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Effects of Energy Efficiency Design Index on Resistance, Hydrostatics and Ship Design Using Hughes-Prohaska Method

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ABSTRACT
In this study, the investigation of the effects of energy efficiency design index on resistance, hydrostatics and ship design was successfully carried out. The goal is to determine how much the current EEDI formulations improve or conflict with ship design, vessel resistance, and hydrostatic laws. A parametric case study of a Roll-on Passenger (Ropax), Tugboat, and Reefer vessel is conducted for this reason. This group of vessels was picked because of how much energy they use naturally. To determine the impact of EEDI law on these three types of vessels, Ship speed, Water Line Length (LWL), Beam (B), Draft (T) and Prismatic Coefficient (Cp) were examined. The results of the towing tank-model resistance tests were extrapolated to the three big ships, after the Hughes-Prohaska technique was used to evaluate the overall ship resistances and effective power of each of the models. In order to calculate the effective power, permissible power, and EEDI achieved, the resistance values previously extrapolated for the big ships were used. Based on correlation analysis of the data, the results indicate that there was an almost 89% agreement between the EEDI referenced and the EEDI attained. When the Hughes-Prohaska method's resistance data was verified against test data from an existing vessel model, an average error of 2% and a maximum error of 4% were discovered. It was deemed permissible to make this mistake. Effective power per unit displacement was plotted against each relevant parameter to examine the implications of EEDI on ship design, resistance, and hydrostatics. This is being done to ascertain the behavior of the EEDI attained. Additional findings showed that, with constant specific fuel consumption (SFC) and altering speed from 12 knots to 24 knots, the attained EEDI is proportional to the power (kW)/dead weight (tonne). It has been shown that at low speed, longer ships perform better on EEDI. However at higher speed, longer ships modify the L/B ratio, B/T ratio, draft, hydrostatic coefficients, increase resistance, and ultimately increase the ship's energy consumption. Further evidence suggest that in order to lower the EEDI, it is necessary to lower the pragmatic coefficient, optimize the hull, and decrease ship speed. In this instance, the 14% decrease in EEDI would be caused by the 13% sacrifice made to ship speed at the design stage. The graphs that were produced show that a ship may operate more efficiently and have a less environmental effect when the EEDI decreases.

KEYWORDS: Energy Efficiency Design Index, Ship parameters, Hughes-Proshaka, Model Resistance Test.

I. INTRODUCTION

The two major problems facing marine transportation today are energy consumption and environmental pollution, yet the industry is nevertheless vital to the global transportation system because of its enormous trade volume (seaborne trade) and cheap cost per unit of transportation. According to [1]over 70% of global commerce by value and over 80% of global trade by volume are transported by water and handled by ports throughout the world. The business will continue to grow as globalization intensifies, and although while shipping is already the most

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effective method of transporting cargo, more can be done, according to the industry. The basis for good transformation is laid by better designs and optimized engines. The International Maritime Organization (IMO) has defined new requirements for increased efficiency throughout all phases of a ship's lifespan in collaboration with key stakeholders. The Energy Efficiency Design Index (EEDI), one such indicator, is the ideal illustration of this challenging objective [2]. The performance of a ship's sailing is determined by the compatibility of the ship, engine, and propeller. This also has an impact on the economy and emissions of the ship. To better understand the interaction between these three parts and to advance the fundamental matching theory, some research on the ship-engine-propeller matching has been conducted [3], [4], and [5]. Additional exports must be asked in order to reduce and slow down CO_2 emissions in light of past data on air pollution caused by CO_2 emissions and the fact that maritime transport is a "green transport" in comparison to other modes of transport [6].After being made required at the 62nd MEPC conference in July 2011, Energy Efficiency Design Index has recently gained prominence in the marine sector.At that conference, it was resolved that starting on January 1, 2013, all new ships must meet the EEDI's minimal requirements. It becomes both intriguing and frightening for the majority of ship owners, shipping businesses, and ship design firms [7].Some researchers avoid the Hughes-Prohaska resistance and power prediction method due its time consuming factors, rigorous experimental procedures and cost of running experiments in the towing tank despite the obvious revelation that the current method of using the Holtrop and Mennen method is only theoretical, relatively unreliable and as such could pose great risks on ascertaining a vessel’s energy efficiency design index. Hypothetically, the level of unreliability of the Holtrop-Mennen method suggest that the resistance and power predicted therefrom disfigures any analysis on energy efficiency design index of ships and therefore, inform wrong policies to be imposed.

The implementation of the Energy Efficiency Existing Ship Index (EEXI) is primarily aimed at enhancing the energy efficiency of newer ships compared to older vessels, with the overarching goal of expediting the global fleet replacement to align with the International Maritime Organization's (IMO) strategy to reduce Greenhouse Gas (GHG) emissions in the maritime sector. This paper begins by providing an overview of the swift development and acceptance of the EEXI as a fresh mandate within the International Maritime Organization (IMO) to address the reduction of carbon intensity in existing ships. Furthermore, it emphasizes the noteworthy level of non-compliance within the current global fleet, necessitating attention that is at least as critical as that given to the Energy Efficiency Design Index (EEDI). Finally, the paper delves into an examination of potential measures for improving a ship's EEXI performance, followed by a detailed discussion of the technical challenges associated with EEXI implementation. These challenges include considerations related to Engine Power Limitation (EPL), the assessment of minimum propulsion power, power reserve, and the determination of reference speed [8]. The criticality of shipping operations in global trade requires a comprehensive understanding of its sustainability. This depends on the integrity/performance of the ship structure and vital systems, such as the ship propulsion engine. The current research paper presents the application of an adaptive machine learning formalism, the Bayesian network, for failure assessment of a ship propulsion engine considering nonlinear and none sequential failure interactions. The model captures critical failure influencing factors and their complex interactions to predict the failure probability of the ship energy system. Sensitivity and uncertainty analysis was carried out to establish the degree of influence of vital failure influencing factors as they affect the ship propulsion engine’s reliability and the associated uncertainty in the prior data processing. The model is tested on the propulsion engine of an ocean going vessel to forecast the likelihood of failure based on the logical dependencies among failure causative factors. Two scenarios were analyzed based on canonical probabilistic algorithms, and the results show that upon evidence on the three critical failure modes, the ship propulsion engine failure likelihood increased by 11.8%, 8.2%, and 9.4%, respectively. The model shows an adaptive and dynamic capability to capture new failure information and update the system’s failure probability. The proposed approach provides a condition monitoring tool and early warning guide for integrity management of critical ship energy systems [6]. [9] noted the following environmental and economic benefits of EEDI; Reduced GHG Emissions, Minimized Environmental Impact, Sustainable Maritime Fleet, Conceptual Solutions, Reduced Fossil Fuel Consumption and Feasibility Assessment. The International Maritime Organization (IMO) has introduced three regulatory measures to enhance the energy efficiency of the global maritime fleet and reduce CO_2 emissions. These measures include the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ships Index (EEXI), and the Carbon Intensity Index (CII). The EEDI, initially applied to new-builds in 2013, became a reference point for energy efficiency standards with phased adoption and clear enforcement mechanisms. The EEXI has equalized power reduction onboard across vessels and brought older vessels in line with EEDI-compliant ones. The CII emphasizes operational efficiency, requiring collaboration among stakeholders for improved ratings[10].

The studies of earlier research relied on theoretical calculations and assumptions rather than model resistance experiments to ascertain the actual resistance and real effective power of the vessel under considerations. Additionally, prior research did not pay specific attention to the combined impact of design factors, resistance, and hydrostatic details on a ship's energy usage. This study will highlight the elements needed to regulate shipping-related CO_2emissions. An analytical comparison will be done on fuel consumption, carbon emission, and total power needs as consequences of inadequate ship design parameters and hydrostatics because the fundamental formulation of EEDI is based on the ratio of total CO_2 emission per tonne. Therefore, the main objectives of this study is to investigate the effects of energy efficiency design index on resistance, hydrostatics and ship design using the Hughes-Prohaska method for vessels to be operated in the Gulf of Guinea. Other specific objectives are to;Prepare models of geometrical and hydrodynamic similarity with the large ships being tested for; conduct model resistance tests using ship models at the towing tank facility of the Centre of Excellence in Marine and Offshore Engineering of the Rivers State University; and apply the results from the model tests using Hughes-Prohaska methods to predict the Total Resistance and Effective Power of the Ropax, Tugboat and Reefer boats to be operated in the Gulf of Guinea;Carry out detailed analysis on ship design parameters such as resistance, breadth, draft and length for the determination of attained EEDI values for the different ship types and to carry out result validation between the EEDI reference to the EEDI attained and also for Allowable Power for both the referenced and attained for each of the ships. With the state of the economy and the environment as it is now, energy efficiency has gained more and more importance. The goal of this dissertation is to map the current status of energy efficiency for ships operating in the Gulf of Guinea, both on a ship-by-ship and industry-wide basis. Model resistance tests for the three boats employed in this project's case study will be the initial area of attention, followed by a review of the shipping industry's regulatory environment with regard to energy efficiency. The operations carried out on ships with the intention of reducing their consumption and emissions come next. These actions vary from adjustments to the design to changes to the operational procedures. The possible innovations that the industry could put into practice on a larger scale to improve the overall sector's efficiency will come after that. Finally, a summary of the key challenges to putting these steps into action will be looked at. While the present guidelines are only a short-term fix and some of the most notable advances need more research, the ongoing work raises this industry's potential for progress. This study has the added benefit of expanding the amount of knowledge already available about how energy-efficient ships are, but more importantly, it will provide ship designers and operators a better understanding of the relationship between hydrostatics and energy efficiency. Researchers who require it as a source of information for more research in this field or on related topics would greatly benefit from the study.The focus of this study will be restricted to assessing how the energy efficiency design index affects the hydrostatics and ship design of just Ropax, Tugboat, and Reefer boats operating in the Gulf of Guinea. The primary focus of this study will be on the International Maritime Organization's (IMO) perspective on the creation and application of this index. The chosen ship classes, which are the biggest and use the most fuel in shipping, will be covered by the EEDI implementation in this effort. This research excludes ships using hybrid, steam, and diesel-electric propulsion systems.

II. MATERIALS AND METHODS

1.1 Materials

2.1.1. Ship Selection

The chosen ship classes, which use the most fuel in shipping, will be covered by the EEDI analysis in this effort. This research excludes ships using hybrid, steam, and diesel-electric propulsion systems. These following ship types were used for this study;

a. Roll-on passenger carrier (Ropax);
b. Tugboat and;
c. Reefer vessel.

The specifications of the vessels above are presented in **Table 1**

2.1.2 Tool Selection

A software tool will be utilized to compute the resistance, effective power, and propulsion power of the ship, followed by the EEDI, in order to comprehend the effects of EEDI on ship design parameters and hydrostatics. Making parametric evaluations for all sorts of ships that take into account the most recent EEDI formulations and IMO standards is achievable with this tool.

2.1.3 Ship Design Parameters

There are three parameters that keep boats and ships on (or just above) the water, viz; the weight of the water displaced, the lift created by the foil moving through the water rises with the speed of the vessel until the vessel is foil carried, which is important to know when designing ships and the total displacement of the vessel which pushes downwards on the water's surface. When the strength of the upward and downward forces are equal, a vessel is in balance. A vessel's weight doesn't change when it is lowered into the sea, but the amount of water that is displaced by its hull does. The boat floats when the two forces are equal. The forces are the weight of the water displaced and the total displacement of the vessels. It floats without trim or heel if weight is distributed equally across the whole vessel.

Table 1. Specification of the various ship types that will be used for this study

Ship Type	**Vessel Speed - V (knots)**	**Length (m)**	**Froude Number (Fn)**	**Beam (m)**	**Draft (T)**	**L/B**	**B/T**	**C_P**	**C_B**
Ropax	12	94.5-	0.14-0.21	16.0-	4.67-	5.9	3.43	0.73	0.70
carrier	24	200	0.15-0.29	30.64	6.10	6.5	5.01	0.78	0.72
Tugboat	12	32.7-	0.13-0.20	12.82-	5.90-	2.6	2.20	0.60	0.57
vessel	18	40.0	0.25-0.39	14.00	6.20	2.9	2.25	0.65	0.60
Reefer vessel	12	135-	0.12-0.16	20.60	5.22-	6.5	3.94	0.83	0.65-
	24	200	0.18-0.24	30.64	6.10	5.9	5.01	0.88	0.70

Source: [11]

2.1.4. Ship Hydrostatics Considerations

The hydrostatic performance of a vessel is highly dependent on its maneuvering waterways. The existence of the banks and bottom, as well as the presence of the other vessels, could have a significant influence on a ship's hydrostatic behavior. The parameters which determine a ship's hydrostatic performance include; Vessel speed (Vs), Vessel draft (T), Ship beam (B), Prismatic Coefficient (C_P) and Block Coefficient (C_B). In order to understand the effect of each parameter, a systematic parameter study is indispensable.

2.2 Method

2.2.1 Theory of Energy Efficiency Design Index (EEDI) of the Ship

To gauge a ship's energy efficiency, the International Maritime Organization (IMO) placed the EEDI into legislation. The projected CO_2 emissions generated per unit of travel during the ship design process are measured by a ship's EEDI; the lower the EEDI, the lower the CO_2 emissions. EEDI is based on a complex algorithm that considers the emissions, capacity, and speed of the ship. The International Council on Clean Transportation (ICCT)'s definition of EEDI states that it can be calculated, as shown by Equation (1), and Figure 1 shows the equipment's computing power. P stands for the individual engine power at 75% of MCR, C for the CO2 emission factor based on the fuel type used by the specified engine, SFC for the specific fuel used per unit of engine power, certified by the manufacturer, and f for the non-dimensional factors that were added to the EEDI equation to account for some particular existing conditions. Deadweight tonnage (DWT) of a ship is its capacity, and its maximum design load speed is Vref.

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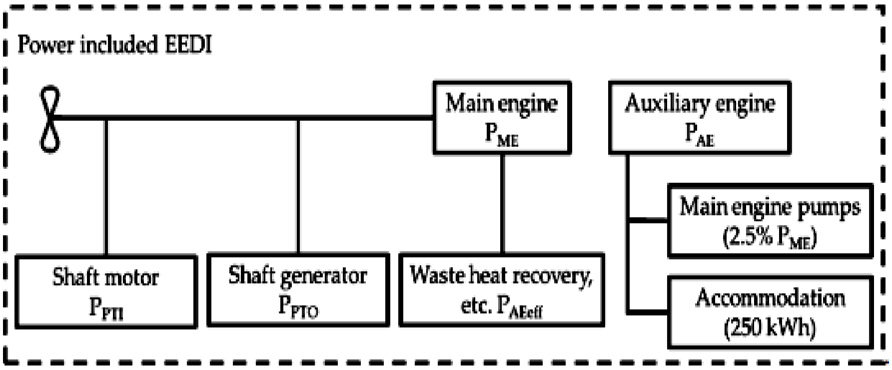

Figure 1: The power flowchart in the calculation of energy efficiency design index (EEDI).

2.2.1.1 Description of Energy Efficiency Design Index (EEDI)

2.2.1.1.1 Emission from the Main Engine = $\left(\prod_{j=1}^{M} f_i\right) * \left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right)$ (1)

2.2.1.1.2 Emission from Auxiliary Engine $= (f_{AE} * C_{FAE} * SFC_{AE})$ (2)

2.2.1.1.3 Emission from shaft motor = $\left(\prod_{j=1}^{M} f_i\right) * \left(\sum_{i-1}^{nPTI} PTI(i) - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) * C_{FAE} * SFC_{AE}$ (3)

2.2.1.1.4 Efficient technology reduction = $\left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)$ (4)

2.2.1.1.5 Capacity multiplied with the reference speed = $f * DWT\ Capacity * V_{ref} * f_w$ (5)

2.2.1.1.6 Energy Efficiency Design Index (EEDI) $= \frac{CO_2\ Emission}{Transport\ \ work}\left\{\frac{gCO_2}{Tonne * nautical\ \ mile}\right\}$(6)

$$= \frac{Power * Specific\ fuel\ consumption * CO_2 conversion\ factor}{Capacity * Speed}$$

Adding up equations (1), (2), (3),(4) and dividing by equation (5) gives equation (7);

$$= \frac{Emission\ from\ Main\ Engine + Emission\ from\ Auxiliary\ Engine + Emission\ for\ running\ shaft\ motor - Efficient\ Tech.Reduction}{Capacity * Reference\ Speed}$$

$$= \frac{\left(\prod_{j=1}^{M} f_i\right) * \left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)}\right) + (f_{AE} * C_{FAE} * SFC_{AE}) + \left(\prod_{j=1}^{M} f_i\right) * \left(\sum_{i-1}^{nPTI} PTI(i) - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) * C_{FAE} * SFC_{AE} - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)}{f * DWT\ Capacity * V_{ref} * f_w}$$

(7)

$$\left[\frac{k_w * \frac{g_{fuel}}{kw\ hr} * \frac{gCO_2}{g_{fuel}}}{Tonne * nauticalmile\ \ /hr}\right]\left[\frac{gCO_2}{Tonne * nautical\ \ mile}\right]$$

Where;
C_F, non-dimensional Conversion Factor between fuel consumption measured in g and CO_2 emission also measured in gram based on carbon content.
Mei, Main Engine (kW)
AEi, Auxiliary Engine (kW)
V_{ref}, Ship speed (knot)
Dwt, Deadweight or Capacity (Tonne)
P, Power of the main and auxiliary engines, measured (kW)
$P_{ME(i)}$, 75% of the rated installed power (MCR) for each main engine (kW)
$PPT_{(i)}$, 75% output of each shaft generator installed (kW)
$P_{eff(i)}$, 75% of the main engine power reduction due to innovative mechanical energy efficient technology
$P_{AEeff(i)}$, Auxiliary power reduction due to innovative electrical energy efficient technology
P_{AE}, Auxiliary engine power to supply normal maximum sea load including necessary power for propulsion machinery/systems and accommodation.

SFC, Specific fuel consumption, measured in g/kWh, of the engines. The subscripts ME (i) and AE (i), refer to the main and auxiliary engine(s), respectively.
Fj, Correction factor to account for ship specific design elements. fj should be taken as1.0.
fw, Non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed. fw should be taken as one (1.0)
$f_{eff(i)}$, Availability factor of each innovative energy efficiency technology. f_{eff}(i) for waste energy recovery system should be 1.

fi, Capacity factor for any technical/regulatory limitation on capacity, and can be assumed one (1.0) if no necessity of the factor is granted.

2.2.1.2 Conversion Factor, C_F

Fuel consumption in grams and CO2 emissions, which are likewise measured in grams based on carbon content, are converted using the non-dimensional factor CF. The main and auxiliary engines are denoted by the subscripts MEi and AEi, respectively. CF is the fuel identified in the relevant EIAPP Certificate as the one utilized to calculate SFC. Table 3.2 provides the conversion factor values, or CF.

Table 2: C_F values for different types of fuel.

Type of fuel	Reference	Carbon content	C_F (t-CO2/t-Fuel)
Diesel/Gas Oil	ISO 8217	0.875	3.206
Light Fuel Oil (LFO)	ISO 8217	0.86	3.15104
Heavy Fuel Oil (HFO)	ISO 8217	0.85	3.1144
Liquefied Petroleum Gas (LPG)	Propane	0.819	3.0
	Butane	0.827	3.03
Liquefied Natural Gas (LNG)	Ethane	0.75	2.75

2.2.2 Hughes–Prohaska Method for Resistance and Effective Power Determination

These methods for estimating the approximate resistance and power in displacement and semi-displacement vessels are extremely well known. But not all ship types are covered by these techniques. The approximations are based on the hydrostatic theory and use coefficients found by a regression analysis of the outcomes of 334 tests on ship model. Since Ropax, Reefer, Tugboat, and Reefers are displacement vessels, this strategy works well for them. This approach decomposes the total resistance coefficient as follows:

$$C_T = (1+k) * C_{FO} + C_w \quad (8)$$

Both form factor (1 + k) and wave resistance coefficient C_w are assumed to be the same for model and full scale, i.e. independent of Reynolds's number (Rn). The model test serves primarily to determine the wave resistance coefficient. The procedure is as follows:

Step 1: Determine the total resistance coefficient (C_{Tm}), in the model test from the ITTC 1957 method:

$$C_{Tm} = \frac{R_{Tm}}{\frac{1}{2}\rho_m * V_m^2 * S_m} \quad (9)$$

Step 2: Determine the wave resistance coefficient C_w, same for model and ship:

$$C_w = C_{Tm} - C_{F0m} * (1+k) \quad (10)$$

Step 3: Determine the total resistance coefficient C_{Ts}, for the ship:

$$C_{Ts} = C_w + C_{Fos} * (1+k) + C_A \quad (11)$$

Step 4: Determine the total resistance R_{Ts}, for the ship:

$$R_{Ts} = C_{Ts} * 1/2 \rho_S V_s^2 S_s \quad (12)$$

The frictional coefficients C_{F0}, for flat plates are determined by Hughes' formula:

$$C_{F0} = \frac{0.067}{(\log_{10} R_n - 2)^2} \quad (13)$$

The correlation coefficient C_A differs fundamentally from the correlation coefficient for the ITTC 1957 method. Here C_A does not have to compensate for scaling errors of the viscous pressure resistance. ITTC recommends universally $C_A = 0.0004$.

The Hughes–Prohaska method is a form factor method. The form factor (1+ k) is assumed to be independent of Froude number, F_n and Reynold's number, R_n and the same for model and ship. The form factor is determined by assuming:

$$\frac{C_T}{C_{F0}} = (1 + k) + \alpha \frac{F_n^4}{C_{F0}} \quad (14)$$

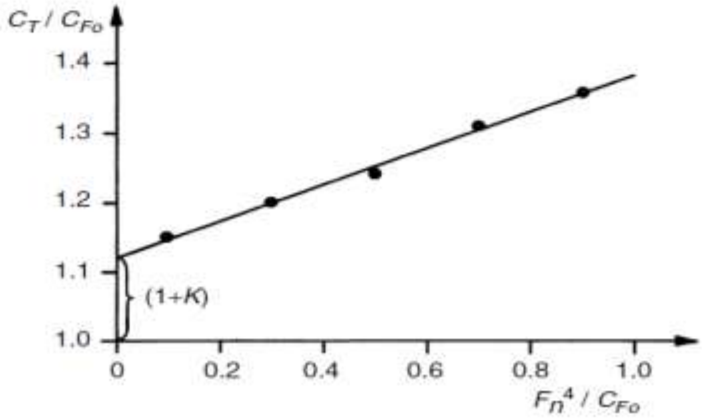

Figure 2: Extrapolation of form factor

Model test results for several Froude numbers (e.g. between 0.12 and 0.24) serve to determine ‹ in a regression analysis. For this analysis, assumption will be made to the effect that the form factor, 1+k = 1.12, 1+k = 1.16, and 1+k = 1.13 for Ropax, Tugboat and Reefer vessels respectively.

Step 5: Determine the Effective Power of the Ship;

$$P_e = R_{TS} * V_s \quad (15)$$

The Allowable Power with respect to the Maximum Continuous Rating (MCR);

$$P_{MCR} = P_e * \eta_x \quad (16)$$

Where P_e is the effective Power, R_{TS} is the total ship resistance and V_s is the design vessel speed and

η_x is the efficiency factor for Power (energy generated)
.

2.2.3 Model Resistance Test at the Towing Tank

(i) Procedures for conducting model resistance test

The procedure for conducting Model resistance test at the towing tank of the Centre of Excellence of the Rivers State University, Port Harcourt is stated in itsmanual.

(ii) Method of estimating Model wetted surface area, Sm

In the absence of a detailed lines plan, it may be useful to estimate the wetted surface area based on a few dimensions. In this study, the Mumford's equation will be applied.

Mumford's Equation;

$$S = 1.7LT + C_B LB \quad (17)$$

Where;

C_B is the block coefficient, L is the length over all of the model, T is the draft of the model and B is the breadth moulded.

(iii) Data of the Models used for the resistance test

Table 3: Shows the data of the different models used for the Model resistance test at the Towing tank facility. The data of the models are extrapolated and correlated for the big ships.

Table 3: Shows the data of the different models used for the Model resistance test at the Towing tank facility

Data of the model used for the resistance test at the towing tank

MODEL Particulars	**Computed Formulae**	**Units**	**Ropax**	**Tugboat**	**Reefers**
Froude Number	Fr		0.14	0.13	0.12
Length of Ship	L	m	94.5	32.7	135

Beam of the Ship, B	B	m	16	14	20.6
Ship Speed, Vs	Vs	knots	12	12	12
Draft of the Ship, T	T	m	4.67	5.9	5.22
Ship Kinematic Viscosity at 15 degrees (1025kg/m2)_Seawater	υ	m2/s	0.00000119	0.00000119	0.00000119
Scale between model and ship	λ		1: 25	1: 25	1:25
Density of freshwater	ρ_{fw}	kg/m3	1000	1000	1000
Density of Seawater	ρ_{sw}	kg/m3	1025	1025	1025
Model Block Coefficient (CB)	Same for Model & Ship		0.72	0.6	0.7
Model Kinematic Viscosity at 10 degrees (1025kg/m2)_Fresh water	υ	m2/s	0.00000135	0.00000135	0.00000135
Length of the Model, LM (m)	$L_M = \frac{L}{\lambda}$	m	3.78	1.308	1.69
Model Beam, BM	B_M B	m	0.64	0.56	0.824
Model Draft, T_M (m)	$T_M = \frac{T}{\lambda}$	m	0.1868	0.236	0.2088
Model Speed, VM	V_M ____	m/s	0.852527583	0.501494774	0.570040735
Model Wetted Surface area, SM	$SM = 1.7LT + CB * L$	m2	2.9422008	0.9642576	1.5746744

Ship Wetted Surface area, Ss	$S_s = S_M \lambda^2$	m2	1838.8755	602.661	984.1715

2.2.3 Parameters for determination of reference values for the different ship types

If the design of a ship allows it to fall into more than one of the above ship type definitions, the required EEDI for the ship shall be the most stringent (the lowest) required EEDI. The Reference line values shall be calculated as follows:

Reference line value = $a * b^{-c}$

Table 4: Parameters for determination of reference values for the different ship types

Ship Type Defined in Regulation	a	b	C
Ropax Vessel	961.79	DWT of the ship	0.477
Reefer vessel	1218.80	DWT of the ship	0.488
Tugboat ship	174.22	DWT of the ship	0.201

2.2.4 Reduction Factors (in percentage) for the EEDI Relative to the EEDI Reference line

Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size, n/a means that no required EEDI applies.

Table 5: Reduction factors (in percentage) for the EEDI relative to the EEDI Reference line

Vessel Type	Deadweight Category	Phase 0	Phase 1	Phase 2	Phase 3
Ropax vessel	20,000 DWT and above	0	10	20	30
	10,000 -20,000 DWT	n/a	0-10*	0-20*	0-30*
Reefer vessel	55,000 DWT and below	0	10	20	30
	40,000 – 55,000 DWT	n/a	0-10*	0-20*	0-30*
Tugboat carrier	5,000 DWT and above	0	10	20	30
	10,000 – 55,000 DWT	n/a	0-10*	0-20*	0-30*

*Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size. n/a means that no required EEDI applies.

2.2.5 Microsoft Excel

Microsoft created the spreadsheet program Excel for use with Windows. The calculating or computing capabilities, graphing tools, pivot tables, and the Visual Basic for Applications macro programming language were used to analyze data from the experiments and was further processed with relevant equations.

III. RESULTS AND DISCUSSIONS

3.1 Results from the analysis of EEDI for the different vessel types

As previously mentioned, the effects of EEDI on ship design parameters and coefficients are examined for three different types of boats. Ropax, Tugboat, and Reefer vessels were picked as case studies because they are the most commonly utilized commercially for shipping the most commodities at sea and for vessel assistance at ports. As a result, they use the most energy and tend to pollute the marine environment the most unintentionally.

3.1.1 Results from the Model Resistance Tests carried out at the Towing tank

The findings of the various model resistance tests performed at the towing tank facility of the Centre of Excellence in Marine and Offshore Engineering of the Rivers State University, Port Harcourt, are shown in Tables 6, 7, 8, 9 and 10 and the remaining complete results are computed and placed as appendices. The large ship at a ratio of 1:25 was used to extrapolate the model findings.

3.1.2 Effect of energy efficiency design index (EEDI) on the change in ship speed for the various vessels

Particulars considered for the analysis are as shown in the following table. The values displayed in the table are initial computed values, other values can be found in the appendices.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

Table 6: Change in ship speed for the various vessels

Ship Type	Ship Speed -V (knots)	Effective Power (Pe) (kW)	Displacement (Disp)(Tonne)	Pe/Disp
Ropax	12-24	5880	5000	1.176
Tugboat	12-18	2539	5000	0.5078
Reefer	12-24	5717.33	5000	1.14347

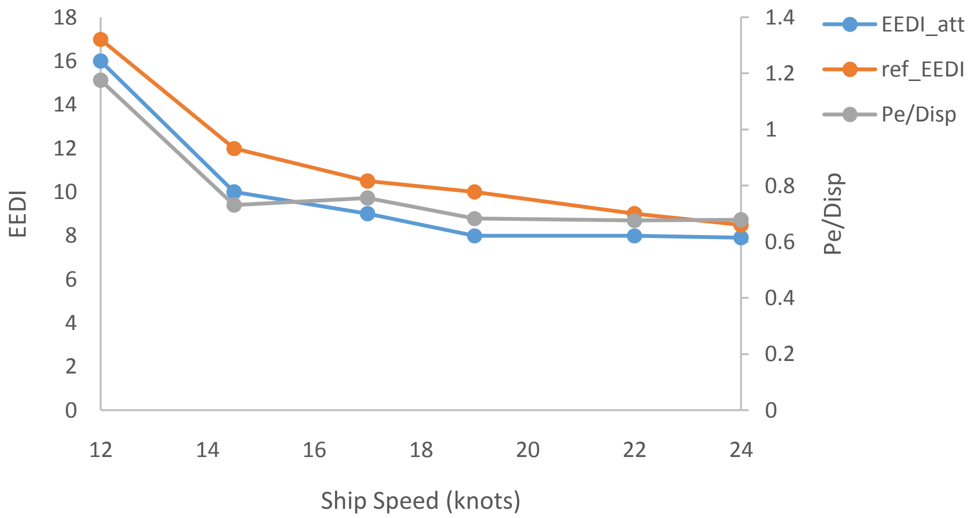

Figure 3: Effect of EEDI on speed of Ropax carrier from 12 to 24knots.

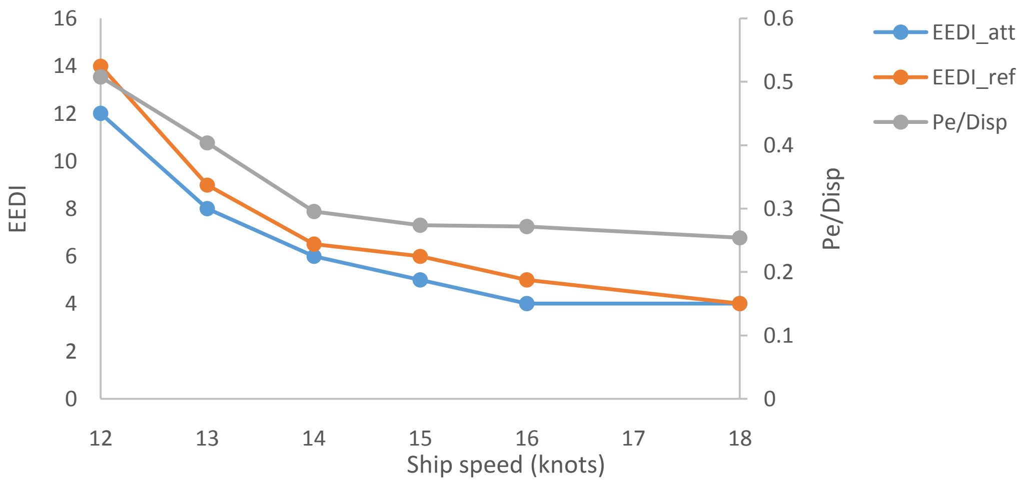

Figure 4: Effect of EEDI on speed of Tugboat vessel at 12knots to 18knots

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Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

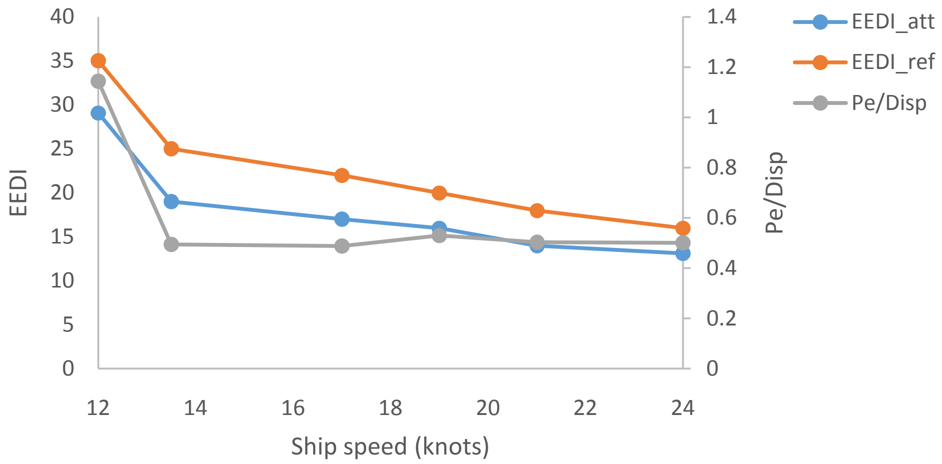

Figure 5: Effect of EEDI on Speed of Reefer vessel at 12knots to 24knots.

3.1.3 Effect of EEDI on Change in Waterline Length (LWL)of the ship considered for the analysis

Particulars considered for the analysis are as shown in the following table. The values displayed in the table are initial computed values, other values can be found in the appendices.

Table 7: Change in waterline length for the various vessels

Ship Type	Length (m)	Effective Power (Pe)	Displacement (Disp)	Pe/Disp
Ropax carrier	94.5 - 200	5880	5000	1.176
Tugboat ship	32.7 - 40	2539	5000	0.5078
Reefer vessel	135 – 200	5717.33	5000	1.14347

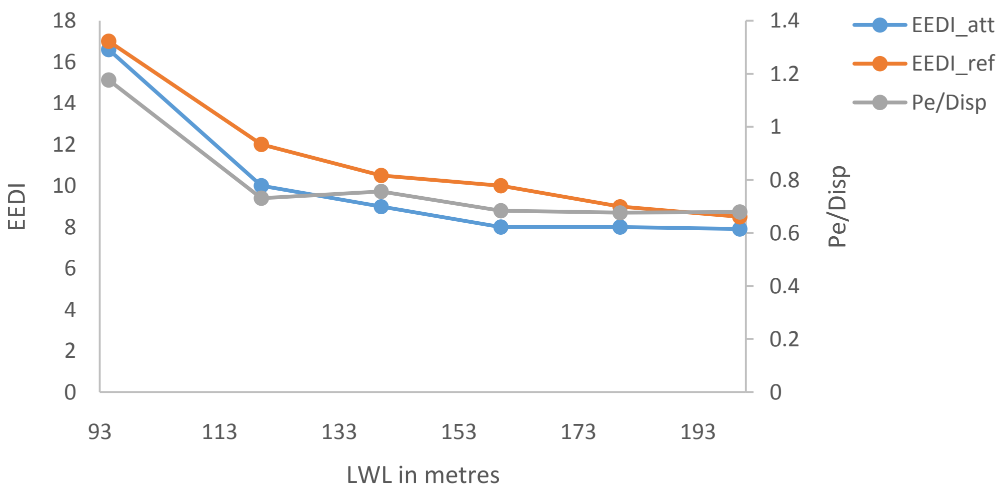

Figure 6: Effect of EEDI on Length of Ropax ship at 12knot Speed.

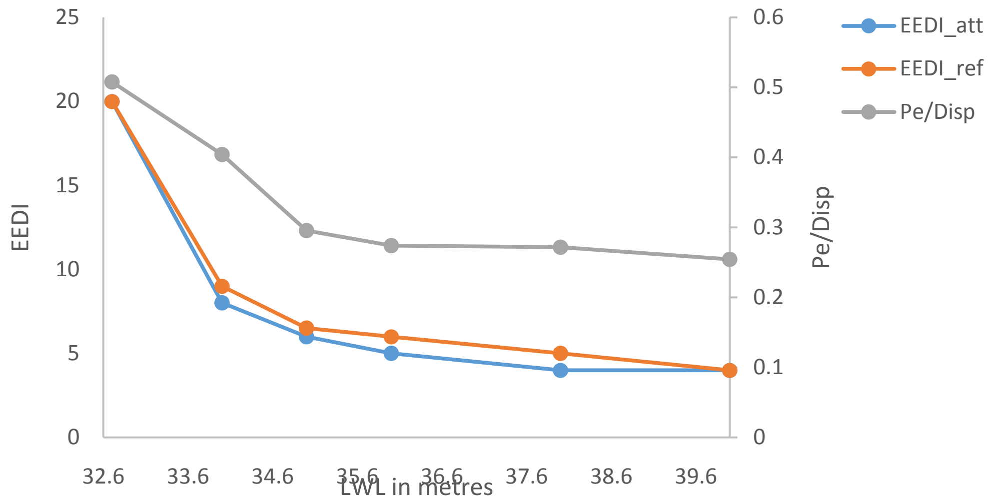

Figure 7: Effect of EEDI on length of Tugboat vessel at 12knot Speed

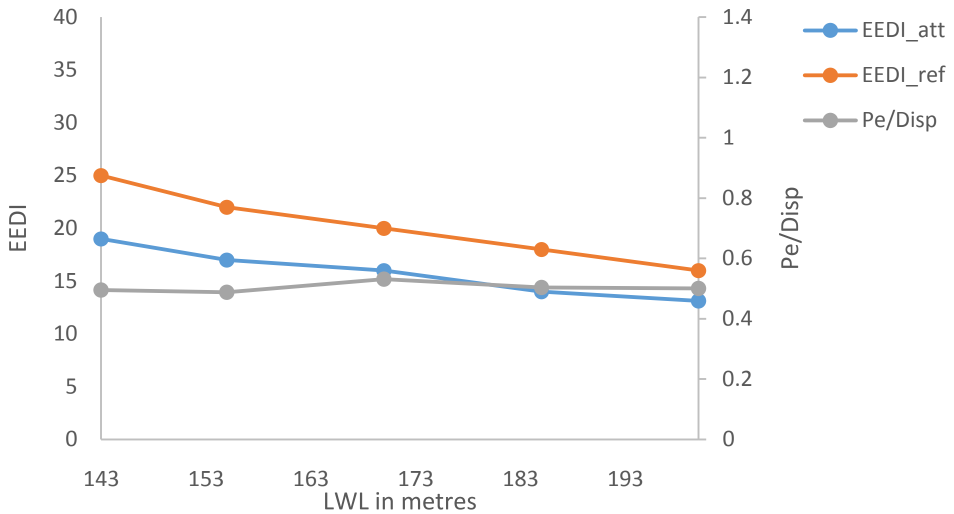

Figure 8: Effect of EEDI on length of Reefer vessel at 12 knot

3.1.4 Effect of EEDI on Change in Beam of Ship Particulars considered for the analysis

The details taken into account for the analysis are shown in the following table. Other values can be found in the appendices; the values shown in the table are initial calculated values.

Table 8: Change in Beam for the various vessels

Ship Type	Beam (m)	Effective Power (Pe)(kW)	Displacement (Disp) (T)	Pe/Disp
Ropax ship	28.1 - 39.2	5880.0	5000	1.176
Tugboat vessel	22.2 - 33.3	2539.0	5000	0.5078
Reefer vessel	28.0 - 39.2	5717.33	5000	1.14347

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

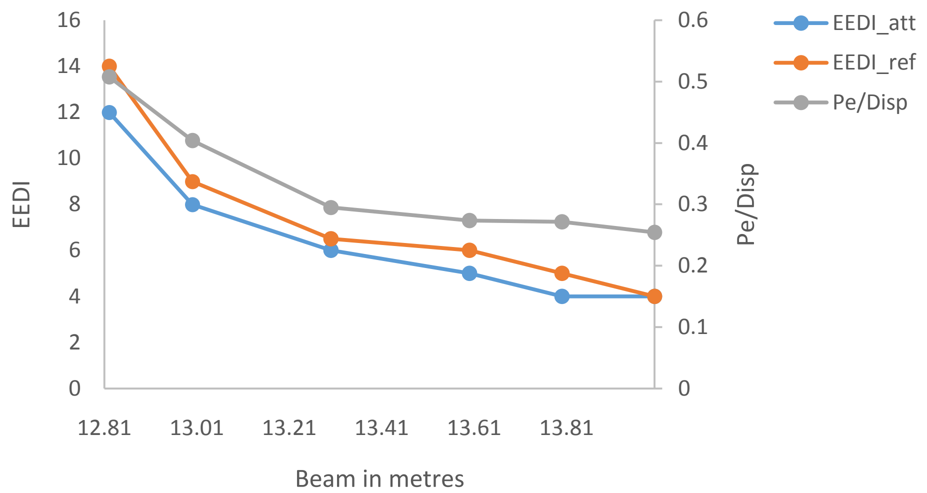

Figure 9: Effect of EEDI on Beam of Ropax from 12knot

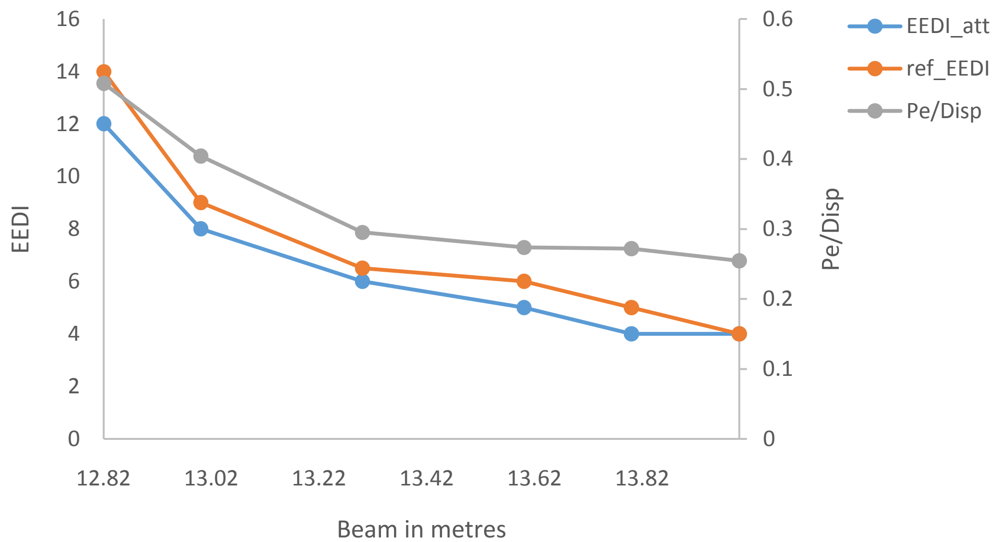

Figure 10: Effect of EEDI on Beam of Tugboat at 12knot speed.

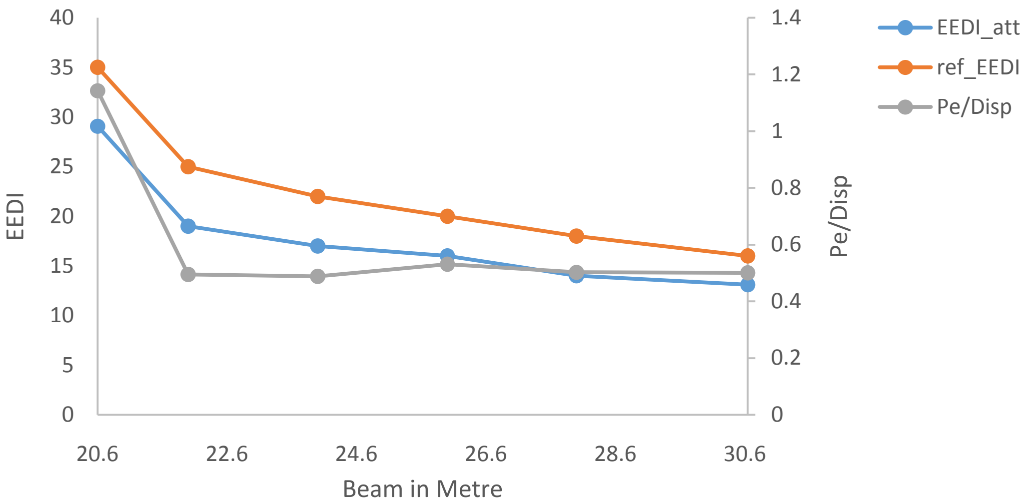

Figure 11: Effect of EEDI on the Beam of Reefer vessel at 12knot speed

3.1.5 Effect of EEDI on Change in draft (T) of the ship types considered for the analysis

Particulars considered for the analysis are as shown in the following table. Other values are placed in the appendices section.

Table 9: Change in Draft for the various vessels

Ship Type	Draft (T) (m)	Effective Power (Pe)(kW)	Displacement (Disp)(T)	Pe/Disp
Ropax ship	4.70 - 6.10	5880.0	5000	1.176
Tugboat vessel	5.90 - 6.20	2539.0	5000	0.5078
Reefer vessel	5.22 -6.10	5717.33	5000	1.14347

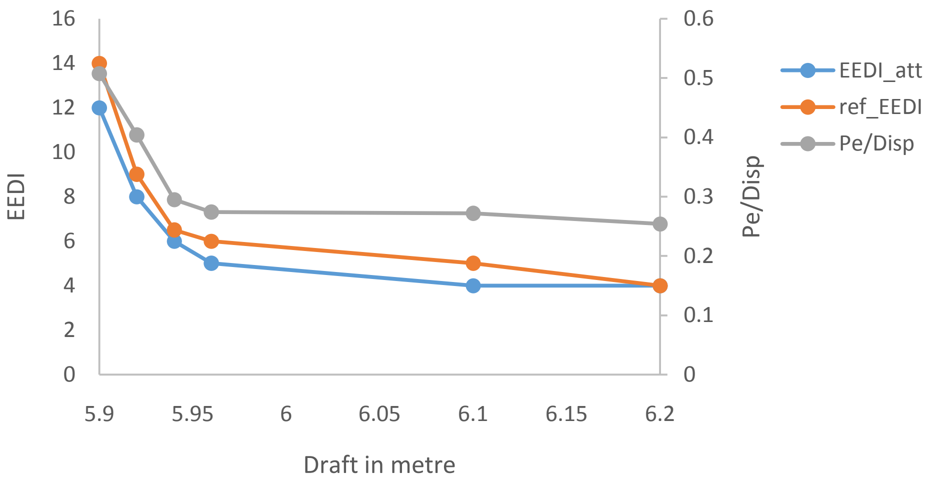

Figure 12: Effect of EEDI on Draft of Ropax at 12 knot speed.

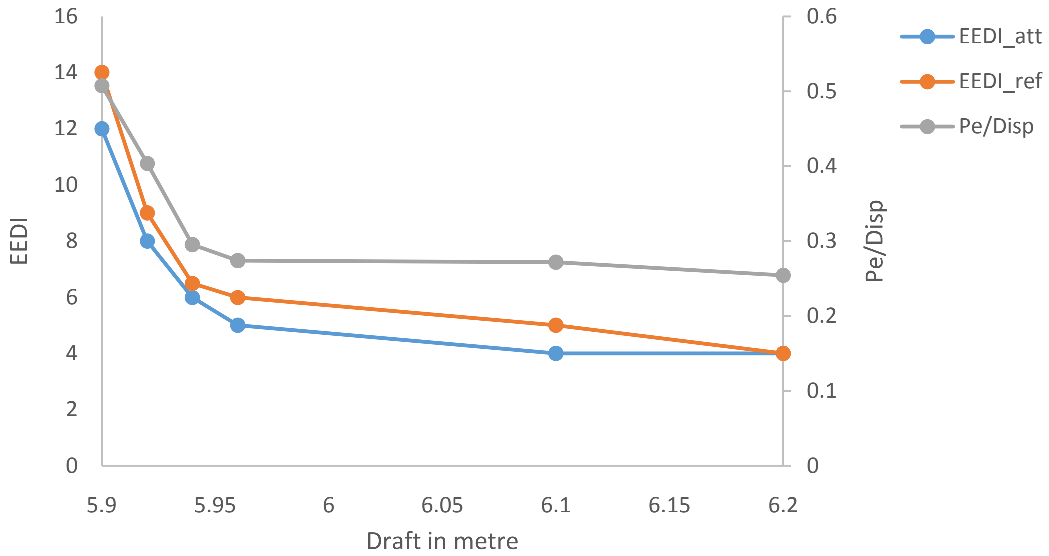

Figure 13: Effect of EEDI on Draft of Tugboat at 12 knot speed

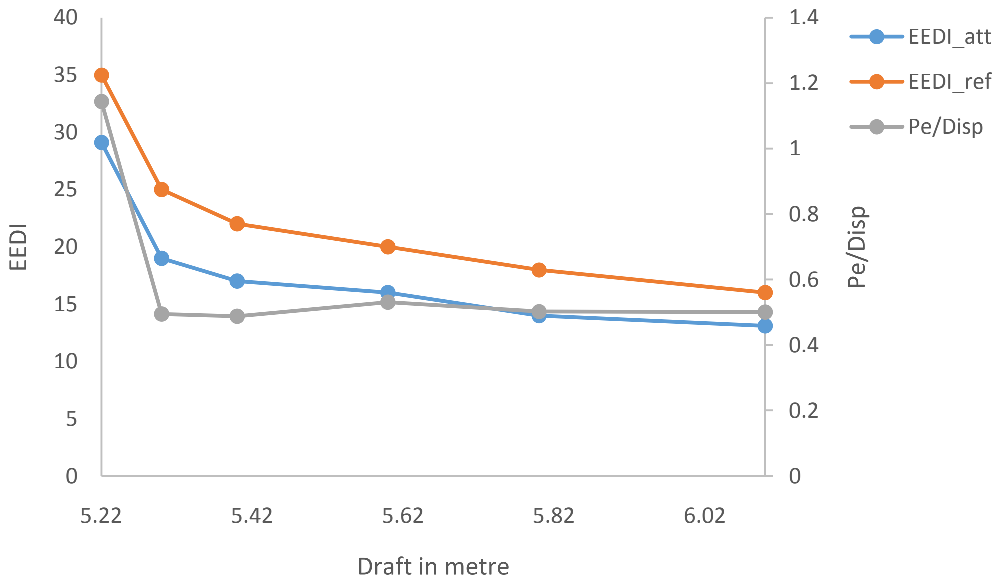

Figure 14: Effect of EEDI on Draft of Reefer vessel at 12 knot.

3.1.8 Effect of EEDI on the rate of Change in Prismatic coefficient, C_P for the various vessels

Table 10: Change in Prismatic coefficient, C_P of vessels

Ship Type	Prismatic Coefficient (Cp)	Effective Power (Pe)(kW)	Displacement (Disp)(T)	Pe/Disp
Ropax ship	0.73	5880.0	5000	1.176
Tugboat vessel	0.6	2539.0	5000	0.5078
Reefer vessel	0.8	5717.33	5000	1.14347

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

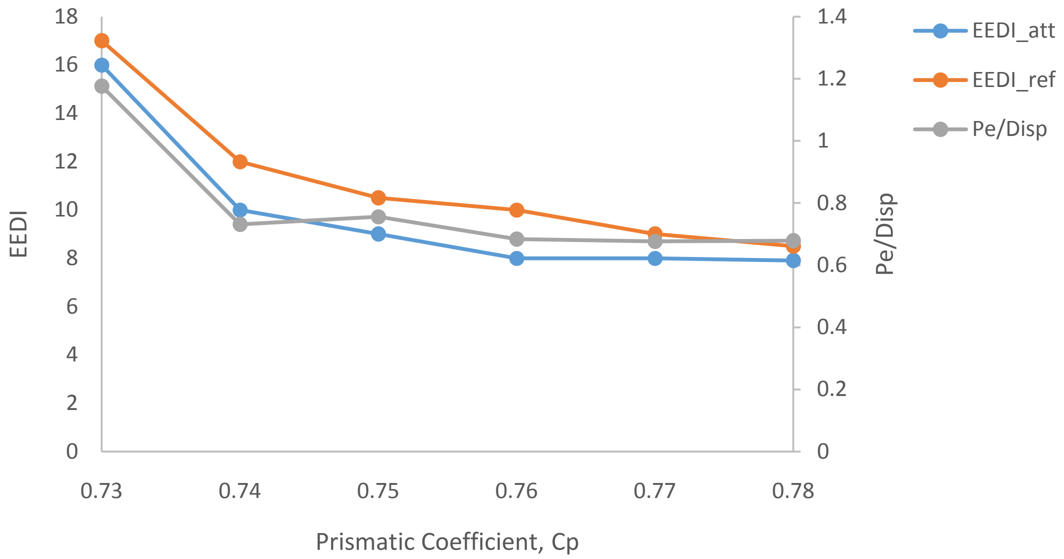

Figure 15: Effect of EEDI on Prismatic coefficient of Ropax at 12 knot Speed

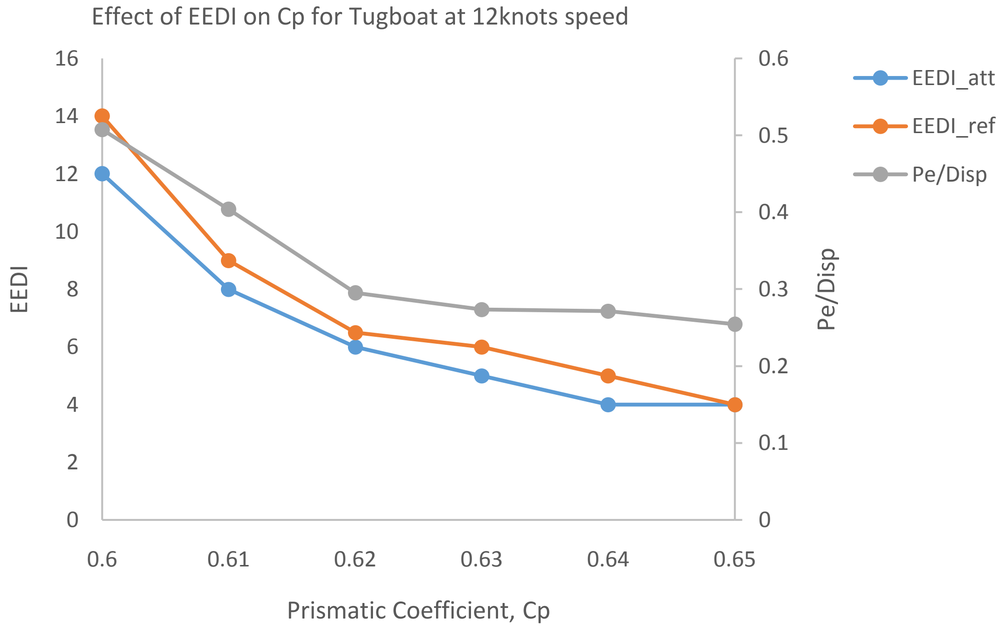

Figure 16: Effect of EEDI on Prismatic coefficient of Tugboats at 12 knots

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Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

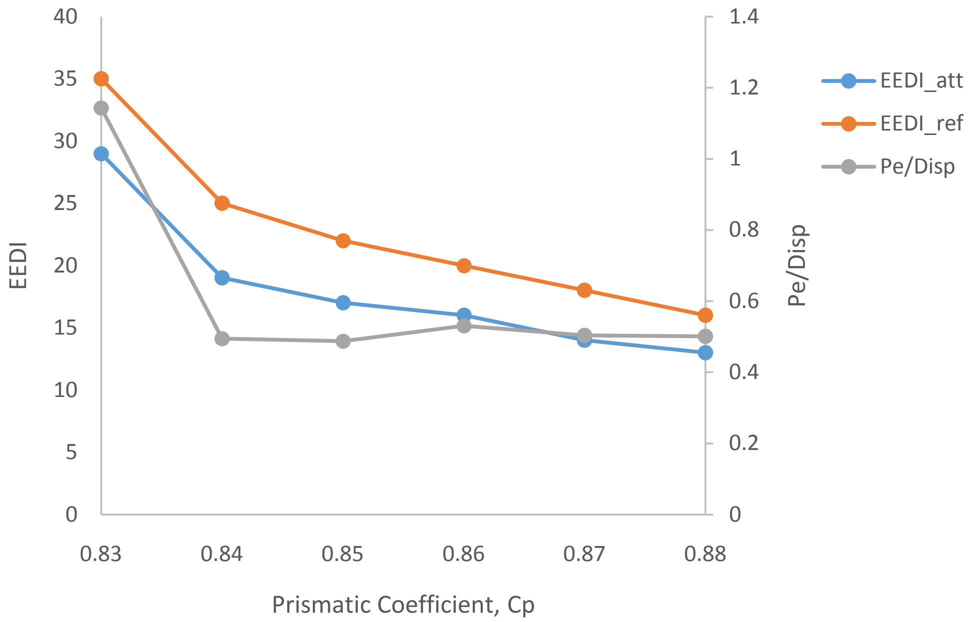

Figure 17: Effect of EEDI on Prismatic coefficient of Reefer vessels at 12knots Speed

3.1.9 Validation between the Present EEDI reference line and the EEDI attained in terms of CO_2/Tonne-mile emission and in terms of Allowable Power

For various types of vessels, the maximum permissible power at the moment is shown in Figures 18 and 19 together with the EEDI reference line. It's quite intriguing to watch how closely the achieved lines for each of the ship types adhere to the reference line. The inclusion of highly specialized tonnage under the classification of Ropax ships is the cause of the significant dispersion and poor correlation of the reference line values.

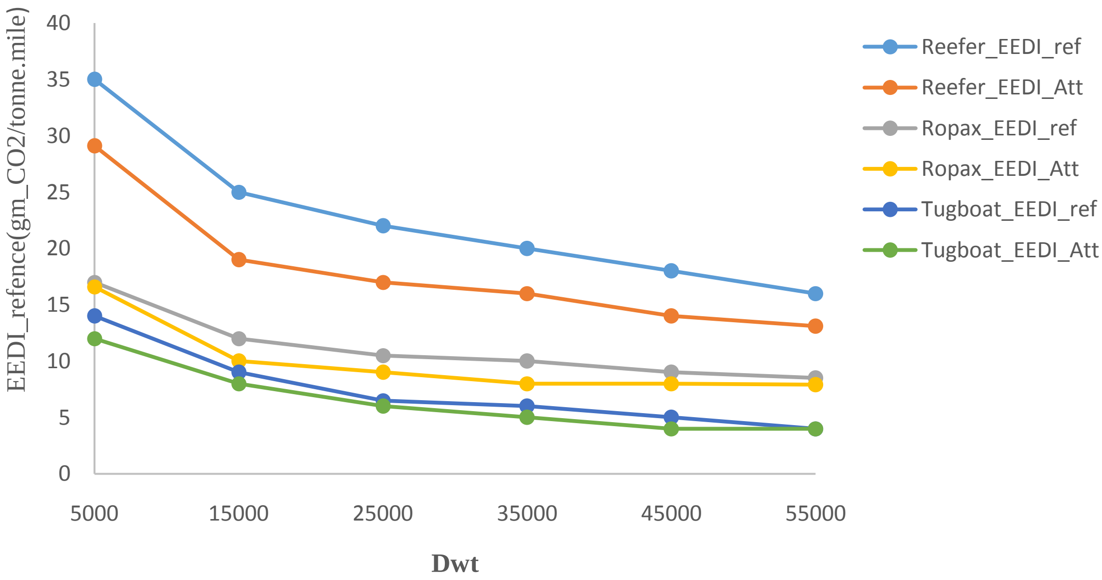

Figure 18: Validation of EEDI_reference and EEDI_attained as per CO_2/Tonne-mile emission for all vessel types.

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 01 Jan 2024, pp: 399-418 www.ijaem.net ISSN: 2395-5252

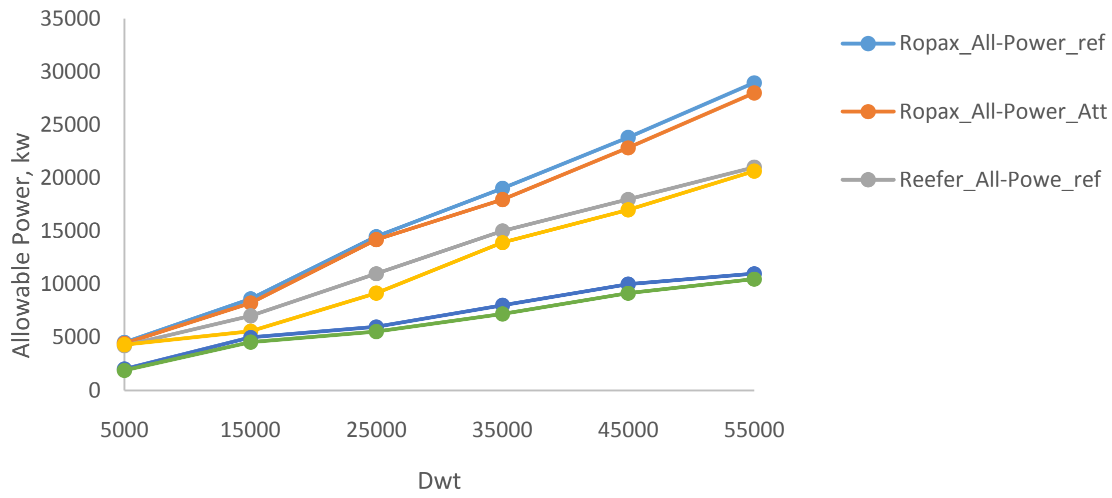

Figure 19: Validation of Maximum Allowable Power of EEDI reference and EEDI Attained for the three (3) vessel types

3.2 Discussions

When running at low speed inside or below 12 knots, it is evident that the EDDI for all of the vessels was improved due to their short length, breadth, draft, and prismatic coefficient. This is due to the observation that lowering these settings causes the EEDI achieved value to fall. In contrast, it is preferable to raise L/B and B/T at low speeds while lowering them at high speeds. The reason for this is because the current EEDI formula will encourage ship designers and owners to construct tiny ships (in terms of dimension) that operate at low speeds.

The influence of speed, length, beam, and draft have the biggest impact on EEDI, followed by the prismatic coefficient, which has a less significant impact on the aforementioned index, according to our analysis of the curves for various ship characteristics. Therefore, it was highlighted that the speed and length should be taken into account before the beam, draft, and prismatic coefficient if a designer wants to adjust the value of EEDI for a certain ship. To examine the variance in EEDI achieved and the Effective Power/Displacement curve with various ship design specifications, an Effective Power/Displacement curve is generated for each example.

This ratio truly includes every ship's hydrostatic impact. The fact that the EEDI formula used today does not violate the hydrostatic rules of naval architecture can be seen in the variation of EEDI obtained and the Effective power/Displacement curve with various ship specifications that revealed a similar trend.

3.2.1 The Effects of EEDI on ship design parameters of Ropax, Tugboat and Reefer vessels

The estimates made by EEDI for changing different design elements of the Reefer, Tugboat, and Ropax vessels resulted in the numbers below. The objective is to demonstrate how various ship design details and coefficients were impacted by the energy efficiency design index. At 12 and 24 knots for Ropax and Reefer vessels and 12 and 18 knots for tugboat vessels, all design parameters were examined. Investigating the effect at both low and high Froude numbers is the goal.

3.2.2 Effect of energy efficiency design index (EEDI) on the change in ship speed

The differences between reference EEDI (EEDI_ref) and Attained EEDI (EEDI_attained) are increasingly pronounced with increasing speed as seen in Figures 3, 4 and 5. The greatest speed that may be achieved is shown by the effective power and displacement ratio, which for Ropax, Tugboat, and Reefer boats, respectively, intercepts the speed line at 15 knots, 13 knots, and 15 knots. At slower speeds, the impact of speed on EEDI achieved is noticeably less. The EEDI reference line and EEDI reached have comparable trends. There is no disputing the fact that EEDI performs best at low speeds.

3.2.3 Effect of EEDI on Change in Waterline Length (LWL)of the ship considered for the analysis

It is clear from Figures 6, 7 and 8 that the difference between the reference EEDI and the

EEDI achieved reduces with length at 12 knot speeds, but grows with length at higher speeds. This is in part due to the fact that wave resistance increases at higher speeds. Smaller vessels (30-90 meters) are more affected by EEDI than big vessels, such as Ropax and Tugboats. Take note of the identical pattern between the EEDI achieved and Effective Power (Pe)/Displacement lines.

3.2.4 Effect of EEDI on Change in Beam of Ship Particulars considered for the analysis

According to Figures 9, 10 and 11 at 12 knots of speed, the difference between EEDI ref and EEDI achieved diminishes with increasing breadth, but increases at higher speeds (18 and 24 knots). Effective Power (Pe)/Displacement line shows a similar pattern to EEDI achieved.

3.2.5 Effect of EEDI on Change in draft (T) of the ship types considered for the analysis

The gap between EEDIref and EEDI achieved, as seen in figures 12, 13 and 14, reduces with increasing draft at 12 knot speeds but increases with increasing draft at faster speeds (12 and 24 knots). - Effective Power (Pe)/Displacement line shows a similar pattern to EEDI achieved. It is simple to conclude that a little draft is preferable at low speeds and vice versa.

3.2.6 Effect of EEDI on the rate of Change in Prismatic coefficient, C_P of vessels

As may be seen from figures 15, 16, and 17, plotted graphs demonstrate that a low prismatic coefficient will not increase a vessel's EEDI regardless of speed. As the prismatic coefficient and rises from 0.73 to 0.78, the disparity between EEDIref and EEDIattained reduces. The Effective Power (Pe)/Displacement line and EEDIattained show different patterns.

3.2.7 Validation between the Present EEDI reference line and the EEDI attained in terms of CO2/Tonne-mile emission and in terms of Allowable Power

For various types of vessels, the maximum permissible power at the moment is shown in Figures 18 and 19 together with the EEDI reference line. It's quite intriguing to watch how closely the achieved lines for each of the ship types adhere to the reference line. The inclusion of highly specialized tonnage under the classification of Ropax ships is the cause of the significant dispersion and poor correlation of the reference line values.

The Ropax and Reefers are permitted to have increased engine power or faster speed, as shown in Figure 19. The data shows that historically, Tugboats are not permitted to have higher engine power and speed than Ropax and Reefers. Therefore, a ship owner is not permitted to increase the pace of his tugboat (particularly in short shipment). In that situation, there is a chance of fraud since the ship owner may register the boat as general cargo rather than a tugboat. The decision of whether to base the reference line on historical data or only hydrostatic calculations arises at this stage.

IV. CONCLUSION

4.1 Conclusion

This dissertation examined how ship design and hydrostatics for boats operating in the Gulf of Guinea were affected by the energy efficiency design index. The International Maritime Organization (IMO) passed the EEDI as a required regulation of ship CO2 emissions in order to benchmark energy use and regulate pollution. It was used to conduct a case study of three vessels, the Ropax, Tugboat, and Reefer.

In the study of EEDI, the perspective of ship engine-propeller design and matching receives little attention; however, since the ship propulsion system is where the majority of CO_2 emissions originate, this study used the Hughes-Proshaka method to extrapolate the results to large scale vessels in order to determine the actual resistance and effective power of such ships. The particulars were taken from several already-existing ships, but assumptions were established based on the displacements of the vessels so that the analysis of their EEDIs could be statically determine. From the investigations carried out, it can be concluded thusly.

i. According to the authorized reference power plots, the model resistance and effective power test performed at the towing tank demonstrated some excellent agreement with actual power. The benchmark data proved this method's accuracy, which was greater than 95% and suitable for use.
ii. For a traditional marine propulsion system without emission abatement techniques, EEDI is a great way to regulate pollution from ships. For these ships, the relatively low EEDI limiting CO_2 emissions means a trend of high propulsive efficiency and eliminates the low energy efficiency ships.
iii. From the perspective of Hughes-Prohaska, the key methods of reducing EEDI were to reduce the ship speed, optimizing the ship hull and maintain the lower block or pragmatic coefficient. In this case, the 13%

sacrifice of ship speed at design stage would result in the 14% reduction of EEDI. This made the ship speed reduction an easy method to meet the EEDI requirements.

iv. The data of the relevant design parameters to meet the EEDI at different phases were calculated, however, these data were subject to change due the sudden nature of improvement in energy saving technologies and toughing of regulations on emission index to include Nitrogen Oxide (NOx) and Particulate Matter (PM).

The highest quantity of goods that may be transported with the least amount of fuel usage is considered by the EEDI as a measure of transport efficiency. Although reducing CO2 emissions from the shipping industry is the main goal of adopting EEDI, it also forces the industry to build more and more energy-efficient ships because CO_2 emissions are almost proportional to fuel consumption, which is a reflection of total hull resistance. So an increase in a ship's EEDI also indicates an increase in the resistance of the ship's hull.

It might be argued that the fact that tiny vessels are permitted to have greater EEDI levels is unfair, and this is what causes confusion when comparing the EEDI of small and big vessels. It might be claimed that current EEDI allows tiny boats to have greater EEDI and vice versa if the current reference line is the only one used. It implies that smaller vessels are permitted to go at a faster rate than huge vessels. The present reference line allows for a greater EEDI for tiny boats, according to the EEDI computation, however this does not imply that small vessels can achieve low EEDI.

Conflict of Interests

The authors declare that there is no conflict of interest in the publication of this paper.

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