

Review

Investigating Fuel Reduction Methods Through Propeller Optimization on Coastal Ro-Ro Liner Vessels

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Abstract: In light of efforts to reduce GHG emissions, liner ship operators in coastal navigation are undertaking numerous activities to contribute to the reduction of fossil fuel consumption during the transitional period toward environmentally friendly propulsion systems without compromising their regular operations. Regular ship overhauls, which include removing fouling from the underwater part of the hull and optimizing propellers, also contribute to this goal and are the focus of this research. The ship propeller, as a key component of the propulsion system, plays a significant role in ensuring reliable, safe, and economical navigation. Proper selection and regular maintenance of the propeller are essential for achieving optimal performance. This paper presents the optimization of a fixed-pitch propeller according to the ISO 484/2 standard to Class I using Metrascan 3D technology. This technology enables a detailed analysis of the propeller geometry, identification of irregularities, correction, and adjustment to achieve better hydrodynamic characteristics. The pitch corrections of the propeller resulted in improved overall vessel performance and fuel consumption, as demonstrated by comparing the consumption before and after the optimization.

Keywords: fuel consumption (reduction); propeller optimization; Ro-Ro liner ships



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1. Introduction

The following article emerged in response to increasingly stringent European Union regulations aimed at reducing CO₂ emissions. As part of the effort to lower diesel fuel consumption and minimize the ecological footprint of maritime operations, this research provides concrete results and recommendations for optimizing ship propellers on Ro-Ro liner vessels engaged in coastal navigation. This study was conducted using real-world data in collaboration with the shipping company Jadrolinija and Adriatic Propeleri. The goal was to enhance the performance of ship propellers within Jadrolinija's fleet, focusing on reducing fuel consumption and improving energy efficiency.

Maritime transport, as one of the most common forms of transportation, is responsible for nearly 3% of global greenhouse gas emissions, making it the sixth-largest emitter of CO₂ worldwide [1]. The International Maritime Organization (IMO) has introduced strict regulations to reduce emissions and improve energy efficiency. The Energy Efficiency Design Index (EEDI) established by the IMO requires new ships to meet minimum energy efficiency standards. There are several measures to improve the energy efficiency of ships, including bow optimization [2], improved propeller distribution [3], innovative ship propulsion solutions [4], speed adjustments, and the use of renewable energy sources and alternative fuels. Operational systems, such as different propeller and rudder designs [5], are also being optimized. All of these measures have varying impacts on efficiency and require different levels of investment. This paper focuses on propeller optimization as a method for reducing fuel consumption, which requires a relatively low investment. The optimization can be carried out during the ship's regular overhaul without requiring additional time outside the regular sailing schedule.

This research represents a continuation of the pilot project “Increasing Propulsion Efficiency Through Propeller Optimization” from 2022, conducted by Adriatic Propeleri on a single propeller (PS2—left-handed propeller No. 2) as a demonstration example. The results of the optimization, considering that only 1/4 of the propulsion system was optimized, showed minimal but noticeable fuel savings. This is described in more detail in Section 2.2.

The purpose of this scientific article is to present our research findings, analyze them, and discuss their practical applications, as well as contribute to the development of sustainable solutions in shipping. We hope that the results of this research will provide valuable insights and guidance for future projects focused on improving energy efficiency and reducing the environmental impact of maritime operations.

Propeller optimization is a crucial element in the design of a ship’s propulsion system, as it directly impacts the vessel’s efficiency, performance, and economy. The propeller represents a vital component that converts the engine’s mechanical energy into the thrust force needed to propel the vessel through the water. Therefore, it is essential to understand the fundamentals of propeller optimization to achieve the desired vessel performance.

One of the key factors in propeller optimization is its geometry, including the number and shape of the blades, as well as the length and diameter of the propeller. Additionally, it is important to consider the characteristics of the engine, such as power, torque, and rotational speed, to ensure that the propeller operates within an optimal load range.

The goal of propeller optimization is to achieve maximum thrust force with minimal fuel consumption. This is accomplished by properly balancing the propeller’s rotational speed and pitch to achieve an optimal speed-to-thrust ratio. A pitch that is too short can result in an excessive engine load and reduced efficiency, while a pitch that is too long may lead to insufficient thrust and increased fuel consumption.

It is also important to consider hydrodynamic effects such as cavitation and turbulence when optimizing the propeller. Cavitation occurs when the water pressure drops below the vapor pressure, which can result in propeller damage and reduced efficiency. Therefore, it is crucial to ensure that the propeller design minimizes the risk of cavitation.

The main goal of optimizing ship propellers is to achieve maximum propulsion efficiency. Increased propeller efficiency directly reduces fuel consumption, contributing to lower operational costs. Given the continuous rise in oil prices, strict regulations regarding air pollution, and the limitation of NO_x and SO_x emissions, shipowners are increasingly investing in efforts to develop more efficient propellers [6]. At the same time, to avoid issues with vibration and noise in the ship’s hull, it is important to minimize cavitation, although it is a common occurrence with most propellers. Cavitation occurs when local pressure drops below the vapor pressure of the liquid at a given temperature. Propeller blades are subjected to local lift forces that can cause a pressure drop. When the surrounding water pressure falls below the vapor pressure, bubbles or cavities form. Due to the specific geometry and rotational conditions under which ship propellers operate, cavitation is almost inevitable. The occurrence of cavitation can cause serious safety issues, increase maintenance and repair costs, and lead to additional hydrodynamic energy losses [7]. However, it is possible to influence the occurrence of cavitation during propeller design, while optimization can only have a limited effect on it [7].

Advanced techniques such as computer simulation and modeling are also used in propeller optimization. The computational tools include software for processing data obtained through scanning with the Creaform—Metrascan 3D device [8], where the data are processed (graphically and in tables) using the GOM Inspect Suite 2020 tool [9]. The choice of tools is at the discretion of the optimizer [10]. Other authors [11,12] who researched propeller optimization used the Prop Scan system for propeller testing and diagnostics. The software processes the data and displays the shape of the propeller blade in both linear and bar charts. It detects defects or abnormalities on the propeller surfaces. Minor damage or abnormalities can significantly impact propeller performance, causing vibrations, lower fuel efficiency, and inefficient ship handling. After diagnostics, some modifications to

the propeller are necessary, specifically pitch correction, by the basic framework of the new propeller blade design (linear diagram). Pitch correction is carried out mechanically (using hammers of various sizes and weights, hydraulic presses, clamps, and chains) and through heating, argon welding, grinding, balancing, and finishing. These corrections ensure consistent pitch values at the same measurement points on each propeller blade. Such a propeller operates uniformly and smoothly, without slippage or vibrations, which is the essence of propeller optimization.

Finally, it is important to note that propeller optimization does not end with design. Regular maintenance and proper adjustment of the propeller are essential to maintaining its efficiency and extending its service life. Therefore, regular inspections and servicing of the propeller are crucial to ensuring its optimal functioning throughout the vessel's lifespan.

2. Why Conduct Propeller Optimization?

Shipowners engaged in coastal liner transport of passengers and vehicles often encounter the opportunity to optimize the propellers on their Ro-Ro vessels during regular maintenance at repair shipyards. The optional nature of this procedure, which involves certain costs, has often been avoided due to the relatively small fuel savings that result from propeller optimization. Regular maintenance of Ro-Ro vessels is typically associated with connecting the mainland to nearby or somewhat distant islands, where the regularity and punctuality of transportation are of primary importance. Since these services generally occur over relatively short distances and in favorable weather conditions for most of the year, greater attention has traditionally been given to cleaning fouling from the ship's hull, with propeller optimization being carried out only in exceptional cases (such as replacement after a breakdown) [13].

As the era of cheap and readily available Fossil Fuels Gasoil (D2) [14] wanes, unnecessary fuel consumption is increasingly viewed as pollution due to GHG emissions, prompting more consideration of ways to reduce it. One option available to shipowners in this context is the process of propeller optimization, which enhances the efficiency of the energy used for vessel propulsion [15].

The connection between propeller optimization and alternative energy sources as a means of propulsion in terms of reducing GHG emissions was explored by [12], analyzing cost efficiency by comparing the conversion of existing ships to solar power, wind-powered ships, and propeller optimization. Their SWOT analysis highlighted numerous advantages of solar power plants and wind energy compared to propeller optimization from the perspective of GHG emissions, but it also pointed out significant drawbacks such as dependence on solar insolation and wind conditions, as well as high initial investments in ship conversions. On the other hand, when comparing alternative fuels like methanol, LNG, or hydrogen, propeller optimization as a propulsor will further reduce GHG emissions.

This study will present the optimization of four four-blade propellers on a Ro-Ro passenger ship that operates a route of 4 nautical miles, with a duration of approximately 12 min. The service frequency is seasonal, ranging from 16 to 20 departures in the summer months, while in the winter period, the frequency is between 10 and 12 departures. During the peak season, vehicle and passenger loading takes up to 15 min, while unloading is completed in 5 to 7 min. During loading and unloading, the ship's propulsion system operates at minimum power to keep the vessel in a position suitable for loading/unloading. All of this is dependent on numerous additional factors, such as wind strength, sea conditions, waiting for a free berth, or delays due to VIP transport.

Propeller optimization aims to improve the efficiency of existing systems on ships, resulting in lower fuel consumption and emissions. This paper presents a case study of propeller optimization on Ro-Ro passenger ships. This research examined data from sea trials conducted before and after propeller optimization to gain insights into fuel consumption. Furthermore, the results of this case study are aligned with the regulatory and policy frameworks governing maritime operations, highlighting its importance in meeting environmental standards. The proven effectiveness of propeller modification in

reducing CO₂ emissions aligns with the primary goals of international agreements, such as the IMO regulations on greenhouse gas emissions for ships.

Propeller optimization is one of several methods that hold promise for developing sustainable practices in the maritime industry. The combination of alternative fuels or electric (battery) propulsion with propeller optimization has the potential to achieve even more significant results.

Future research will explore the effects of various parameters that contribute to optimal energy resource management, with the aim of reducing harmful gas emissions and increasing energy efficiency.

Therefore, it is nearly impossible to calculate the exact fuel consumption per trip, so approximate average values are used, which should not significantly affect the calculation of fuel consumption before and after propeller optimization.

2.1. Propeller Efficiency Losses

Engineers encounter the efficiency of a machine or process, quantified numerically as the degree of effectiveness, on a daily basis. This property is not only associated with economic benefits, which are often the most important, but it also affects some additional characteristics of the observed vessel. For example, for a warship, a high value of the propeller efficiency (η_P) allows for a reduction in the required power of the main engine and, consequently, the weight of the propulsion system, which permits an increase in the ship's operational range or the loading of additional useful cargo and equipment [16].

On a Ro-Ro ship, a high propeller efficiency (η_P) also means a less expensive main engine and—especially important given the heightened sensitivity to environmental protection—a reduction in exhaust gas emissions [17]. For a liner Ro-Ro ship with short coastal voyages, profitability is crucial to achieving the highest possible earnings. Among many diverse factors, reducing the ship's operating costs plays a very important role. These costs depend not only on the propeller's efficiency but also on the main engine. Since the main engine and the propeller are interdependent, greater economic efficiency can only be achieved if these two elements of the ship's propulsion system are optimized. However, when selecting this system, it is also important to consider the other components of the ship as a global, integrated system [18]. The fixed costs of a ship in service, due to the significant reduction in crew size thanks to automation, have been minimized to safety limits, making fuel costs more prominent. Regardless of the constant fluctuations in fuel prices, it is essential to reduce fuel consumption on board, not only to save money but also to protect the environment from pollution. Fuel savings are achieved through improvements in the thermodynamic process and the design of propulsion engines, as well as by enhancing the hydrodynamic properties of the ship (resistance, propulsor efficiency, interaction between the hull, propulsor, and rudder, etc.), and by striving to make the best possible use of the heat generated by fuel combustion [19].

2.2. Propeller Optimization Process

Ro-Ro passenger ships in coastal navigation operate under the extremely seasonal conditions typical of tourist-oriented countries, where in the summer months, a large number of vehicles and passengers need to be transported to the islands, demanding extra effort from both the ships and their crews. In contrast, during the winter months, they provide only the essential service of connecting the island population with the mainland and vice versa. Therefore, the off-season period is used for the routine maintenance of ship equipment, engines, hull cleaning, and any necessary repairs. Table 1 presents basic data on the m/v Cres, which, during the observed period, was providing regular service on the Prizna–Žigljen route and vice versa.

Table 1. Ship particulars [20].

Main Technical Data		Machinery	
Length between perpendiculars, Lpp (m):	80	Type and number of main propulsion engines:	Diesel, four stroke, single acting, 4
Length overall, Loa (m):	87.6	Builder:	VOLVO PENTA A/B
Breadth (m):	17.5	Licensee and type:	VOLVO PENTA 165A
Depth (m):	3.7	Total power output (kW):	1.616
Draught (mm):	2.400	Number and type of propellers:	4, Fixed blade
Freeboard (m):	75.85	Number and total power of generators (kW):	3.444
Freeboard (mm):	1.312		
TMC 69 gross tonnage, GT:	2.474		
TMC 69 net tonnage, NT:	781		
Speed (kn):	11.5		

2.2.1. Accuracy Classes

The accuracy class is selected by the client commissioning the optimization. The indications in the table serve as guidelines for this choice (Table 2).

Table 2. Accuracy Classes [21].

Class	Manufacturing Accuracy			
S	Very high accuracy			
I	High accuracy			
II	Medium accuracy			
III	Wide tolerances			
Designation of pitch	Class			
	S	I	II	III
(a) Local pitch with a minimum of	±1.5%; ±10 mm	±2%; ±15 mm	±3%; ±20 mm	—
(b) Mean pitch per radius of each blade with a minimum of	±1%; ±7.5 mm	±1.5%; ±10 mm	±2%; ±15 mm	±5%; ±25 mm
(c) Mean pitch per blade with a minimum of	±0.75%; ±5 mm	±1%; ±7.5 mm	±1.5%; ±10 mm	±4%; ±20 mm
(d) Mean pitch for propeller with a minimum of	±0.5%; ±4 mm	±0.75%; ±5 mm	±1%; ±7.5 mm	±3%; ±15 mm

The planned work on propeller optimization was carried out in a dry dock during the vessel's regular overhaul. The work consisted of:

- Propeller optimization according to the ISO 484/2 standard [21] to Class I;
- Propeller balancing;
- Inspection for potential cracks using penetrant testing;
- Grinding and polishing of the propeller blades.

As stated in Table 1, the ship had 4 propellers, 1350 mm in diameter × 1065 mm pitch, with 4 blades made of NiBrAl CU3 material (Brodosplit Shipyard, Split, Croatia). The propellers needed to be optimized to Class “S”, meaning that the pitches and thicknesses of the sections were brought within the tolerances for Class “S”, thereby reducing vibrations in the propulsion system and, consequently, reducing fuel consumption.

2.2.2. Propeller Blade Optimization

For the optimization of the propeller blade as a standalone component, the propeller's geometry was defined by [22]:

- Propeller diameter;
- Rotational speed;
- Pitch height;
- Chord length.

The gradients were based on spline curves, with the bases defined by parameters. Moreover, adjustments to the propeller's rotational speed were allowed. The required thrust could still be achieved even with a lower area ratio (A_E/A_0) relative to a constant diameter (D) by varying the pitch ratio (P/D), chord length (C), and propeller rotational speed (n). Altogether, the optimization algorithm adjusted nine parameters and provided them to the simulation tool, indicating the decision space had nine dimensions. The goal of this optimization was to maximize propeller efficiency (η) while maintaining the required thrust (T_{req}) with an allowable deviation of no more than 4%.

The following images and tabular comparisons illustrate the optimization process for one of the four propellers (the left-handed propeller of the No. 1 propulsion engine PS1). The process is the same for all other propellers, and therefore, they are not presented separately in this study.

The propeller was scanned using the optical Metrascan 3D, designed for performing highly precise and repeatable metrological measurements and 3D geometric surface inspections [8].

3D scanning is an optical measurement method that uses a laser to create a mesh of the measured object, which is then compared to the nominal CAD file. 3D scanning with the Metrascan device (Creaform/Ametek, AMETEK, Leinfelden-Echterdingen Germany) shows excellent results when scanning propeller blades, as most of the measured points fall within the specification according to the ISO 484 standard [23]. It operates on the principle of a 3D camera and laser sensors. Based on the 3D camera's range and the optimal distance of the laser sensor, the scanning path of the inclined ship propeller blade is planned with a resolution of 0.1 mm [24]. The advantage of this scanning method is the visualization, which uses a color spectrum to indicate necessary adjustments to the blades for optimization purposes (Figure 1).

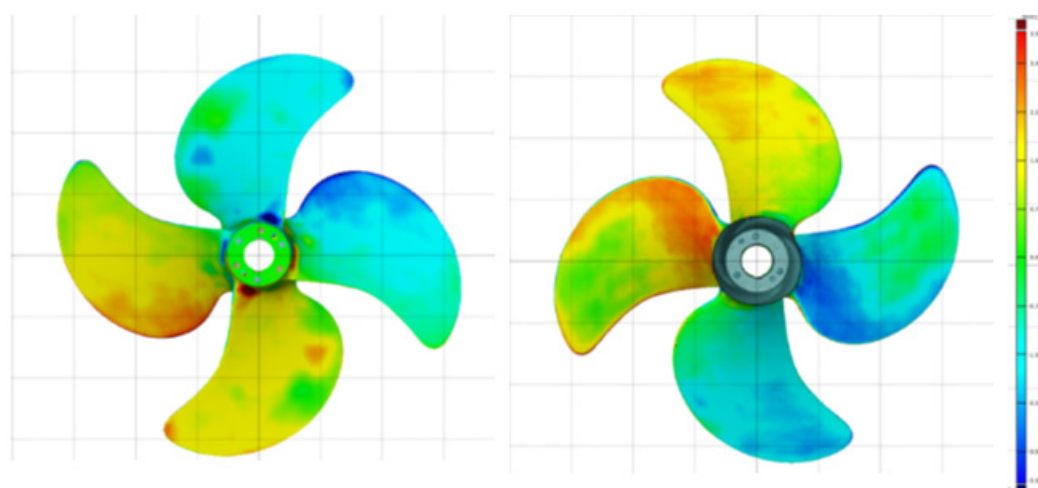


Figure 1. 3D view of the comparison between the front and back of the propeller after a 180-degree rotation [8].

In Figure 1, a comparison of the front (left) and back (right) of the four-blade left-handed propeller No. 1 is shown, with dimensions $D = 1350 \text{ mm} \times P = 1056 \text{ mm}$. The colors visually indicate imperfections and highlight the areas requiring corrections. The

color spectrum ranges from cool blue (−3.5 mm) to red (+3.50 mm), with values indicated on the spectrogram in the image (right) [8].

Figure 2 shows the comparison of Blade No. 1 with the other blades of the propeller. The colors suggest the necessary corrections according to the spectrogram.

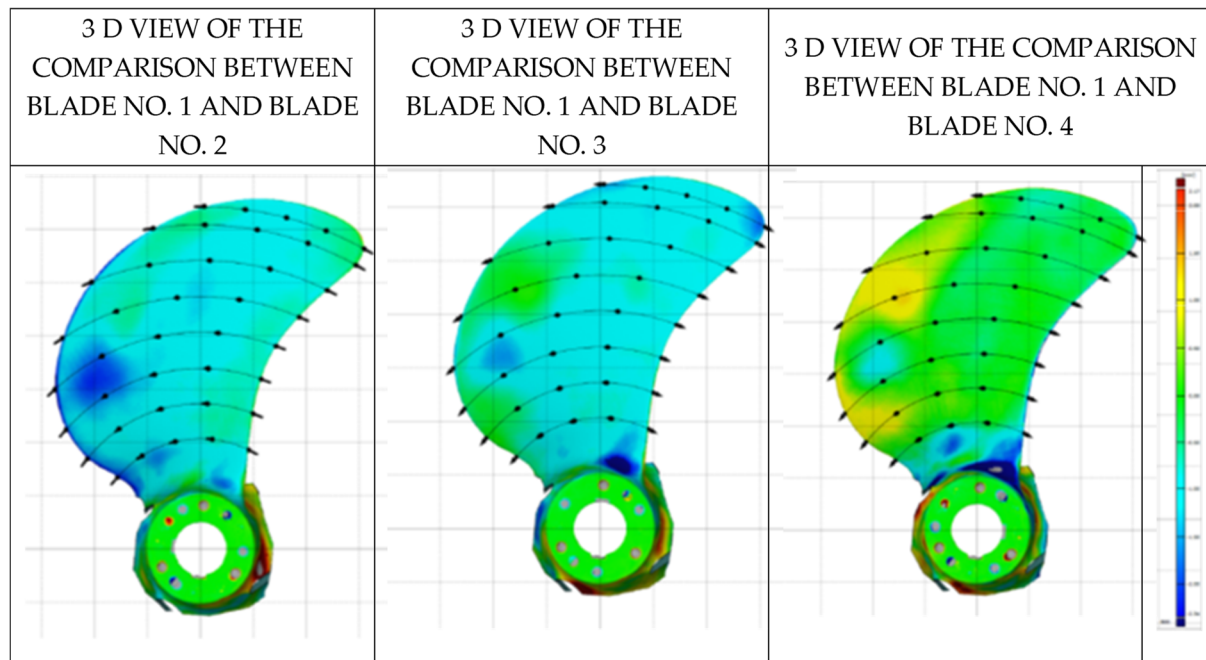


Figure 2. 3D view of the comparison between Blade No. 1 and Blade Nos. 2, 3, and 4 [8].

The following table shows the comparison of the wings of the first and second screws. Analogously, a tabular representation of the comparison of wing 3 and wing 4 with the first wing is done as well as a comparison of all four screws, which is not presented due to the reduction of this article's space.

The allowable tolerances for accuracy Class “S” are shown as yellow dashed rectangles representing the tolerance ranges for the initial and final testing, and are as follows:

- $\pm 1.5\%$ for deviation;
- -1.5% for differential;
- $\pm 2.3\%$ for the sum.

Table 3 presents the comparative measurement results of Blades 1 and 2. The measured values of 46 points are displayed. The deviations cause inaccuracies from the optimal pitch. Positive deviation values indicate a depression on the blade face surface, while negative values indicate a ridge on the blade face surface relative to the optimal pitch line. The depression is positive because, during pitch correction, the blade face surface must rise toward the optimal pitch line, while the ridge is negative because the blade face surface must fall during pitch correction. Considering the values of the depressions and ridges, the shape and appearance of the blade face cross-section were irregular, which lead to irregular propeller operation. This reduced propeller efficiency and could cause vibrations, along with the other issues already mentioned.

The red sections are intended for physical finishing, which achieves the set goals through optimization, i.e., to reach the ISO “S” standard.

Table 3. Tabular comparison of the pitch and section lengths of Blade 1 and Blade 2 [10].

ELEMENT	CHEK	DEV	OUT	TOL−	NOMINAL	ACTUAL	TOL+
Section Length 95		4.16		−7.00	358.56	362.72	7.00
Section Length 9		−3.14		−7.00	425.24	422.10	7.00
Section Length 8		−1.26		−7.00	485.56	483.81	7.00
Section Length 7		−5.28		−7.00	496.67	491.39	7.00
Section Length 6		0.02		−7.00	482.56	482.58	7.00
Section Length 5		0.12		−7.00	449.62	449.50	7.00
Section Length 4		−0.36		−7.00	402.80	402.45	7.00
Section Length 3		−1.57		−7.00	340.79	339.22	7.00
95 Section 95		−0.91		−1.30	86.80	85.89	1.30
95-4		−0.24		−0.31	2.99	2.75	0.31
95-3		0.31		−0.32	21.06	21.37	0.32
95-2		−0.32		−0.33	22.00	31.68	0.33
95-1		−0.66	−0.32	−0.34	22.75	22.09	0.34
9 Section 9		−0.70		−1.50	109.24	108.54	1.50
9-4		−0.14		−0.39	25.95	25.81	0.39
9-3		0.15		−0.40	26.87	27.01	0.40
9-2		−0.66	−0.24	−0.42	28.00	27.35	0.42
9-1		−0.05		−0.43	28.43	28.38	0.43
8 Section 8		−1.50	0.00	−1.50	140.84	139.34	1.50
8-4		−0.40		−0.51	33.82	33.42	0.51
8-3		0.01		−0.52	34.98	35.04	0.52
8-2		−0.96	−0.42	−0.54	36.15	35.18	0.54
8-1		−0.20		−0.54	35.90	35.70	0.54
7 Section 7		−1.14		−1.50	167.68	166.54	1.50
7-4		−0.47		−0.61	40.65	40.17	0.61
7-3		0.17		−0.61	40.60	40.76	0.61
7-2		−1.40	−0.76	−0.64	42.86	51.46	0.64
7-1		0.56		−0.65	43.57	44.14	0.65
6 Section 6		−1.45		−1.50	181.61	180.16	1.50
6-4		−0.62		−0.66	43.82	43.20	0.66
6-3		−0.13		−0.66	43.88	43.76	0.66
6-2		0.40		−0.69	45.81	46.21	0.69
6-1		−1.10	−0.38	−0.72	48.10	47.00	0.72
5 Section 5		−1.37		−1.50	195.23	193.87	1.50
5-4		−0.38		−0.71	47.54	47.16	0.71
5-3		−0.23		−0.71	47.25	47.02	0.71
5-2		0.25		−0.74	49.29	49.54	0.74
5-1		−1.01	−0.25	−0.77	51.15	50.13	0.77

Table 3. Cont.

ELEMENT	CHEK	DEV	OUT	TOL−	NOMINAL	ACTUAL	TOL+
4 Section 4		−1.37		−1.50	207.60	206.24	1.50
4-4		−0.70		−0.74	49.60	48.91	0.74
4-3		−0.26		−0.76	50.47	50.21	0.76
4-2		−0.47		−0.79	52.52	52.05	0.79
4-1		0.06		−0.83	55.02	55.08	0.83
3-3		0.48		−0.74	49.41	49.89	0.74
3-2		−0.42		−0.79	52.62	52.20	0.79
3-1		0.05		−0.83	55.44	55.19	0.83

3. Correlation Between Fuel Consumption and Propeller Optimization

The basis for investigating fuel consumption concerning propeller optimization can be found in the study using the example of a fishing vessel [11]. The results of their study showed a minimal fuel savings of only 1.32%, but the fishing vessel gained speed at the same engine RPM, increasing by 9.72% from 7.2 knots to 7.9 knots in free sailing, and a significant 21.74% increase from 2.3 knots to 2.8 knots in towing (trawling). The most significant contribution of the optimization was that once successfully implemented, it was sufficient for the next 10 years, making it cost-effective in the long term, with the researchers noting that engine vibrations were reduced to a minimum [11].

The observed example of a Ro-Ro ship with four engines and four propellers presented a more complex study, considering that the ship spent most of its time in free sailing due to the specific task of connecting the island with the mainland over a relatively short distance, but also a significant portion of time in maneuvering, as illustrated in the following table.

3.1. Research Methodology

The following section presents the complex methodological and technological procedure of propeller optimization using the example of the motor Ro-Ro ship *Cres*, owned by Jadrolinija, performed by the company Adriatic Propeleri, Bibinje, Croatia. The process included initial and final testing with a comparison of the most important geometric characteristics of the propellers. This research was conducted in short coastal navigation on a route with small variations in sea temperature and minimal current influence. The navigation occurred in a NE–SW direction and vice versa, over a distance of 4 NM, with the effects of sea currents and wind neutralized. The propeller optimization was carried out by equalizing the pitch values. Subsequently, the fuel consumption per operating hour was analyzed before the propeller optimization, after the optimization of the left-handed propeller No. 2, and after the optimization of the remaining three propellers.

The aim of this research was to optimize the ship's propeller system on the Ro-Ro vessel *Cres* to reduce the fuel consumption and improve propulsion efficiency. The optimization process involved several phases: detailed 3D scanning of the propeller geometry, mechanical corrections of the blade pitch and thickness, balancing, and final testing under real sailing conditions. Each phase played a crucial role in enhancing the vessel's performance and achieving significant fuel savings.

Step 1: 3D scanning of the propellers

Initially, Metrascan 3D technology was employed to conduct precise scanning of the geometry of all four propellers. This technology enabled a detailed analysis of the propeller's geometrical characteristics, including the pitch and blade thickness. The scanning revealed deviations in pitch and blade thickness, ranging from −3.5 mm to +3.5 mm, as illustrated in the spectral color analysis in Figure 1. The blue areas indicated depressions on the propeller surface (negative deviations), while the red areas represented protruding sections above the optimal geometry (positive deviations). These deviations significantly

impacted the hydrodynamic efficiency by increasing water resistance and reducing propulsion effectiveness.

Based on the collected data, the engineering team was able to precisely identify the areas requiring correction to achieve the optimal geometry that would contribute to fuel savings.

Step 2: Pitch correction and propeller geometry optimization

Following the analysis of the 3D scanning data, mechanical pitch corrections were performed to reduce the deviations from ± 3.5 mm to within the tolerances of ± 1.5 mm, as specified by the ISO 484/2 standard for propulsion systems. The correction process involved the use of hydraulic presses, hammers of various sizes, precise grinding, and balancing of the blades. The goal of the correction was to ensure a consistent pitch across all the blades, thereby improving the conversion of engine mechanical energy into thrust with minimal losses.

The corrections also included heating specific areas of the propeller to ensure material homogeneity after the mechanical interventions, as well as argon welding where deeper irregularities were identified. Through the balancing process, the propeller's stability was ensured, reducing vibrations to a minimum. Minimizing vibrations not only enhances operational comfort but also extends the lifespan of critical system components and reduces maintenance costs.

Step 3: Balancing and penetrant testing

After completing the pitch and geometry corrections, all the propellers underwent balancing to ensure operational stability at various engine speeds. Balancing is crucial for minimizing vibrations and achieving maximum propeller efficiency with reduced fuel consumption. In addition to balancing, penetrant testing was conducted to detect potential cracks or other structural imperfections on the blades. This testing ensured the long-term durability and safety of the optimized propellers.

Step 4: Testing under real sailing conditions

Upon completion of all the mechanical corrections and balancing, the ship returned to service, and the optimized propellers were tested under real sailing conditions on the Prizna–Žigljen route. The testing was conducted during the vessel's regular operations, measuring key parameters such as vessel speed, fuel consumption, and vibration levels of the propulsion system. This route was selected due to its relatively stable maritime and weather conditions, allowing for consistent evaluation of the optimized propeller performance.

After the optimization of all four propellers, the fuel consumption was reduced by 8.56%. This reduction was a result of the improved hydrodynamic efficiency of the propellers, achieved through precise pitch corrections and reduced vibrations in the propulsion system. Vibrations were decreased by a significant percentage, further enhancing the vessel's overall operational efficiency and reducing the impact on the system components.

The general operational data of the ship's engines are presented in Table 4.

Table 4. Data on the operation of the ship's propulsion system [25].

	2021	2022	2023	2024 *
Hours of Ship in Navigation	342.95	1348.77	1382.00	329.77
Hours of Ship in Maneuvering	117.47	495.97	438.33	121.20
Hours of Ship in Port	2083.58	6078.27	5827.42	1589.03
Hours of Ship in Overhaul	0.00	837.00	1174.00	0.00
Hours of Delay in Navigation	0.00	0.00	0.00	0.00
Total Hours	8760.00	8760.00	8760.00	2040.00
Total Distance Covered in Navigation (NM)	2634.80	10527.00	9555.70	2541.80
Total Distance Covered in Maneuvering (NM)	352.40	1442.20	1306.90	361.20
Average Speed of Ship in Navigation (knots)	7.96	7.82	8.04	7.71
Average Fuel Consumption of 1 GM in Navigation (liters/hour)	32.88	29.99	31.58	29.93

* means that this data is estimated.

The table shows a reduced number of engine operating hours in 2021 due to decreased demand for sailing as a result of the COVID-19 crisis [25].

Fuel consumption per engine (PS1, PS2, PS3, PS4) and their total consumption, analyzed as the consumption of the main engine (GM) on a monthly basis, was examined for the period from January 2022 to February 2024. During this period, the ship underwent two overhauls: in April 2022, when the fouling was cleaned from the hull in preparation for the season, and the propeller on PS2 (left-handed propeller No. 2) was optimized; and in April 2023, when, in addition to the overhaul work and preparing the ship for the season, the fouling was cleaned from the hull and the propellers on PS1, PS3, and PS4 were optimized, specifically, the left-handed propeller No. 1, the right-handed propeller No. 1, and the right-handed propeller No. 2. This completed the optimization of all four propellers. According to the optimization contractor, Adriatic Propeleri, the optimization warranty is valid for 10 years, meaning that no further interventions on the propellers (except for removing fouling) are expected over the next decade. Experience suggests a fuel consumption reduction of at least 1.5% under the same sailing conditions (maneuvering + free sailing).

In the first phase, monthly fuel consumption per operating hour was analyzed for the period from January 2022 to May 2023, as presented in Table 5 and the corresponding Chart 1.

Table 5. Average monthly fuel consumption in l/h before and after the 2022 overhaul [25].

Month	PS1	PS2	PS3	PS4	GM
22 January	279.83	300.14	279.42	303.43	290.70
22 February	282.68	303.20	282.27	306.52	293.67
22 March	285.54	306.26	285.12	309.62	296.64
22 April	Overhaul, Cleaning of Fouling, and Optimization of Left-Handed Propeller NO. 2 (PS2) to "S" Standard				
22 May	256.98	255.73	256.61	278.66	262.00
22 June	259.84	258.79	259.46	281.75	264.96
22 July	262.69	261.86	262.31	284.85	267.93
22 August	264.12	263.39	263.74	286.40	269.41
22 September	265.55	264.92	265.17	287.94	270.89
22 October	268.41	267.98	268.02	291.04	273.86
22 November	269.83	269.51	269.44	292.59	275.34
22 December	274.12	274.11	273.72	297.23	279.79
23 January	279.26	279.62	278.85	302.81	285.13
23 February	281.17	281.68	280.77	304.89	287.13
23 March	285.10	285.88	284.68	309.14	291.20
23 April	Overhaul, Cleaning of Fouling, and Optimization of 3 Propellers on PS1, PS3, and PS4				

The dynamics of the average monthly fuel consumption in l/h between the two overhauls are presented using a color spectrum, from lower to higher values. The expected reduction in average monthly fuel consumption was achieved in line with the predictions of Adria Propeller, showing a 0.6% decrease for PS2, while the overall propulsion system saw a slightly smaller reduction of 0.4%. This is visually represented in the following graph.

The second phase began in May 2023 after the removal of fouling and the optimization of all the propellers. The analysis of the average monthly fuel consumption values in l/h for the period from May 2023 to March 2024 followed, as presented in the Table 6 and the corresponding Chart 2.

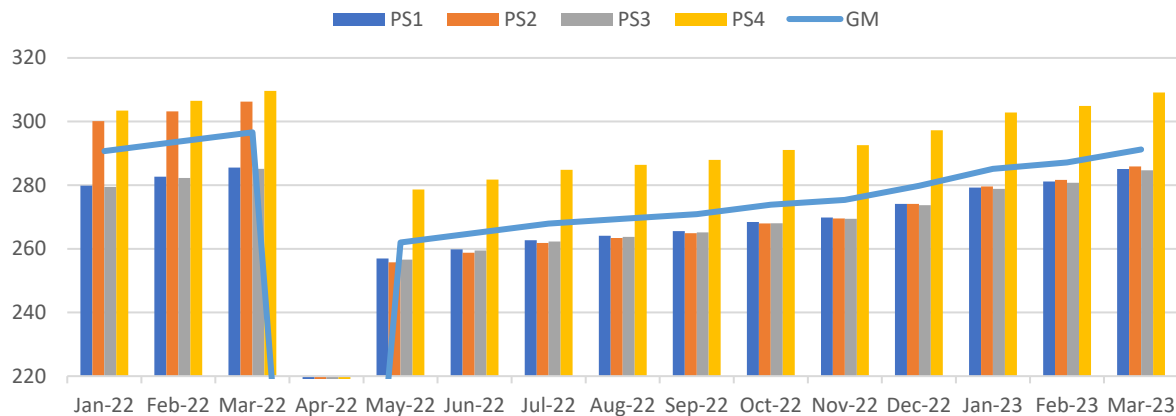


Chart 1. Comparative display of monthly fuel consumption before and after the 2022 overhaul.

Table 6. Average monthly fuel consumption in l/h after the 2023 overhaul [25].

Month	PS1	PS2	PS3	PS4	GM
May-23	245.32	245.92	245.58	247.02	245.96
Jun-23	247.77	248.38	248.04	249.49	248.42
Jul-23	250.23	250.84	250.49	251.96	250.88
Aug-23	252.68	253.30	252.95	254.43	253.34
Sep-23	255.13	255.76	255.40	256.90	255.80
Oct-23	257.59	258.22	257.86	259.37	258.26
Nov-23	258.81	259.45	259.09	260.61	259.49
Dec-23	260.04	260.68	260.31	261.84	260.72
Jan-24	261.27	261.90	261.54	263.08	261.95
Feb-24	262.49	263.13	262.77	264.31	263.18
Mar-24	263.72	264.36	264.00	265.55	264.41

The dynamics of the average monthly fuel consumption in l/h after the 2023 overhaul are presented using a color spectrum, from lower to higher values. The expected reduction in the average monthly fuel consumption was achieved in line with the predictions of Adria Propeller, showing a 0.6% decrease for each PS, which was reflected in the overall average monthly fuel consumption in l/h. This is visually represented in Chart 2.

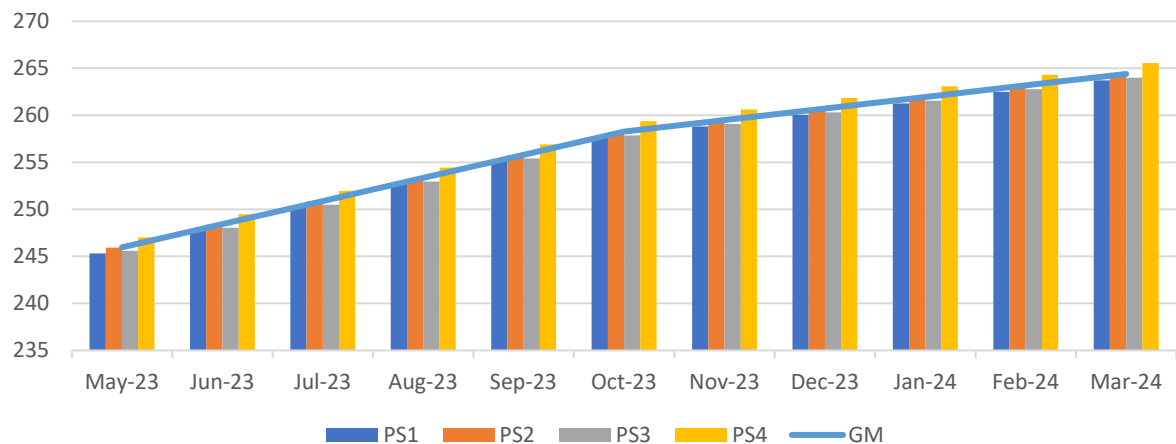


Chart 2. Comparative display of monthly fuel consumption before and after the 2023 overhaul.

The last three months before the overhaul were taken for comparison (Table 7).

Table 7. Comparison of average quarterly fuel consumption in l/h before the overhaul.

	PS1	PS2	PS3	PS4	GM	INDEKS 23*/22*	INDEKS 24*/23*	INDEKS 24*/22*
2022 *	282.68	303.20	282.27	306.52	293.67	GM 98.01	GM 91.44	GM 89.62
2023 *	281.84	282.39	281.43	305.61	287.82			
2024 *	262.49	263.13	262.77	264.31	263.18			

* Refers to the first quarter of the current year (before the overhaul). Source: data from Tables 4 and 5.

3.2. Results

The average monthly fuel consumption in l/h is an indicator that can be used to compare the effects of removing fouling from the underwater part of the ship and the conducted propeller optimization. This indicator is only acceptable for analysis if, as in the analyzed case, the vessel operates on a consistent route over a relatively long period. Two periods of 11 months each were observed after fouling removal and propeller optimization. In the first optimization phase, in April 2022, only one propeller driven by the PS2 engine (left-handed propeller No. 2) was optimized. In the next overhaul, in April 2023, the second phase of optimization was conducted, during which the propellers driven by the PS1, PS3, and PS4 engines were optimized, specifically, the left-handed propeller No. 1 and the right-handed propellers No. 3 and No. 4.

The correlation between the propeller optimization and average fuel consumption was examined by taking the average quarterly fuel consumption [l/h] before any interventions on the propellers (2022*) as the initial reference value. The effect of the propeller optimization cannot be immediately discerned after fouling removal, as the fuel consumption naturally decreased, so the period was monitored until this reduction was neutralized.

The effect of the first phase of optimization, expressed as the index 2023*/2022*, is 98.01, indicating that the optimization of propeller No. 2 on the PS2 engine led to an overall reduction in average quarterly fuel consumption [l/h] of nearly 2%. This is a significant saving, considering that the ship typically consumes around 170,000 L of fuel per month, depending on the season, during maneuvering and free sailing.

The second phase of optimization resulted in an even greater cost savings, with the index 2024*/2023* at 91.44, representing an 8.5% reduction in fuel consumption. This reduction not only translates into significant cost savings but also plays a crucial role in reducing GHG emissions.

After the propeller optimization, an average fuel savings of 8.56% was recorded. These savings directly contribute to reducing CO₂ emissions, as lowering fossil fuel consumption results in a proportional reduction in greenhouse gas emissions. According to data from the IMO, a 1% reduction in fuel consumption on ships leads to an approximate 3% decrease in CO₂ emissions, highlighting the significant environmental contribution of propeller optimization.

Hull and propeller cleaning also play a key role in improving energy efficiency. Hull and propeller fouling increases the vessel's resistance in water, requiring more energy to maintain the same speed. Studies have shown that hull cleaning can reduce fuel consumption by up to 10%, and combined with propeller optimization, the method can result in an overall emissions reduction of 10–15% [6]. These savings not only contribute to operational efficiency but also help reduce the ship's environmental footprint.

Similar studies, such as those conducted by [12] on propeller optimization in combination with alternative energy sources, show that propeller optimization not only reduces CO₂ emissions but also increases the energy efficiency of ships by over 9%. The results align with our findings, where fuel savings were observed immediately after the optimization, with long-term benefits in cost reduction and emissions mitigation.

Regularly scheduled propeller optimization and hull cleaning can extend the lifespan of the propulsion system, reduce maintenance needs, and contribute to sustainable shipping

operations. These methods represent a critical step toward achieving the IMO's goals for reducing greenhouse gas emissions and establishing sustainable maritime practices.

This study has demonstrated the significant potential of propeller optimization in improving fuel efficiency and reducing emissions in coastal Ro-Ro liner vessels. However, further research is required to fully explore the broader implications of propeller optimization in maritime operations.

First, future research could investigate the performance of optimized propellers under varying operational and environmental conditions, such as extreme weather, sea currents, and temperature fluctuations. Understanding how these variables affect propeller efficiency could provide more precise guidelines for ship operators.

Second, it would be valuable to explore the integration of propeller optimization with emerging propulsion technologies, such as hybrid systems or renewable energy solutions, including wind and solar power. The combined effects of these technologies on fuel efficiency and emissions could represent a significant advancement in sustainable maritime practices.

Finally, future studies could focus on the applicability of propeller optimization across different types of vessels beyond Ro-Ro ships, particularly in high-traffic coastal and cargo operations. This would help establish propeller optimization's scalability as a universal method for improving energy efficiency across various shipping industry segments.

4. Conclusions

The conducted measurements and analysis, comparing the output performance of the Ro-Ro ship before and after propeller optimization, confirm the successful implementation of the propeller optimization process with a constant pitch and justify the application of the Creaform—Metrascan 3D technology. It can be concluded that, for nearly the same fuel consumption B (kg/h) and the same diesel engine speed $n = 1100 \text{ min}^{-1}$, the average speed increase of the Ro-Ro ship after optimizing all four propellers from Class "II" to Class "S" was 14.28%. Additionally, the vibrations, which were quite pronounced before optimization, were reduced to a minimum. The same speed of this Ro-Ro ship was now achieved with lower diesel engine speeds. The diesel engine was properly loaded. Fuel consumption was reduced by 8.56%, making the optimization process both economically and environmentally justified. This optimization process not only contributed to operational cost savings but also played a significant role in achieving the international goals of reducing greenhouse gas emissions, particularly in line with the International Maritime Organization (IMO) targets for CO₂ reduction.

The limitation of this research lies in the fact that the propeller optimization was carried out in a dry dock during regular overhaul, and the fouling was removed during this process. Historical data indicate that as a result, the average fuel consumption decreases from 9.1% (in the first 2 months after the overhaul) to 4.4% (8 months after the overhaul) over the next 6–10 months, suggesting that the average fuel savings after optimization is 5.18%, which should remain constant until the next overhaul, given that propeller fouling is minimal on ships that are constantly in operation.

This study has demonstrated that propeller optimization through pitch equalization contributes to resolving the issue of optimal propeller operating characteristics. It has also shown that reducing propeller drag improves the propeller's efficiency (η_0). Propellers in service must be free of fouling, and the blade surfaces must be smooth. The synthesis of the technological process for maintaining ship propellers with the demonstrated optimization has been confirmed.

Propeller optimization is one of the key methods for improving sustainable practices in the maritime industry. The synergistic application of solar and wind energy, combined with propeller optimization, offers the potential for achieving even more significant results. Future research will focus on analyzing the various factors affecting optimal energy resource management to reduce harmful gas emissions and improve energy efficiency. The main scientific contribution will be determining the optimal number of ships equipped with renewable energy sources to increase energy efficiency. Additionally, the key parameters

that influence energy efficiency and emissions in the environment will be identified, and an optimization algorithm will be developed to define the optimal number of renewable energy sources, thus reducing gas emissions and ensuring more efficient energy resource management.

The findings of this study confirm that propeller optimization is a cost-effective and environmentally beneficial method for improving fuel efficiency and reducing emissions in Ro-Ro liner vessels. The 8.56% reduction in fuel consumption demonstrates both the economic and ecological advantages of this approach, which can be implemented with minimal investment during routine overhauls. However, the full potential of propeller optimization is yet to be realized.

Future research should focus on three key areas: the impact of varying environmental conditions on propeller efficiency, the synergy between propeller optimization and renewable energy or hybrid propulsion technologies, and the potential application of optimization techniques to a broader range of vessels.

Such studies could further enhance the maritime sector's transition toward sustainable and energy-efficient operations, contributing to global efforts to reduce greenhouse gas emissions in line with the IMO regulations.

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Abbreviations

η_0	Propeller efficiency
3D	Three dimensional
B	Breadth
CHEK	Checked
CO ₂	Carbon Dioxide
CPP	Controllable Pitch Propellers
D	Diameter
DEV	Deviation
FC	Fuel Consumption
FPP	Fixed Pitch Propeller
GHG	Greenhouse Gas
IMO	International Maritime Organization
n	Propeller Speed
NM	Nautical Miles
NO _x	Nitrogen Oxides
P/D	Pitch Diameter Ratio

PSO	Particle Swarm Optimization
PS	Propulsion System
ROPAX	Roll-On/Roll-Off Passenger Ship
Sox	Sulphur Dioxides
TOL	Tolerance
VA	Advance speed
Vs	Ship Speed
x	Number of variables
Z	Number of blades

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