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RESEARCH ARTICLE

Advanced operational measure for reducing fuel consumption onboard ships

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Abstract
Environmental issues and targets to reduce greenhouse gas emissions have reinforced attempts to increase energy efficiency for all stakeholders, including the shipping industry. International maritime organization (IMO) has prescribed operational and design measures to develop energy efficiency and decrease ship emissions, and one of the effective operational measures is trim optimization, which is a feasible measure because it does not necessitate ship structural modification or engine advancement, but it can reduce the ship resistance and decrease fuel consumption. The study of trim optimization can be implemented by conducting experimental tests, but it is a difficult, expensive method and consumed more time. Therefore, the present paper proposes a numerical method to predict the optimum trim which achieves the minimum ship resistance and lower fuel consumption. The current paper investigated two types of ships as a case study, bulk carrier, and container ship. The optimization process has studied several trim conditions, ship drafts, and speeds. The results showed that positive trim (trim by bow) have an increasing effect on fuel consumption, while the negative trim (trim by stern) have a decreasing effect on fuel consumption. Fuel-saving based on using optimum trim at each speed is a significant quantity to be benefited as it would reduce the operating costs and increase the energy efficiency.

Keywords Energy efficiency · Trim optimization · Fuel consumption · Emission reduction · Ship speed

Introduction

Nowadays, the maritime transportation is the key driver to the world's economy as almost 90% of global trade is mobilized by it. It is estimated that ships produce 3% of global carbon dioxide (CO_2) emissions, 15% nitrogen oxide (NOx) emissions, and 16% sulfur oxide (SOx) emissions (Elkafas et al. 2021a). International Maritime Organization (IMO) espoused many goals to decrease ship emissions and accomplish a blue economy (Psaraftis and Kontovas 2021). One of those goals is to reach a 50% reduction in the percentage of greenhouse gases (GHG) emitted from ships by 2050 contrasted to 2008 (Joung et al. 2020; Elkafas and Shouman 2022). The decarbonization of the shipping sector can be implemented by operational and design measures (Bouman et al. 2017; Xing et al. 2020), but, for existing ships, design measures may be not feasible. Thus, operational-based measures can be used to develop energy efficiency and decrease ship discharges such as speed lessening, weather routing, voyage optimization, auxiliary power reduction, and trim optimization (Rehmatulla et al. 2017; Elkafas et al. 2021b).

Trim optimization is one of the easiest and cheapest methods for ship performance optimization and fuel consumption reduction. Its theory depends on the fact that ship faces various resistance for the same speed and load condition based on different trim conditions; therefore, selecting the minimum resistance condition leads to decrease propulsion power and fuel consumption. In contrast to many other energy-saving technologies for ships, trim optimization does not necessitate ship structural modification or engine advancement, but it can decrease the ship resistance, achieve energy-saving effects, and reduce ship emissions only by adopting reasonable stowage and

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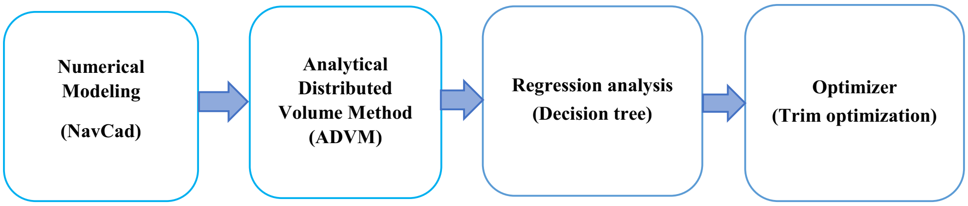


Fig. 1 Optimization process flowchart

adjusting the draft at the bow and stern of the ship by ballast water management and load distribution (IMO 2016; Elkafas 2022). Ships face different resistance conditions based on their trim at the same speed and draft. Thus, trim optimization supports the selection of minimum resistance for a specific trip condition (Islam and Guedes Soares 2019).

The study of trim optimization can be performed based on model testing or by means of computational fluid dynamics (CFD) and the literature review has an extensive number of research on it. Hochkirch and Mollol (2013) examined the impact of trim on power adjustment by using CFD and experimental methods, they concluded that there is an agreement between two methods. Iakovatos et al. (2013) proved the importance of trim optimization by conducting experimental testing in calm water for different ships. Viola et al. (2014) studied the effect of trim at different speeds on the ship resistance by using experimental tests. Sherbaz and Duan (2014) implemented numerical simulations based on CFD to determine the total resistance of container ships in different trim conditions and found the specified trim linked with the lowest resistance. Reichel et al. (2014) showed that trim adjustment by 2–3% can achieved a reduction in fuel consumption up to 15% compared with the conventional condition. Deng et al. (2015) inspected the influence of different trim conditions on the trimaran resistance by using experimental and numerical simulations. Coraddu et al. (2017) examined the relation between fuel consumption and trim optimization for tankers under different working conditions. Islam and Guedes Soares (2019) determined the effect of Froude number and draft values on the optimum trim by using the Reynolds-Averaged Naiver-Stokes (RANS) method. Elkafas et al. (2019) studied the hydrodynamic drag of container ships at different ship speeds by using numerical simulation through CFD. Shivachev et al. (2020) performed numerical approach and experimental testing to analyze the effect of trim on wave resistance of container ships.

All the previous studies, whether research projects or research papers that dealt with the trim optimization onboard ships, confirm that that technology is necessary for a specific ship draft and speed condition. Moreover, it confirms that experimental testing might be the best option to study the effect of trim on the performance of ship, but it is difficult and more expensive to build the appropriate model and provide the proper test facility. Thus, numerical calculations can be used to predict the optimum trim by considering various speeds and drafts.

The aim of this paper is to perform numerical calculations to predict the optimum trim at different ship speeds and drafts. The approach can select the optimum trim based on the minimum resistance and lower fuel consumption in different conditions which can be applied for any type of ship by identifying the relevant characteristics of the ship. As a case study for the investigation, two different ships are selected as test cases, bulk carrier, and container ship.

Methodology

Ship resistance calculation method

The fuel consumption and the propulsive power of ship are based on the total ship resistance. The total ship resistance can be determined by using the method presented in the International Towing Tank Conference (ITTC) Resistance and Propulsion Performance Committee as shown in Eq. (1) (ITTC 2017) in which ρ, V, S, and C_T are water density, ship speed, wetted surface area of the ship, and total resistance coefficient, respectively.

$$R_T = \frac{1}{2}\rho S V^2 C_T \tag{1}$$

The wetted surface area is determined at rest condition without trim or sinkage. The effect of wetted surface area on the total resistance is related to the presence of a large stern area which nonetheless has a relatively small effect of up to 0.5% of the total resistance of the even keel condition, while the total resistance coefficient is calculated as shown in Eq. (2) (Elkafas and Shouman 2021).

Table 1 Basic parameters of investigated ships

Parameters/ship type	Bulk carrier	Container ship
Maximum deadweight (ton)	200,000	145,600
Length between perpendiculars (m)	294	381
Breadth (m)	50	49
Depth (m)	24	30.2
Design draft (m)	16.5	13.5
Service speed (knots)	15	24
Main engine power (MCR)	17,734	65,522

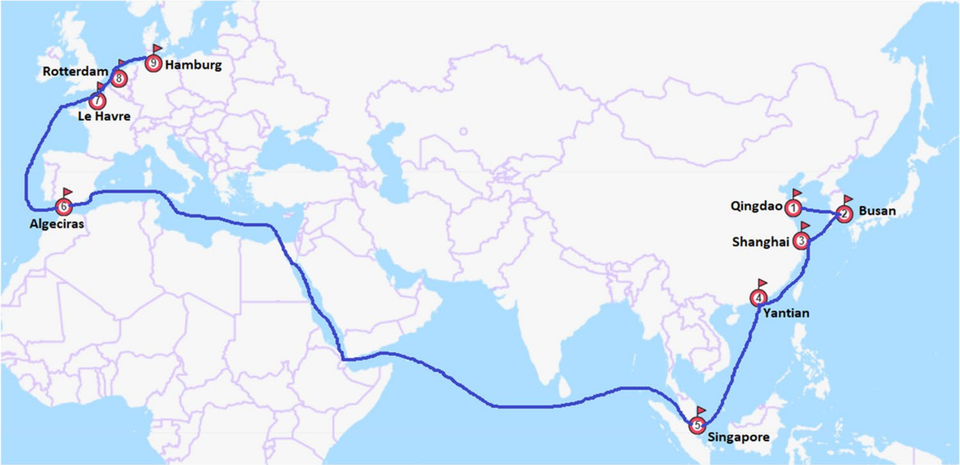


Fig. 2 Ship route description from Asia to Northern Europe

$$C_T = C_F + C_R + C_A + C_{AA} \tag{2}$$

where C_F, C_R, C_A, and C_{AA} are frictional, residual, roughness correction, and air resistance coefficients. C_F can be calculated for the full-scale ship according to the ITTC-1957 model-ship correlation line equation as shown in Eq. (3) in which R_e, V, L_{WL}, and ν are Reynolds number, ship speed, waterline length, and water kinematic viscosity, respectively (Ammar et al. 2019).

$$C_F = \frac{0.075}{\left(\log_{10} Re - 2\right)^2}, Re = \frac{V \bullet L_{WL}}{v} \tag{3}$$

The above formula shows that the waterline length is inversely proportional with the frictional resistance coefficient. But, the inverse proportion results in an increase or decrease in the propulsive power of only 0.5% which is a small percentage of saving compared to the potential savings.

The air resistance coefficient (C_{AA}), caused by the movement of the ship through the air, shall be included in the resistance calculation procedure. Based on the analysis in (Kristensen and Lützen 2013), the following air resistance coefficient C_{AA} formula for container ship is recommended in which TEU stands for the twenty-foot equivalent unit which can be used to measure a ship's cargo-carrying capacity.

$$1000 \bullet C_{AA} = MAX\ (0.28 \times TEU^{-0.126} \times 10^{-3}, 0.09) \tag{4}$$

When extrapolating the resistance values from the model to full-scale ship, the surface roughness of the hull must be considered in the calculation so that the roughness correction coefficient is added. The literature review shows that correlation coefficient (C_A) can be determined according to the Harvald formula as presented in Eq. (5) (Harvald 1983) in which Δ is the ship displacement.

$$1000 \bullet C_A = 0.5 \bullet \log(\Delta) - 0.1 \bullet (\log(\Delta))^2 \tag{5}$$

The roughness coefficient is normally kept constant unless for vessels with large variation in the draught in loaded/unloaded condition. The residual resistance coefficient is often claimed to be the parameter most affected by trim.

The service allowance is used for the determination of the installed main engine power, which means that it shall be determined based on the expected service area. Harvald (1983) suggests service allowances between range 15–35% and its value will be relatively lower for large ships compared to small ships. Recently, the effective power can be calculated by using total resistance and the corresponding speed. Then, the main engine's output power (P_p) can be calculated by dividing the effective power by the total propulsion system efficiency which can be calculated by using the procedure which discussed in (Breslin and Anderson 1994).

Table 2 Definition of variable data ranges

Ship type	Bulk carrier	Container ship
Design draft (m)	16.5, 17.5	11.5, 13.5
Ship speed (knots)	12–17	18–24
Trim (m)	−1.5–1.5	−1.5–1.5

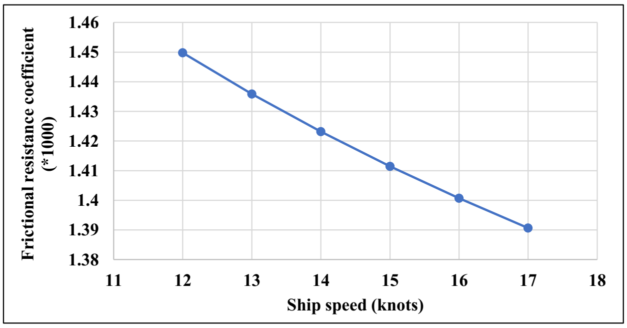


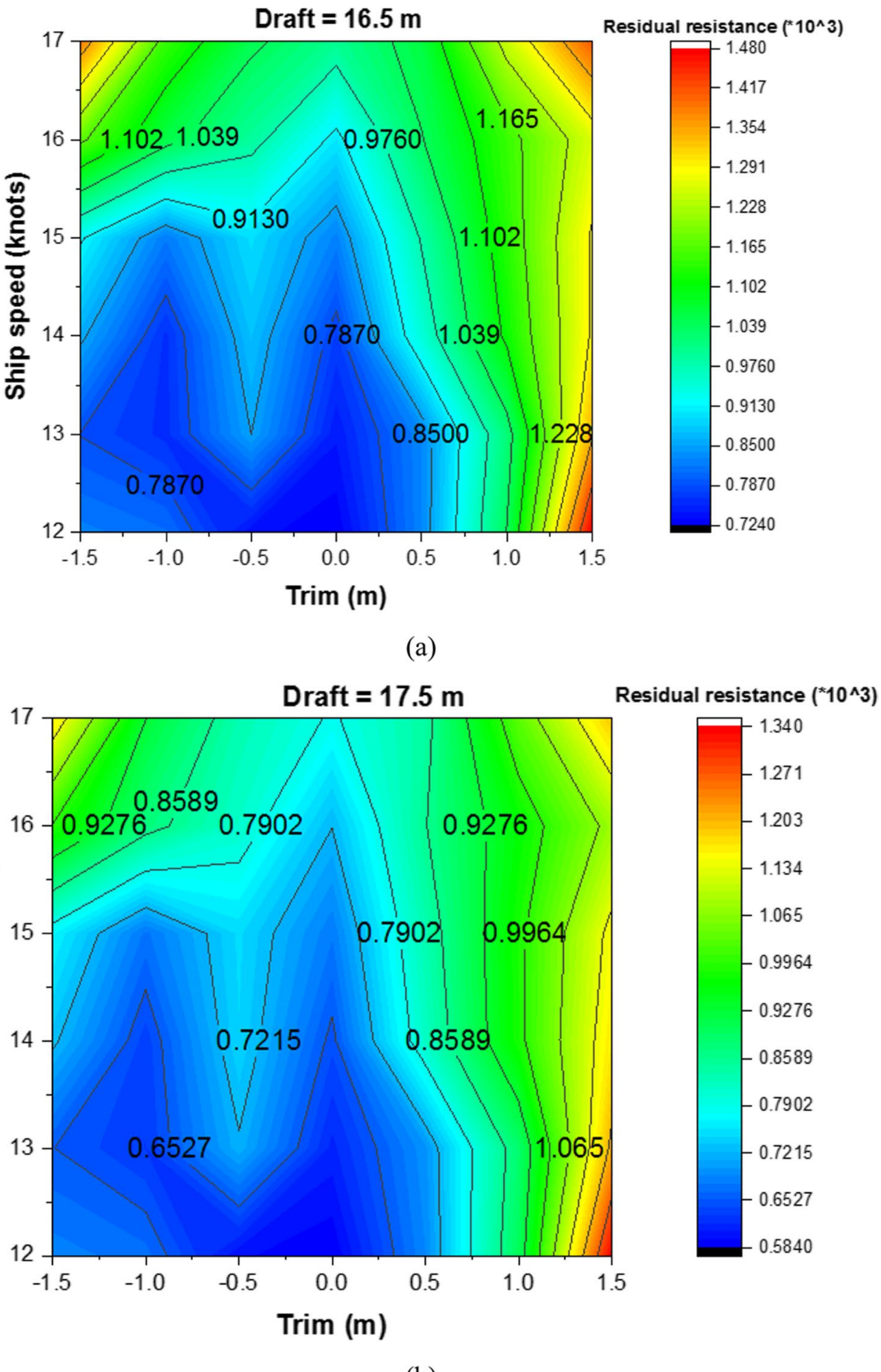
Fig. 3 Frictional resistance coefficient results of bulk carrier at different speeds

Power will play a role in how much fuel is consumed with changes in speed. Thus, derivation of a direct relationship between fuel consumption (FC) and main engine's output power, which can be obtained using the basic equations of power, and fuel, can be expressed as displayed in Eq. (6) (Elkafas and Shouman 2021):

$$FC = P_p * SFC_i \tag{6}$$

where P_p is the main engine's output power and SFC_i is the specific fuel consumption of main engine.

From literature review, the changes in the trim have little influence on frictional resistance compared with residual resistance. Therefore, the change in the residual resistance



(a)

(b)

Fig. 4 The predicted residual resistance coefficient for bulk carrier at different trim conditions and ship speeds **a** draft = 16.5 m, **b** draft = 17.5 m

Fig. 5 Fuel consumption of bulk carrier at different ship speed and trim conditions **a** draft = 16.5 m, **b** draft = 17.5 m

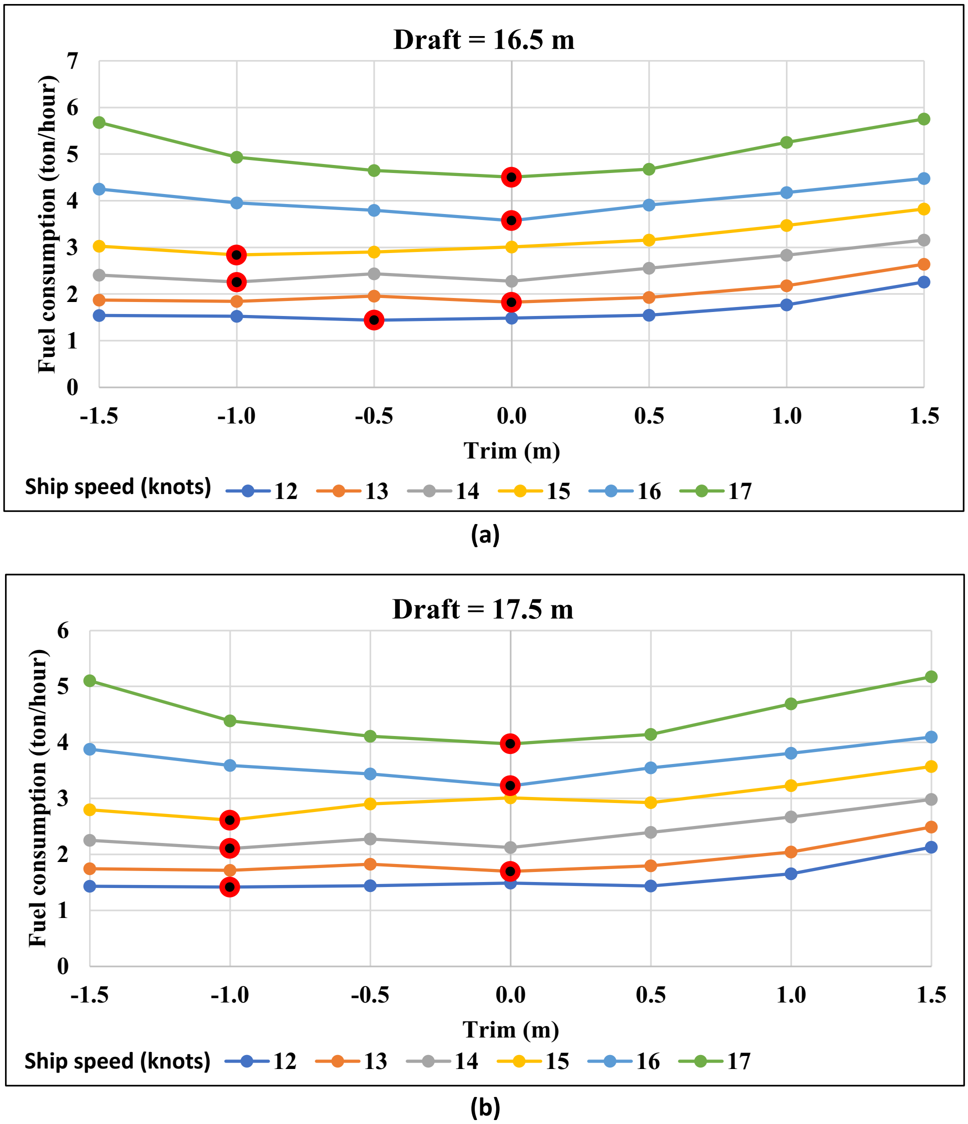
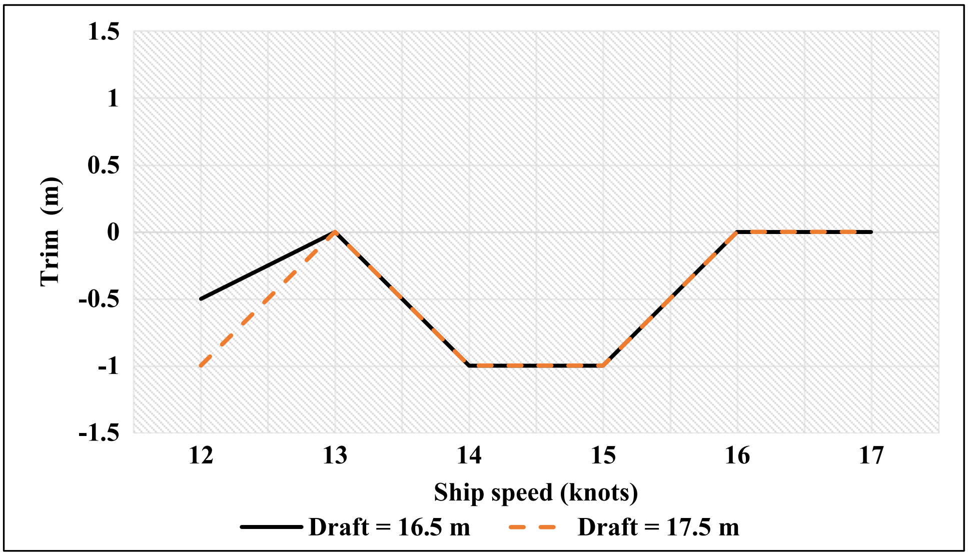


Fig. 6 Optimum trim condition for the bulk carrier at two draft states



can replace the change in the total resistance. According to Froude's law, the residual resistance coefficient of a real ship is equal to that of the ship model, so the residual resistance coefficient of the ship model was selected as the value of the resistance prediction. Dimensionless parameters were selected to reduce the influence of non-uniform changes in the ship size on the resistance prediction results. The residual resistance coefficient can be predicted by using the Analytical Distributed Volume Method (ADVM) which is based on 2D numerical modeling, and it is suitable for commercial ships.

Optimization algorithm

The optimization process consists of three components of numerical modeling, resistance prediction, and optimizer. Numerical modeling is conducted through NavCad program for the selected case study. In resistance prediction, ADVM approach is performed to predict the residual resistance at certain ship speed and draft. Then, regression analysis is performed to break down a dataset into smaller and smaller subsets. Finally, optimizer is performed to obtain the objective function. The applied optimization process is displayed in Fig. 1.

The present optimization problem for selecting the optimum trim based on the minimum fuel consumption which can be expressed as shown in Eq. (7).

$$minimize\ f(X) = FC\ subject\ to\ X \in S \subseteq R^N \quad (7)$$

where f is the objective function that is defined as fuel consumption and based on residual resistance. Also, $S \subseteq R^N$ is the feasible solutions set, while the constraint prohibits feasible design space. Vector of design variables is defined by X in N dimensions which corresponds with various trim conditions in the optimization process. The trim was taken as the first parameter of the input of the numerical model, and the ship speed was the second parameter.

The present paper involves regression prediction for the optimum trim, the classification, and regression analysis can be done by using a decision tree algorithm. Decision tree builds regression or classification models in the form of a tree structure. It breaks down a dataset into smaller and smaller subsets while at the same time an associated decision tree is incrementally developed. The result is a tree with decision nodes and leaf nodes. A decision node has two or more branches, each representing values for the attribute tested. Leaf node represents a decision on the numerical target. The topmost decision node in a tree which corresponds to the best predictor called root node. Decision trees can handle both categorical and numerical data.

Case study description

The analysis of trim optimization performed in this paper based on two different ships. The trim optimization includes certain drafts and speeds for the selected ships. The selected ships for the analysis include bulk carrier and container ship, whose characteristics are presented in Table 1.

The selected ships normally serve the Far East route from Asia to Northern Europe through the Suez Canal as shown in Fig. 2.

The resistance calculations were carried out for the bare hull with rudder and other appendages. The trim scale range affects directly the optimum trim prediction accuracy. The scale selection should not be too large, if it is too large, the selected trim will have a large probability to avoid the optimum trim with a large deviation, thus rendering the final prediction result inaccurate. The scale selection should not be too small as the residual resistance coefficient is small which can lie to a prediction error, which has a significant impact on the selection of the optimum trim. The distribution of the trim is mainly distributed between – 1.5 m and 1.5 m. Inserting the data features into the prediction model of the optimum trim enables prediction of the residual resistance

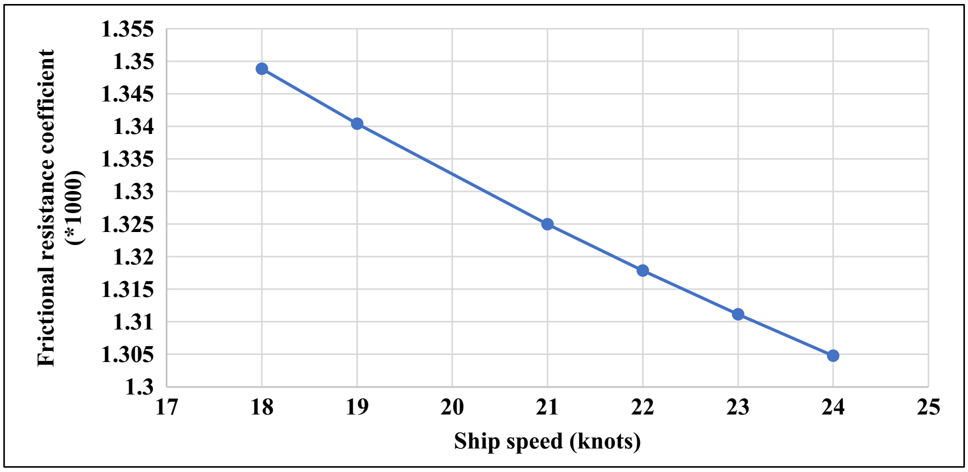


Fig. 7 Frictional resistance coefficient results of container ship at different speeds

coefficient, and the trim corresponding to the smallest residual resistance coefficient is the optimum trim. The present paper studied two different drafts and various ship speeds for each ship type as presented in Table 2. With regard to trim, the negative sign is defined to trim by stern while positive sign is for trim by bow.

Results and discussions

Trim optimization for bulk carrier

The optimization process was applied for the bulk carrier at different ship speed conditions between 12 and 17 knots

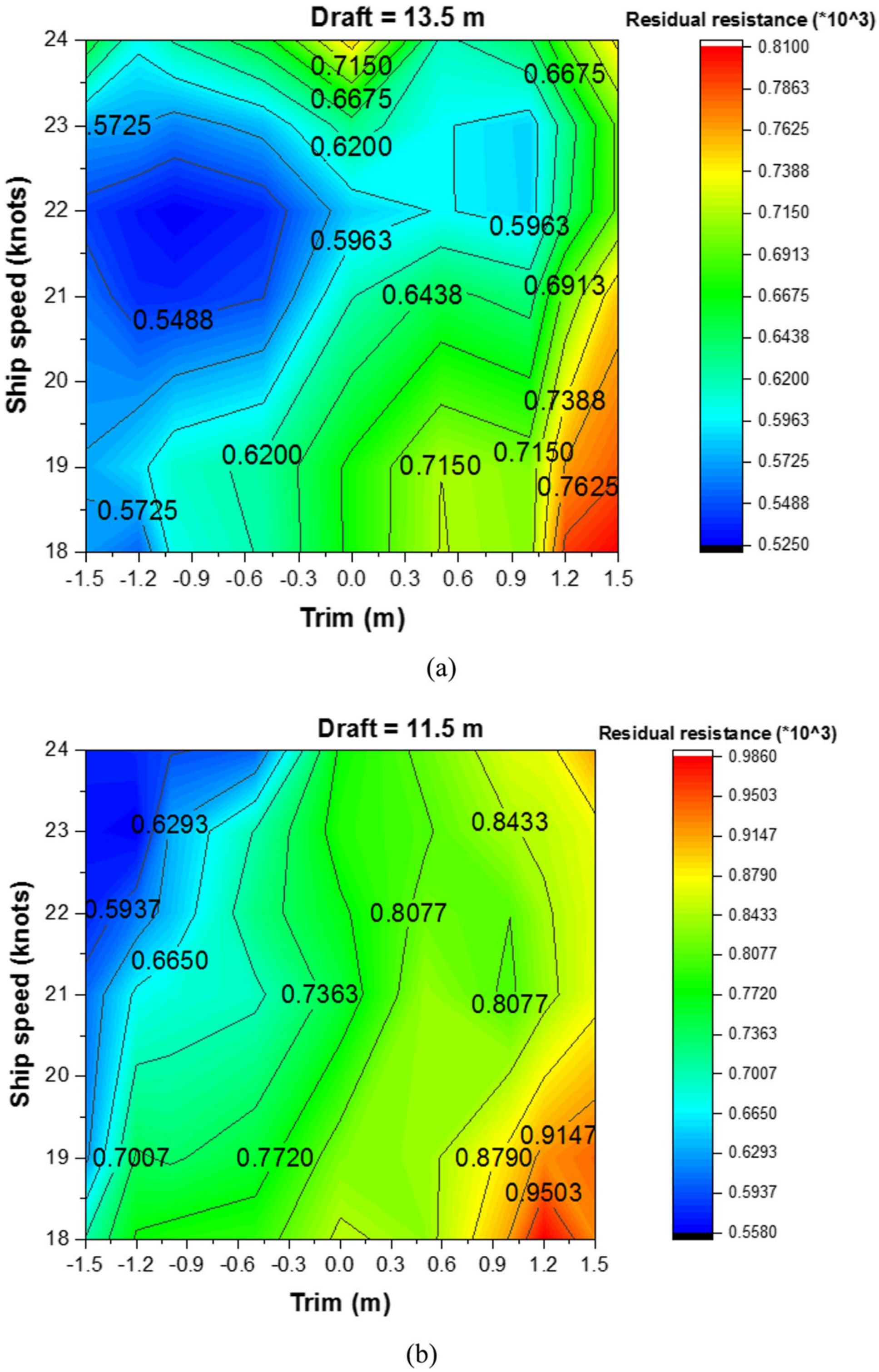


Fig. 8 The predicted residual resistance coefficient for container ship at different trim conditions and ship speeds **a** draft = 13.5 m, **b** draft = 11.5 m

and different two drafts of 16.5 m and 17.5 m. To obtain the total resistance of the ship, the calculations has been divided to two process frictional resistance coefficient calculation and residual resistance coefficient prediction which are independent and dependent on the trim condition, respectively. Firstly, the frictional resistance is calculated based on the main parameters of the bulk carrier as shown in Fig. 3.

Then, the predicted residual resistance coefficients for the bulk carrier are shown in Fig. 4, where the horizontal coordinates correspond to the trim condition which displayed from – 1.5 to 1.5 m, and the vertical coordinates correspond to the speed of the ship which displayed from 12 to 17 knots, while the residual resistance coefficient (C_r) are presented as color contour marks.

Figure 4a shows that the lowest residual resistance values for ship at draft of 16.5 m are defined in blue and light blue in the range between 12 and 15 knots at trim adjustment from – 1.5 to 0.5 m. After that, the color is changed to green for ship speed above 15 knots at all trim conditions. In contrast, when the ship draft is increased to 17.5 m, as shown in Fig. 4b, the minimum resistance value for ship speeds up to 17 knots is occurred at trim between – 1 m and even keel condition. Thus, more clarification is required for the expected optimum trim at the specified speeds, as this can be done by drawing a relationship between the ship's speed and the fuel consumption at each trim condition in the region between – 1.5 and 1.5 m as shown in Fig. 5 as the minimum fuel consumption is highlighted by using red circle.

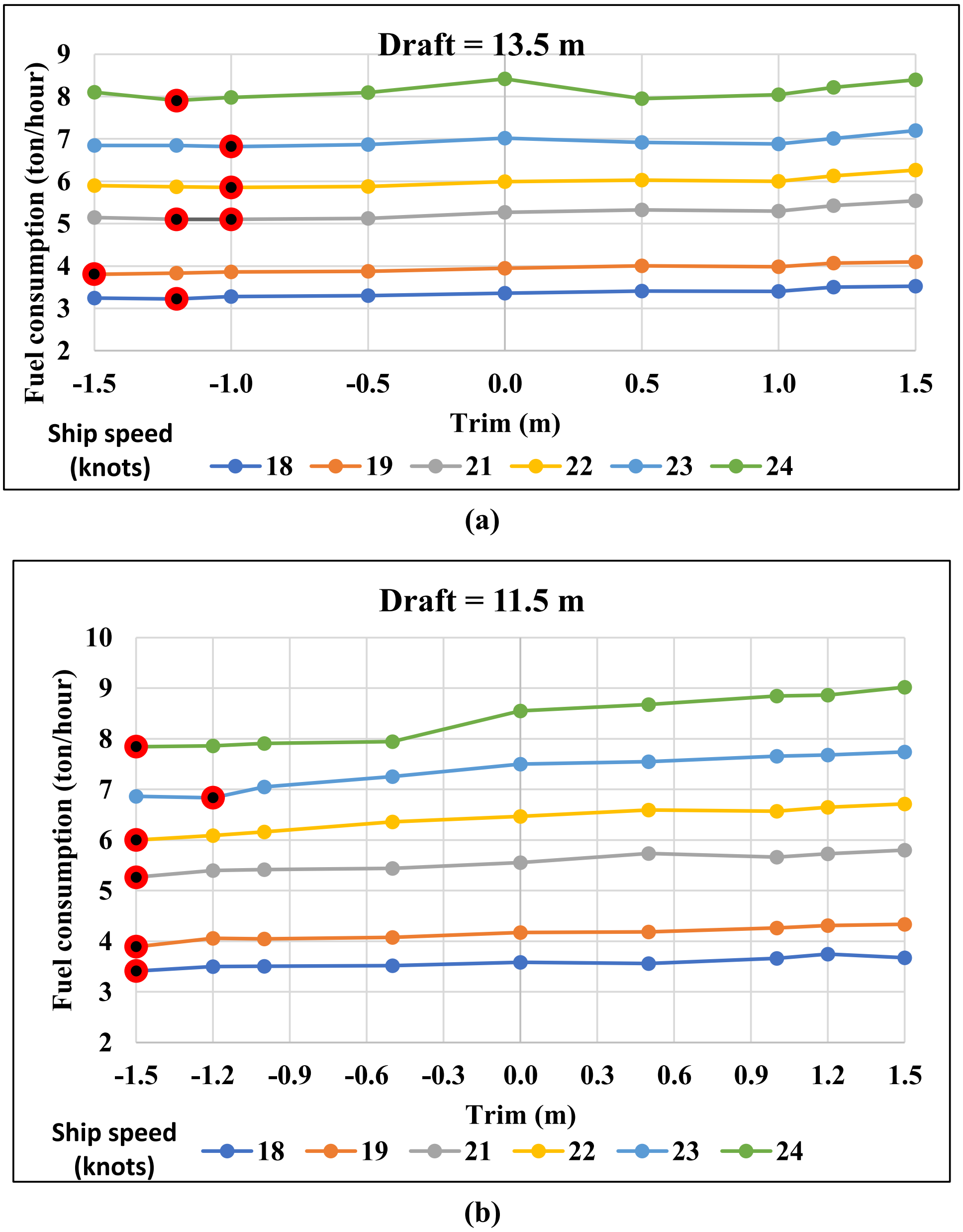
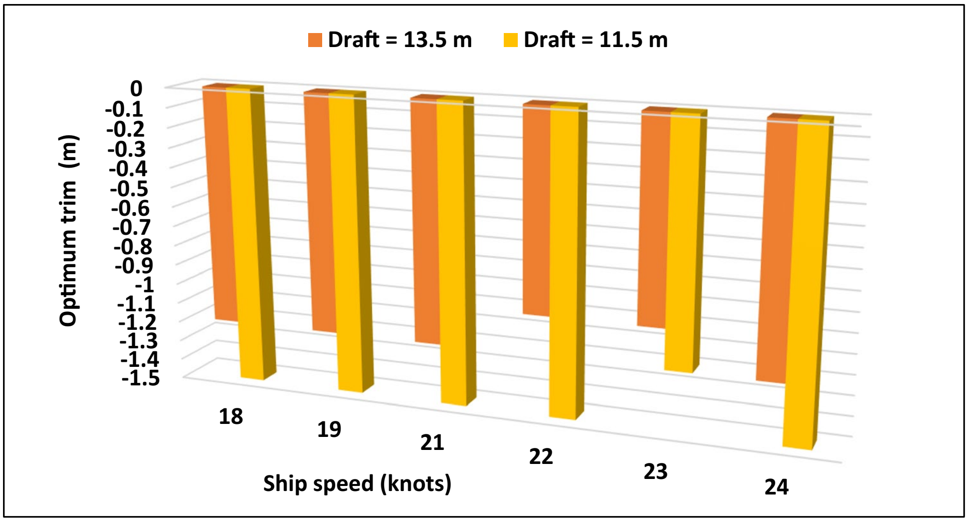


Fig. 9 Fuel consumption of container ship **a** $T = 13.5$ m, **b** $T = 11.5$ m

Fig. 10 Optimum trim for the container ship at two draft states



It is clear from the results presented in Fig. 5a, the optimum trim for the bulk carrier at a draft equal to 16.5 m is – 0.5 m for ship speed condition 12 knots, while it is equal to zero for ship speed condition 13, 16, and 17 knots. Moreover, it is clear from the results presented in Fig. 5b, the optimum trim condition for the same bulk carrier at the 17.5-m draft is even keel condition or – 1 m for almost all ship speed conditions.

Figure 6 shows a comparison between the predicted optimum trim conditions for the bulk carrier under draft conditions equal to 16.5 m and 17.5 m at different speeds.

It is clear from the comparative study in Fig. 6, the two studied drafts are identical in the prediction value for the optimum trim of the bulk carrier except at a ship speed of 12 knots which has a different value in both states.

Trim optimization for container ship

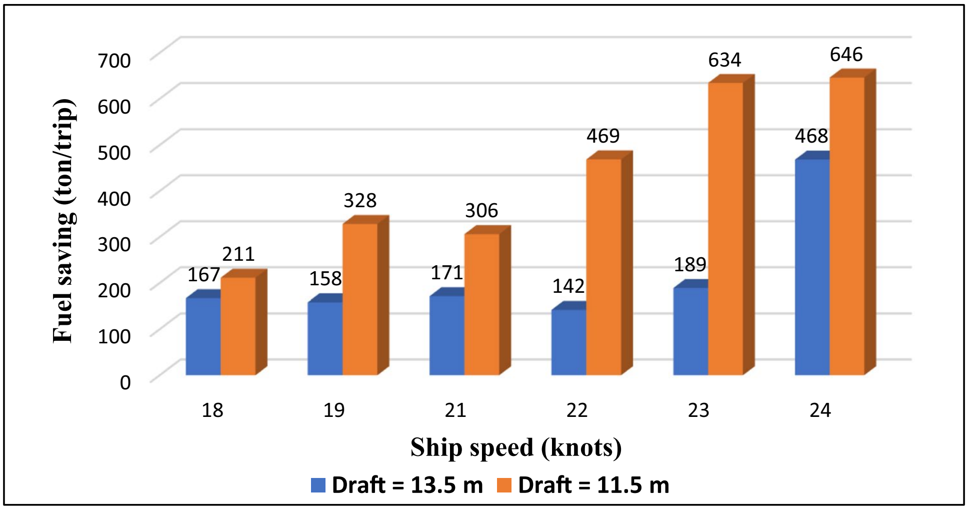
The optimization process was applied for the container ship with 13,000 TEU at different ship speeds and two drafts. Like the procedure done for the bulk carrier, the analysis has been initialized with the calculation of frictional resistance coefficient as shown in Fig. 7.

Then, the predicted residual resistance coefficients for the container ship are shown in Fig. 8, where the horizontal coordinates correspond to the trim which is displayed from – 1.5 to 1.5 m, and the vertical coordinates correspond to the speed of the container ship, while the residual resistance coefficient (C_r) are presented as color contour marks.

It is noticeable in Fig. 8 that the lowest values of resistance are in the far west of the figure, which lies between two values of trim, which are – 1 m and – 1.5 m. Therefore, more clarification is required for the expected optimum trim at the specified speeds, as this can be done by drawing a relationship between the ship's speed and the fuel consumption at each trim condition in the region between – 1.5 and 1.5 m as shown in Fig. 9 as the minimum fuel consumption is highlighted by using red circle.

It is noticeable from the predicted fuel consumption presented in Fig. 9a that the value of the optimum trim changes

Fig. 11 Quantity of fuel saving by using optimum trim compared to the even keel condition



between three points and they are – 1, – 1.2, and – 1.5 m at the draft of 13.5 m. While it is clear from the results presented in Fig. 9b, the optimum trim for the same container ship at 11.5 m draft is almost – 1.5 m for ship speed adjustment between 18 and 22 knots, and 24 knots, while it is equal to – 1 m for ship speed condition of 23 knots. Figure 10 shows a comparison between the predicted optimum trim for the container ship under draft equal to 13.5 m and 11.5 m at different ship speed.

It is clear from the comparative study in Fig. 10, the best prediction value for the optimum trim of the 13,000 TEU container ship is – 1.5 m for most ship speed conditions, and in some cases, it is predicted to be – 1.2 m. Therefore, it is important to study the comparison between even keel condition (Trim = 0) and the optimum trim condition at each speed based on the fuel-saving per one trip (two rounds) as shown in Fig. 11.

As shown in Fig. 11, the fuel-saving based on using optimum trim at each speed is a significant quantity to be benefited as it would reduce the operating costs and increase the energy efficiency of a container ship. Hence, the exhaust emissions will be reduced by using optimum trim compared to the even keel condition. The comparative study showed that the operating condition at a draft of 11.5 m has a higher fuel-saving amount than the operating condition at a draft of 13.5 m.

Conclusions

Ship trim optimization is considered one of the operational measures to increase energy efficiency and reduce ship emissions for existing ships in operation. It is a practical measure as it does not require hull structural modification or engine upgrade. The study of trim optimization can be conducted based on experimental testing in towing tanks, but this method is difficult and more expensive to build the appropriate model and provide the proper test facility. Thus, the present paper is suggested an optimization technique based on numerical calculations to determine ship resistance at various trim conditions and select the optimum trim. The potential benefits of using numerical calculation over experimental testing are saving money and reducing the time consumed during performing the technique.

In the present paper, the trim optimization technique has been applied to bulk carrier and container ship. The trim adjustment lies between – 1.5 and 1.5 m at different ship speeds and different design drafts. The present study is limited to being applied to ships under calm water conditions not heavy weather conditions. Moreover, the paper is not discussed the wake effect on propellers and its effect on ship maneuverability. Generally, even though the study limitations, the numerical modeling calculates well the optimum trim at various ship speeds and can significantly develop ship operational efficiency and decrease ship emissions.

The results showed that positive trim (trim by bow) have a significant increasing effect on fuel consumption, while the negative trim (trim by stern) have a significant decreasing effect on fuel consumption. As an example, the best prediction value for the optimum trim of the container ship is – 1.5 m for most ship speed conditions, and in some cases, it is predicted to be – 1 m. Also, the best prediction value for the optimum trim of the bulk carrier is lied between 0 and – 1 m for the ship speed adjustment between 12 and 17 knots.

Also, the fuel-saving based on using optimum trim at each speed is a significant quantity to be benefited as it would reduce the operating costs and increase the energy efficiency. Hence, the exhaust emissions will be reduced by using optimum trim compared to the even keel condition.

Author contribution Ahmed G. Elkafas: conceptualization, methodology, writing draft paper, software, visualization, investigation, original draft, and revision version preparation.

Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Ammar NR, Elgohary MM, Zeid A, Elkafas AG (2019) Prediction of shallow water resistance for a new ship model using CFD simulation: case study container barge. J Sh Prod Des 35:198–206. https://doi.org/10.5957/jspd.11170051

Bouman EA, Lindstad E, Rialland AI, Strømman AH (2017) State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. Transp Res Part D Transp Environ 52:408–421. https://doi.org/10.1016/j.trd.2017.03.022

Breslin JB, Anderson P (1994) Hydrodynamics of ship propellers. Cambridge University Press, Cambridge, UK

Coraddu A, Oneto L, Baldi F, Anguita D (2017) Vessels fuel consumption forecast and trim optimisation: a data analytics perspective. Ocean Eng 130:351–370. https://doi.org/10.1016/j.oceaneng.2016.11.058

Deng R, Li C, Huang D, Zhou G (2015) The effect of trimming and sinkage on the trimaran resistance calculation. Procedia Eng 126:327–331. https://doi.org/10.1016/j.proeng.2015.11.199

Elkafas AG (2022) Assessment of station keeping capability for dynamically positioned offshore supply vessel. J Sh Prod Des 1–12 https://doi.org/10.5957/JSPD.08210018

Elkafas AG, Elgohary MM, Shouman MR (2021a) Numerical analysis of economic and environmental benefits of marine fuel conversion from diesel oil to natural gas for container ships. Environ Sci Pollut Res 28:15210–15222. https://doi.org/10.1007/s11356-020-11639-6

Elkafas AG, Elgohary MM, Zeid AE (2019) Numerical study on the hydrodynamic drag force of a container ship model. Alexandria Eng J 58:849–859. https://doi.org/10.1016/j.aej.2019.07.004

Elkafas AG, Khalil M, Shouman MR, Elgohary MM (2021b) Environmental protection and energy efficiency improvement by using natural gas fuel in maritime transportation. Environ Sci Pollut Res 28:60585–60596. https://doi.org/10.1007/s11356-021-14859-6

Elkafas AG, Shouman MR (2022) A study of the performance of ship diesel-electric propulsion systems from an environmental, energy efficiency, and economic perspective. Mar Technol Soc J 56:52–58. https://doi.org/10.4031/MTSJ.56.1.3

Elkafas AG, Shouman MR (2021) Assessment of energy efficiency and ship emissions from speed reduction measures on a medium sized container ship. Trans R Inst Nav Archit Int J Marit Eng 163:121–132. https://doi.org/10.5750/ijme.v163iA3.805

Harvald SA (1983) Resistance and Propulsion of Ships. Wiley, New York. https://doi.org/10.1016/0191-2607(84)90024-4

Hochkirch K, Mallol B (2013) On the importance of full-scale CFD simulations for ships. In: 12th International conference on computer applications and information technology in the maritime industries (COMPIT 2013). Technische Universität Hamburg, Cortona (Italy), pp 85–89

Iakovatos MN, Liarokapis DE, Tzabiras GD (2013) Experimental investigation of the trim influence on the resistance characteristics of five ship models. In book: developments in maritime transportation and exploitation of sea resources, 1st edn. Taylor & Francis, London, pp 23–32.https://doi.org/10.1201/b15813

IMO (2016) Guidelines for the development of a ship energy efficiency management plan (SEEMP). In: Resolution MEPC.282(70). International Maritime Organization, London, pp 1–19

Islam H, Guedes Soares C (2019) Effect of trim on container ship resistance at different ship speeds and drafts. Ocean Eng 183:106–115. https://doi.org/10.1016/j.oceaneng.2019.03.058

ITTC (2017) 1978 ITTC Performance Prediction Method. In: Propulsion Committee (ed) 28th ITTC conference. International towing tank conference, Wuxi, China, pp 1–15

Joung T-H, Kang S-G, Lee J-K, Ahn J (2020) The IMO initial strategy for reducing greenhouse gas (GHG) emissions, and its follow-up actions towards 2050. J Int Marit Safety, Environ Aff Shipp 4:1–7. https://doi.org/10.1080/25725084.2019.1707938

Kristensen HO, Lützen M (2013) Prediction of resistance and propulsion power of ships. Project no. 2010-56, Work Package 2, Report no. 04. Denmark

Psaraftis H, Kontovas CA (2021) Decarbonization of maritime transport: is there light at the end of the tunnel? Sustainability 13:237. https://doi.org/10.3390/su13010237

Rehmatulla N, Calleya J, Smith T (2017) The implementation of technical energy efficiency and CO2 emission reduction measures in shipping. Ocean Eng 139:184–197. https://doi.org/10.1016/j.oceaneng.2017.04.029

Reichel M, Minchev A, Larsen NL (2014) Trim optimisation - theory and practice. TransNav Int J Mar Navig Saf Sea Transp 8:387–392. https://doi.org/10.12716/1001.08.03.09

Sherbaz S, Duan W (2014) Ship trim optimization: assessment of influence of trim on resistance of MOERI container ship. Sci World J 2014:1–6. https://doi.org/10.1155/2014/603695

Shivachev E, Khorasanchi M, Day S, Turan O (2020) Impact of trim on added resistance of KRISO container ship (KCS) in head waves: an experimental and numerical study. Ocean Eng 211:107594. https://doi.org/10.1016/j.oceaneng.2020.107594

Viola IM, Enlander J, Adamson H (2014) Trim effect on the resistance of sailing planing hulls. Ocean Eng 88:187–193. https://doi.org/10.1016/j.oceaneng.2014.06.025

Xing H, Spence S, Chen H (2020) A comprehensive review on countermeasures for CO2 emissions from ships. Renew Sustain Energy Rev 134:110222. https://doi.org/10.1016/j.rser.2020.110222