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Investigation of Hull Design Modifications on Fuel Consumption and Energy Efficiency Design Index (EEDI)

Abstract

Currently, efforts are focused on reducing emissions to support carbon neutrality by 2050 through green technology. Green technology applies to the ship's design, port, engine selection, fuel, and operation. This study modified the hull to reduce drag and improve fuel efficiency. Changes were made based on variations in the deadrise angle, which were analyzed using numerical simulation. In the current situation, the deadrise angle is changed from 9° to 10°, 15°, and 20°. On the angle variation, the effects of changes in ship drag, fuel, and energy efficiency design index were analyzed (EEDI). The method simulates computational fluid dynamics with a Holtrop calculation method validation approach. At 12 and 6 knots above the current deadrise, resistance is reduced by 8.2% and 6.8%, respectively. The fuel efficiency achieved is 6.9% at 6 knots and 8.2% at 12 knots, resulting in monthly fuel savings of 2.43 tonnes. Furthermore, the phenomenon of the EEDI value at the lowest resistance and highest speed has a decreased performance value. Reducing the speed from 12 to 9 knots improves the performance of EEDI by 66%.

Keywords: Fuel efficiency, Deadrise angle, Hull, Ship resistance, EEDI

1. Introduction

The world community is dealing with the same challenge: global warming and climate change. It must be quickly eliminated since it creates calamities and reduces the quality of human existence. The cause is the excessive emission of greenhouse gases and other wastes from manufacturing, industrial, and transportation activities. Shipping transportation is one of the international supports where 80-90 percent of shipments utilizing shipping services are the core of the world economy. (Balcombe et al., 2019). The increasing demand for shipping lanes has direct implications for increasing ship operations, fuel consumption and exhaust emissions, and new problems worldwide. The shipping sector contributes 2–3% of total global greenhouse gas emissions (Bows–Larkin et al., 2014).

The preceding facts and trends have prompted the international community, through the IMO, to take a few strategic initiatives in response to rising emissions in the shipping sector. Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, the International Maritime Organization (IMO) has approved new measures to limit air pollution from ship emissions. It has implemented Annex VI of the MARPOL Convention 73/78 (TOKUŞLU, 2020). The new rules concentrate on green technology in the shipping sector as an efficiency and emission prevention measure. One of the outputs is a regulation known as the Energy Efficiency Design Index (EEDI) in

2011. This new measure aims to reduce CO_2 emissions and global environmental pollution by using fewer fossil fuels and generating fewer greenhouse gas emissions. EEDI enforces minimum energy use and CO_2 emissions for unit loads per tonne/mile on various ship types and models in progress from the design stage (Brodie, 2021) (International Maritime Organization, 2020). The smaller the EEDI value of the ship, the more energy-efficient it is and the less CO_2 emissions it emits. Recent studies have shown that ship energy-saving measures are applicable and beneficial for reducing CO_2 emissions. Marine green technology is a technology that includes increasing energy efficiency on ships in addition to the scope of its positive impact on the environment and the quality of human life. Energy efficiency measures include ship material selection, ship design, hull coating related to resistance, and those related to fuel use, propulsion systems, and ship scheduling optimization. (Bouma et al., 2017)(Mallouppas & Yfantis, 2021)(Rehmatulla et al., 2017)(Bows–Larkin et al., 2014)("DNV GL Says Oil & Gas Industry Sees Hydrogen as Key to Decarbonisation," 2020)(DNV GL - Maritime, 2019)

In ship design planning, the hull shape is one of the factors considered to reduce ship resistance, which is correlated with fuel efficiency and carbon emissions. According to (Prabowo et al., 2022)(Kim et al., 2013) (Kim et al., 2013) all modifications can reduce ship drag. According to (Yousefi et al., 2013) hull geometry characteristics consist of the dead-rise angle, chine, and spray rail. One of the modifications that have a lot is the optimization of the deadrise angle. It was done in the studies (Putranto et al., 2017)(Prabowo et al., 2022)(Pranatal, 2020), studies conducted by previous researchers, it did not correlate with design energy efficiency. Ship indices review changes in resistance, seakeeping, and ship stability. The deadrise angle itself is the angle formed in the cross-sectional plane between the hull and the horizontal section. It is measured at the center of the ship. According to (Kim et al., 2013) the configuration of this deadrise angle will affect the trim angle and ship stability.

The research aims to investigate how improvements in the geometry parameters of the dearies angle from existing hull conditions of 9° to 10° and 15° and 20°can are achieved by reducing fuel consumption and CO_2 emissions to implement green technology toward zero carbon 2050.

2. Methods

Ship Data

The detailed data on existing ships is shown in Table 1.

Tabel.1. Ship Data

Main Dimensions	M_0
LWL (m)	43,728
Beam (m)	11,962
Draft (m)	2,15
Displaced volume (m^3)	823,077
Wetted area (m^2)	570,424
Prismatic coeff. (C_p)	0,784
Waterpl. area coeff. (C_{wp})	0,92
1/2 angle of entrance	38,1
LCG from midships (+ve for'd)	-0,102
Max sectional area (m^2)	24,021
Deadrise at 50% LWL	1,1

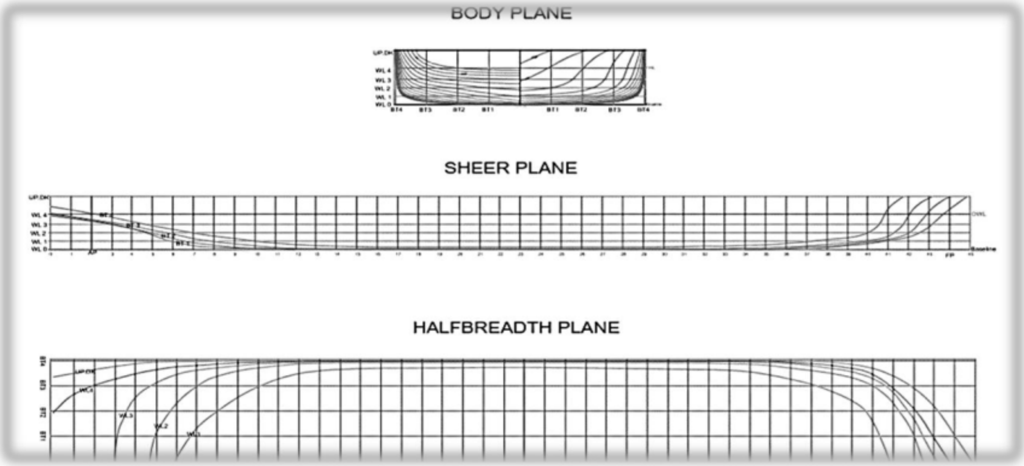
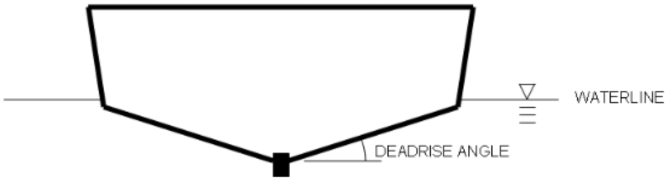
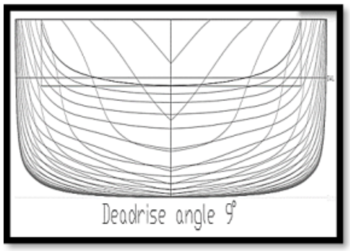


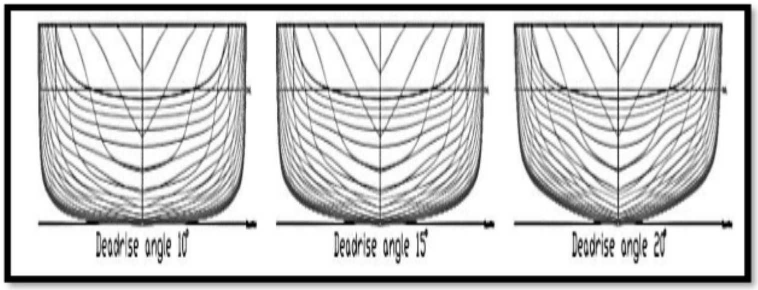
Fig.1 Lines plan of XYZ ship

The optimum deadrise angle design, efficient fuel consumption, and (EEDI) will obtain using a methodology that utilizes a computational Maxsurf model using a Holtrop method calculation methodology. Numerical analysis of the effect of modifications in deadrise angle on resistance, fuel consumption, and EEDI. We have two-speed selections in this method: 6 and 12 knots. After the modeling, a measurement test of the deadrise modifications on resistance, consumption level, and EEDI of the changed hull model is conducted compared to the existing ship model. M_0 and M_1 are used for the existing ship model, M_2 for the 15° deadrise angle ship model, and M_3 for the 20°-deadrise-angle ship model. The deadrise is the angle measured in the section plane between the hull and the horizontal at the midship position (Bentley, 2013)-. Modifying the deadrise angle affects the trim angle, with the rise of the deadrise angle negatively correlated with the trim angle. At low speeds, the deadrise angle also affects the ship's stability, and high trim angles can interfere with the ship's transverse stability (Hasanudin et al., 2019). On a ship of this size, however, it has no significance.





(a)



(b)

Fig 2. Figure 2. Existing model (a) and variation of deadrise angle (b)

The parameters taken and analysed are ship resistance, power, fuel consumption level, and EEDI value for each model.

Ship Resistance Calculation

According to (Holtrop & Mennen, 1982) the total resistance of a ship can be expressed by the following formula:

$$R_T = \frac{1}{2}\rho.V^2.\ S_{tot}\ [C_f\ (1+k) + C_A) + \frac{Rw}{W}\ w \qquad (1)$$

$$R_T = R_f\ (1+k) + R_{APP} + R_W + R_B + R_{TR} + R_A \qquad (2)$$

R_f = Frictional Resistance according to the ITTC 1957 formula

$1+k$ = form factor of the hull

R_{AFF} = Appendage resistance

R_W = Wave resistance

R_B = Additional pressure resistance of bulbous bow near the water surface

R_{TR} = Additional pressure resistance due to transom immersion

R_A = Model ship correlation resistance

Meanwhile, the ship resistance according to the ITTC standard is explained by the formula:

$$R_T = \frac{1}{2}\rho.V^2.S.\ C_T \qquad (3)$$

Fuel Consumption Rate

The specific fuel consumption is based on the torque delivered by the engine with respect to the mass flow of fuel delivered to the engine. Fuel consumption is the amount of fuel used per unit of time. The unit usually used is gr/kWh. Calculating fuel consumption can be done with the following formula:

$$W_{hfo} = P \text{ x } S_{foc} \text{ x } t \text{ x } C.10^{-6} \qquad (4)$$

Where:

P = Power of main engine (kW)

S_{foc} = Spesific fuel oil consumption (gr/kWh)

T = Cruise time (hour)

C = Constant addition of fuel (1.3 – 1.5)

EEDI calculation

To calculate EEDI, the following formula can be used:

$$EEDI = \frac{P \text{ x } Sfc \text{ x } Cf}{C \text{ x } V} \qquad \mathbf{(5)}$$

Where:

EEDI = Energy Efficiency Design Index (gr CO_2/ton mill)

P = Power (kW)

Sfc = Spesific Fuel Consumption (gr/kWh)
Cf = Conversion of CO_2
C = Ship Capacity (DWT atau GT)
V = Speed (knots)

The EEDI value obtained must not exceed the required EEDI. The required EEDI is formulated as

$$EEDI_{required} = \left(1 - \frac{X}{100}\right) RLV \quad (6)$$

3. Results and Discussion

Table 2. shows the changes in ship size because of changes to the ship's deadrise angle. The table depicts changes in the beam, ship displacement, wetted area, prismatic coefficient C_p, waterpl coefficient C_{wp} area, and other variables.

Table 1. Changes in ship size

	M_0	M_1	M_2	M_3
LWL (m)	43,728	43,728	43,728	43,728
Beam (m)	11,962	11,961	11,913	11,776
Draft (m)	2,15	2,15	2,15	2,15
Displaced volume (m^3)	823,077	815,71	774,359	705,128
Wetted area (m^2)	570,424	567,313	554,368	531,761
Prismatic coeff. (C_p)	0,784	0,783	0,777	0,766
Waterpl. area coeff. (C_{wp})	0,92	0,92	0,917	0,912
1/2 angle of entrance	38,1	38,1	38,1	37,8
LCG from midships (+ve for'd)	-0,102	-0,1	-0,075	-0,034
Max sectional area (m^2)	24,021	23,818	22,794	21,058
Deadrise at 50% LWL	1,1	1,4	3,2	6,7

By changing the deadrise angle from 9° to 20°, there is a 14.3% change in the wetted area. This is generally very beneficial in reducing the value of ship resistance. Although it is still necessary to check the stability and overall seakeeping of the ship. While the change is 14.3% in ship displacement. In this research, the value of ship displacement becomes a dynamic parameter along with changes in the geometry of the ship's hull, which is different from several previous studies (Pranatal, 2020) (Putranto et al., 2017) which maintains displacement by revising the width of the ship

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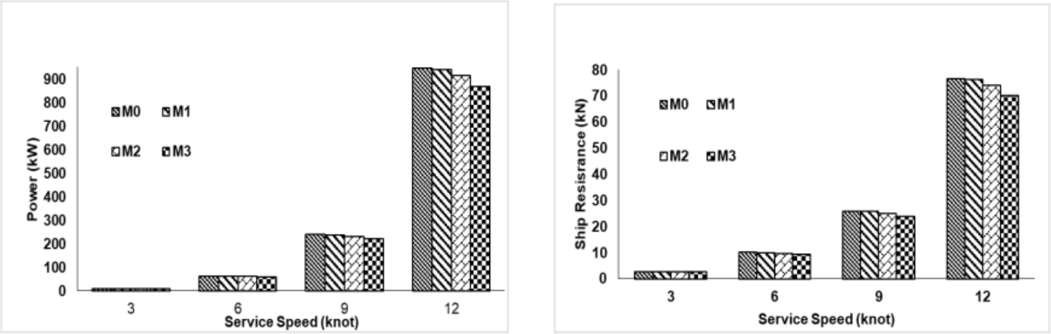
Resistance and Power



(a) (b)

Fig.3 Power to speed variation (a) and resistance to speed variation (b) to hull model variation

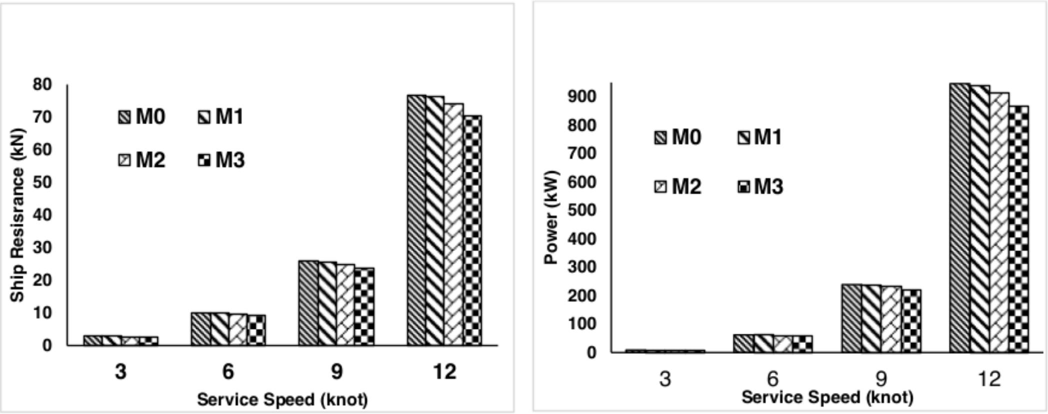
Modifications made to the deadrise angle cause the displacement value to decrease with the addition of the deadrise angle, as shown in table 1. This will cause the resistance value to decrease because the submerged area is reduced. From Figure 3. (a) above, by changing the deadrise angle from 9° to 20°, an efficiency of 8.2% occurs at 12 knots. The greater the deadrise angle, the greater the efficiency of the engine. At the same speed, it requires less power. It is related to Figure b, whereby modifying the deadrise angle to 20^0, the resistance value decreases by 8.2% from 76.6 kN to 70.3 kN at 12 knots. Meanwhile, reducing the speed from 12 to 6 knots reduced resistance on existing ships by 86%. At a speed of 6 knots, the change in deadrise angle from 9° to 20° causes the resistance to decrease by 6.9%. The power efficiency occurs at 12 knots compared to 6 knots. The decrease in power from the modified deadrise angle of 9° to 20° by 8.97% occurred at 12 knots and 7.2% at 6 knots. The amount of power is directly proportional to the value of the ship's resistance. This is in line with the results of research conducted by (Aryawan & Putranto, 2018) (Putranto et al., 2017) where the smallest resistance occurs with a larger deadrise angle. In contrast to the results obtained (Pranatal, 2020) where the smallest resistance actually occurs at the smallest deadrise angle, this is due to other modifications that maintain displacement so that the influence parameter is ship trim. Where the greater the trim angle of the ship, the ship's resistance also becomes large.

Resistance and Power

Table 2. Ship resistance and power to service speed

Speed (knots)	Resistance				Power			
	Mo	M_1	M_2	M_3	M_0	M_1	M_2	M_3
3	2.8	2.8	2.7	2.6	8.612	8.57	8.364	8.001
6	10.1	10	9.8	9.4	62.343	62.036	60.517	57.847
9	25.8	25.7	25	23.8	239.01	237.82	231.41	220.36

12	76.6	76.2	74	70.3	945.49	940.58	913.64	867.61



(a) (b)

Fig.3 Resistance to speed variation (a) and power to speed variation (b) to hull model variatio

Fuel Efficiency

Calculation of fuel consumption is carried out within one month of the active period of the cruise. It is planned that the distance travelled by the ship from port X to port Y will be 43.8 miles, with a travel time of 6 hours at a service speed of 6 knots and 2.99 hours at a service speed of 12 knots. In one day, the ship makes two trips. Meanwhile, based on the engine catalog, the specific fuel consumption is 221.1 gr/kWh. The amount of fuel consumption will at least be influenced by engine power, specific fuel consumption, and sailing time. The following graph shows data on the level of fuel consumption for one month of operation without a break on three models of variations in hull shape parameters and changes in deadrise angles to existing ships (Ariesta et al., 2021) .

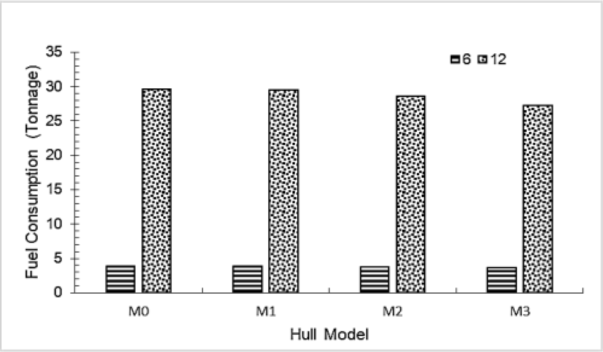


Fig.4 Fuel consumption in speed variations

Changing the deadrise angle from 9° to 20° at 6 knots can reduce the level of fuel consumption by 6.9% and at 12 knots by 8.2%, which means a savings of 0.2 tonnes of fuel at 6 knots and 2.43 tonnes at 12 knots. Changing the deadrise from 9° to 10° has the lowest decrease of 0.9% at 6 knots and 0.5% at 12 knots. It means savings of 0.038 tonnes at 6 knots and 0.154 tonnes at 12 knots. As the deadrise angle increases, the area submerged in water decreases, as shown in table 2, which causes reduced resistance and a positive effect on reducing the ship's power so that the level of fuel consumption also decreases. As also the results of research that has been carried out by (Putranto et al., 2017)(Prabowo et al., 2022), although in every consideration, the choice of deadrise angle depends on priority, whether resistance and fuel efficiency or cargo space.although in every consideration the choice of deadrise angle depends on priority whether resistance and fuel efficiency or cargo space.

Table. 3 Fuel consumption in speed variation

Speed (knots)	Hull Model			
	M_0	M_1	M_2	M_3
6	3.918	3.880	3.802	3.646
12	29.638	29.484	28.632	27.201

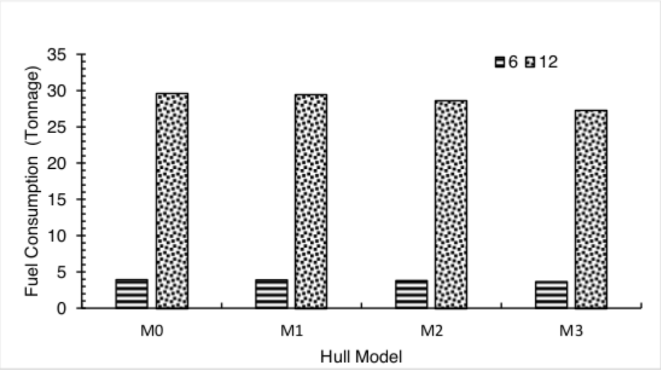


Fig.4 Fuel consumption in speed variations

Energy Efficiency Design Index

The EEDI calculation illustrates how the ship's design impacts the environment and operational benefits. The EEDI is calculated from the design to the EEDI value that should exist on the type of ship. Based on the analysis of resistance and the fuel consumption a priority for selecting the best geometric design model is M3. Then, the EEDI test of the speed variation parameter was carried out.

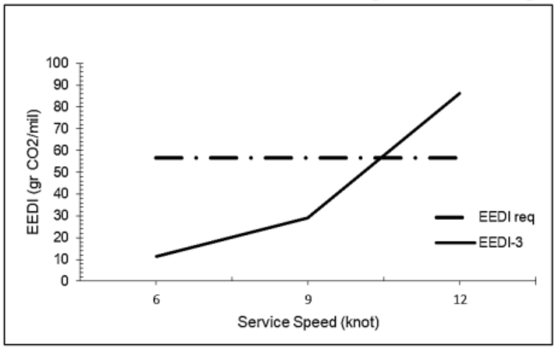


Fig.5 EEDI on M_3 speed variation

At a speed of 6 knots and 9 knots, the EEDI value is still below the recommended EEDI. An increase to 12 knots causes the EEDI value to exceed the required limit. (TOKUŞLU, 2020) stated that EEDI performance can be improved by reducing speed, increasing dead weight tonnage, and technological intervention. By lowering the speed from 12 knots to 9 knots, there is a significant decrease in EEDI of 66%, while lowering the speed from 12 knots to 6 knots, there is a decrease of 86.6%.

Energy Efficiency Design Index

Table.4 EEDI on M_3 speed variation

Speed (knots)	EEDI req	EEDI-3
6	56.672	11.48
9	56.672	29.15
12	56.672	86.10

4. Conclusion

There are several important conclusions from the research, namely:

1. Changes in hull geometry in the form of variations in deadrise angles cause significant changes in resistance, fuel consumption, and ship EEDI values.
2. The resistance becomes smaller in the hull model with a larger deadrise angle, so that the level of consumption improves. By changing the deadrise angle from 9° to 20°, the resistance decreased by 8.2% at 12 knots and was able to save 2.43 tonnes in a monthly period.
3. The energy efficiency design index at the lowest resistance along with the increase in speed decreased performance. The performance improvement is 66% by reducing from 12 knots to 9 knots.
4. The performance of the energy efficiency design index can be improved through reduced speed, increased DWT, and technological intervention.

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