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RETROFITTING THE BOW OF A GENERAL CARGO VESSEL ANDEVALUATING ENERGY EFFICIENCY OPERATIONAL INDEX

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ABSTRACT

This report examines the feasibility and impact of retrofitting the bulbous bow on a general cargo ship, in terms of the energy efficiency operational index (EEOI), in the areas of Western Europe and the Eastern Mediterranean. Three ship forms were developed and analysed: with a bulbous bow, without a bulbous bow, and with a modified bulbous bow. The goal in developing the ship forms and conducting the analysis was to achieve minimal differences in the ship's characteristics with the same volumetric displacement, aided by PolyCAD software. A route was selected between two ports: Varna and Rotterdam. The labour intensity of the bulbous bow retrofitting process was evaluated and approximate values of labours costs and cost for the task were determined. The results obtained for resistance during ship motion, EEOI, and fuel consumption reductions, or increases, were compared against the retrofitting values. The return cost of retrofitting is evaluated and measured in terms of fuel saved.

Keywords: retrofitting, bulbous bow, energy efficiency design index, return costs

INTRODUCTION

In recent years, the International Maritime Organization (IMO) introduced requirements for reducing emissions to the environment. The IMO strategy aims to reduce freight rate carbon emissions by 40% by 2030, compared with 2008, and up to 70% by 2050 [1]. On January 1 2023, new regulations took effect, relating a ship's Energy Efficiency Existing Ship Index (EEXI) calculations to energy efficiency and initiating the annual operational carbon intensity indicator (CII) [2].

Taking the International Maritime Organization regulations into account, ship owners are required to take measures to improve the energy efficiency of their fleet as part of the global effort. Some of the measures to improve the energy efficiency of ships consist of methods to reduce the ship's resistance, use renewable energy, converting conventional diesel engines to operate on liquefied natural gas, modifying the bow design, or simply changing the configuration of the bulbous bow.

Retrofitting bulbous bows is an interesting process, not only for large container vessels, but also for other types of merchant ships. Force technology is carried out in the retrofitting of the bulbous bow of multipurpose vessels with 9100 DWT. The result is a 17.5% resistance saving [3].

A numerical analysis of retrofitting a bulbous bow for a modern container ship, operating with a slow-steaming profile, was presented in [4]. The retrofit analysis served as an illustrative example of a design process that relies on high-fidelity CFD simulations and surrogate modeling. The bulbous bow design candidates were generated by parametrically modifying the original bow geometry. These alternative designs were assessed using the open-source CFD toolbox Open FOAM, and the resulting effective power predictions were used to rank each design throughout the entire operating profile. Moreover, the impacts of the different bulbous bow designs on wave-making resistance and propeller performance were thoroughly examined. Surrogate models were then employed to explore the parameterized design space and establish a sequence of design exploration and exploitation cycles in the retrofit analysis, aiming to achieve an enhanced bow shape as the ultimate objective.

An assessment of the design and operational energy efficiency index of a group of container ships from Class A13, A15, and A19 was conducted in [5]. It transpired that, based on these indicators, the best performer was the container ship from Class A19, while Class A13 would need to reduce its speed by 45% to meet the requirements for lowering index values. The possibility of using a liquefied natural gas engine for the Class A19 ship could enhance its energy efficiency, resulting in savings of approximately $27 million [5].

A possible solution for reducing harmful emissions into the atmosphere is a hybrid propulsion system. Applied to a container ship of Class A19, respective reductions of NOx, SOx, and CO_2, by 52.0%, 63.7%, and 30.4%, were achieved, compared to a conventional system. Additionally, it is a more efficient option concerning environmental regulations, with an energy cost of $0.07/kWh and profitability of $21.9/ton [6].

The implementation of a double-hull bulb on the bow of a fishing vessel with a non-optimized hull directly impacted its operational efficiency. Following the modernization of the shape and towing tests, a reduction in resistance of approximately 10% was observed [7].

An evaluation of the resistance of a tanker during beam seas was conducted in [8]. Through simulation, the maximum and minimum wave angles were identified, at which the additional resistance reached its maximum and minimum values. These were 180 and 150 degrees for the maximum angle and 130 degrees for the minimum angle, taking into account that the degrees of freedom also directly influenced this effect.

In [9], a new type of bulbous form for ships, with a Froude number ranging from 0.4 to 0.5, was introduced, significantly differing from the conventional ones. This bulb shape reduced wave generation at high speeds but was sensitive to precise mounting position and velocity. The tests were conducted in a towing tank and software simulations were undertaken for a ship with a Froude number of about 0.45.

The aim of this study was to analyze the economic effect of retrofitting a ship's hull to improve the EEOI. Alongside all the efforts to improve the energy efficiency of existing ships, an economic analysis of the benefits must also be carried out, since such actions are costly and time-consuming, because the ship is not in operation. Retrofitting the bow of a ship is directly linked to the ship's stay in dry dock. From a technological perspective, such a task may not be overly complex, but the economic analysis is more challenging. Therefore, the article presents and analyses the benefits and return on investment in retrofitting the bow of a general cargo ship.

METHODOLOGY AND SECTION MODELLING

The methodology and section modelling are related to modernisation process descriptions in different stages of the calculations.

ENERGY EFFICIENCY OPERATIONAL INDICATOR EVALUATION

The IMO guidelines [10] define the methodology for the calculation of the Energy Efficiency Operational Indicator (EEOI) based on voyage parameters and the type of main engine fuel. EEOI is defined individually for cargo ships and bulk carriers in a wide deadweight range [11] but it can be calculated by the following equation [1]:

$$EEOI = \frac{\sum \boldsymbol{FC * Ccarbon}}{\sum \boldsymbol{mi * D}}, \frac{\boldsymbol{tCO_2}}{\boldsymbol{tnm}} \qquad (1)$$

where *Fc* is the specific fuel consumption (g/kWh), *Ccarbon* is the fuel mass to CO_2 mass conversion factor for fuel, *mi* is the cargo carried (t), and *D* is the distance in nautical miles to the cargo carried or work done (nm).

Proper evaluation of the retrofitting effect on the energy efficiency operational index has to calculate the fuel cost before and after retrofitting. Fuel cost is calculated by:

$$Fuel\ cost = FC * Vs * Cfuel * D, \$ \qquad (2)$$

where *Fc* is the specific fuel consumption (l/h), *Vs* is the ship service speed (kn), *Cfuel* is the fuel per $/l, and *D* is the distance in nautical miles to cargo carried or work done (nm).

WEIGHT OF SHIP HULL

The weight of the ship's hull is determined at the construction design stage and modernisation is based on working drawings and construction models. Mathematically, the weight can be explained by the followed expression:

$$W_{hull} = W_{main\ hull} + W_{BHD} + \cdots \ldots \ldots \ldots \ldots \ldots . Wi \qquad (3)$$

where *Wmain* hull is the weight of the ship's main hull (t), *WBHD* is the weight of transverse bulkheads in the ship's main hull (t), and *Wi* is all of the other constructions in the ship's hull (t).

MODERNISATION COST CALCULATION

Modernisation costs include the cost of billable hours for retrofitting and hull fabrication costs. The billable hours for fabricating and retrofitting parts of the ship's hull are calculated with the simple equation:

$$MH = W_{hull} * MH_{steel}, mh \quad (4)$$

where $Whull$ is the weight of the ship's hull (t) and $MHsteel$ are the billable hours per ton of steel construction (mh/t).

Hull fabrication costs closely depend on the steel price and the weight of modernised hull parts, see Eq. (5).

$$HFC = W_{hull} * Csteel, \$ \quad (5)$$

where HFC is the hull modernisation cost (\$), $Whull$ is the weight of the ship's hull (t), and $Csteel$ is the final steel price in the country (\$/t).

HULL MODELLING

The hull form was generated by PolyCAD software. To assess the effect of the modification of the ship's bow, the resistance was calculated using the Holtrop and Mennen method, for speeds ranging from 0-17 knots. The advantage of the software is the possibility of recalculating ship characteristics in the event of some form of change. After retrofitting, a small difference in mass displacement appeared.

MODEL VALIDATION AND VERIFICATION

In this type of analysis, it is important for the calculations to be within a range of 5% tolerance, which is assumed for engineering calculations. Otherwise, if there is more than 5% tolerance, the impact on the characteristics is significant. The retrofitting process consisted of modernising the forward ship hull's form without making changes to the ship's main dimensions.

The change in the geometry of the bow was achieved by mounting a bulb with a specific geometry that corresponds to the original ship's form. In this case, in order to ensure a constant displacement of water, changes were made to the coefficients of the shape, specifically the prismatic coefficient (Cp) and, consequently, the block coefficient (Cb). The coefficient of the mid-ship section remained the same for all shapes. Differences in Cb were within 2.5%, and differences in Cp were in the range 0.7-2.5%; higher differences in Cw coefficients were in the range 1.8-3.5%. The maximum difference in mass displacement was 0.46 t.

In the evaluation of the model shape, a mesh with rectangular and triangular elements was used. Each type of element was used in different areas of the ship's hull. For example, in the bow and stern regions where the hull shape has complex curvature in two directions, triangular mesh elements were used, while rectangular elements were used in the remaining areas. The transition elements between rectangular and triangular elements were rhomboidal. The grid spacing was 0.2 m with a key nudge of 0.002 m; the number of elements is shown in Fig. 1.

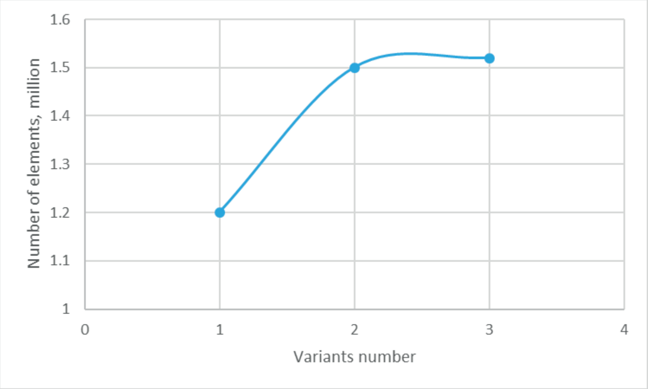

Fig. 1. Diagram of mesh independence

HULL FORM GENERATION

The main dimensions of the ship were L=120.62 m, B= 16.00 m, D= 9.03 m, and d= 6.67 m. The ship had a double bottom and double side, single deck and one hold, with a 116 TEU container capacity. The hold length was about 84.5m, with a double sided width of 1.3 m per side and a maximum hold breadth of 13.4 m. The service speed was 15 kn and the main engine type was a '5S35ME' with main engine power of 4350 kW. Three different forms with similar hull coefficients are shown in Table 1. The original hull form was without a bulbous bow (VAR1), while the other two had bulbous bows, where the dimensions of the bulb were different.

Tab. 1. Hull form coefficients

	VAR1	VAR2	VAR3
Cb	0.78	0.76	0.76
Cp	0.78	0.77	0.76
Cm	0.99	0.99	0.99
Cw	0.90	0.89	0.87
Δ, m^3	10518.34	10518.64	10518.80

The analysed ship was a general cargo ship with one hold of 7000 tDW. The location of the collision bulkhead was at 7% of Lpp, while the engine room bulkhead was at 23% Lpp, see Fig. 2 to Fig. 4.

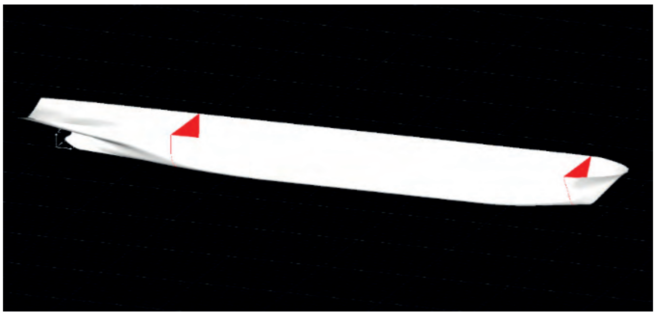

Fig. 2. Variant one (original hull form) without bulbous bow

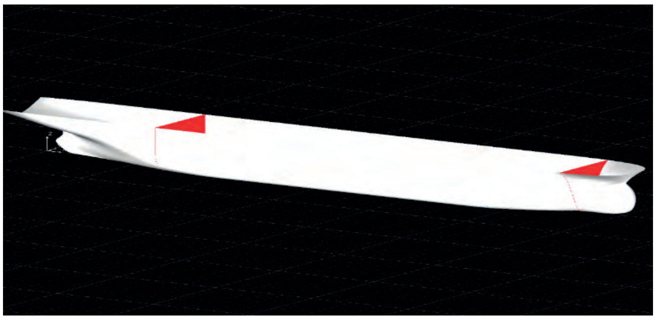

Fig. 3. Hull form variant VAR2 with bulbous bow

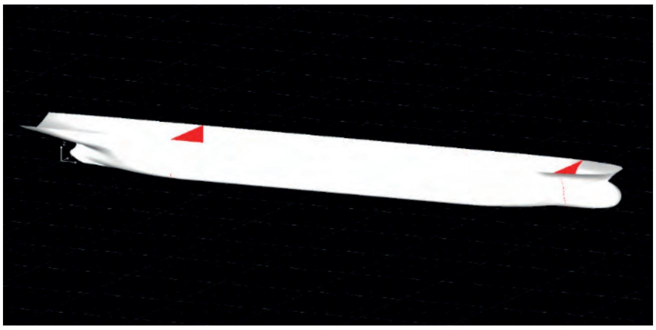

Fig. 4. Hull form variant VAR3 with modified bulbous bow

Retrofitting the forward part of the ship's hull with a bulbous bow decreases the total resistance by about 18% for a service speed of 15 knots (Fig. 5), decreasing the necessary main engine power and reducing carbon dioxide in the atmosphere.

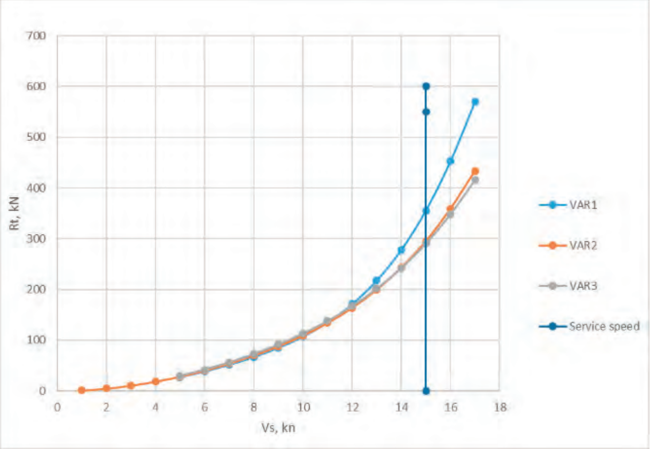

Fig. 5. Total resistance of ship hulls

After the established positive effect of the modification of the ship's bow, it was necessary to determine whether, and to what extent, it led to an improvement in the energy efficiency index of the ship, as well as the return on investment, in terms of resources and time invested in the modification for regular voyage distances.

VOYAGE PARAMETERS

Voyage parameters were selected in accordance with shipping trends and the transportation of goods between the Black Sea and Western European ports. The distance from the port of Varna to the port of Rotterdam is 3940 nm, as shown in Fig. 6.

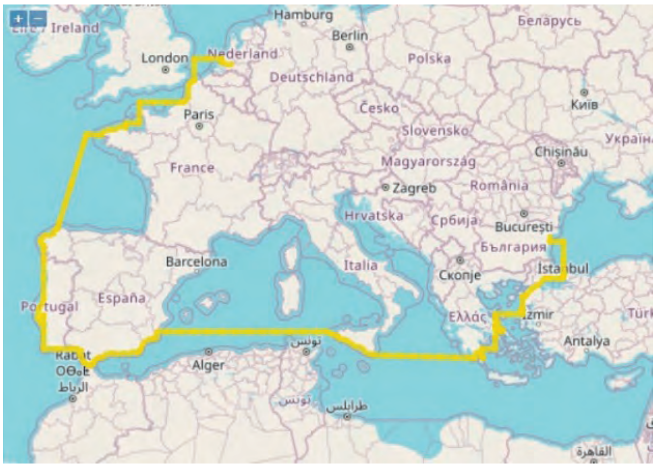

Fig. 6. Voyage distance map

The distance of 3940 nm was travelled in 11 days, at an operational speed of 15 kn in good weather conditions. The ship's main engine was a '5S35ME' type, with the specific fuel consumption and fuel costs shown in Fig. 7. The maximum consumption occurred with the first hull form, which is without a bulbous bow, and the minimum occurred with a modified bulbous bow.

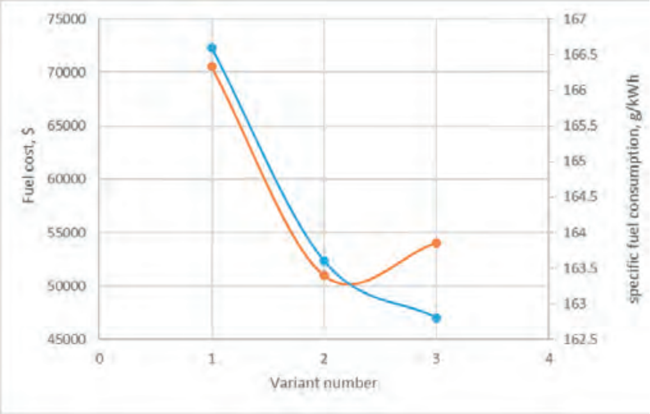

Fig. 7. Voyage fuel cost and specific fuel consumption

Considering the main engine-specific consumption, ship service speed, distance between ports, and marine diesel prices, the fuel cost for one voyage was calculated using the CEAS engine calculator (specific for different engine powers) and is presented in Fig. 6. Average marine diesel oil costs 0.42 €/liter, which corresponds to 546.5 $/mt of very low sulfur fuel oil (according to prices from July 19, 2023) [12].

Despite the fact that the specific fuel consumption for the second variant of the ship's hull form is the lowest, it does not result in the lowest overall fuel cost when evaluating the total fuel expenses. This is due to the fact that the difference in specific fuel consumption between the second and third variants is only 0.8 g/kWh in favor of the second one, which does not make a significant impact on the end result, as the resistance that needs to be overcome with the second hull form is higher than the third one.

ENERGY EFFICIENCY OPERATIONAL INDEX EVALUATION BASED ON VOYAGE PARAMETERS

EEOI is an indicator for evaluating ship energy efficiency and CO_2 emissions to the environment during a ship's operation and through her life cycle. Using the equation for EEOI offered in [10], for generated ship hulls, indexes are calculated considering voyage parameters and actual ship conditions. For a voyage from the port of Varna to the port of Rotterdam with a speed of 15 kn, a distance of about 3940 nm, a deadweight of about 7000 t, and a fuel carbon content of 0.86 for light fuel oil [13], the EEOI calculated by Eq. (1) is presented in Fig. 8.

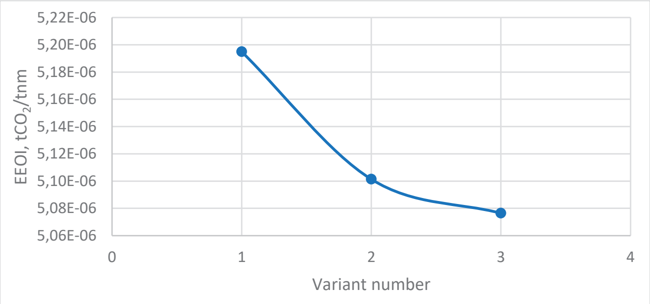

Fig. 8. Energy Efficiency Operational Index for hull forms

After retrofitting the forward part of the ship hull, EEOI is improved, which leads to a reduction of CO_2 emissions. The reduction measured (as a percentage) is about 4% for ship hull variant VAR2 and about 3% for hull variant VAR3. The retrofitting effect is not so high but, related to the ship dimensions, it is satisfactory.

CAPITAL EXPENDITURE FOR RETROFITTING AND RETURN COSTS

The effects of forward part retrofitting will be clearer after calculating capital expenditure, return costs, and time for return costs. To study this effect, it is necessary to calculate the hull steel weight, billable hours for its fabrication, and their differences for different forms. After production calculations, the return cost and time are calculated.

Ship steel hull weight estimation can be evaluated by the mathematical equations presented in [14] but they are not appropriate in this case, because hull weight is calculated in relation to weight displacement. In the case study, the volumetric and weight displacement are the same for all forms, and computer model development is used for hull weight evaluation. The results are shown in Table 2.

Tab. 2. Ship hull weights

	VAR1	VAR2	VAR3
WEIGHT HULL, T	835.1	852.0	894.0
Bulb area, m^2	0.00	10.30	9.03
Bulb length, m	0.00	2.00	3.00
Bulb radius, m	0.00	1.50	2.00

The difference in hull weights, after retrofitting, is about 17 t of steel construction for variant VAR2 and 59 t of steel construction for variant VAR3. Differences of such magnitude do not affect the ship's carrying capacity since, during the conceptual design stages, a 1% reserve displacement is provided; the results are shown in Fig. 9.

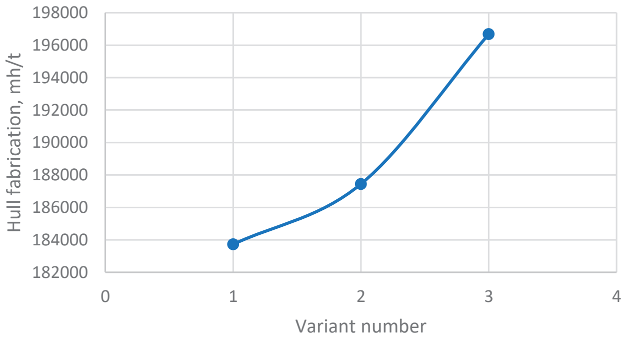

Fig. 9. Billable hours for steel hull fabrication

The thickness of hull plating in all variants is 16 mm, which, according to [15], is necessary for 220 mh per ton of steel construction. This means that, with increasing hull weight, the billable-hours for fabrication and costs increase too. The Chinese steel price is 500 $/t [16], while the USA steel price is 680 $/t [17]. The steel price in Bulgaria is about 450$/t. For the purpose of this study, the price of steel in Bulgaria is averaged to 600 $/t, including the cost of work, cost of transportation, cost of blasting and painting, and the cost of cutting in Bulgaria (Table 3).

Tab. 3. Hull cost for different variants

	VAR1	VAR2	VAR3
Hull Fabrication Cost, $	501,060	511,200	536,400

The difference in hull cost price between variant VAR2 and variant VAR1 (the original) is about $10,000, which is about €9000, and equal to about 41 t of very low sulphur fuel oil. For a voyage from the port of Varna to the port of Rotterdam, the fuel price is about €60,000, which means that, after forward hull part retrofitting and EEOI improvement, the return cost is very fast, i.e. after the second voyage after retrofitting.

CONCLUSIONS

This paper studied the possibilities and effects of retrofitting the forward part of a ship's hull designed without a bulbous bow. To evaluate these effects, three ship hull forms were developed. The original form was without a bulbous bow, while the other two had a bulbous bow.

Calculations of resistance and engine power were carried out using the Holtrop and Mennen method and the hull form was generated by PolyCAD software. In new form generation, the volumetric displacement of the original ship hull was preserved for the newly generated forms. There were small changes in the block and prismatic coefficients.

After forward hull part retrofitting, the total resistance was reduced by about 18%, which lead to a necessary engine power reduction. To study the numerical retrofitting effects, a ship voyage between the port of Varna and the port of Rotterdam was selected, with a distance of 3940 nm. The specific fuel consumption for all designed forms were found and it should be noted that variant VAR3 has a minimum specific fuel consumption, but the fuel cost for the voyage is not minimal because the necessary power is higher.

Hull shape variant VAR3 is optimal for EEOI but not optimal for retrofitting or building costs. The capex cost is about $35,000 higher than variant VAR1 (the original) and about $25,000 higher than variant VAR2. The difference in fuel cost between variant VAR3 and variant VAR2 is about $3800 per voyage, while the difference between VAR1 and VAR3 is $16,500, and between VAR1 and VAR2 it is about $20,000.

Retrofitting of the forward part of the ship hull is more reasonably carried out using variant VAR3, with a modified bulbous bow, so that the EEOI is at its lowest and approximately 35 t of very low sulphur fuel oil is saved. Capex costs are higher and equal to 64 t of very low sulphur fuel oil, which means that, after the second voyages, the capex cost will be returned.

DECLARATION OF COMPETING INTERESTS

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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