



Modeling and Simulation of Ship Propulsive Efficiencies Related Characteristics with Energy Efficiency Design Index in Focus

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Abstract: Computer-based simulation of ship propulsion system performance parameters related characteristics was conducted with energy efficient design index (EEDI) in focus in this study. A tanker vessel-MT Diamond is selected as a case study. EEDI related studies on propulsion system conducted by several researchers are based on maximizing specific fuel consumption, trim and draft optimization, block coefficient optimization amongst other. This lent credence to the need for a research window in this direction which this research tries to fill by studying the relationship between EEDI and ship propulsive efficiencies. The computational development of modeling and simulation for this research was brought to fruition utilizing MATLAB. Focus was given to performance parameters that influence the overall performance of the propulsion system. A detailed program code was developed and implemented to simulate the behavior of some propulsion system efficiencies such as the brake specific fuel consumption (bsfc), brake thermal efficiency, η_b , propulsive efficiency, η_p , overall ship efficiency, η_{sp} and EEDI. The cumulative analysis revealed that the optimal ship effective power is 8.20kW at a vessel speed of 13knot and with a decay constant of $0.049s^{-1}$, the EEDI shows a commensurate improvement of 3.5% when the optimal overall propulsive efficiency of the ship is 0.507398386. Results from the simulation analysis carried out to reproduce the propulsion behaviour of the ship indicate the validity of the mathematical models. Also, improvement in the propulsion system performance parameters gives a commensurate improvement in the EEDI, specific fuel consumption (sfc) and emission level of the vessel.

Keywords: Simulation, Propulsive Efficiencies, Energy Efficiency Design Index, Modeling, Computational Development

1. Introduction

In boosting international trade, maritime transport and shipping plays a pivotal role as the mainstay with the most cost effective and energy efficient means of cargo transportation, making significant contributions to global prosperity [1]. This astronomically increases the number of vessels of the world commercial fleet over the last few decades and results to the quest for larger and faster vessels.

Vessels require a means in order to move from one location to another - the propulsion system. Propulsion

system is the mechanism that develops thrust for navigation and maneuverability of vessels. A propulsion system is basically made up of: the prime mover (s), transmissions shaft (s) and thruster (s) that provide the momentum and power required to overcome resistance and produce acceleration. Higher requirements are placed on the propulsion system design in order to meet some critical criteria such as: load on the engine, sfc and EEDI regulations which is an indication of ship's energy efficiency.

Engine-propeller-hull matching (EPHM) and optimized propulsion system are critical for a vessel to achieve its

desire speed and allow for high engine performance [2]. They play essential role in determining the performance of a vessel and certainly influences ship's economy, emissions and particularly EEDI. Properly optimized propulsion system reduces vibration induced stresses, which may contribute to already existing stresses of engine and wave loads on the [3].

Considering the complexity of marine propulsion system and the quest for more energy efficient ships, this places higher requirements on vessels propulsion system design to meet the EEDI regulations, thus making optimization of propulsion system a key problem in ship design. Present day economy requires minimum time and money spent in developing and preparing for experimentation and analysis of object's technical condition at all stages of the life cycle and swift alteration to products design parameters [4, 5].

The use of mathematical model allows a systematic and analytical assessment of propulsion configuration and reduces the use of experimental or hardware model tests. A computer-based analysis is extremely useful because rudimentary physical processes occurring in design and off-design operation provides the basis of design evaluation and review [1]. It therefore makes engineering sense to take advantage of the very desirable characteristics and the versatility of software to create models, simulate and optimize engineering systems with high degree of predictability, precision and accuracy [6].

The computational development of modeling and computer-based simulation for this study was brought to bear utilizing MATLAB. Concentrated attention is given to performance parameters that influence the overall performance of the propulsion system in this work. A

detailed program code was developed and implemented to simulate the behavior of selected parameters of interest of the propulsion system of Moving Tanker (MT) DIAMOND to achieve the best performance scenario and understand its robustness on EEDI. Results from the simulation shows that the model predicts the performance output of the system with high degree of accuracy. Also, improvement in the propulsion system performance parameters gives a commensurate improvement in the EEDI, sfc and emission level of the vessel.

2. Methodology

This section deals a methodology of assessing the performance of ship propulsion system and offers the much-needed realistic simulation when benchmarked against real-time test bed measured data utilized for optimization purposes. This will establish a rational foundation for a computer-based performance assessment of marine propulsion system. This research will focus on modeling the prime mover and transmission system using mean value engine model (MVEM) with thermodynamics & energy balance equations.

2.1. Ship Propulsion System Interaction and Modelling

The basic propulsion system of the vessel - MT DIAMOND considered in this work is shown in figure 1 and consists of the marine diesel engine, shaft and propeller. The diesel engine is a two-stroke turbocharged type for high power output.

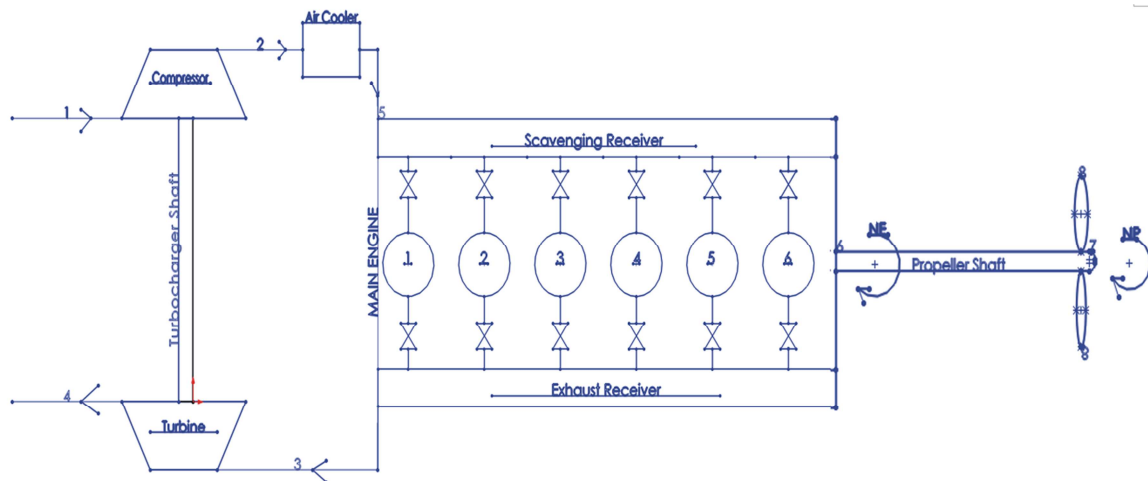


Figure 1. Schematic Diagram of MT DIAMOND Propulsion System.

2.1.1. Analytical Model of the Propulsion Plant

Important performance parameters of the marine diesel engine relevant to this work will be captured in the modeling. A cycle MVEM and thermodynamic equations will be applied to mathematically model the propulsion plant components. The argument in favour of this approach is its ability to capture, predict and represent the engine parametric

characteristic with sufficient accuracy and speed, while requiring limited amount of input data and quite a reasonable time of execution [7, 8].

2.1.2. Engine Shaft Speed

The engine and propulsion shaft speed according to Guan et al. (2015) is obtained from the expression in equation (1):

$$\frac{dN_E}{dt} = \frac{30(\eta_s \eta_{GB} Q_E - Q_p)}{l_E + l_{GB} + l_s + l_p} \quad (1)$$

Since for two stroke diesel engines, there is no installation of reduction gear box, then the respective terms in equation (1) are: $\eta_{GB} = 1$ and $l_{GB} = 0$ respectively [9] provides the relationship for obtaining the engine torque and brake power as given by Equation (2) to (4).

$$Q_E = \frac{P_b V_D}{2\pi \text{ rev}_{cy}} \quad (2)$$

$$B_P = \frac{\pi N_E Q_E}{30} = \frac{10 P_b L A_{cy} N_E K}{6} = \frac{5 P_b L \pi D^2 N_E K}{12} \quad (3)$$

$$i_p = \frac{10 P_i L A_{cy} N_E K}{6} = \frac{5 P_i L \pi D^2 N_E K}{12} \quad (4)$$

Bsfc as shown in equation (5) is a measure of the fuel efficiency of any prime mover that burns fuel and produces rotational, or shaft power.

$$bsfc = \frac{\dot{m}_f}{B_P} \quad (5)$$

Similarly, the bsfc is also given by:

$$bsfc = \frac{3.6 \times 10^6}{\eta_b \times Q_L} \quad (6)$$

A measure of overall efficiency of the engine is given by the brake thermal efficiency, η_b :

Equating equations (5) and (6), a relation for brake thermal efficiency of the prime mover is obtain as shown in equation (7):

$$\eta_b = \frac{3600 \times \text{Brake Power}}{\text{Feul Energy}} = \frac{3600 B_P}{\dot{m}_f Q_L} \quad (7)$$

2.1.3. Propeller Hydrodynamic Modelling

From the perspective of diesel engine, the brake power, B_P is transmitted to the delivered powered and is given by the expression of equation (8):

$$P_D = 2\pi n_p Q_p \eta_R = B_P \eta_{trm} \quad (8)$$

Since a two-stroke diesel engine is considered in this work, the shaft power, P_s is assumed to be equivalent to the brake power of the engine, B_P because of the absence of reduction gear and the shaft efficiency is calculated from the relationship of equation (9):

$$\eta_s = \frac{P_D}{P_s} \quad (9)$$

The consideration is that the propeller rotation speed is equal to the two-stroke marine engine speed. The propeller will be modeled using the polynomial equations for Wageningen B propeller series. These non-dimensional parameters according to Ogar et al. (2018) are defined by the expressions of equations (10) and (13):

$$J = \frac{V_A}{n_p \times D_p} = \frac{V_s \cdot (1 - \omega)}{n_p \times D_p} \quad (10)$$

$$K_T = \frac{T_p}{\rho_{sw} \times n_p^2 \times D_p^4} \quad (11)$$

$$Q_p = \frac{P_D}{2 \times \pi \times n_p} \quad (12)$$

$$K_Q = \frac{Q_p}{\rho_{sw} \times n_p^2 \times D_p^5} \quad (13)$$

Propeller open-water efficiency defined in terms of thrust power P_T and the delivered power P_D is given by equation (14): The propeller open water efficiency which is imperative and is regarded as the goal of matching [9, 10]:

$$\eta_o = \frac{P_T}{P_D} = \frac{T_p V_A}{2\pi Q_p n_p} = \frac{K_T \times \rho_{sw} \times n_p^2 \times D_p^4 \times V_A}{2\pi \times K_Q \times \rho_{sw} \times n_p^2 \times D_p^5} = \frac{K_T \times J}{2\pi \times K_Q} \quad (14)$$

The propeller quasi propulsive coefficient that gives a description of the vessels propulsion system efficiency is obtained from the expression:

$$\eta_D = \frac{P_E}{P_D} = \frac{R_T V_s}{\omega M_D} = \frac{R_T V_s}{2\pi n M_D} = \frac{R_T V_s}{T_p V_A} \times \frac{T_p V_A}{\omega Q_p} \times \frac{Q_p}{M_D} = \eta_H \eta_o \eta_R \quad (15)$$

Considering and taking into account the mechanical efficiency of the shaft line, the propulsive coefficient is obtained from the relationship given in equation (16):

$$\eta_P = \frac{P_E}{P_D} = \frac{P_E}{P_D} \times \frac{P_D}{P_s} = \eta_D \times \eta_s = \eta_H \times \eta_o \times \eta_R \times \eta_s \quad (16)$$

In order to estimate the total ship propulsion system efficiency, the expression of equation (17) is used:

$$\eta_{sp} = \frac{P_E}{Q_f} = \eta_b \eta_P = \eta_b \times \eta_H \times \eta_o \times \eta_R \times \eta_s \quad (17)$$

2.2. EEDI Modeling and Its Relationship with Propulsion System Efficiencies

EEDI estimates the amount of CO_2 emitted by ship during the vessel's design phase. Therefore, the lower a vessel's EEDI, the lesser the emitted CO_2 . EEDI in its simplest form is represented by the quotient of emitted CO_2 to the transport work [11-13] as shown in equation (18):

$$EEDI = \frac{CO_2 \text{ Emitted}}{\text{Transport work}} = \frac{(f_j \times P_{ME} \times SFC_{ME} \times C_{f_{ME}}) + (P_{AE} \times SFC_{AE} \times C_{f_{AE}})}{f_i \times f_c \times f_w \times \text{Capacity} \times V_s} \quad (18)$$

According to Tran (2016) the referenced EEDI is given by the expression of equation (19):

$$\text{Reference EEDI} = a \times b^{-c} \quad (19)$$

In studying and understanding the relationship between EEDI and propeller open water efficiency η_o , the sfc is usually assumed as a constant [5, 14]. Taking this into consideration, the EEDI formula can be represented by equation (20):

$$EEDI = \frac{(f_j \times P_{ME} \times SFC_{ME} \times C_{f_{ME}}) + (P_{AE} \times SFC_{AE} \times C_{f_{AE}})}{\frac{f_i \times f_c \times f_w \times \text{Capacity} \times V_s}{K_1 \times P_{ME} + K_2}} = \frac{K_3 \times V_s \times \text{Capacity}}{K_1 \times P_{ME} + K_2} \quad (20)$$

Specifically, from the propulsion energy chain, according to Huilin et al. (2019), power from the main engine, P_{ME} can

be calculated from the vessel's effective power and certain related efficiency as given in equation (21).

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_D} = \frac{P_E}{\eta_s \times \eta_H \times \eta_O \times \eta_R} \quad (21)$$

The EEDI will be given by equation (22) after carrying out proper substitutions and evaluations:

$$EEDI = \frac{K_4 \times P_E}{V_s \times \text{capacity} \times \eta_O} + \frac{K_5}{\text{capacity} \times V_s} \quad (22)$$

If the Capacity, vessel speed, V_s and effective power, P_E of a vessel are given, equation (23) satisfies the relationship requirement for EEDI and open water:

$$EEDI = \frac{K_6}{\eta_O} + K_7 \quad (23)$$

Equation (23) shows that as the open water efficiency of the propulsion system is optimized, the EEDI is also optimized.

Models relating the ship propulsive efficiency and overall ship efficiency with EEDI are expressed in equation (26) and (27). They are obtained from the power developed by the main engine which is related to the propulsive efficiency as given by the expression of equation (24):

$$P_{ME} = \frac{P_E}{\eta_s \times \eta_D} = \frac{P_E}{\eta_s \times \eta_H \times \eta_R \times \eta_O} = \frac{P_E}{\eta_p} \quad (24)$$

Substituting equation (24) into equation (20) we have expression of equation (24):

$$EEDI = \frac{f_j \times P_E \times SFC_{ME} \times C_{f_{ME}}}{f_i \times f_c \times f_w \times \eta_p \times V_s \times \text{Capacity}} + \frac{P_{AE} \times SFC_{AE} \times C_{f_{AE}}}{f_i \times f_c \times f_w \times V_s \times \text{Capacity}} \quad (25)$$

Simplifying further, equation (25) will yield equation (26):

$$EEDI = \frac{K_8 \times P_E}{\eta_p} + K_9 \quad (26)$$

Similarly, following the procedures used above, and keeping other parameters and terms constant and simplifying equation (20) appropriately, yields the expression relating EEDI and overall ship efficiency as given by equation (27):

$$EEDI = \frac{K_{10} \times P_E}{\eta_{ship}} + K_{11} \quad (27)$$

3. Results and Discussion

To achieve low sfc and an improved EEDI at the designed speed of a vessel, it requires certain critical performance parameters of the propulsion system to be numerically analyzed and optimized. Based on previous researches reviewed, several researchers had carried out studies involving marine propulsion system. However, most researchers dwelled on MATLAB-SIMULINK simulation model, propulsion system matching optimization with particular attention to open water efficiency, η_o and propulsion system matching in relation to EEDI. The impact of ship draft, trim, block coefficient and route on EEDI had been extensively investigated. Propulsion system study with interest on sfc and emission had been widely researched [15]. From literature, it is obvious that the major objective for most researchers in propulsion system is based on engine-propeller-hull matching, mathematical modelling and sfc minimization. It is important to note that there are other propulsion system parameters whose influence on the performance of propulsion system characteristics and EEDI need to be investigated. It therefore makes sense to delve into understanding the influence of these propulsive parameters on EEDI. This gap is filled by this research.

Based on this, a thorough investigation of MT Diamond propulsion system parametric characteristics using MATLAB was evaluated and analyzed. In analyzing the propulsion system model with respect to performance parameters of interest and to ascertain the suitability of the models for engineering application, a computer-based simulation was carried out. Figure 2 shows a computational framework for the propulsion system analysis and simulation. This provided the platform for computation, data generation and assessing the characteristics of the propulsion system performance parameters with EEDI in focus.

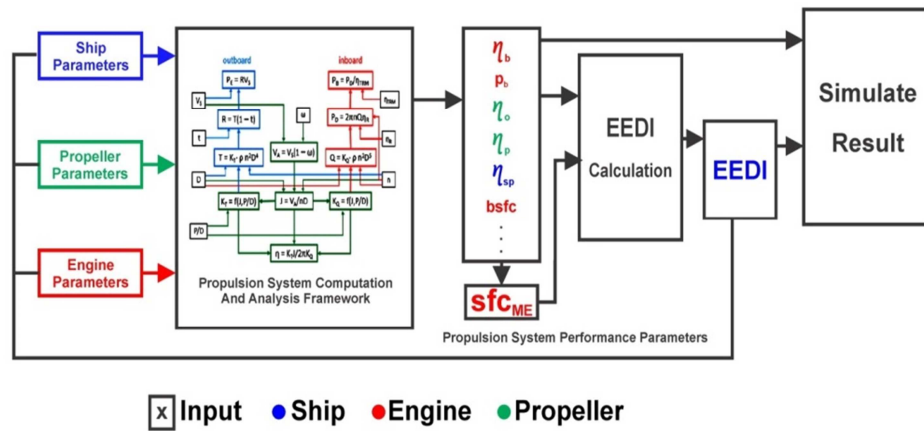


Figure 2. Framework for Propulsion System Study and Analysis with EEDI in Focus.

A section of the data generated by the MATLAB code for some performance parameter of the propulsion system is shown in Table 1.

Table 1. Extract of Data Generated for Some Performance Parameter of the Propulsion System.

$PE \times 10^1$	$\eta_P \times 10^2$	$\eta_{sh} \times 10^2$	P_{ME}	EEDI	$\eta_o \times 10^1$	$bsfc \times 10^1$	$\eta_b \times 10^{-1}$
0.25625	0.003541	0.005465	72.36289	43.39334	0.017048	0.055544	1.543171
1.081149	0.007706	0.011087	140.2954	18.25987	0.0371	0.059579	1.438675
2.641458	0.012685	0.017111	208.2279	11.64682	0.061071	0.063546	1.348846
5.103095	0.018479	0.023483	276.1604	8.596281	0.088962	0.067449	1.270797
8.631978	0.025086	0.030162	344.0929	6.841005	0.120772	0.071289	1.202354
13.39403	0.032508	0.037119	412.0254	5.7008	0.156502	0.075066	1.141847

Several plots of some performance parameters were simulated and generated. The plots happen to show trend and profiles envisioned, giving an indication of the models' accuracy. Figure 3 shows Engine Power against the Vessel's Speed. The power developed by the engine from the graph show a direct proportional relationship with the speed of the vessel. As the engine power increases, the vessel speed increases linearly to optimal level.

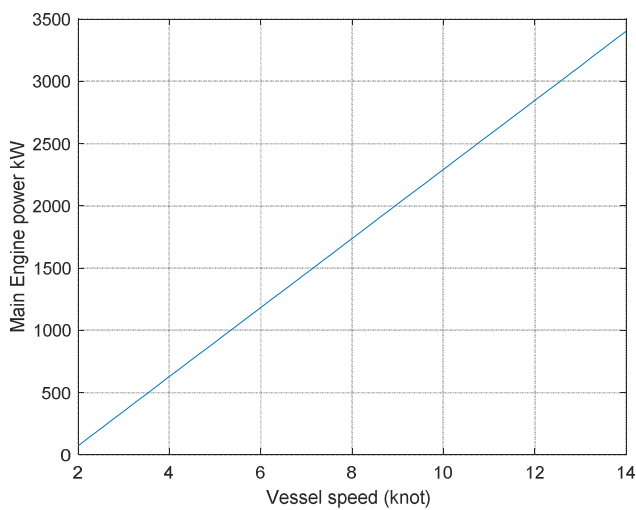
**Figure 3.** Engine Power against Vessel Speed.

Figure 4 shows a graph of bsfc against EEDI. A measure of the fuel efficiency of the prime mover is described by bsfc. From the graph, the bsfc reduces as the EEDI improves. The bsfc improves swiftly from 0.25% to 0.7% following a corresponding improvement in the vessel's EEDI. This can be accounted for by the fuel conversion efficiency and the brake thermal efficiency of the propulsion system prime mover. Figure 4 closely expresses the effect of bsfc on EEDI and its attendant impact on the vessel's emission level.

Brake thermal efficiency is a single parameter that describes the performance capability of a marine diesel engine. Figure 5 is a graph of brake thermal efficiency against EEDI. It is observed that from Figure 5, EEDI decreases with increasing brake thermal efficiency of the vessel. Therefore, optimizing the vessels brake thermal efficiency which is one of the propulsion system parameters of interest in this work, can significantly reduce sfc and improves EEDI of the vessel. From Figure 5, the EEDI reduces gradually as the brake thermal efficiency increases rapidly to 0.2%, but gradually to about 0.85% before stabilizing. Beyond this point, any further improvement of the brake thermal efficiency can possibly reduce the EEDI to zero, considered impossible in engineering.

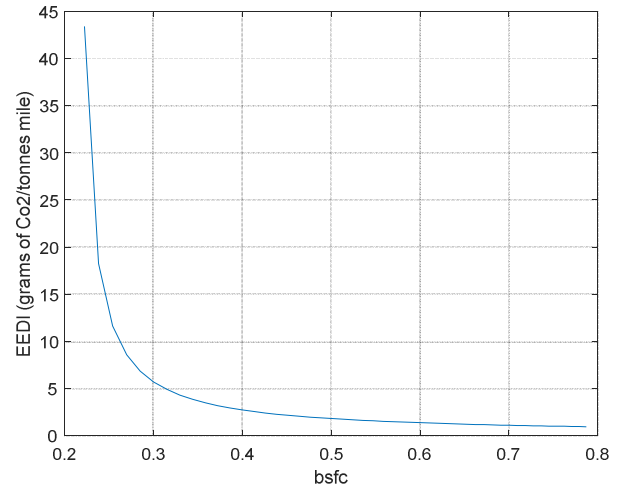
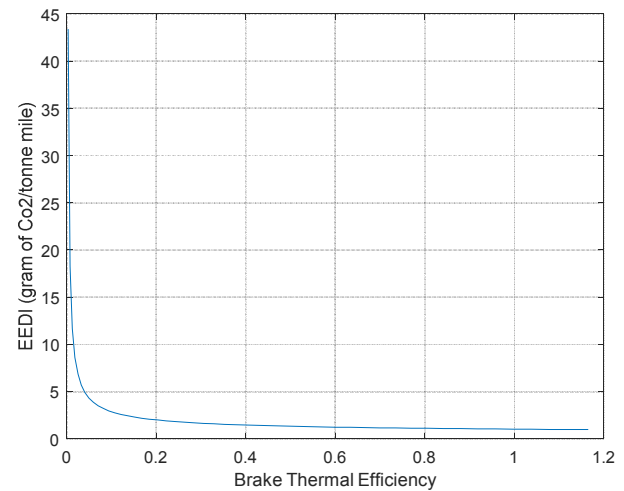
**Figure 4.** EEDI against bsfc.**Figure 5.** EEDI against Brake Thermal Efficiency.

Figure 6 shows a graph of EEDI against propulsive efficiency. The propulsive efficiency takes into account the propeller open water efficiency which is imperative and regarded as the goal of EPHM. Optimizing the propulsive efficiency correlates as an integral measure that reduces the load on the prime mover translating into improved sfc, EEDI and CO₂ emission. This means that as the propulsive efficiency increases, the EEDI reduces vis-à-vis the sfc and CO₂ emission. The EEDI reduces swiftly from 35 g of CO₂/ton m to 4.5 g of CO₂/ton m before decreasing gradually following a corresponding improvement in the vessel's propulsive efficiency from 0.12% to about 0.75%. This can be accounted for by accurate EPHM utilizing the propeller open water efficiency, reduced load on the engine and the vessel's hull resistance.

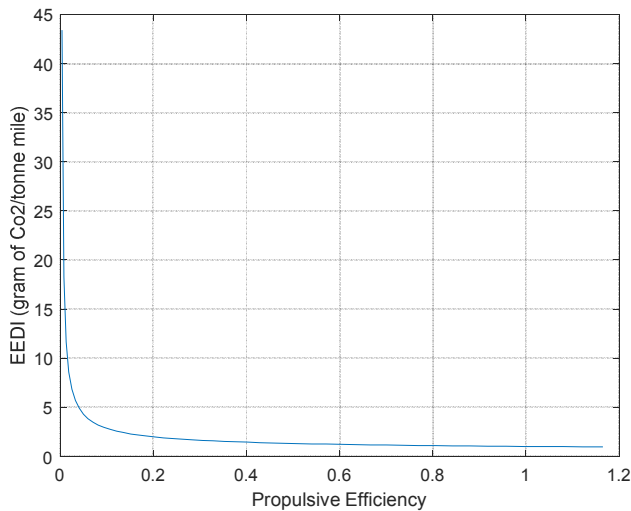


Figure 6. Graph of EEDI against Propulsive Efficiency.

As shown in Figure 7, is a graph of EEDI against overall ship efficiency. Optimizing the overall ship efficiency correlates as an integral measure that improves the entire ship efficiencies of the ship. This means that as the overall ship efficiency increases, there is an improvement of EEDI, sfc and CO₂ emission. The EEDI improves swiftly from 46 g of co₂/ton m to 4.5 g of co₂/ton m before decreasing gradually following a corresponding improvement in the vessel's overall ship efficiency from 0.11% to about 0.8%. The significance of this graph gives a representation of optimized performance parameters of a vessel that enhances improvement in operational cost, environmental impact via emission and satisfying international maritime Organization regulations in the operation of marine vessels.

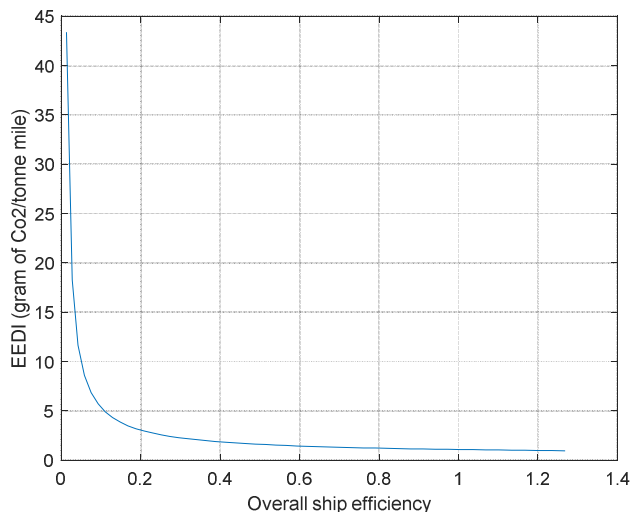


Figure 7. Graph of EEDI against Overall Ship Efficiency.

Furthermore, figures 6 and 7 indicate that continuous improvement of overall ship efficiency help to give a better performance of each of the input variables such as brake specific fuel consumption, brake thermal efficiency, ship propulsive efficiency, EEDI and also buttresses the validity of the model developed in this work.

4. Conclusion

The modeling and simulation of a vessel's propulsion system is presented in this paper. A computer program code was generated and implemented in MATLAB2019a environment utilizing the propulsion system data of MT Diamond obtained. A computer-based simulation followed, to authenticate the model developed and to further understand the behaviour of some performance parameters of interest of the vessel's propulsion system and its relationship with EEDI. Results from the simulation analysis carried out indicate the validity of the mathematical models. Also, with an overall ship efficiency 50.7% at a speed of 13 knots, the vessel's propulsion system experiences an improvement of about 3.5% of the EEDI which also translates to improvement of sfc and emission level of the vessel.

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