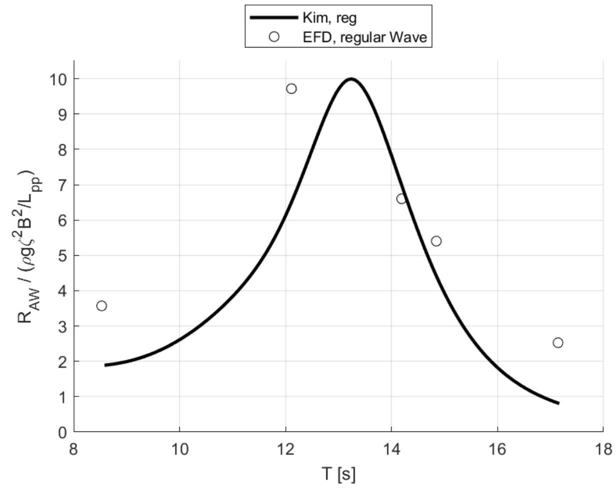

FIGURE 3: ADDED RESISTANCE IN REGULAR WAVES OF VARYING PERIOD

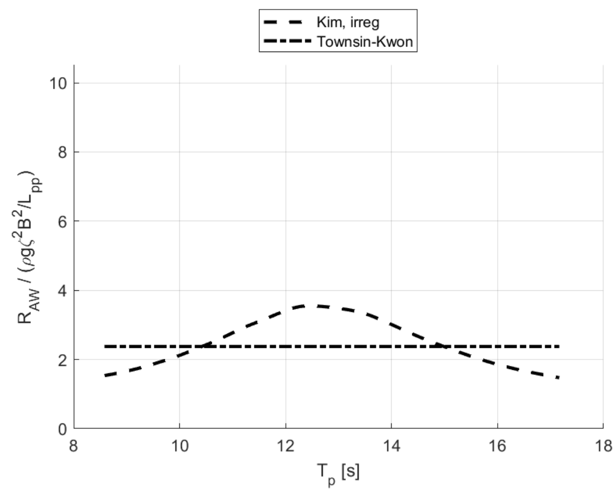

FIGURE 4: ADDED RESISTANCE IN IRREGULAR WAVES OF VARYING PEAK WAVE PERIOD

the mean distance between nodes is 500 km. The maximum distance for the segments at which weather data is sampled when traversing between nodes is set at 50 km. When travelling at design speed, the vessel will take about an hour for each connection segment. It is expected that weather conditions change only to an acceptable degree within this time span. All required weather data is obtained from the European Union's climate data store, except for the wave spreading parameter of the cosine-power angular distribution function, which is set at a constant value of 1.

6. RESULTS

Based on the methods detailed in Sect. 2 - Sect. 4, results were obtained for the case described in Sect. 5. Before the routing algorithm is investigated, exemplary results for wave added resistance models and power calculation are presented.

6.1 Resistance & Power Calculation

As a first assessment of the wave added resistance modelling based on the approach developed by Kim, results for added resistance of the KCS vessel in regular head waves are compared against experimentally obtained values. All results in Sect. 6.1 are based on the vessel design speed. The experimental results were initially presented in [26]. Lee at al [27] calculated the wave added resistance coefficients, which are used for comparison in this work, from these results. In Fig. 3 the coefficient of additional resistances due to waves is plotted against wave period. While the empirical method captures the peak value with good accuracy, the peak location occurs at wave periods differing about 10%. Furthermore, values predicted for small and large wave period show large differences when compared with the experimental results. Error values reach 45% and 65% for wave periods of $\approx 8.5s$ and $\approx 17s$, respectively. These value ranges are in line with discrepancies occurring between experiments conducted at different experimental facilities. For the KCS case, Lee et al. [27] have presented experimental results obtained by FORCE Technologies towing tank (Denmark), University of Iowa and University of Osaka, which show similar peak values but differences between each other which exceed 50% for small and high wave periods.

Figure 4 shows the coefficient of additional resistances due to an irregular wave field, obtained via the Kim model and the Townsin-Kwon method. The seaway was taken according to the considerations in Sect. 2, with the parameters for the JONSWAP spectrum defined as given in Table 3. If not specified otherwise, calculations presented in Sect. 6.1 for resistance and power demand in irregular waves are based on these parameters. The peak wave period is set according to the values given in Fig. 4. For calculation of the resistance coefficient, the significant wave height is utilized. While the Kim model and the Townsin-Kwon formula give similar mean values, considerable differences occur based on the wave peak period. The error value of results obtained with the Townsin-Kwon formula reach up to 50% with respect to the results from the Kim model. Since the peak wave period is not taken into account in the Townsin-Kwon formula, a constant

TABLE 3: SEA STATE PARAMETERS

Parameter	Value
Significant Wave Height	4m
Peak Wave Period	13s
Mean Wave Angle of Attack	0°
Peak Enhancement Factor	3.3

value is predicted across the entire period range. Comparing the results for irregular waves to the values obtained for regular waves, it is apparent that wave resistance is smaller in irregular waves, since the overall energy is not solely found in a single wave but spread to waves of multiple periods and angles of attack. Maximum resistance values for regular and irregular waves differ by a factor of approximately 2.75. It should be noted that the spreading parameter used for this comparison is quite small and a more moderate difference between regular and irregular waves is expected for higher parameter values, which are more prevalent in realistic conditions.

It is expected that the influence of the wave added resistance models on the routing algorithm will, to a large extent, depend on if and how the models account for the (mean) wave angle of attack. Figure 5 presents the results for added wave resistance coefficient obtained via Kim method and Townsin-Kwon method for varying mean wave angles of attack. While the Townsin-Kwon method

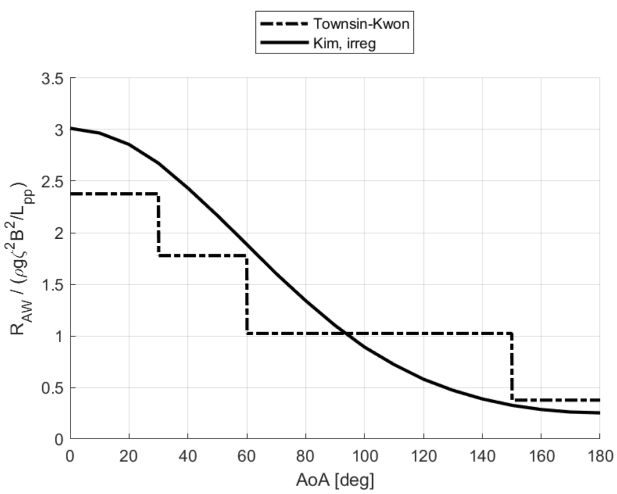

FIGURE 5: ADDED RESISTANCE IN IRREGULAR WAVES OF VARYING MEAN WAVE ANGLE OF ATTACK

displays a step-wise dependency on angle of attack, the Kim method yields a continuous, smooth dependency. Nevertheless, the basic features of the interplay of resistance and angle of attack are retained. For this case, the overall error between both methods amounts to just over 20%. Since the Townsin-Kwon method does not take into account wave period, agreement between both methods is subject to changes based on the respective value.

While wave resistance has a substantial influence on overall vessel resistance, the effect on power demand is not clear at this point. For the seaway parameters given in Table 3, the Kim

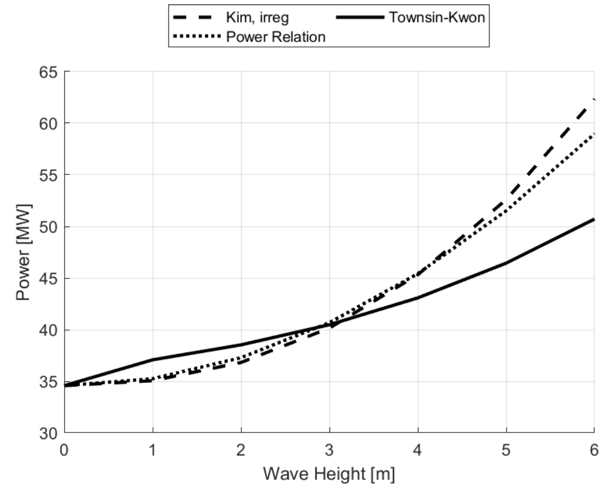

FIGURE 6: POWER DEMAND OVER WAVE HEIGHT

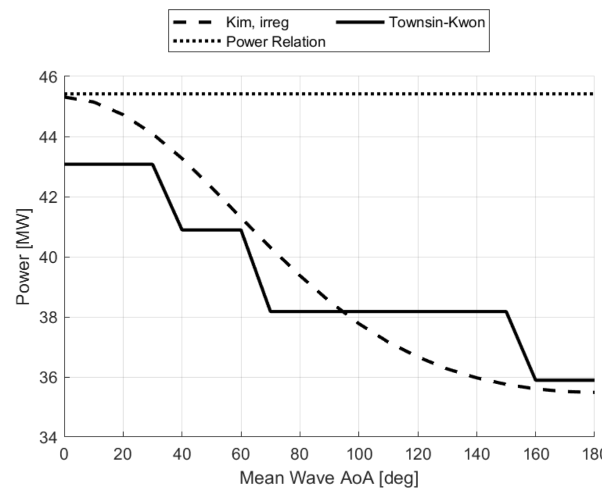

FIGURE 7: POWER DEMAND OVER ANGLE OF ATTACK

method predicts a resistance value that amounts to approximately 20% of calm water resistance. To provide further insight on how the respective models affect overall power demand, power demand against wave height is plotted in Fig. 6. In this particular case, there is remarkably good agreement between the Kim method and the power relation. This agreement is rather attributed to coincidence than to performance of the calculation approach though. Out of the wave related parameters, the power relation takes into account only wave height while neglecting all others. Figure 7 illustrates the vessel power demand in relation to mean wave angle of attack. While the more sophisticated methods both yield similar trends, the power relation approach predicts a constant power value for all angles of attack. Comparing the results obtained for power demand with those for wave resistance, see Fig. 5, the difference between Kim method and Townsin-Kwon is smaller, with a maximum of roughly 5% with respect to the Kim method results.

6.2 Routing

A single start event, situated on January 1st, 2016, is investigated in detail. While the year of the starting date was chosen randomly, the month was placed during winter since it is expected that wave conditions during that time will be harshest, highlighting the respective influence of the wave added resistance models. The great circle path along with the optimized route, based on the Kim method for irregular waves, is plotted in Figure 8. In

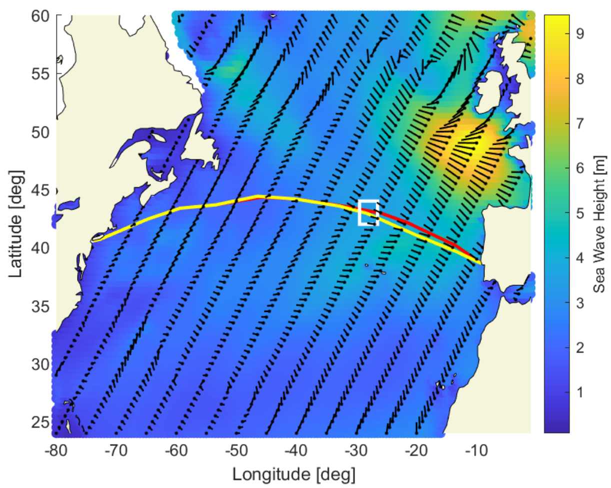

FIGURE 8: SNAPSHOT OF WAVE HEIGHT, WAVE DIRECTION (ARROWS) ALONG WITH GREAT CIRCLE ROUTE (RED) AND OPTIMIZED ROUTE VIA KIM, IRREG (YELLOW). WHITE BOX MARKS VESSEL POSITION.

addition, Fig. 8 illustrates the significant wave height by means of the color bar, the mean wave direction via the black arrows, as well as the position of the vessel at the time the weather snapshot was taken, see the white rectangle. The arrow length is scaled with significant sea wave height. The snapshot is taken at the time when the routing algorithm takes the decision which leads to the largest geographical difference between great circle path and optimized route. By aligning the travel direction with the wave direction, overall energy demand along the route is reduced despite the increased distance that needs to be traversed. Figure 9 presents the power demand over time for the optimized route, obtained via Kim method and Townsin-Kwon formula. While the increased power demand towards the end of the journey is attributed to high(er) wave heights, the spike in power at about 82 hours of travel time is caused by an increase in vessel speed to comply with the arrival time constraint. Table 4 presents the overall results obtained for this start event. Therein, "GC Energy" denotes the energy demand when traveling on the great circle route at design speed while "Opt Energy" refers to the energy demand for the optimized route. "Diff. GC" is the difference in energy demand between great circle route and optimized route and "Diff. Kim, irreg" is the difference between results obtained with the respective method and the Kim method for irregular waves. The comparison of Kim method and the others approaches is drawn since the Kim method is deemed the most complex and hence accurate. Route optimization was successful for all methods, yielding energy savings of approximately 4.5% - 8%, depending on the method. Energy savings obtained for Kim method and Townsin-Kwon differed by only 0.6% for this single case, while results from the power relation differ by about 10%.

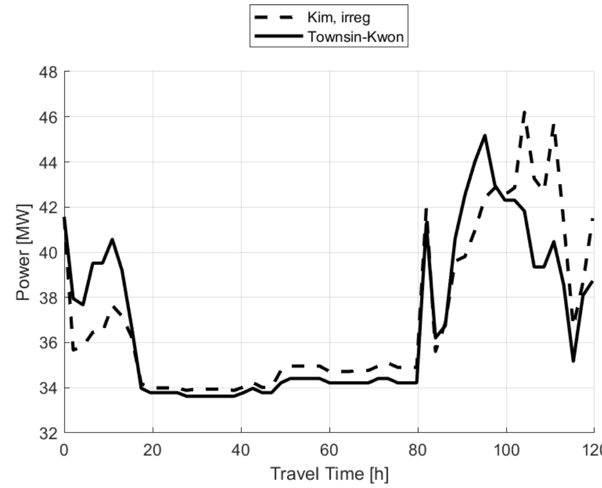

FIGURE 9: POWER DEMAND OVER TIME (KIM METHOD, TOWNSIN-KWON METHOD) FOR OPTIMIZED ROUTE

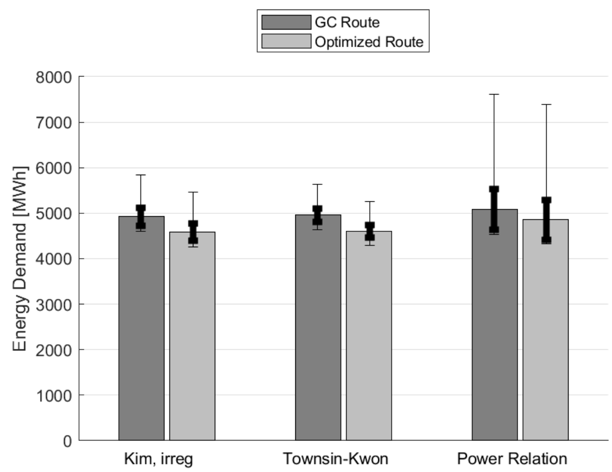

FIGURE 10: MEAN ENERGY DEMAND (BAR HEIGHT), MINIMUM AND MAXIMUM VALUES (THIN LINES) AND STANDARD DEVIATION (THICK LINES) FOR ALL START EVENTS

Route simulations were performed for starting dates distributed throughout the year 2016. Start events were set for the 1st, 15th and 25th day of each month at 00:00 and 12:00, yielding 72 calculations for each wave added resistance model. Figure 10 shows the calculated mean energy demand for each model, along with minimum and maximum values, as well as standard deviation. For all models, power demand on the optimized route is lower than on the great circle route. In fact, it was found that the algorithm never actually "failed" - in the worst case, power demand was the same as on the original route. The difference between extreme values and mean values was highest for the power relation, reaching values of 50% with regard to the mean value. This could either indicate that the power relation

TABLE 4: ROUTING RESULTS FOR START EVENT ON JANUARY 1ST, 2016 AT 00:00

Case	GC Energy [MWh]	Opt Energy [MWh]	Diff. GC [%]	Diff. Kim, irreg [%]
Kim, irreg	4895.1	4509.2	7.88	-
Townsin-Kwon	4847.3	4482	7.53	0.6032
Power Relation	5233.6	4983	4.78	10.52

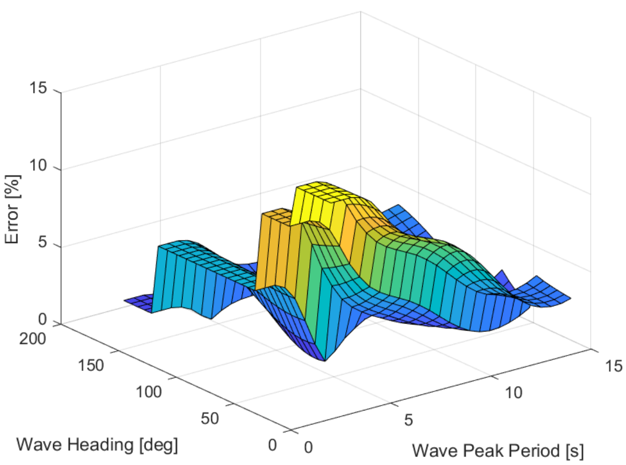

FIGURE 11: ERROR PERCENTAGE BETWEEN KIM, IRREG AND TOWNSIN-KWON FOR POWER RESULTS AT SIGNIFICANT SEA WAVE HEIGHT OF 2.5 METERS

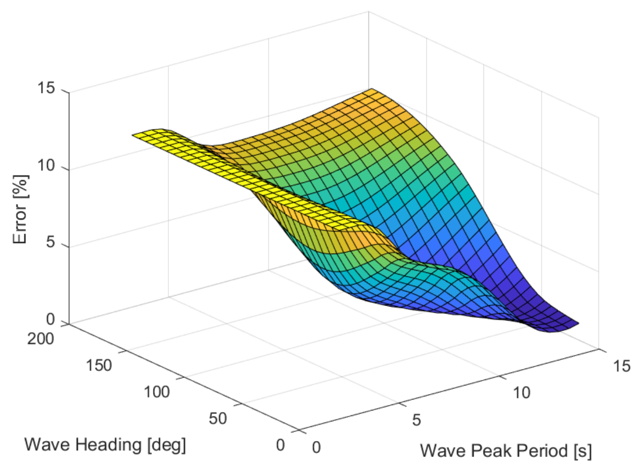

FIGURE 12: ERROR PERCENTAGE BETWEEN KIM, IRREG AND POWER RELATION FOR POWER RESULTS AT SIGNIFICANT SEA WAVE HEIGHT OF 2.5 METERS

severely overestimates power demand in adverse wave conditions or that the incentive for the routing algorithm to avoid such areas is not as pronounced as for the other methods. It should be noted that the calculated maximum power values would likely exceed the installed power on an actual ship, requiring a lower vessel speed. This is ignored to highlight the differences between the algorithms. Compared to the maximum values, minimum values are closer to the mean since here, at least for the power relation and Townsin-Kwon method, a floor value is given by the power in calm water conditions. In the Kim method, depending on wave angle of attack and ship speed, waves can theoretically generate thrust. However, for a vessel with high design speed, such as the KCS ship, this does not occur in realistic conditions. The mean energy demand predicted by each approach is remarkably similar, especially when comparing with the exemplary results presented in Fig. 4 - Fig. 7. The reason for this can be found by means of an exploration of the weather conditions the vessel experiences during routing. Table 5 lists the mean, maximum, as well as minimum values along with the standard deviation for significant sea wave height, peak wave period, mean wave angle of attack and wind velocity. Elaborating further, Fig. 11 and Fig. 12 give the error percentage between results for power obtained by the Kim method, the Townsin-Kwon and the power relation approach, respectively. For the significant sea wave height, a value of 2.5 m was assumed while all other parameters are taken as listed in Tab. 1 and Tab. 3. At the mean significant sea wave height encountered during routing, error values between the methods retain moderate values, mostly below 10% for all wave headings and wave peak periods.

Table 6 summarizes the differences between great circle route and optimized route for all employed wave resistance models. Predicted energy savings, as well as the difference between maximum values, are larger for the more sophisticated methods. The reason for this is likely to be found in the fact that the power relation does not take into account wave direction, thus limiting the options for energy savings to avoidance of areas of high wave heights. Figure 13 shows the energy demand on great circle route and optimized route for all start events in 2016. For all models, the expected seasonal trend of less power consumption during summer is recorded. Results obtained with Townsin-Kwon method and Kim method show good agreement between each other for almost all start events, with a maximum difference of 5%, while the power relation approach yields a maximum difference of about 35%, each taken with respect to the results from the Kim method.

7. CONCLUSION

In this work, vessel resistance and power demand of the KCS container ship was assessed by means of a semi-empirical method presented by Kim et al. [16], which builds up on the SNNM method recommended by ITTC and IMO, the Townsin-Kwon formula, as well as simple relation between ship speed, wave height and power. The respective results were utilized in an A* Algorithm with time dependent costs to perform optimization of a route traversing from New York to Lisbon.

TABLE 5: WEATHER CONDITIONS ENCOUNTERED DURING ROUTING FOR ALL START EVENTS IN 2016

Parameter	Mean	Standard Deviation	Maximum	Minimum
Sea Wave Height [m]	2.52	1.3	9.39	0.38
Peak Wave Period [s]	8.14	1.7	14.1	4.1
Mean Wave AoA [deg]	165.12	88.26	359.9	0.02

TABLE 6: COMPARISON OF GREAT CIRCLE AND OPTIMIZED ROUTING RESULTS FOR ALL START EVENTS IN 2016

Case	En.Diff. [%]	Maxima Diff. [%]	Minima Diff. [%]	Std. Dev. Diff. [%]
Kim, irreg	6.88	7.1177	7.4571	3.7515
Townsin-Kwon	7.2193	7.0584	7.6055	9.5846
Power Relation	4.5001	3.0707	4.78	1.1530

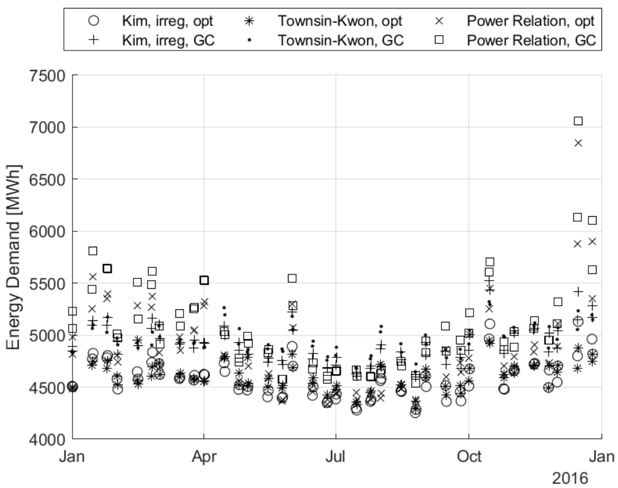

FIGURE 13: ENERGY DEMAND FOR ALL START EVENTS IN 2016

Exemplary results from the respective models were presented and compared against each other, highlighting the differences in each approach. While the power relation utilizes only the power demand in calm water conditions, the Townsin-Kwon formula also takes into account the wave heading. The Kim method additionally takes into account wave period as well as multiple other input parameters, such as bow and rear opening angle.

Routing optimization with the presented algorithm proved successful, yielding energy savings of about 4.5% with the power relation approach and and 7% with the more sophisticated methods. These results agree with findings found in literature [6, 8, 10], in which savings ranging from 3% to 10 % are reported.

The results obtained from the routing analysis suggest that even simple methods, such as the Townsin-Kwon formula, can yield satisfactory results, provided they account for the directionality of the waves. Results based on the power relation showed high error values. Since Townsin-Kwon formula and Kim method both utilize simplified relations to model the directionality of the waves, it might be possible to derive a similar approach for the power relation, thus enabling routing optimization based on minimal input data. It should be noted, however, that the Townsin-Kwon formula, due to the limited number of input parameters, is highly tailored to specific ship types. Especially with regard to shorter ships, the method underestimates wave resistance and is expected to perform worse regarding quantification of power demand.

Depending on the ratio of calm water resistance and wave resistance, the influence of the choice of wave resistance model on weather routing might change drastically. It is therefore planned to extend this case study to a more systematic approach, encompassing multiple ship types and a range of ship main dimensions, which can yield generalizable findings. At present, the routing algorithm does not take into account ice, safety considerations or otherwise restricted areas. Further work might address these shortcomings.

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