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Modifying The KL Barombong: Influence of Length Extension on Speed, Resistance, and Fuel Consumption

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***Abstract*—This study investigates the effects of extending the hull length of the KL Barombong training vessel, specifically on speed resistance, engine power requirements, propeller efficiency, and fuel consumption. The objective is to assess how these modifications impact overall vessel performance, particularly fuel efficiency and operational costs. Using Maxsurf simulation software, we analyzed the vessel's performance before and after the modification. Results show that extending the hull increased hydrodynamic resistance, requiring more engine power and raising fuel consumption by 12-15%. Additionally, the propeller efficiency declined due to the higher load. These findings emphasize the need for engine-propeller optimization during vessel modifications to ensure operational efficiency and sustainability. Recommendations for future modifications and system upgrades are also provided.**

Keywords—Ship length modification, vessel performance, resistance analysis, fuel consumption, training vessel, Maxsurf simulation.

I. INTRODUCTION

The maritime industry continues to play a crucial role in global transportation, constantly seeking innovations to improve vessel efficiency and performance [1], [2]. One common modification is hull lengthening [3], [4], which is often implemented to increase cargo capacity or, in the case of training vessels, to accommodate more trainees and improve the learning experience. However, such modifications come with significant trade-offs, particularly concerning hydrodynamic resistance, propulsion efficiency, and fuel consumption, which can negatively impact the overall operational performance of the vessel [5].

The KL Barombong, a training vessel used by cadets at BP2IP Barombong, was originally 37 meters in length. The vessel underwent a modification to extend its length to 45.1 meters to enhance its capacity for educational purposes by increasing onboard space. However, modifications that increase a vessel's length often lead to greater frictional and wave-making resistance, directly affecting fuel consumption and operational efficiency [6]. The increase in surface area caused by lengthening the hull can significantly raise resistance, especially at higher speeds, thus demanding more engine power to maintain operational performance. This presents a problem for vessels like the KL Barombong, where the balance between training utility and operational efficiency is vital.

The hull length modification of the KL Barombong aimed to improve training capacity, but it introduced several challenges: increased hydrodynamic resistance, higher fuel consumption, and reduced propulsion efficiency. These issues not only escalate operational costs but also pose environmental concerns due to higher fuel consumption and carbon emissions. Addressing these challenges is critical to ensure that the educational benefits of the vessel are not outweighed by its operational inefficiencies.

While ship modifications like hull lengthening have been studied extensively, this research brings novelty by focusing on a training vessel, the KL Barombong, rather than a commercial or cargo ship. The study emphasizes the dual function of the vessel—as both a training platform and an operational vessel—making the findings particularly relevant for maritime education programs. Additionally, the use of Maxsurf software for detailed resistance and propulsion simulations provides new insights into how modifications affect training vessels in terms of hydrodynamic performance, fuel consumption, and propeller efficiency. This research also offers practical recommendations for future vessel modifications, contributing to both the academic field of naval architecture and the operational practices of maritime training institutions.

II. LITERATURE REVIEW

Ship modification, particularly hull lengthening, is a well-established area of study in naval architecture, as it plays a crucial role in determining the overall performance of a vessel. Modifications to the hull, especially increasing its length, can enhance a vessel's capacity but often come with trade-offs in terms of hydrodynamic resistance, propulsion efficiency, and fuel consumption. These aspects are particularly important for training vessels like the KL Barombong, which must balance operational efficiency with their role in maritime education.

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A. Ship Modifications and Hydrodynamic Resistance

Hydrodynamic resistance is the force that opposes a vessel's movement through water, significantly influencing the power required to propel the ship at a given speed. Resistance is categorized into two primary types: frictional resistance, caused by the interaction of water with the ship's surface, and wave-making resistance, which results from the vessel's motion creating waves [5].

Several studies have documented the impact of hull modifications, such as lengthening, on these resistance components. Harvald and Schneekluth & Bertram found that lengthening a vessel's hull increases the wetted surface area, thereby raising frictional resistance [6], [7]. This increase is particularly significant at higher speeds, where wave-making resistance also becomes more pronounced. These factors combined can result in a disproportionate rise in total resistance, demanding greater engine power and higher fuel consumption.

In the context of training vessels, such modifications must be carefully considered to avoid unintended operational inefficiencies. The extension of the KL Barombong's hull from 37 meters to 45.1 meters was primarily aimed at increasing capacity, but the associated rise in resistance presents new challenges for maintaining speed and fuel efficiency. This relationship between hull modifications and operational performance has been a recurring focus in naval architecture, with various studies emphasizing the need for a detailed analysis of the trade-offs involved [8], [9], [10].

B. Engine-Propeller Matching and Propulsion Efficiency

The efficiency of a ship's propulsion system, often referred to as engine-propeller matching, is crucial to maintaining optimal performance after hull modifications. When a vessel's hull is lengthened, the propulsion system must be adjusted to handle the increased resistance. Improper matching between the engine power and propeller performance can lead to reduced fuel efficiency, increased fuel consumption, and lower operational speeds [11].

Research by Molland et al. [5] highlighted the importance of optimizing both the engine and propeller when modifications are made to the hull structure. Failure to appropriately adjust the propulsion system after a modification can result in increased wear and tear on the engine and propeller, as these components are forced to work harder to overcome the additional resistance. For training vessels like the KL Barombong, these inefficiencies can also affect the educational objectives of the vessel, as cadets must be trained in real-world operational conditions. Ensuring that engine-propeller matching is optimized is therefore critical, both for maintaining vessel performance and for providing a valuable learning environment for trainees.

A study by several researchers emphasized that changes to a vessel's hull, particularly lengthening, require corresponding adjustments in propulsion systems to maintain efficiency [12], [13], [14], [15]. This research further demonstrated that failing to upgrade or modify the propulsion system can lead to excessive fuel consumption and reduced operational efficiency. Given the rising fuel costs and the need to minimize environmental impact, the optimization of propulsion systems post-modification is becoming increasingly important.

C. Fuel Consumption and Environmental Impact

Fuel consumption is a key consideration in ship modifications, as increased hydrodynamic resistance directly translates into higher fuel use. Studies by Gorski et al. [8] and Papanikolaou [9] have shown that hull lengthening generally leads to increased fuel consumption, with a direct relationship between resistance and fuel usage. The higher the resistance, the more power the engine must generate to maintain a certain speed, which in turn increases fuel consumption.

The global push towards reducing greenhouse gas emissions in the maritime sector further underscores the importance of optimizing fuel efficiency in modified vessels. [16] found that modifications such as hull lengthening often result in substantial increases in fuel consumption, especially if the engine-propeller system is not adapted to account for the increased resistance. These findings highlight the need for ship operators to consider not only the operational costs but also the environmental impact of such modifications.

In the case of the KL Barombong, the fuel consumption increased by 12-15% after the hull modification, a trend consistent with the findings in the literature. While the increased vessel capacity offers benefits in terms of training, the rise in fuel consumption represents a significant operational cost and an environmental challenge. Molland et al. [5] suggested that strategies such as improving hull shape or upgrading to more efficient engines could help mitigate the negative impact of increased resistance on fuel consumption.

D. Novel Contributions and Focus on Training Vessels

While previous studies have extensively explored the impact of hull modifications on commercial and cargo ships, this study offers novel insights by focusing on a training vessel. Training vessels like the KL Barombong serve a dual purpose: they must not only function efficiently in operational terms but also provide a conducive environment for maritime education. This dual purpose introduces unique challenges, as any modification must balance operational efficiency with the vessel's educational role.

This study contributes to the literature by addressing these challenges through detailed simulations using Maxsurf software. By comparing the vessel's performance before and after the modification, this research offers specific insights into how hull modifications affect training vessels, highlighting the need for careful planning to avoid compromising educational outcomes. Additionally, the study provides recommendations for future modifications to ensure that the vessel can continue to fulfill its dual function without incurring excessive operational costs or environmental impact.

III. METHOD

This research aims to evaluate the impact of the hull length modification on the performance of the KL Barombong, focusing on resistance, speed, and fuel consumption. The study involved a combination of computational simulations and empirical data analysis. The first stage of the research involved collecting data on the vessel before and after modification. The vessel originally had a length of 37 meters, which was later extended to 45.1 meters. Data collected included both pre- and post-modification dimensions, engine power, propeller specifications, and fuel consumption rates. The ship's main dimensions and engine characteristics were crucial for a comparative analysis of the vessel's performance before and after the modification.

The next stage involved using Maxsurf software to model the vessel and simulate resistance. Maxsurf is widely used in naval architecture for assessing hydrodynamic performance. A 3D model of the vessel was created based on the lines plan and hull data, reflecting both the original and modified versions of the ship. This model was then input into Maxsurf Resistance to calculate the total resistance acting on the ship at different speeds, which includes frictional and wave-making resistance. The resistance data were generated for speeds of 10, 11, and 12 knots. The results allowed for a comparative analysis of the resistance before and after the modification, showing the increase in hydrodynamic drag due to the hull lengthening.

Following the resistance analysis, the study focused on the engine-propeller matching process. This step was essential to ensure that the vessel's propulsion system could handle the increased resistance resulting from the hull modification. The existing propeller's characteristics, including its diameter, pitch, and RPM, were analyzed and compared with the power output of the newly installed engines. The engine-propeller matching analysis was conducted to determine whether the engine power was sufficient to maintain operational speed at 12 knots, taking into account the increased resistance due to the extended hull. Based on this analysis, theoretical calculations were made to estimate the power required to overcome the resistance and maintain the desired speed.

The final step of the research involved analyzing the fuel consumption before and after the modification. Using specific fuel oil consumption (SFOC) data from both the pre- and post-modification engines, fuel consumption rates were calculated. The formula used for this calculation was:

$$Fuel\ Consumption \left(\frac{liters}{Hour}\right) = HP \times BJ \times KoM$$

Where HP represents the engine's maximum horsepower, BJ is the specific gravity of the fuel (0.85 kg/liter for high-speed diesel), and KoM is the engine age coefficient (ranging from 0.08 to 0.20, depending on the engine's operational years). The fuel consumption data were compared for various speeds, and the results were plotted to illustrate the percentage increase in fuel consumption following the hull lengthening. The analysis showed a 33% increase in fuel consumption post-modification, reflecting the additional power required to overcome the higher resistance.

TABLE 1.
MAIN DIMENSIONS OF KL BAROMBONG (BEFORE AND AFTER MODIFICATION)

Parameter	Before Modification	After Modification
Length (LPP)	37 m	45.1 m
Breadth (B)	8 m	8 m
Draft (T)	2.4 m	2.4 m
Hull Volume	325.5 m³	418.74 m³

Source: data processing

The comparison of pre- and post-modification performance involved analyzing three key metrics: resistance, speed, and fuel consumption. Table 1 summarizes the main dimensions of the vessel before and after the modification, while Table 2 provides detailed specifications of the engines used in both configurations. These comparative analyses highlighted the impact of the hull extension on the ship's operational efficiency.

TABLE 2.
ENGINE SPECIFICATIONS (BEFORE AND AFTER MODIFICATION)

Parameter	Before Modification	After Modification
Engine Manufacturer	YANMAR	MITSUBISHI
Engine Type	6HA2M-WHT	S6A3-MPTK
Engine Power (kW)	297 kW	445 kW
Number of Engines	2	2
RPM	1950 RPM	1950 RPM
Specific Fuel Consumption (SFOC)	211 g/kWh	176 g/kWh

Source: data processing

III. RESULTS AND DISCUSSION

A. *Software Simulation*

The impact of the hull length modification of the KL Barombong was evaluated through detailed computational simulations using Maxsurf software. A 3D model of the vessel, both before and after modification, was created in Maxsurf Modeler. This model was subsequently used in Maxsurf Resistance to simulate and compare the total hydrodynamic resistance acting on the hull at various speeds.

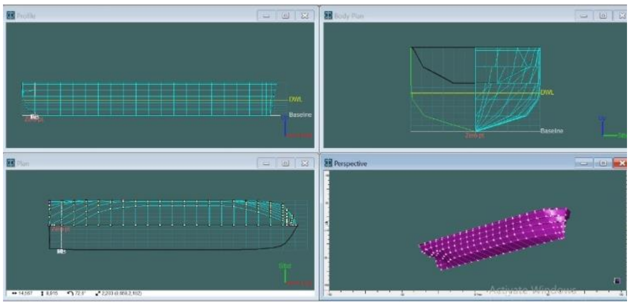
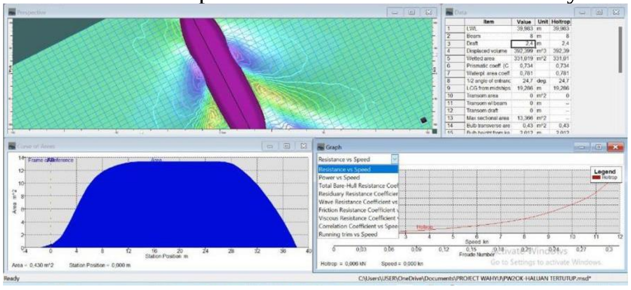


Figure 1. Ship Design in *Maxsurf Modeler*
Source: author documentation

The results of the simulation are shown in Figure 1. Design Model of the Ship in Maxsurf Modeler, which visualizes the hull's structure and dimensions both before and after the length extension. The simulation provided insights into how the modifications affected the vessel's hydrodynamic behavior. As shown in Figure 2. Resistance Analysis in Maxsurf, the total resistance increased substantially after the hull modification.



	Item	Value	Unit	Holtrop
1	LWL	39,983	m	39,983
2	Beam	8	m	8
3	Draft	2,4	m	2,4
4	Displaced volume	392,399	m^3	392,39
5	Wetted area	331,019	m^2	331,01
6	Prismatic coeff. (C	0,734		0,734
7	Waterpl. area coeff.	0,781		0,781
8	1/2 angle of entranc	24,7	deg.	24,7
9	LCG from midships	19,286	m	19,286
10	Transom area	0	m^2	0
11	Transom wl beam	0	m	--
12	Transom draft	0	m	--
13	Max sectional area	13,366	m^2	--
14	Bulb transverse are	0,43	m^2	0,43
15	Bulb height from ke	2,012	m	2,012

Area = 0,430 m^2 Station Position = 0,000 m

Holtrop = 0,006 kN Speed = 0,000 kn

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Figure 2. Resistance Analysis
Source: data processing

At a speed of 12 knots, for example, the total resistance increased from 50.5 kN to 60.7 kN post-modification, representing a 20% rise. Table 3. Comparison of Main Ship Dimensions Before and After Modification provides a detailed breakdown of the resistance at different speeds, illustrating the significant increase in resistance across the vessel's operational range.

TABLE 3.
COMPARISON OF MAIN SHIP DIMENSIONS BEFORE AND AFTER MODIFICATION

Speed (knots)	Resistance Before (kN)	Resistance After (kN)	Percentage Change
10	25.9	24.9	-4%
11	35.2	40.7	16%
12	50.5	60.7	20%
13	74.7	73.7	-1%
14	91.6	92.1	1%

Source: data processing

The relationship between speed and resistance is further visualized in Figure 3. Power vs Speed Graph in Maxsurf Resistance, which shows the nonlinear increase in resistance as speed increases. This trend is typical for modified hulls, where an increase in wetted surface area results in higher frictional and wave-making resistance.

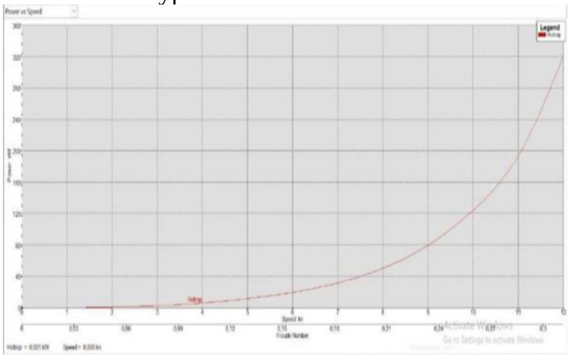

Figure 3. Power vs Speed in Maxsurf Resistance
Source: data processing

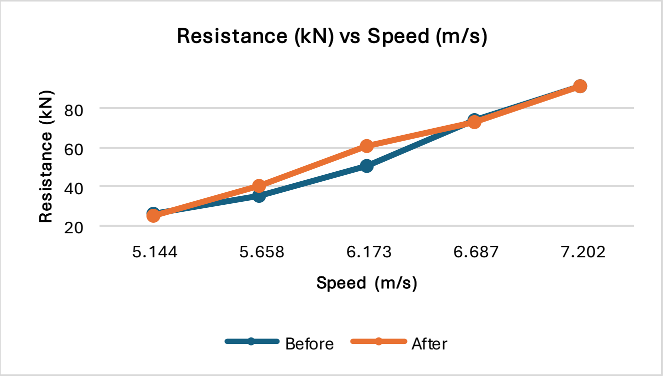

Figure 4. Resistance (kN) vs Speed (m/s)
Source: data processing

The polynomial relationship between speed and resistance is captured in Figure 4. Resistance (kN) vs Speed (m/s), where the second-order polynomial equation derived from the simulation is displayed. This equation, presented in Table 4. Mathematical Model of Ship Resistance (2nd Order Polynomial) can be used to predict total resistance at different speeds based on the vessel's dimensions after modification.

TABLE 4.
MATHEMATICAL MODEL OF SHIP RESISTANCE (2ND ORDER POLYNOMIAL)

Condition	Equation
Before	$y = 6.491x^2 + 46.924x - 94.455$
After	$y = -0.494x^2 + 38.639x - 160.995$

Source: data processing

B. Wake (w), Thrust Deduction Fraction (t), Speed Advance (Va), and Thrust (Th)

The performance of a ship's propulsion system is affected by various factors, including the wake fraction, thrust deduction fraction, speed advance, and thrust. These parameters help in determining how efficiently the ship moves through water and how much power the propulsion system needs to maintain the desired speed. The hull length modification significantly influenced these parameters, as shown in Table 5. Wake, Thrust Deduction Fraction, Speed Advance, and Thrust Before and After Length Modification.

TABLE 5.
WAKE, THRUST DEDUCTION FRACTION, SPEED ADVANCE, AND THRUST BEFORE AND AFTER LENGTH MODIFICATION

Speed (m/s)	Wake (w) Before	Thrust Deduction (t) Before	Speed Advance (Va) Before (m/s)	Thrust (Th) Before (kN)	Wake (w) After	Thrust Deduction (t) After	Speed Advance (Va) After (m/s)	Thrust (Th) After (kN)
5.144	0.174	0.182	4.25	51.85	0.196	0.197	4.14	56.44
5.658	0.174	0.182	2.67	59.59	0.196	0.197	4.55	65.88
6.173	0.174	0.182	5.1	71.35	0.196	0.197	4.96	75.91
6.687	0.174	0.182	5.52	76.02	0.196	0.197	5.38	86.45
7.202	0.174	0.182	5.95	84.58	0.196	0.197	5.79	97.43

Source: data processing

1) Wake (w)

The wake fraction (w) refers to the portion of the ship's speed that is lost in the turbulent water created by the hull's movement. After the hull length modification, the wake fraction increased from 0.174 to 0.196, as seen across all speed ranges. This increase indicates that more energy is being lost to the wake, reducing the efficiency of the propulsion system.

2) Thrust Deduction Fraction (t)

The thrust deduction fraction (t) represents the portion of the engine's thrust that is negated due to the drag created by the hull's movement through water. In other words, it's the amount of thrust that doesn't contribute to moving the ship forward. The increase in the thrust deduction fraction from 0.182 to 0.197 post-modification indicates that a larger portion of the engine's power is being used to counteract drag, rather than propel the ship forward.

3. Speed Advance (Va)

Speed advance (Va) refers to the effective speed at which the water reaches the propeller. After the modification, the speed advance decreased, as seen in Table 5. For example, at a speed of 6.17 m/s, the speed advance dropped from 5.10 m/s before the modification to 4.96 m/s after. This reduction in speed advance suggests that the propeller is now working less efficiently, as more energy is being lost to the wake and drag.

4. Thrust (Th)

Thrust (Th) is the force generated by the propeller to push the ship forward. After the hull modification, the thrust required to maintain similar speeds increased significantly. At 6.17 m/s (approximately 12 knots), the thrust increased from 71.35 kN before the modification to 75.91 kN after. This increase in required thrust reflects the greater resistance encountered by the ship due to the longer hull and the changes in wake and thrust deduction fractions.

C. Correlation Between Resistance and Ship Propeller Performance

The hull length modification caused an increase in resistance, which directly impacted on the performance of the ship's propeller. To better understand the propeller's performance after modification, we examine the relationship between the thrust coefficient (KT) and the advance ratio (J).

The propeller's load characteristics are defined by the thrust coefficient (KT), which is a function of the advance ratio (J). Table 6. Propeller Load Characteristics Before and After Modification presents the mathematical equations for the thrust coefficient before and after the hull length modification under both seatrial and seamargine conditions.

TABLE 6.
PROPELLER LOAD CHARACTERISTICS BEFORE AND AFTER HULL LENGTH MODIFICATION

Item	Condition	Equation
KT	Before Modification	KT = 0.703 J^2 (Seatrial)
	After Modification	KT = 0.846 J^2 (Seatrial)
	Before Modification	KT = 0.809 J^2 (Seamargine)
	After Modification	KT = 0.973 J^2 (Seamargine)

Source: data processing

As seen in Table 6, after the hull length modification, the thrust coefficient increased from KT = 0.703 J^2 to KT = 0.846 J^2 under seatrial conditions, and from KT = 0.809 J^2 to KT = 0.973 J^2 under seamargine conditions. These equations indicate that the propeller now needs to generate more thrust to overcome the increased resistance, placing a higher load on the engine.

TABLE 7.
RELATIONSHIP BETWEEN KT AND J BEFORE AND AFTER MODIFICATION

Advance Ratio (J)	J^2	KT (Seatrial) Before	KT (Seatrial) After	KT (Seamargine) Before	KT (Seamargine) After
0	0	0	0	0	0
0.1	0.01	0.007	0.008	0.008	0.01
0.2	0.04	0.028	0.032	0.032	0.04
0.3	0.09	0.063	0.073	0.073	0.09
0.4	0.16	0.113	0.129	0.129	0.16
0.5	0.25	0.176	0.202	0.202	0.24
0.6	0.36	0.253	0.291	0.291	0.35
0.7	0.49	0.345	0.396	0.396	0.48
0.8	0.64	0.45	0.518	0.518	0.62
0.9	0.81	0.57	0.655	0.655	0.79
1	1	0.703	0.809	0.809	0.973

Source: data processing

Additionally, Table 7. Relationship Between KT and J Before and After Modification presents a breakdown of the thrust coefficients at different advance ratios, illustrating how the propeller's performance deteriorates after the hull length extension, which corresponds to the increased hydrodynamic resistance.

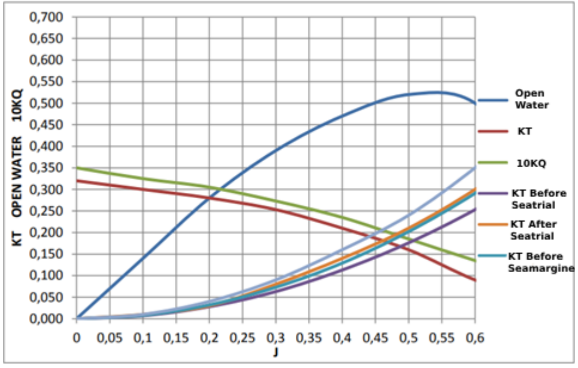

Figure 5. Open Water Propeller Test Graph
Source: data processing

The relationship between the thrust coefficient (KT) and the advance ratio (J) is also illustrated in Figure 5. Open Water Propeller Test Graph, which shows how the propeller operates less efficiently after the modification, requiring more energy to maintain similar speeds.

D. *Determining Main Engine Power Requirements*

The hull modification on the KL Barombong led to increased resistance, which necessitates a higher engine power to maintain the desired operational speed. In this section, we evaluate the relationship between the engine's power output and the vessel's speed to determine the additional power required after the modification.

The engine power required to overcome the increased resistance is influenced by the vessel's hydrodynamic characteristics and the efficiency of the propulsion system. To calculate the required engine power, we use the brake horsepower (BHP), which represents the power that the engine delivers to the propeller shaft. This is derived from the delivered horsepower (DHP) and shaft horsepower (SHP).

The results of the calculations are summarized in Table 8. Main Engine Power Requirements Before and After Modification, where the required engine power is shown for both pre- and post-modification conditions. These calculations indicate the additional engine power necessary to achieve the same performance as before the hull length extension.

TABLE 8.
MAIN ENGINE POWER REQUIREMENTS BEFORE AND AFTER MODIFICATION

Condition	DHP (kW) Before	SHP (kW) Before	BHP (kW) Before	DHP (kW) After	SHP (kW) After	BHP (kW) After
Seatrial	631.64	651.17	817.24	738.77	761.63	923.74
Seamargine	650.78	670.91	842	768.93	792.71	961.45

Source: data processing

As shown in Table 8, the main engine's brake horsepower (BHP) increased significantly after the modification. For example, in seatrial conditions, the BHP increased from 817.24 kW before the modification to 923.74 kW after the modification. Similarly, in seamargine conditions, the BHP increased from 842.00 kW to 961.45 kW after the hull extension.

Figure 6. Speed vs BHP Graph illustrates the relationship between the vessel's speed and the brake horsepower (BHP) required to maintain those speeds. The graph shows that as the vessel's speed increases, the required engine power also increases, especially after the hull modification.

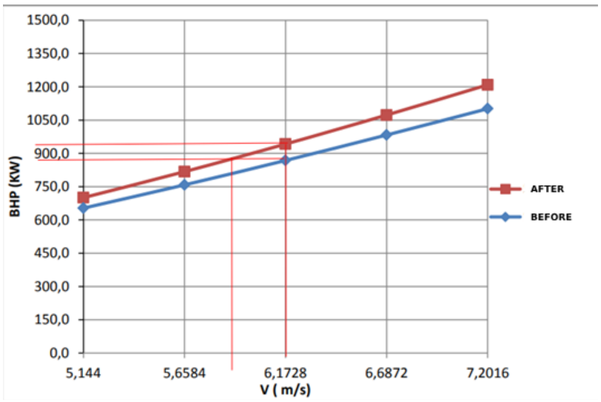

Figure 6. Speed vs Brake Horsepower (BHP) Graph
Source: data processing

The results of this analysis indicate that the hull length modification has increased the engine power demand, particularly at higher speeds. To maintain a speed of 12 knots, the required engine power after the modification is approximately 961.45 kW, compared to 842.00 kW before the modification. This represents an increase of nearly 15%, highlighting the impact of the additional resistance on engine performance.

In conclusion, the increase in the vessel's resistance following the hull length modification necessitates a significant increase in engine power to maintain similar speeds. This increased power demand will result in higher fuel consumption and operational costs, as discussed in the following sections.

E. Characteristics of the Ship's Main Engine

The hull length modification of the KL Barombong not only affected the vessel's resistance and required power but also had a direct impact on the characteristics of the ship's main engine. The engine's performance across different operating conditions is crucial for understanding how efficiently the vessel can maintain speed after modification.

In this section, we analyze the performance of the main engine in terms of brake horsepower (BHP) at various engine revolutions per minute (RPM) before and after the hull modification. Table 9. Main Engine Brake Horsepower (BHP) at Different RPM presents a comparison of the engine's performance before and after the modification, showing the power output (BHP) as a function of engine RPM.

TABLE 9.
MAIN ENGINE BRAKE HORSEPOWER (BHP) AT DIFFERENT RPM BEFORE AND AFTER MODIFICATION

% RPM	RPM	RPS	BHP (kW) Before	BHP (HP) Before	BHP (kW) After	BHP (HP) After
0%	0	0	0	0	0	0
10%	190	3.167	89	119.35	96.145	128.93
20%	380	6.333	178	238.7	192.29	257.87
30%	570	9.5	267	358.05	288.435	386.8
40%	760	12.667	356	477.4	384.58	515.73
50%	950	15.833	445	596.75	480.725	644.66

% RPM	RPM	RPS	BHP (kW) Before	BHP (HP) Before	BHP (kW) After	BHP (HP) After
60%	1140	19	534	716.11	576.87	773.6
70%	1330	22.167	623	835.46	673.015	902.53
80%	1520	25.333	712	954.81	769.16	1031.46
90%	1710	28.5	801	1074.16	865.305	1160.39
100%	1900	31.667	890	1193.51	961.45	1289.33

Source: data processing

As seen in Table 9, the brake horsepower (BHP) of the main engine increased at all RPM levels after the modification. For example, at 100% RPM (1900 RPM), the BHP increased from 890 kW to 961.45 kW after the hull lengthening, reflecting the need for more engine power to maintain similar speeds.

This increase in BHP across all RPM levels highlights the additional strain placed on the engine due to the increased resistance from the longer hull. The engine now has to work harder at each power level to produce the required thrust.

Figure 7. Relationship Between Engine Power (BHP) and RPM illustrates the increase in BHP at different RPM levels before and after the modification. The graph shows that, for any given RPM, the modified engine now delivers more power, indicating a higher load on the engine.

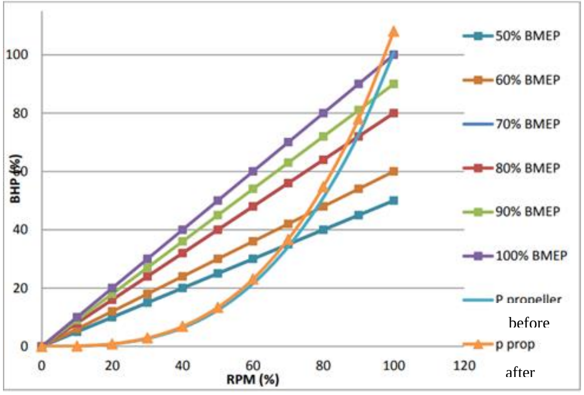

Figure 7. Relationship Between Engine Power (BHP) and RPM
Source: data processing

The increased BHP at different RPM levels can have implications for fuel efficiency and engine wear. The more power the engine has to produce to overcome the increased resistance, the greater the fuel consumption and the faster the wear and tear on engine components.

In conclusion, the hull length modification has significantly altered the characteristics of the ship's main engine. The engine now operates at higher brake horsepower levels across all RPM ranges, which, while necessary to maintain speed, leads to increased fuel consumption and possibly higher maintenance costs due to the greater strain on the engine.

F. Analysis of Ship Fuel Consumption

The hull length modification of the KL Barombong not only impacted the resistance, thrust, and engine power requirements, but also had a significant effect on the vessel’s fuel consumption. Increased resistance leads to higher engine power requirements, which in turn results in greater fuel consumption. In this section, we examine how the ship’s fuel consumption changed after the hull modification and the extent of the increase across different operating conditions.

Fuel consumption was calculated based on the engine’s brake horsepower (BHP) and specific fuel oil consumption (SFOC) data. The relationship between fuel consumption and BHP at various speeds before and after the hull modification is presented in Table 10. Fuel Consumption at Different Speeds Before and After Hull Length Modification. These results highlight the additional fuel required to maintain operational speeds post-modification.

TABLE 10.
FUEL CONSUMPTION AT DIFFERENT SPEEDS BEFORE AND AFTER HULL LENGTH MODIFICATION

Speed (knots)	BHP (kW) Before	Fuel Consumption Before (liters/hour)	BHP (kW) After	Fuel Consumption After (liters/hour)	Percentage Increase
10	445	21.82	480.72	24.91	14%
11	550	27.02	576.87	30.44	13%
12	617	30.29	673.02	34.91	15%
13	732	35.93	769.16	40.26	12%
14	890	44.36	961.45	50.78	14%

Source: data processing

As shown in Table 10, fuel consumption increased across all speeds after the hull length modification. For example, at 12 knots, the fuel consumption increased from 30.29 liters per hour before the modification to 34.91 liters per hour after, representing a 15% increase in fuel usage. Similar increases are observed at other speeds, with the most substantial increases occurring at higher speeds.

This increase in fuel consumption is further illustrated in Figure 8. Relationship Between Speed and Fuel Consumption, where the fuel consumption before and after the modification is plotted against speed. The graph clearly shows the greater fuel demands placed on the engine at each speed post-modification.

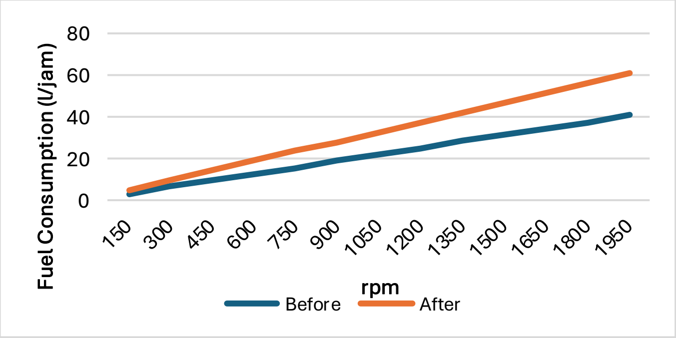

Figure 8. Relationship Between Speed and Fuel Consumption
Source: data processing

The results indicate that the ship's fuel consumption has risen significantly due to the higher power demands following the hull modification. As more engine power is required to overcome the increased resistance, the ship's fuel efficiency is negatively affected, particularly at higher speeds.

In conclusion, the hull length modification has led to an overall increase in fuel consumption across all operational speeds. This rise in fuel consumption is primarily due to the increased resistance and the corresponding need for greater engine power to maintain speed. The fuel consumption increase, ranging between 12% and 15%, will result in higher operational costs for the vessel and may also impact on the ship's environmental footprint due to the increased fuel usage.

IV. Discussion

The results of this study reveal significant insights into the impact of hull length modifications on the performance of training vessels, specifically the KL Barombong. The most notable findings are the increases in hydrodynamic resistance, engine power requirements, and fuel consumption, all of which have practical implications for the vessel's operational efficiency and educational function. This section will delve deeper into these findings and highlight the novelty of this research in the broader context of maritime vessel modifications, particularly for training ships.

1) *Hydrodynamic Resistance and Its Operational Impact*

One of the most critical findings is the substantial increase in hydrodynamic resistance after the hull length modification. The resistance increase, particularly at higher speeds, aligns with existing research in naval architecture, where extended hulls typically exhibit higher frictional and wave-making resistance [6], [7], [17]. However, the novelty of this study lies in the specific application of these findings to a training vessel rather than a commercial ship. For the KL Barombong, this increased resistance means that more engine power is required to maintain the same speed, which directly impacts the vessel's fuel efficiency and operational costs.

The implications of this resistance increase are particularly significant for training vessels, where operational efficiency must be balanced with educational objectives. Unlike commercial vessels, where performance and cost-efficiency are the primary concerns, training vessels such as the KL Barombong also serve as educational platforms for maritime cadets. The rise in resistance and its subsequent impact on fuel consumption introduces additional challenges for ensuring that the vessel can still perform optimally while providing a conducive learning environment. The novelty of this study lies in addressing these dual objectives, offering insights into how ship modifications can affect both operational and educational outcomes.

2) *Engine-Propeller Matching: A Critical Consideration*

Another critical finding from this study is the reduced efficiency of the vessel's propulsion system after the hull length modification. The results show that the propeller's load increased significantly, leading to a decline in overall efficiency. This issue of engine-propeller matching is well-documented in naval architecture [11], [18], [19], but the specific application to a training vessel like the KL Barombong adds a new dimension to this body of research. In training vessels, where students are learning to operate and navigate ships, propulsion efficiency is key not only for operational success but also for ensuring that trainees gain practical, real-world experience.

The increase in engine power requirements, as demonstrated by the higher brake horsepower (BHP) needed post-modification, reflects the challenges of maintaining operational performance under increased resistance. This finding has significant implications for ship operators and designers, as improper engine-propeller matching can lead to higher fuel consumption, greater engine wear, and reduced vessel longevity. For training vessels, this inefficiency can disrupt educational objectives by reducing the vessel's operational range or increasing downtime due to maintenance issues. Thus, this study highlights the importance of incorporating propulsion system upgrades when modifying training vessels, ensuring that operational and educational efficiency are not compromised.

3) *Fuel Consumption and Environmental Sustainability*

Perhaps the most practical finding from this study is the 12-15% increase in fuel consumption following the hull length modification. This finding is consistent with research on the relationship between hydrodynamic resistance and fuel consumption [8], [12], [16]. However, in the context of a training vessel, this increase in fuel consumption has broader implications beyond operational costs. Training vessels like the KL Barombong are typically used for extended periods of time, often operating under variable load conditions as cadets learn different aspects of ship operations. The rise in fuel consumption thus presents a dual challenge: increased operational costs and a higher environmental footprint.

Given the global emphasis on reducing carbon emissions in the maritime sector, the environmental impact of increased fuel consumption cannot be overlooked. The novelty of this study lies in its focus on how hull modifications affect training vessels, where operational efficiency must be aligned with sustainability goals. The findings suggest that training vessels undergoing hull modifications must adopt more fuel-efficient technologies, such as hybrid engines or optimized propeller designs, to mitigate the environmental impact. This is particularly important in the context of maritime education, where future generations of ship operators and engineers must be trained in sustainable practices.

What sets this study apart from previous research is its focus on the unique dual-purpose nature of training vessels. While much of the existing literature on hull modifications focuses on commercial and cargo vessels, this study addresses the specific challenges faced by training vessels like the KL Barombong. These vessels not only need to perform efficiently in operational terms but also serve as educational platforms for maritime cadets. The findings from this study emphasize the delicate balance required to maintain both operational performance and educational value after a vessel undergoes structural modifications.

Moreover, the use of Maxsurf simulation software to model the vessel's performance before and after the modification provides detailed insights into how these changes affect both hydrodynamic behavior and propulsion efficiency. While previous studies have used computational tools to assess hull modifications, the application of these tools in the context of a training vessel introduces a new perspective. The detailed simulation results provide practical recommendations for optimizing propulsion systems and engine power requirements, ensuring that training vessels like the KL Barombong can continue to meet their dual objectives without incurring excessive operational costs or environmental harm.

4) *Practical Implications and Future Directions*

The findings from this study have several practical implications for shipbuilders, maritime training institutions, and vessel operators. First, it is crucial to consider the trade-offs involved in hull modifications, particularly for vessels that serve an educational function. The increase in resistance, fuel consumption, and engine power demand underscores the need for comprehensive planning and optimization before undertaking such modifications. For future modifications, shipbuilders should consider integrating advanced propulsion technologies, such as more fuel-efficient engines or redesigned propellers, to mitigate the adverse effects of increased resistance.

Second, this study highlights the importance of maintaining operational efficiency while ensuring that training vessels remain effective educational platforms. Future research could explore the development of hybrid systems that combine simulation-based training with modified vessels, reducing the need for extensive sea trials while still providing valuable learning experiences for cadets. Additionally, further studies could examine the environmental impact of vessel modifications in greater detail, exploring alternative fuels or low-friction hull coatings as potential solutions to the challenges posed by increased fuel consumption.

V. CONCLUSION

The primary objective of this study was to analyze the impact of hull length modification on the performance of the KL Barombong training vessel, focusing on hydrodynamic resistance, fuel consumption, and operational efficiency. Using Maxsurf simulation software, the study revealed that extending the vessel’s hull led to significant increases in resistance, particularly at higher speeds. This increased resistance resulted in a 12-15% rise in fuel consumption, along with greater demand on engine power to maintain operational speeds. The increased load on the propeller further reduced propulsion efficiency, emphasizing the need for proper engine-propellers to match the following modifications.

These findings highlight the operational challenges associated with hull length modifications, especially in the context of training vessels, where the balance between capacity enhancement and operational performance is critical. The study underscores the importance of careful planning and optimization of the propulsion system when modifying vessels, as failure to do so can lead to reduced efficiency, increased fuel costs, and a greater environmental footprint.

In light of these results, it is recommended that future vessel modifications incorporate system optimization strategies such as engine upgrades, propeller redesigns, or the use of more fuel-efficient technologies. These measures could help mitigate the negative effects of increased resistance and ensure that training vessels like the KL Barombong maintain their dual function of operational efficiency and educational effectiveness. By addressing these challenges, maritime training programs can continue to provide practical learning experiences without compromising on performance or sustainability.

REFERENCES

[1] S. Murad, “IMPACT OF SERVICE QUALITY ON CUSTOMER SATISFACTION IN RESTAURANT INDUSTRY,” 2015.

[2] B. Guo, P. Gupta, S. Steen, and H. A. Tvete, “Evaluating vessel technical performance index using physics-based and data-driven approach,” *Ocean Engineering*, vol. 286, p. 115402, Oct. 2023, doi: 10.1016/j.oceaneng.2023.115402.

[3] L. D. Leal-Ruiz, C. P. Camargo-Díaz, E. Paipa-Sanabria, C. Castro-Faccetti, and J. E. Candelo-Becerra, “Effect of Speed and Hull Length on the Hydrodynamic Performance of a Semi-Planing Hull of a Shallow-Draft Watercraft,” *JMSE*, vol. 11, no. 12, p. 2328, Dec. 2023, doi: 10.3390/jmse11122328.

[4] A. Trimulyono, W. Ananda, K. Kiryanto, and A. W. B. Santosa, “Investigation of The Effect Hullvane and Bow Foil on Flat-Hull Ship Using CFD Approach,” *International Journal of Marine Engineering Innovation and Research*, vol. 8, no. 1, Art. no. 1, Mar. 2023, doi: 10.12962/j25481479.v8i1.14687.

[5] A. F. Molland, S. R. Turnock, and D. A. Hudson, *Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power*, 2nd ed. Cambridge University Press, 2017. doi: 10.1017/9781316494196.

[6] H. Schneekluth and V. Bertram, *Ship design for efficiency and economy*, 2nd ed. Oxford Boston: Butterworth-Heinemann, 1998.

[7] S. A. Harvald, *Resistance and propulsion of ships*. in Ocean engineering. New York: Wiley, 1983.

[8] W. Gorski, T. Abramowicz-Gerigk, and Z. Burciu, “The influence of ship operational parameters on fuel consumption,” *Scientific Journals*, pp. 49–54, 2013.

[9] A. Papanikolaou, “Estimation of Building Cost,” in *Ship Design: Methodologies of Preliminary Design*, A. Papanikolaou, Ed., Dordrecht: Springer Netherlands, 2014, pp. 439–447. doi: 10.1007/978-94-017-8751-2_6.

[10] A. Papanikolaou, “Selection of Main Dimensions and Calculation of Basic Ship Design Values,” in *Ship Design: Methodologies of Preliminary Design*, A. Papanikolaou, Ed., Dordrecht: Springer Netherlands, 2014, pp. 69–292. doi: 10.1007/978-94-017-8751-2_2.

[11] W. Duran F., *The Resistance and Propulsion of Ships*. Ulan Press, 2012.

[12] B. Ariani, R. C. Ariesta, R. Prasetya, M. Oktaviani, and M. H. Hakim, “Investigation of Hull Design Modifications on Fuel Consumption and Energy Efficiency Design Index (EEDI),” *Kapal*, vol. 19, no. 3, pp. 133–140, Oct. 2022, doi: 10.14710/kapal.v19i3.47029.

[13] B.-S. Kim, M.-J. Oh, J.-H. Lee, Y.-H. Kim, and M.-I. Roh, “Study on Hull Optimization Process Considering Operational Efficiency in Waves,” *Processes*, vol. 9, no. 5, p. 898, May 2021, doi: 10.3390/pr9050898.

[14] A. Papanikolaou, “Ship’s Hull Form,” in *Ship Design: Methodologies of Preliminary Design*, A. Papanikolaou, Ed., Dordrecht: Springer Netherlands, 2014, pp. 293–357. doi: 10.1007/978-94-017-8751-2_3.

[15] D. S. Staples, J. S. Hulland, and C. A. Higgins, “A Self-Efficacy Theory Explanation for the Management of Remote Workers in Virtual Organizations,” *Journal of Computer-Mediated Communication*, vol. 3, no. 4, pp. 0–0, Jun. 2006, doi: 10.1111/j.1083-6101. 1998.tb00085.x.

[16] A. La Ferlita, Y. Qi, E. Di Nardo, O. El Moctar, T. E. Schellin, and A. Ciaramella, “A Comparative Study to Estimate Fuel Consumption: A Simplified Physical Approach against a Data-Driven Model,” *JMSE*, vol. 11, no. 4, p. 850, Apr. 2023, doi: 10.3390/jmse11040850.

[17] F. Ogheard, T. S. Daugbjerg, J. Sluše, J. Geršl, J. A. Wippold, and V. Silverio, “Assessing Hydrodynamic Resistance in Microfluidics: A Case Study,” Jun. 03, 2024. doi: 10.20944/preprints202406.0049.v1.

[18] A. Papanikolaou, “Machinery Installation, Propulsion and Steering Devices,” in *Ship Design: Methodologies of Preliminary Design*, A. Papanikolaou, Ed., Dordrecht: Springer Netherlands, 2014, pp. 393–437. doi: 10.1007/978-94-017-8751-2_5.

[19] T. G. Tran and H. C. Kim, “A study on the matching problem of engine, propeller, and ship hull under actual service conditions,” *International Journal of Naval Architecture and Ocean Engineering*, vol. 15, p. 100538, 2023, doi: 10.1016/j.ijnaoe.2023.100538.