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Influence of ship routes on fuel consumption and CO_2 emission

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ABSTRACT: The influence of various parameters, such as ship heading angle and weather conditions on ship fuel consumption and CO_2 emission is presented. A reliable methodology for estimating the attainable speed in different sea states is described. Correlation of speed loss with sea states allows predictions of propulsive performance in actual seas. If the computation is used for weather routing purposes, values for various ship speed and heading for each realistic sea-state is provided. To illustrate the presented concept, the ship speed and CO_2 emissions in various routes of the Atlantic Ocean are calculated using representative environmental design data for the track of the routes where the ship will sail. The analysis has been done for various ship heading angles. The voluntary speed loss is taken into account. The influence of the ship speed loss on various parameters such as fuel consumption and emissions is presented.

1 INTRODUCTION

The recent emphasis on reducing GHG (greenhouse gases) emission has resulted in renewed interests for further optimization of ship performance. A recent IMO MEPC58/INF.21 study (IMO, 2008) indicated that while weather routing can achieve 2–4% reduction in fuel consumption and associated GHG emission, as much as 50% improvement could be achieved through technical and operational measures such as speed management and fleet planning. The benefits of voyage routing optimization with respect to classical weather routing were described and analyzed by Chen et al. (1998).

Traditional weather routing (Delitala et al., 2010; Gershanik, 2011) has served its purpose of avoiding bad weather in the past. However, it has reached its limitations as shipping companies attempt to minimize fuel consumption by slow steaming, super slow steaming and virtual arrival approach (Intertanko, 2011). A ship slows down either involuntarily due to increased resistance from the wind and waves, or voluntarily due to navigation hazards or fear of heavy weather damage from excessive ship motions and accelerations, propeller racing, slamming or boarding seas (Kwon, 2008; Minoura and Naito, 2008; Dallinga et al., 2008.; Prpić-Oršić and Faltinsen, 2012).

Knowing ship speed at any heading angle with respect to the current and future sea state is one of the most significant factors of the decision making phase in the entire chain of maritime economy. From optimal routing point of view, precisely estimated ship speed at any weather conditions is essential for minimization of sailing time. Regardless to whether that is necessary for economic-logistical reasons (Wang and Meng, 2012), such as a more precise prediction of the estimated time of arrival to the port, or in order to increase the safety of navigation when dealing with a more precise navigation planning for a safer and more reliable collision avoidance (Tsou et al., 2010), or because of a more precise fuel consumption calculation for a more ecologically acceptable navigation with decreased GHG emissions (Kim et al., 2012; Qi and Song, 2012), or for completely different reasons, the fact remains that a better prediction of ship speed depending on the external disturbances has a wide range of implementation possibilities in maritime affairs.

The more reliable the weather (wind/waves) forecasts (Vlachos, 2004, Rusu and Guedes Soares 2014) and the performance simulation of ships in a seaway become, the better they serve to identify the best possible route in terms of criteria like estimated time of arrival, fuel consumption, GHG emissions, safety of ship, crew, passengers and cargo, etc. This establishes a multi-objective, non-linear and constrained optimization problem in which a suitable compromise has to be found between opposing targets.

Without modelling the ship performance, it is not possible to minimize the fuel consumption for a given arrival time without exceeding the safe operating limits (Tsujimoto and Hinnenthal, 2008; Panigrahi et al., 2012). Speed and heading should both be integrated into routing optimization, making the problem multi-dimensional (Shao et al., 2012).

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2 REDUCTION OF FUEL CONSUMPTION AND CO$_2$ EMISSIONS

2.1 *Ship hull design*

A ship performance in operational conditions changes significantly under real weather factors. Important factors are significant wave height, wave period, wind speed, ship heading, ship speed and ship particulars (principal dimensions and hull shape, superstructure shape, draught etc).

The ship hull design is an iterative process in which compromises must be made among various, in most cases conflicting, requirements. The design of a ship hull can be formulated as determination of a set of design variables subjected to certain relations between variables and restrictions of these variables. In general, many factors must be considered and not all of them are hydrodynamic in nature. The optimal design of the hull shape is basically a multi-objective optimization problem since the improvement of a specific aspect of the global design usually causes the worsening for some other. Therefore, the correct approach to the problem must follow the multi-objective optimization theory, involving the modelling, the development and the implementation of algorithms for the hydrodynamic optimization, i.e. the ship hull optimization regarding the calm water as well as added resistance.

2.2 *Attainable ship speed*

The ship speed, required power and propeller characteristics are usually estimated for calm water conditions. However, during its exploitation, the ship encounters different sea conditions and in many occasions, the seaway influences the resistance and propulsion features. The capability to sustain speed in a seaway is one of the primary objectives in the design of a ship. The added resistance of a ship in a seaway is becoming of great importance because of increasing demand in transportation speed and voyage duration (Guedes Soares et al., 1998) as well as due to increasing conscience of need to reduce emissions from the ships (Prpić-Oršić & Faltinsen, 2009). The added resistance of a ship in waves is mainly a potential flow effect and caused by the ability of the ship to generate waves. When the wavelength of the incident waves is smaller than approximately half the ship length, the wave induced ship motions are small and the added resistance is mainly due to wave diffraction caused by the ship. When the ship motions are significant, they strongly influence the added resistance in waves.

Progress made in seakeeping, in both analytical methods and experimental techniques, makes it possible to determine added resistance with sufficient accuracy for design purposes. However, the accuracy of added resistance calculation depends very much on the accuracy of ship motion predictions. The same is true for the effect of wind loads on speed loss and the effects which lead to voluntary speed reduction based on the ship master judgment (such as slamming, propeller racing, ventilation, excessive accelerations and green water on deck).

2.3 *Ship route planning*

A very important factor in assessing the cost of travel is the ship route planning. Selecting rational ship routes taking into account weather conditions is conducive in not only improving shipping efficiency and in reducing accompanying risks, but also in allowing more precision in predicting ship's estimated time of arrival at destination port. For a selection of the best route from one to the other port, it is necessary to know the ship performance at weather conditions that ship may encounter during voyage. The selection of the best route is influenced by many factors. Primarily, the weather conditions that ship will, with a certain probability, encounter at the particular segment of the route. Of course, it is crucial to be able to assess the dynamic response of the vessel due to real weather conditions (wind and waves) (Pacheco & Guedes Soares 2007). At lower sea states, decrease of ship speed is related to additional resistance due to waves and wind, while at higher sea states the safety of ship operation depends significantly on weather conditions and the full range of adverse dynamic effects must be taken into account. As the weather conditions deteriorate and significant wave height and wind speed increase, the ship behavior differs more from that estimated for calm sea condition. Propulsion system: propeller-engine works in conditions, which are significantly different from those for which it is designed, and the efficiency of both propeller and engine is reduced. In addition, the ship can be subjected to bow and stern slamming, green water, excessive accelerations and roll that jeopardize the safety of the ship and people aboard. In such circumstances, a conscientious master will take measures to reduce those dangerous effects: he will change the course and/or reduce speed. If possible, the master will try to apply the strategy of avoiding dangerous conditions bypassing the storm or simply wait to pass.

While planning the route all before mentioned must be taken into account. The hydrodynamic performance of the ship affects the added resistance, which has an important effect on ship speed and fuel consumption and related CO_2 emissions. The optimal ship speed and heading must be determined, so that fuel consumption is minimized while certain safety constrains are met. The safety constrains could be expressed by limiting values that could not be exceeded. The non-exceedance of these values is ensured by reducing speed and/or changing the course of the ship.

3 NUMERICAL EXAMPLE

The calculations of attainable ship speed, fuel consumption and related CO_2 emission have been performed for the S-175 containership. The main particulars of the ship are given in Table 1 (ITTC, 1978).

3.1 *Involuntary and voluntary speed loss*

The ship speed under rough weather conditions is not only decreased by the natural increase of resistance, but also may be reduced for safety concerns such as avoiding excessive motions, slamming, propeller racing and other dangerous effects. The instantaneous ship speed is calculated according to the method proposed by Journee (Journee 1976, Journee & Meijers 1980) by taking into account propeller in-and-out-of-water effect on ship propulsion. Furthermore, the effect of mass inertia is accounted for. The constant propeller torque condition is assumed. The total resistance is composed of still water resistance, added resistance in waves and wind resistance. The still water resistance is calculated according to Holtrop & Mannen method (Holtrop & Mannen 1982, Holtrop 1984), an approximate procedure which is widely used at the initial design stage of a ship. The method is based on regression analysis of random model experiments and full-scale data, available at the Netherlands Model Basin.

Table 1. Main particulars of the S-175 container ship.

Length between perpendiculars	175.0 m
Breadth moulded	25.4 m
Design draft	9.5 m
Freeboard	7.0 m
Displacement	24272 tonnes

The calculation of added resistance in waves is partly carried out according to the direct pressure integration procedure developed by Faltinsen et al. (1980). The method predicts added resistance, transverse drift force and mean yaw moment on a ship in regular waves of any wave direction. It is not applicable for short wave lengths (when wave length-ship length ratio is lower than 0.5). For the case of short waves the asymptotic theory developed by the same authors give reliable results for moderate Froude numbers and common hull forms. A comparison of this method with other and with experiments can be found in Matulja et al. (2011).

For a diesel engine, it is mostly accepted that the propeller torque remains constant at an increasing loading. In practice, there are some deviations from this assumption, but for a practical purpose of speed calculations, this assumption seems to be sufficiently accurate.

The numerical model used for main propulsion engine modelling is based on a zero-dimensional model of an internal combustion engine. Number of control volumes interconnected with links for mass and energy transfer between them (Medica & Mrakovčić, 2002), represents the main propulsion engine. This model provides satisfactory prediction of engine dynamic response during transients with rather short computational time. In addition, engine fuel consumption can be precisely determined, which represents the basic presumption for estimation of carbon-dioxide emission. Furthermore, use of such a model can be extended to determination of the lowest fuel oil consumption strategy for given sea condition and ship speed with resulting lowest possible CO_2 emissions.

The relation between thrust required by the propeller and the number of revolution for several speeds are obtained by using torque characteristics of an assumed B-series propeller behind the ship and a wake fraction. The open water propeller characteristics are obtained by Oosterveld & Oossanen method (1975). The relationship between torque delivered by the engine and number of revolutions can be calculated from engine characteristics and shaft losses. The sustainable speed for any particular regular wave is calculated from the equilibrium of ship inertia, calculated total resistance and required thrust at given condition taking into account thrust deduction fraction and the loss coefficient due to in-and-out-of-water effect. The time simulation of force equilibrium within one wave period has been done using the fourth order Runge-Kutta method starting with the mean values form the previous wave period.

The thrust loss coefficient values, as function of relative shaft speed n/n_{bp} and relative submergence h/R, are estimated from a simplified ventilation thrust loss model, which is obtained by utilizing known experimental data (Smogeli, 2006). After defining the model, the effect can be estimated knowing the propeller emergence and number of shaft revolutions. A fixed pitch propeller of 5.6 meter diameter with 6 blades is used in the numerical example.

The wave realization is obtained from the two parameter ITTC spectrum. The mean speed loss, obtained as average value during time simulation, represents the reduction from 21.8 kn speed and includes voluntary speed loss in severe seas. In this particular calculation the criteria used for voluntary speed reduction are: slamming, deck wetness, bow acceleration and propeller emergence. Limiting values for slamming, deck wetness and propeller emergence are taken as probability 0.01, 0.05 and 0.1, respectively. For the vertical acceleration, the adopted limiting rms value is 0.215 times gravity acceleration. Values of mean speed loss, both involuntary and voluntary, are obtained for significant wave height from zero to 12 m and the whole range of wave periods and heading angles.

The attainable speed calculated for head and following waves obtained for the most probable zero crossing periods related to specific sea states using ITTC spectrum are shown in Figures 1 and 2. The curves refer to the case of involuntary (full line) and voluntary speed reduction (dashed line).

The results of attainable ship speed for head sea defined by significant wave height higher than 8 m need particular attention. The Figure 1 shows that attainable ship speed estimated for sea state with significant wave height from 8 to 12 m is nearly constant (even slightly higher for significant wave height of 12 m), while for following sea the value of speed drop will continue to grow as expected. This trend could be explained by the fact that the one-parameter wave spectrum is used. So, for very high significant wave height it probably give back a sea-state characterized by very long waves (high zero crossing period), thus there are almost no relative motions. It can also be assumed that is impossible to obtain reliable values of ship speed for such adverse weather conditions where the ship dynamics is affected by many highly nonlinear effects. However, the inaccuracy of those results will not significantly affect the results of mean ship speed for the whole voyage because such extremely high sea states are very rare, and even if the ship is going toward such storm, the master will certainly try to avoid it.

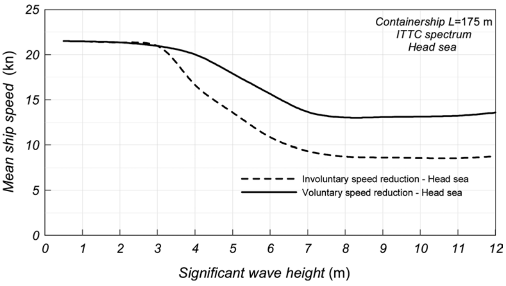

Figure 1. Ship speed loss for head sea.

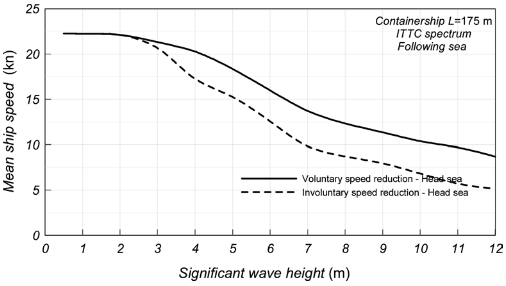

Figure 2. Ship speed loss for following sea.

3.2 *Fuel consumption and CO_2 emissions*

The estimation of fuel consumption and related CO_2 emission from the main engine of containership on North Atlantic routes is based on the mean speed drop for the constant torque conditions. Figures 3 and 4 show the Fuel Consumption (FOC) and CO_2 emission expressed in kg per kilometre of voyage in head and following waves for the whole range of different sea states.

The fuel consumption is assumed to be related to ship speed as estimated in Prpić-Oršić et al. (2013). The emission factors used in the calculations, 3173 g CO_2/kg fuel, named CORINAIR (CORe Inventories AIR), are based on the emission factors presented in the guidebook from EMEP/CORINAIR (CORINAIR, 1999).

As expected, the trends of fuel consumption and CO_2 emissions follow the speed loss trend. It can be noticed that for sea states with significant

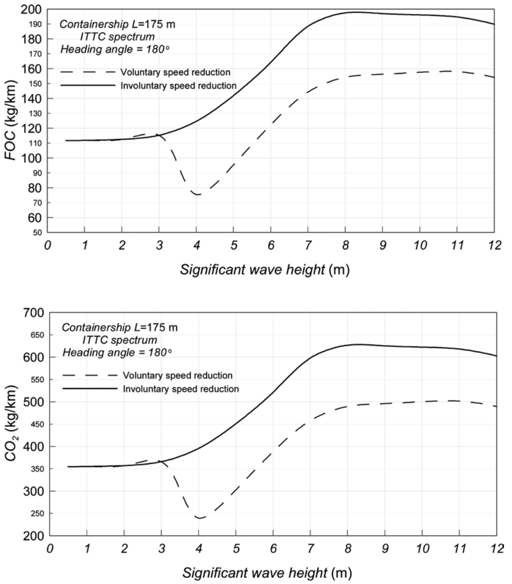

Figure 3. Fuel consumption and CO_2 emissions for head sea.

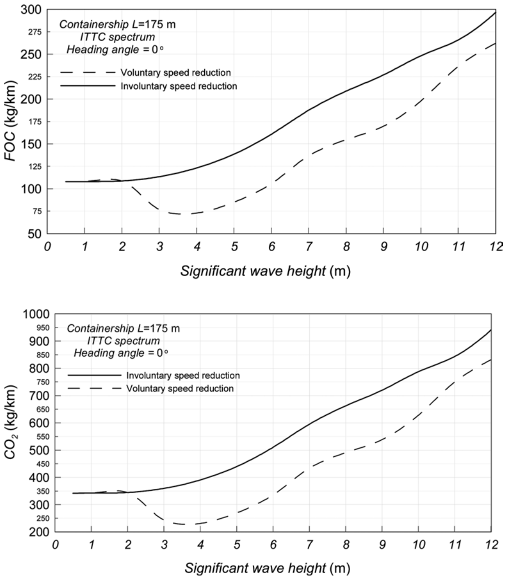

Figure 4. Fuel consumption and CO_2 emissions for following sea.

wave height higher than 4 m, the speed loss significantly increase as well as the fuel consumption and CO_2 emission.

3.3 *Effect of choosing different ship route*

The tracks of the main North Atlantic routes were identified (in Vettor & Guedes Soares, in prep.) by means of the Voluntary Observing Ship (VOS) database following the area with a higher density of reports and with some consideration of global economy and geography.

The following six principal trans-oceanic passages were detected and depicted in Figure 5:

- Route 1: Channel—Puerto Rico (North), [Ch_PR1]
- Route 2: Channel—Puerto Rico (South), [Ch_PR2]
- Route 3: Channel—Virginia, [Ch_VA_total]
- Route 4: Strait—Virginia (North), [St_VA1_total]
- Route 5: Strait—Virginia (South), [St_VA2]
- Route 6: Strait—Miami, [St_MIA]

It was shown that the most travelled route is the one from Northern Europe (the Channel) to the Caribbean Sea (routes 1 and 2) with 36% of the traffic in the considered areas (higher percentages in winter). More than one-third of these ships prefer the northern and shorter orthodrome; in August this percentage rises to 43%.

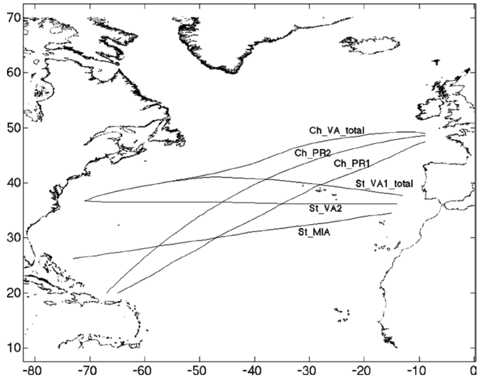

Figure 5. Main North Atlantic trans-oceanic routes.

The transport stream between the Strait of Gibraltar and the North-East Coast of USA (routes 4 and 5) denote a similar concentration with about 32% of the trades, while the routes from the Channel to the Virginia area (route 3) and from Gibraltar to Miami (route 6) contribute 21% and 10% respectively.

When effects such as ship motions, speed loss, fuel consumptions and CO_2 emissions have to be analysed in the long-term period, the sea-state probability in terms of the join probability of significant wave height wave periods and relative wave heading probability is essential.

The initial wave databases of the oceans were constructed from visual observations that were collected in relatively large areas over which statistics were given. More modern databases can be obtained from phase averaging models that predict the spatial and temporal evolution of the directional spectrum solving the spectral energy equation.

One such hindcast data set that was produced in the EU project HIPOCAS (Guedes Soares, 2008) includes a 44 years database (January 1958 to December 2001) of wave, wind and sea level data for the Atlantic Ocean and all seas around Europe. This dataset, which is adopted in this study, consists of 3-hourly fields with a 2.0° × 2.0° grid resolution over the North Atlantic The initial wind forcing was from the NCEP reanalysis, which was used to force a regional wind model (REMO), which finally forced the WAM wave model. The data was validated with buoy measurements establishing its general adequacy (Pilar et al., 2008).

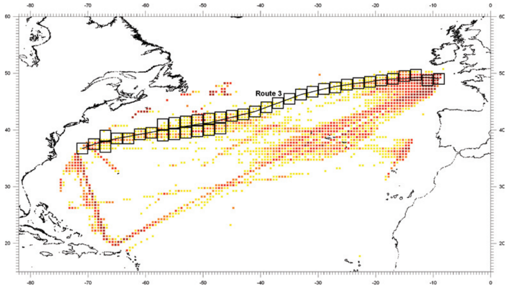

Figure 6. Example of route panels.

Table 2. Calm water condition main parameters.

Power [kW]	26000
SFOC [g/kWh]	171
Speed [kn]	21.9
FOC [kg/km]	104.39
CO_2 [kg/km]	331.21

All the grid points contained in a squared area of 2° × 2° (Fig. 6) around a number of previously defined route points are taken into account for each route. From those grid points the wave data have been extracted to compute the specific scatter diagram of each route.

To illustrate the presented concept, the mean fuel consumptions and CO_2 emission increases for the six different North Atlantic routes were calculated, as well as increase in CO_2 emission relative to calm sea (Dolinskaya et al., 2009). The time percentage of ship operation in each zone is estimated according to the fraction of route distance in each zone (Guedes Soares and Moan, 1991).

In order to compare the fuel consumption and CO_2 emissions on different routes of the North Atlantic the most likely mean values are calculated.

For this purpose, the calculated mean ship speed for a wide range of different sea states (combinations of significant wave heights and zero crossing periods) and heading angles are used.

The appropriate values of ship speed, fuel consumption and CO_2 emissions for calm water conditions are shown on Table 2.

Table 3. Absolute fuel consumption during voyage (calm weather condition).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Length	[nmi]	3210	3253	2811	3048	2740	2762
Time	[h]	147.3	149.2	129.0	139.8	125.7	126.7
FOC	[t]	654.73	663.54	573.34	621.69	558.91	563.32
CO_2	[kg]	2077.5	2105.4	1819.2	1972.6	1773.4	1787.4

Table 4. Fuel consumption and CO_2 emissions (real weather conditions—involuntary speed reduction).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	20.9	20.7	20.2	21.2	20.6	20.8
Time	[h]	153.6	157.2	138.9	143.8	133.2	132.7
	% increase	4.3%	5.3%	7.7%	2.9%	6.0%	4.7%
FOC	[kg/km]	114.7	115.3	115.6	112.7	114.5	113.6
	% increase	4.2%	4.6%	5.0%	2.3%	4.0%	3.1%
CO_2	[kg/km]	364.0	365.7	366.9	357.6	363.4	360.4

Table 5. Fuel consumption and CO_2 emissions (real weather conditions—voluntary speed reduction).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6
Speed	[kn]	20.3	19.9	19.3	20.8	19.8	20.2
Time	[h]	158.4	163.1	145.8	146.7	138.4	136.8
	% increase	7.6%	9.3%	13.1%	4.9%	10.1%	8.0%
FOC	[kg/km]	103.2	102.2	99.5	104.6	100.8	102.2
	% increase	–6.3%	–7.2%	–9.7%	–5.0%	–8.4%	–7.2%
CO_2	[kg/km]	327.5	324.4	315.6	332.0	320.0	324.1

The values of route length, voyage time, fuel consumption and CO_2 for ship sailing on calm water is calculated for different routes as are shown on Table 3. On real weather conditions speed decrease due to involuntary (Table 4) and voluntary (Table 5) speed reduction.

4 CONCLUSIONS

Relative emissions of GHG from ships (kg/tonne-km) are very sensitive to capacity utilization of the vessel, and thus to transport efficiency. One of the potential for reducing emissions is through vessel route planning for increased transport efficiency. Knowing mean attainable ship speed in a specific sea state and heading angle, the prediction of speed loss and CO_2 emissions during the whole route and under various weather and load conditions can be estimated.

In this paper a procedure is proposed to calculate attainable ship speed as well as fuel consumption and CO_2 emission from main engine at the whole range of sea states and heading angles with regards to propulsive performance in actual seas when the ship could be subjected to severe dynamic effects. The mean results for the six main North Atlantic routes are analysed for the case of involuntary and voluntary speed reduction.

The percentage of voyage time increase compared to still water is approximately doubled when considering voluntary speed reduction. For the selected ship the Route 3 seems to be the most demanding from that point of view and at this route "real-weather" voyage duration increased by almost 14% compared to time needed in "calm-weather" conditions. At the same time fuel consumption decreases by 10% as well as CO_2 emission.

Knowing the mean values of speed loos, fuel consumption and CO_2 emission for the whole range of different ship loading cases and service speeds the ship owner would be able to estimate the economic benefit of various voyage regimes taking into account ship safety and, of course, the ship mission.

The proposed method allows reliable prediction of voyage duration and fuel consumption as well as CO_2 emissions from main engine. It allows considering various strategies and scenarios of voyage and selection of the optimal one taking into account ship safety and operability as well as economic and environmental aspects.

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