Analysis of Operational Efficiency of the Proposed Propulsion Systems for Selected Large RoPax Vessel

Analiza radne učinkovitosti predloženih porivnih sustava za odabrani veliki RoPax brod

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DOI 10.17818/NM/2021/3.7
UDK 629.541.2/.4
Review / *Pregledni rad*
Paper accepted / *Rukopis primljen:* 18. 1. 2021.

Summary

This paper presents the characteristics of ferry shipping with particular emphasis on large RoPax vessels operating in the Baltic Sea. A critical review of main propulsion system used on large RoPax ferries has been done. Optimal propeller parameters and required brake power have been estimated on the basis of total resistance of bare hull and appendages approximated according to Holtrop-Mennen method. Main engines and generating sets have been selected for minimized fuel consumption approximated with quadratic regression. Operational parameters and costs of analysed large RoPax main propulsion systems have been compared.

KEY WORDS

Marine propulsion
CODAD
CODEL
CODED
Azipod

Sažetak

U ovome radu prikazane su karakteristike trajektnog prijevoza s posebnim osvrtom na velike RoPax brodove koji plove u Baltiku. Dan je kritički pregled glavnoga porivnog sustava koji se koristi na velikim RoPax trajektima. Procijenjeni su optimalni parametri propelera i potrebna efektivna snaga kočenja na temelju ukupnog otpora samoga trupa i dodataka što je približno izračunato uporabom Holtrop-Mennen metode. Glavni motori i generatori odabrani su za minimalnu potrošnju goriva procijenjenu kvadratnom regresijom. Uspoređeni su radni parametri i troškovi analiziranih velikih RoPax glavnih porivnih sustava.

KLJUČNE RIJEČI

brodski pogon
CODAD
CODEL
CODED
Azipod

1. INTRODUCTION / *Uvod*

Ferry shipping has been an extremely important component of international transport system for decades. Due to their functions, in particular complementary role in respect of the existing routes of land transport and shore outline, ferry routes are largely limited to sea basin with a highly fragmented shoreline [1]. The Baltic Sea is a leading market for ferry services where approximately 17% of international ferry fleet is used [2]. These specific conditions prejudge local advantage of ferry shipping both over land transport and container shipping which is the most popular on a global scale. Implementation of horizontal loading (Roll-On/Roll-Off) of passenger cars and trucks, semi-trailers, wagons and roll-trailers, etc. on board has greatly contributed to facilitation of loading and unloading of ferries while indirectly leading to the decrease of the transport distance, cost and time as well as to the elimination of time-consuming container handling.

The most popular vessels in contemporary ferry shipping are RoPax (Roll-On/Roll-Off – Passenger) vessels with separate decks for passengers and rolling cargo. The first RoPax ferries were constructed as a result of conversion of the existing RoRo ferries with an expansion by a passenger section, whereas the following models were designed bottom-up by adjusting vessel specification to the characteristics of a given route [3]. International trans-Baltic routes are currently dominated by large RoPax vessels with a gross tonnage above 40,000 [2].

Nowadays the development of propulsion systems is aimed primarily at energy efficiency and reduction in emissions of harmful substances. Chapter 4 of the MARPOL Annex VI, put into effect in July 2011, obliged shipowners to use technical solutions to reduce carbon dioxide (CO2) emissions. All vessels over 400 GT built as from January 2013 are subject to the Energy Efficiency Design Index (EEDI). The standard puts a cap on the amount of CO2 allowed per unit of transport work. Until 2025, ships are required to achieve a 30-percent reduction in their CO2 emissions compared with the average emissions of ships built between 1999 and 2009. The EEDI value calculated in accordance with the procedure shown in Figure 1 must be less than or equal to the value required for the type and size of vessel [4]. In addition, according to the findings of the 75th session of the Marine Environment Protection Committee (MEPC), from 2023 all in-service vessels are planned to be subject to minimum energy efficiency standards, as defined by the EEDI-equivalent Energy Efficiency Existing Ship Index (EEXI) [5].

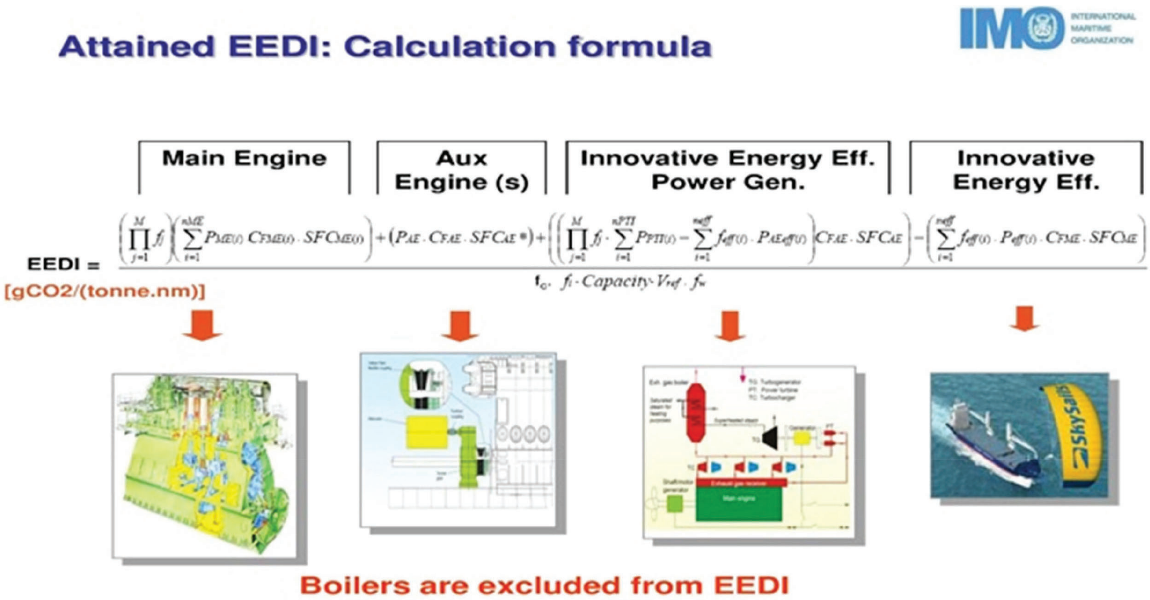

Figure 1 Energy Efficiency Design Index (EEDI)
Slika 1. Indeks dizajna energetske učinkovitosti

Source: Bazari, Z. [4]

However, CO_2 is not the only substance restricted by MARPOL Annex VI. The existing IMO limits on nitrogen oxide NO_X emissions, and fuel sulphur content, are shown in Figure 2. Continually decreasing and territorially expanding restrictions also apply to nitrogen oxides NO_X and sulphur oxides SO_X. They are strictly defined in the current IMO Tier II and Tier III standards. Tier II is global, while the range of the more restrictive Tier III is currently limited to the Baltic and North Sea, and the parts of North American coastal waters. The sulphur content reduction to 0.1%, met by e.g. Marine Gas Oil (MGO) and Liquified Natural Gas (LNG), has also applied in the territorial seas of the European Union Member States [6].

Compliance with MARPOL Annex VI regulations is an important reason why propulsion systems are still being modernised. One of the basic issues having financial consequences is the operational efficiency of the propulsion system. In the design of RoPax vessels, the current priority is the common use of combined propulsion systems [3, 7].

The aim of this paper is to compare the operational efficiency of different main propulsion systems for large RoPax vessels, using certain energy and economic indicators calculated relative to those of the traditional CODAD main propulsion system.

Calculations of resistance based on geometrical data for the m/f Finnstar (45,923 GT) hull were performed by the Holtrop–Mennen method, due to the ease of taking account of differences in resistance caused by appendages. Performance parameters of engines and generating sets were approximated by quadratic regression using data provided by the manufacturers.

2. PROPULSION SYSTEMS OF THE LARGE ROPAX FERRIES / *Porivni sustavi velikih RoPax trajekata*

All European large RoPax ferries (i.e. over 40,000 GT), including both those in operation and those on order books, are still equipped with one of the following propulsion systems [8]:

- Traditional, diesel-mechanical CODAD (Combined Diesel and Diesel);
- Diesel-electric CODEL (Combined Diesel-Electric);

In each of the aforementioned cases, medium-speed engines are used. Despite having lower power and efficiency than low-speed engines, these offer significantly lower height, which is particularly important with regard to the need to reduce the engine room height and improve stability.

The CODAD propulsion system has been associated with RoPax vessels since the 1960s, when the first such units were

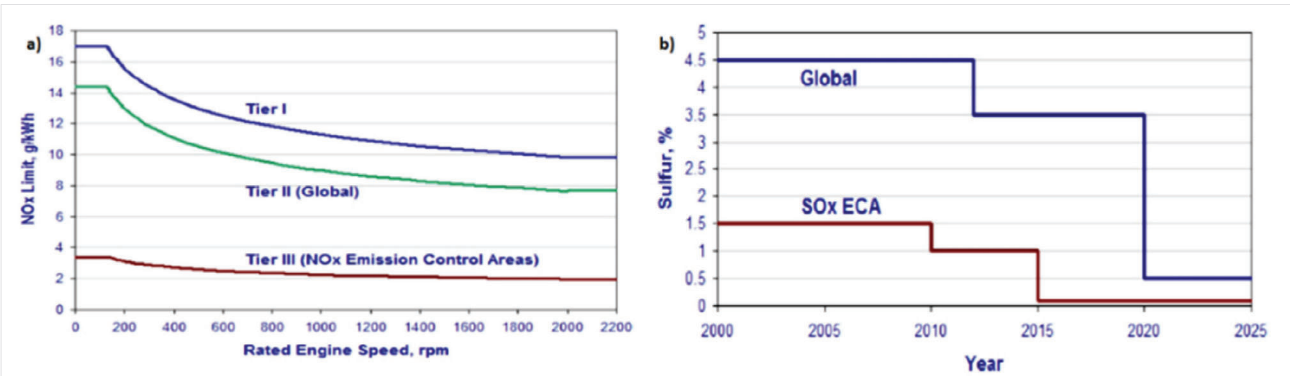

Figure 2 MARPOL Annex VI limits of: a) NO_X emission, b) fuel sulphur content
Slika 2. MARPOL Aneks VI ograničenja: a) NO_x emisije, b) sadržaja sumpora u gorivu

Source: Clausen, N.B. (2015) [6]

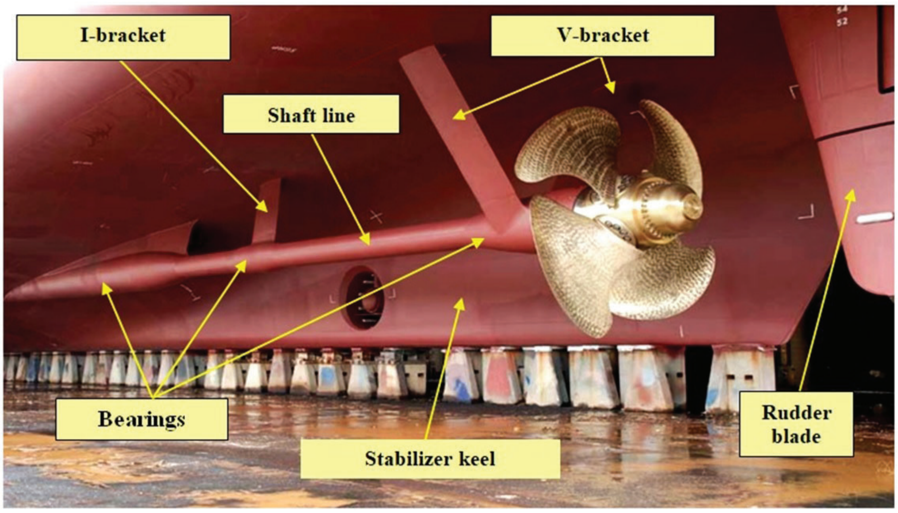

Figure 3 Appendages of the hull equipped with CODAD
Slika 3. Dodatci na trupu opremljenom CODAD-om

Source: Own study on basis [10]

brought into service, and is still the predominant solution. In the most common variant, each pair of main engines (of the same type and with the same or different power) drives one controllable pitch propeller shaft through a reduction gear. Behind the controllable pitch propeller there are a rudder blade and open shaft lines outside the hull separated by a stabilizer keel (Figure 3) [3, 9].

The use of four main engines allows their load to be adjusted in a flexible manner to the required brake power. As a result, engine run time can be maximised within a load range similar to the optimum range [3]. If brake power demand is reduced, engines 3 and 4, connected to the reduction gear with a long shaft, are shut down, so that engines 1 and 2 (Figure 4) may be properly loaded and the entire system avoids inefficient operation at low load range. CODAD is mainly characterised by [3, 11]:

- Moderate investment costs;
- Adoption to longer (e.g. trans-Baltic) shipping routes during which operation under contract load is predominant;
- Difficulty in maintaining the main engines within their optimum load range – at partial loads specific fuel consumption increases;
- Necessity to place the entire engine room in aft part of the hull below waterline.

The CODEL propulsion system (Figure 5) is implemented in e.g. two existing large RoPax vessels (m/f Megastar 49,000 GT and m/f Viking Grace 59,565 GT) serving short routes between ports in the Gulf of Finland, where, due to the route characteristics, operation under contract load is restricted to approximately 20% of shipping time [7, 13]. Moreover, one of Tallink's large RoPax ferries currently under construction (m/f MyStar 49,000 GT) is also to be equipped with CODEL [17]. In this system, diesel generating sets with medium-speed engines powering synchronous generators produce electrical energy supplying two synchronous motors of a fixed pitch propeller system with the use of transformers and frequency converters. In comparison with CODAD, the CODEL system is characterised by [14]:

- Maintaining optimum load of combustion engines regardless of the vessel's speed;
- Easiness of automation;
- Application of more efficient fixed pitch propellers instead of controllable pitch propellers;
- No mechanical connections between the diesel generating sets and the synchronous motors, which allows engine room to be relocated outside of the standard area in aft part of the hull to a suitable place where it is possible e.g. to increase cargo space or reduce the hull's dimensions (and the required brake power) while maintaining current brake power;
- Reduction of vibrations on board to considerably increase crew and passenger comfort;
- Significant losses (by about 8 ÷ 9%) in electrical energy transmission from generators to the propeller motor;
- Installation in a hull of the same form and exterior design.

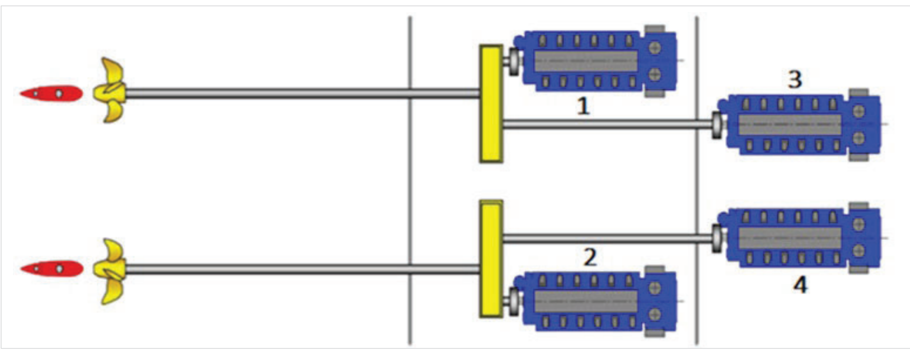

Figure 4 CODAD propulsion system: medium speed engines are marked with numbers 1, 2, 3, 4
Slika 4. CODAD porivni sustav: srednje-hodni motori označeni su brojevima 1, 2, 3, 4

Source: Own study on basis [7]

Figure 5 CODEL propulsion system
Slika 5. CODEL porivni sustav

Source: Łosiewicz, Z. and Łukasik, Z. [14]

Figure 6 Appendages of the RoPax equipped with CODED-CRP
Slika 6. Dodatci na RoPax brodu opremljenom CODED-CRP

Source: Own study on basis [15]

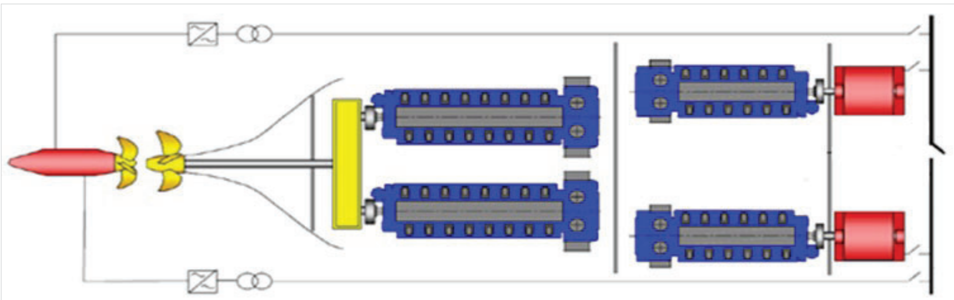

Figure 7 CODED-CRP propulsion system
Slika 7. CODED-CRP porivni sustav

Source: Levander, O. [7]

In this paper the CODED-CRP (Combined Diesel-Electric and Diesel-Mechanical – Contra-Rotating Propeller) system is also considered. Although this system has not been used in large RoPax ferries, it has been successfully implemented in smaller twin Coastal Ferry vessels (m/f Akashia and Hamanasu, 16,810 GT). An illustration of a RoPax equipped with CODED-CRP is shown in Figure 6.

In the CODED-CRP hybrid propulsion system, a pair of medium-speed engines drives a controllable pitch propeller through a reduction gear. In its axis is a podded azimuth thruster (Azipod) with a contra-rotating fixed pitch propeller, which utilises some of the energy of the circular movement of water generated by the controllable pitch propeller. Electrical energy for propulsion purposes is generated by diesel generating sets with medium-speed engines powering the Azipod low-speed synchronous motor through transformers and frequency converters [3]. This system consists of a diesel-mechanical part with a design and principle of operation fully equivalent to those of CODAD, and a diesel-electric part with a design and principle of operation corresponding to a CODEL variant used in Azipod-equipped cruise ferries. Both sections may be operated simultaneously or separately as required. Moreover, the hull of a vessel with such a propulsion system has a form similar to the hull of single-propeller vessels. An exemplary CODED-CRP configuration is shown in Figure 7.

In comparison to both previously discussed propulsion systems, CODED-CRP is characterised by very high investment costs and advantages mentioned in Table 1 [8]:

Table 1 Advantages of the CODED-CRP propulsion system

Tablica 1. Prednosti CODED-CRP porivnog sustava

Economic	Technical
Less fuel consumption per hour	Increased total propulsion system efficiency
Less installed power	Less required service power
Smaller repair costs and longer overhaul periods	Easier to maintain optimal engine load range
No need for use of towing services in ports	Less emission of pollutants from engines operating in the near optimal load range
Limited manoeuvring time in ports	Increased reliability and lifetime
Increased loading space due to possibility of moving the diesel-electric parts of propulsion system to convinient place in hull	Excellent manoeuvrability
No rudder blades	Increased safety in extraordinary situations: storm, emergency maneuvers, crash stop, etc.

Source: Korlak, P. [8]

The basic type of RoPax vessel propulsion system and a reference for other system is the CODAD. Alternative design solutions may be introduced with regard to the characteristics of a given route, e.g. low share of shipping at contractual speed in total sailing time or the need to increase cargo space at limited hull dimensions.

3. RESISTANCE CALCULATIONS AND SELECTION OF THE PROPULSION SYSTEM ELEMENTS / *Izračuni otpora i odabir elemenata porivnog sustava*

The values of effective power and parameters of the propulsion system were estimated using the Holtrop-Mennen method for the three above-mentioned variants. The total resistance is considered to be a sum of the following components [16, 17]:

$$R_T = R_{V_{BH}} + R_{V_{APP}} + R_W + R_B + R_S + R_A \quad (1)$$

Viscous resistance of bare hull and appendages in (1) as a sum of their frictional and viscous pressure resistance were determined through use a form factor [16, 17]:

$$R_{V_{BH}} = R_{F_{BF}} \cdot (1 + k_{BH}) \quad (2)$$

and:

$$R_{V_{APP}} = R_{F_{APP}} \cdot (1 + k_{APP}) \quad (3)$$

R_B and R_S components shown in (1) were omitted in calculations as they represent on average only (0.02÷0.025)% of total resistance [17], thus:

$$R_T \cong R_{V_{BH}} + R_{V_{APP}} + R_W + R_A \quad (4)$$

where:

R_T, kN - Total resistance

$R_{T_{BH}}$, kN - Viscous pressure resistance of bare hull

$(1 + k_{BH})$ - Form factor of bare hull

$R_{F_{BH}}$, kN - Frictional resistance of bare hull according to the ITTC-57 formula

$R_{V_{APP}}$, kN - Viscous pressure resistance of the appendages

$(1 + k_{APP})$ - Form factor of the appendages

$R_{F_{APP}}$, kN - Frictional resistance of the appendages according to the ITTC-57 formula

R_W, kN - Wave resistance

R_A, kN - Model-vessel correlation resistance (incl. such effects as hull roughness of k_S = 150 µm and air drag in conditions of 2 in the Beaufort scale)

R_B, kN - Additional pressure resistance of bulbous bow near the water surface

R_S, kN - Additional pressure resistance due to transom immersion

The estimation was based on actual parameters of the hull of m/f Finnstar ferry equipped with the CODAD provided in Table 2. External and longitudinal section view of m/f Finnstar are presented in Figure 8.

Estimates were made of the total resistance of the bare hull, which is the same for all of the analysed propulsion system

Table 2 Hull parameters of the m/f Finnstar

Tablica 2. Parametri trupa motornog trajekta Finnstar

No.	Parameter	Symbol	Unit	Value
1.	Length overall	L_{OA}	m	218.8
2.	Length between perpendiculars	L_{PP}	m	199.9
3.	Waterline length	L_{WL}	m	211.95
4.	Beam	B	m	30.5
5.	Draught	T	m	7.1
6.	Gross tonnage	GT	-	45,923
7.	Deadweight tonnage	DWT	t	9,653
8.	Lightweight tonnage	LWT	t	17,000
9.	Displacement	Δ	t	26,653
10.	Block coefficient	C_B	-	0.5662
11.	Prismatic coefficient	C_P	-	0.5876
12.	Service speed	V_s	kn	25

Source: DNV – GL [12]

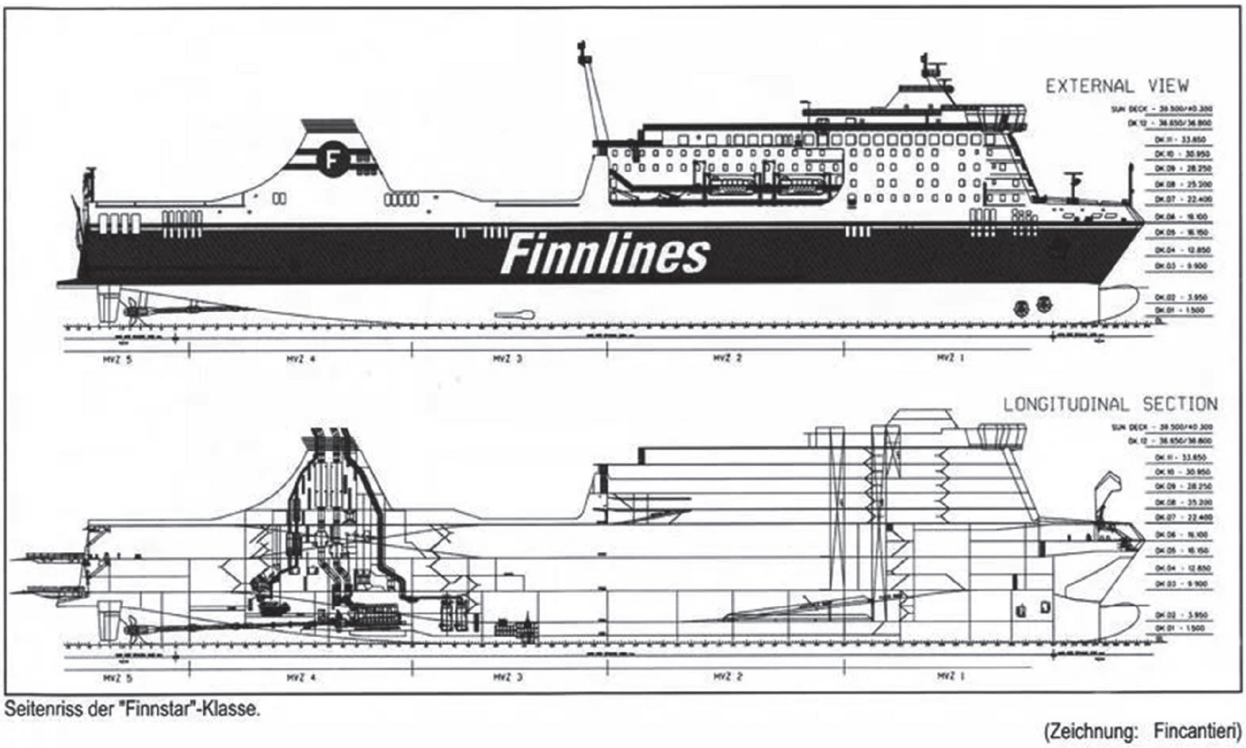

Figure 8 External and longitudinal view of m/f Finnstar

Slika 8. Vanjski i uzdužni presjek m/t Finnstar

Source: Fincantieri [18]

designs, and the resistances of appendages protruding outside the hull, required for a given propulsion system. These two components were added to obtain the value of the vessel's total resistance. The most important values related to the resistance and effective power of a potential vessel with any of the analysed propulsion systems are given in Table 3. Furthermore, values corresponding to sea trial conditions were increased by a sea margin of 15% and an engine margin of 10% to obtain service and maximum values in nominal conditions.

Appendages viscous resistance of a vessel equipped with CODED-CRP is lower by 38.4% (equivalent to 39.68 kN) than the values for CODAD and CODEL, resulting from a smaller wetted surface area and lower form factor of appendages (Table 3), leading to a lower total resistance and effective power for the same service speed under identical sailing conditions. A comparison of appendages viscous resistance is presented in Figure 9.

Table 3 Results of the resistance calculations

Tablica 3. Rezultati izračuna otpora

				CODAD & CODEL	CODED-CRP
No.	Parameter	Symbol	Unit	Value	
1.	Bare hull wetted surface area	S_{BH}	m²	6,353.83	
2.	Bare hull total resistance	$R_{T_{BH}}$	kN	1,392.91	
3.	Bare hull form factor	$(1+k_1)$	-	1.0916	
4.	Appendages wetted surface area	S_{APP}	m²	476.54 100%	338.38 71%
5.	Appendages form factor	$(1+k_2)$	-	1.85 100%	1.61 87%
6.	Appendages viscous resistance	$R_{V_{APP}}$	kN	103.4 100%	63.72 61.6%
7.	**Total resistance for service speed** (sea trials conditions)	$R_{T_{st}}$	kN	1,496.31 100%	1,456.63 97.3%
8.	Total resistance for service speed (nominal conditions)	R_{T_s}	kN	1,724.62	1,674.8
9.	Total resistance for maximum speed (nominal conditions)	$R_{T_{max}}$	kN	1,845.15	1,796.22
10.	Effective power for service speed (nominal conditions)	P_{E_s}	kW	22,128.92	21,542.1
11.	Effective power for maximum speed (nominal conditions)	$P_{E_{max}}$	kW	24,587.7	23,925.67

Source: Own study

Figure 9 Appendages viscous resistance compared to CODAD & CODEL. Value corresponding to CODAD & CODEL is a 100% reference point

Slika 9. Viskozni otpor dodataka u usporedbi s CODAD i CODEL. Vrijednost koja odgovara CODAD i CODEL je 100% referentna točka

Source: Own study

Using the estimated values of effective power, optimum geometric and operating parameters of propellers as well as values of efficiency of propulsion systems with components and the required brake power were calculated according to the following formulae [16, 19]:

CODAD propulsion system:

$$P_{B_{CODAD}} = \frac{P_{E_{CODAD}}}{\eta_{T_{CODAD}}} = \frac{P_{E_{CODAD}}}{\eta_H \cdot \eta_O \cdot \eta_R \cdot \eta_S \cdot \eta_G} \tag{5}$$

where:

P_B, kW - Brake power

P_E, kW - Effective power

η_T - Total efficiency of propulsion system

η_H - Hull efficiency

η_O - Open water propeller efficiency

η_R - Propeller rotative efficiency

η_S - Shaft line efficiency

η_G - Gearbox efficiency

Efficiencies of the components of CODAD propulsion system are shown in Figure 10.

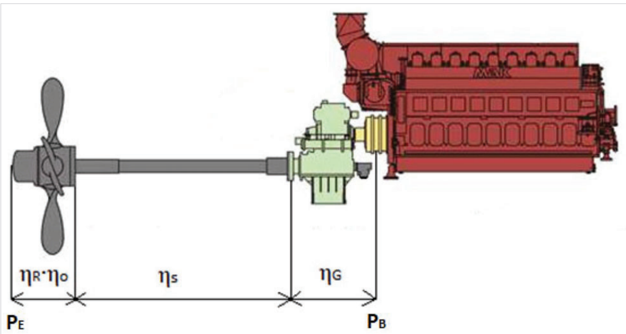

Figure 10 Efficiencies of the CODAD propulsion system components

Slika 10. Učinkovitosti komponenti CODAD porivnog sustava

Source: Leduc, M. [20]

CODEL propulsion system:

$$P_{B_{CODEL}} = \frac{P_{E_{CODEL}}}{\eta_{T_{CODEL}}} = \frac{P_{E_{CODEL}}}{\eta_H \cdot \eta_O \cdot \eta_R \cdot \eta_{Gen} \cdot \eta_{Ele}} \tag{6}$$

where:

η_{Gen} - Generator efficiency

η_{Ele} - Efficiency of electrical energy transmission from generator to motor

Efficiencies of the components of CODEL propulsion system are shown in Figure 11.

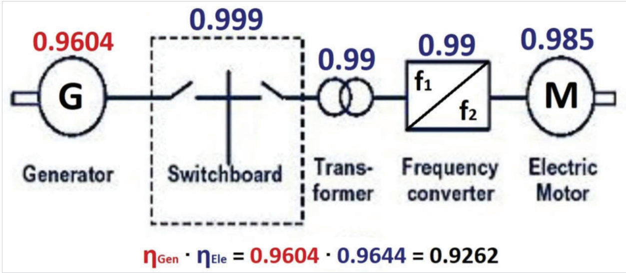

Figure 11 Efficiencies of the CODEL propulsion system components

Slika 11. Učinkovitosti komponenti CODEL porivnog sustava

Source: Own study on basis [14]

CODED-CRP propulsion system:

$$P_{B_{CODED-CRP}} = \frac{P_{E_{CODED-CRP}}}{\eta_{T_{CODED-CRP}}} = \frac{P_{E_{CODED-CRP}}}{\frac{\eta_{T_{mech}} \cdot P_{B_{mech}} + \eta_{T_{el}} \cdot P_{B_{el}}}{P_{B_{mech}} + P_{B_{el}}}} \tag{7}$$

hence:

$$P_{B_{CODED-CRP}} = \left(\frac{P_{E_{mech}}}{\eta_{T_{mech}}} + \frac{P_{E_{el}}}{\eta_{T_{el}}}\right) = \left(P_{B_{mech}} + P_{B_{el}}\right) \tag{8}$$

where:

$\eta_{T_{mech}} = \eta_{T_{CODAD}}$ - Total efficiency of diesel-mechanical part of CODED-CRP

$\eta_{T_{el}} = \eta_{T_{CODEL}}$ - Total efficiency of diesel-electric part of CODED-CRP

The effective power of a hull equipped with CODED-CRP is split into components to estimate the efficiency and the required brake power, corresponding to the diesel-mechanical and the diesel-electric parts of the system, which have different parameters. According to Wärtsilä [15], to ensure the highest energy efficiency, the power should be divided equally between the controllable pitch propeller and fixed pitch propeller. Due to the impossibility of free adjustment of the required power and rotational speed of the low-speed synchronous motor of the Azipod, however, the maximum benefits are not always achievable. Aiming to approach a value of 50% of expected propulsion power and to increase the rotational speed and reduce the propeller diameter by 20% relative to the controllable pitch propeller to avoid cavitation, the Azipod XC1800, with a rated brake power of 13,500 kW and a rotational speed of 195 rpm, was selected [21]. Multiplying the rated brake power of the Azipod by the product of the efficiencies in this section of the propulsion system, according to equation (6), a correct value of effective power was obtained. By subtracting the latter value from the total value, it was possible to obtain a correct value of effective power for the diesel-mechanical part $P_{E_{mech}}$ (9) and to determine the power split according to formulae (7) and (8).

$$P_{E_{mech}} = P_{E_{CODED-CRP}} - P_{E_{el}} \tag{9}$$

Major geometric and operational parameters of all propellers are shown in Table 4:

Table 4 Parameters of the propellers
Tablica 4. Parametri propelera

No.	Parameter	Symbol	Unit	CODAD	CODED-CRP		CODEL
				Value			
1.	Quantity	-	-	2	1	1	2
2.	Propeller type	-	-	Controllable pitch (CPP)		Fixed pitch (FPP)	
3.	Propeller blades geometry	-	-	B–Wageningen series			
4.	Number of blades	Z	-	4	4	5	4
5.	Number of service revolutions (corresponding to engine Nominal Continuous Rating)	n_{NCR}	rpm	115	105	188	115
6.	Diameter	D	m	5.25	5.25	4.2	5.25
7.	Propeller pitch ratio	$\frac{P}{D}$	-	1.4	1.4	1.1	1.4
8.	Expanded area ratio	$\frac{A_E}{A_0}$	-	0.85	1.05	0.75	0.85

Source: Own study

Calculated energy indicators of analysed propulsion systems were discussed below and then shown in Table 5. Hull efficiency is a ratio between effective and thrust power which the propeller delivers to the water, determined as a quotient of thrust deduction coefficient and wake fraction coefficient [9, 16, 22]:

$$\eta_H = \frac{1-t}{1-w} \tag{10}$$

where:
t - Thrust deduction coefficient
w - Wake fraction coefficient

Open water efficiency is a ratio of the thrust power to the power absorbed by the propeller operating without a hull attached, i.e. in open water, determined in relation to thrust loading coefficient [9, 16, 22]:

$$\eta_O = \frac{2}{1+\sqrt{C_{Th}+1}} \cdot 0.81 - 0.014 \cdot C_{Th} \tag{11}$$

where:
C_{Th} - Thrust loading coefficient

Relative rotative efficiency describes a ratio between efficiency of the propeller behind hull and in open water conditions. Value of this parameter was obtained from formula for twin-screw vessels [9, 16, 22]:

$$\eta_R = 0.9737 + 0.111 \cdot \left[C_P - 0.0225 \cdot \left(7 \cdot \sqrt{0.68 - C_B}\right)\right] - 0.06325 \cdot \frac{P}{D} \tag{12}$$

where:
C_P - Prismatic coefficient (Table 1)
C_B - Block coefficient (Table 1)
$\frac{P}{D}$ - Propeller pitch ratio (Table 3)

Shaft line and gearbox efficiency were taken as an average constant values of these parameters for twin-screw vessels. Generator and electrical energy transmission efficiency (Figure 9) are values declared by the manufacturers [14, 23, 24].

Total efficiency of diesel-mechanical and diesel-electric parts were obtained according to (5) and (6), which are equivalent to CODAD and CODEL total efficiency. However, CODED-CRP total efficiency was considered to be a weighted average of the efficiency of both mentioned parts according to (7).

Main engines and diesel generating sets were selected for the capacity to ensure the required brake power, minimise fuel

Table 5 Energy indicators of analysed propulsion systems
Tablica 5. Energetski indikatori analiziranih porivnih sustava

No.	Parameter (efficiency)	Symbol	Unit	CODAD	CODED – CRP	CODEL
				Value		
1.	Hull	η_H	-	0.9837	1.0745	0.9837
2.	Open water (CPP)	η_O	-	0.7315	0.7005	-
3.	Relative-rotative (CPP)	η_R		0.945	0.9706	
4.	Shaft line	η_S		0.985		
5.	Gearbox	η_G		0.97		
6.	Total of diesel-mechanical part	$\eta_{T_{mech}}$		0.6498	0.6979	
7.	Open water (Azipod FPP)	η_O	-	-	0.7077	0.7465
8.	Relative-rotative (Azipod FPP)	η_R			1.0375	0.945
9.	Electrical energy transmission	η_{Ele}			0.9644	
10.	Generator	η_{Gen}			0.9604	
11.	Total of diesel-electric part	$\eta_{T_{el}}$			0.7307	0.6434
12.	**Total of propulsion system**	η_T	-	**0.6498** **100%**	**0.7107** **109.37%**	**0.6434** **99.02%**
13.	**Service brake power (Nominal Continuous Rating)**	$P_{B_{NCR}}$	**kW**	**34,056**	**30,310**	**34,400**
14.	**Power split**	$\frac{P_{B_{mech}}}{P_{B_{el}}}$	-	-	$\frac{0.5675}{0.4325}$	-

Source: Own study

oil consumption and, in the case of the controllable pitch propeller powered by the CODAD and linear (L) cylinder alignment, reduce the volume of engine rooms. Selected models and the values of specific fuel oil consumption (SFOC) under service load in ISO ambient conditions are presented in Table 6 [23, 24].

4. RESULTS AND DISCUSSION / *Rezultati i rasprava*

Comparative analysis of operational efficiency of proposed variants of large RoPax propulsion systems was carried out using the selected energy and economic indicators provided in Table 7 which were referred to the standard CODAD propulsion system [8].

Table 6 Selected main engines and diesel generating sets
Tablica 6. Odabrani glavni motori i dizel generatori

No.	Engine	$P_{B_{NMCR}}$	N_{NMCR}	$P_{B_{MCR}}$	N_{MCR}	$P_{B_{NCR}}$	N_{NCR}	$SFOC_{NCR}$	Quantity	System	Application
		kW	rpm	kW	rpm	kW	rpm	$\frac{g}{kWh}$			
1.	Wärtsilä 8L46F	9,600	600	9,460	597	8,514	576	173.95	4	CODAD	CPP drive
2.				9,555	599	8,600	578	174.15	2	CODED-CRP	
3.	Wärtsilä 12V31	7,320	750	7,283	749	6,555	723	167.96	2		Generator drive
4.	Wärtsilä 16V31	9,760	750	8,600	719	7,740	694	169.95	4	CODEL	Generator drive

Source: Own study on basis [23, 24]

Table 7 Major energy and economic indicators
Tablica 7. Glavni energetski i ekonomski pokazatelji

				CODAD	CODED – CRP	CODEL
No.	Parameter	Symbol	Unit	Value		
1.	Total efficiency of propulsion system	η_T	-	0.6498 100%	0.7107 109.37%	0.6434 99.02%
2.	Service brake power (Nominal Continuous Rating)	$P_{B_{NCR}}$	kW	34,056 100%	30,310 89%	34,400 101.01%
3.	Maximum continuous power (Maximum Continuous Rating)	$P_{B_{MCR}}$		37,840 100%	33,676 89%	38,222 101.01%
4.	Total installed power (Nominal Maximum Continuous Rating)	$\sum P_{B_{NMCR}}$		38,400 100%	33,840 88.12%	38,720 100.83%
5.	Specific fuel oil consumption	$SFOC_{NCR}$	$\frac{g}{kWh}$	173.95 100%	171.47 98.57%	170.05 97.76%
6.	Daily fuel oil consumption	$DFOC_{NCR}$	$\frac{t}{day}$	142.18 100%	124.73 87.73%	140.37 98.73%
7.	Annualy fuel oil consumption (operation time: 2/3 of year)	$AFOC_{NCR}$	$\frac{t}{year}$	34,597.1 100%	30,350.9 87.73%	34,156.7 98.73%
8.	Daily fuel oil costs	-	$\frac{USD}{day}$	78,199 100%	68,601.5 87.73%	77,203.5 98.73%
9.	Annualy fuel oil costs (operation time: 2/3 of year)		$\frac{USD}{year}$	19,028,423 100%	16,693,032 87.73%	18,786,185 98.73%

Source: Own study

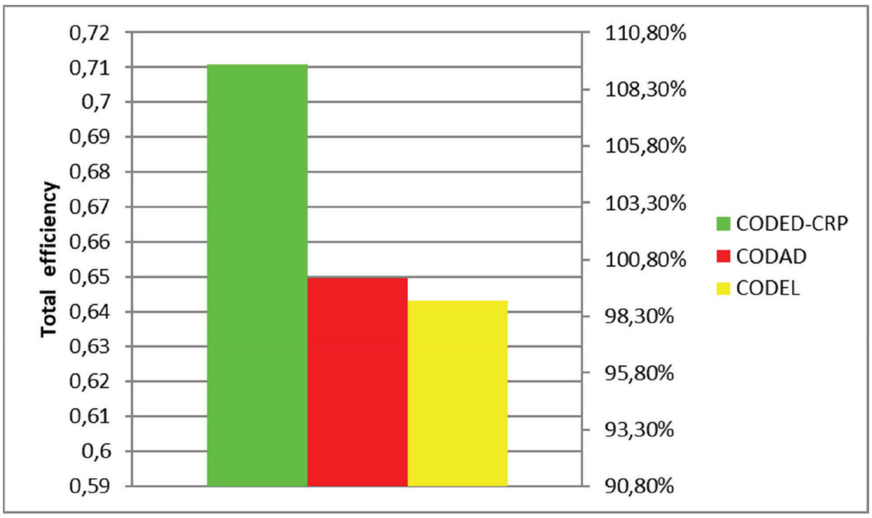

Figure 12 Total efficiency of analysed propulsion systems on their service load compared to CODAD. Its total efficiency 0.6498 is a 100% reference point to others
Slika 12. Ukupna učinkovitost analiziranih porivnih sustava na radnom opterećenju u usporedbi s CODAD. Njihova ukupna učinkovitost 0.6498 je 100 % referentna točka drugima

Source: Own study

On the basis of a comparison of the results of calculations given in Table 6 and shown in Figure 12, it was concluded that a vessel equipped with the CODED-CRP propulsion system has a total propulsive efficiency higher by 6.09 p.p. (9.37%) than the efficiency of CODAD, assuming a value of 0.7107 comparable to that of the direct-drive propulsion system with low-speed engine and fixed pitch propeller. Moreover, both the diesel-mechanical section and the diesel-electric section of the CODED-CRP system have total efficiencies higher than the efficiency of CODAD (Table 4), respectively by 4.81 p.p. (7.4%) and 8.09 p.p. (12.45%), as a result of a considerably higher value of the product of the hull efficiency and relative-rotative efficiency (Table 4), which easily offsets the lower efficiency of the propellers and losses in the generation and transmission of electrical energy. This is due to a more streamlined hull form – very similar to the form used for single-propeller vessels – and the utilisation of part of the energy of the circular movement of water (generated by the controllable pitch propeller) by the Azipod's fixed pitch propeller. The CODEL system has total propulsive efficiency lower by 0.64 p.p. (0.98%) than that of CODAD, yet it is still comparable. This results from the identical total resistance (Table 2) and losses in the generation and transmission of electrical energy that slightly exceed both the power transmission losses in the CODAD system and the gain from the fixed pitch propeller, which has slightly higher efficiency when installed in this system.

To sail with a service speed of 25 knots, CODED-CRP requires brake power of 30,310 kW, which ensures savings up to 3,746 kW (11%) relative to CODAD, with demand lower by 344 kW (1.01%) than that of CODEL. These results, presented in Figure 13, are obtained directly from the aforementioned differences of effective power and total efficiency of the propulsion systems.

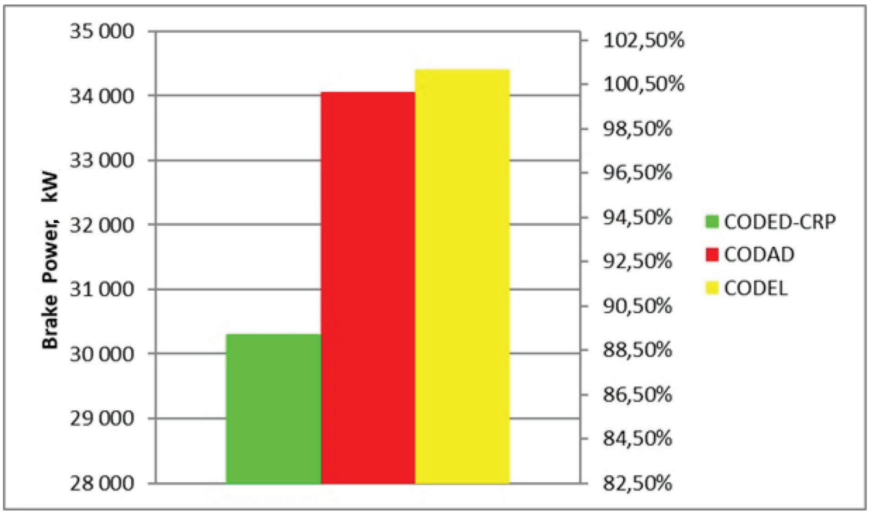

Figure 13 Service load brake power of analysed propulsion systems compared to CODAD. Its service brake power 34,056 kW is a 100% reference point to others

Slika 13. Efektivna snaga kočenja na radnom opterećenju analiziranih porivnih sustava u usporedbi s CODAD. Njihova radna efektivna snaga kočenja 34,056 kW JE 100 % referentna točka drugima

Source: Own study

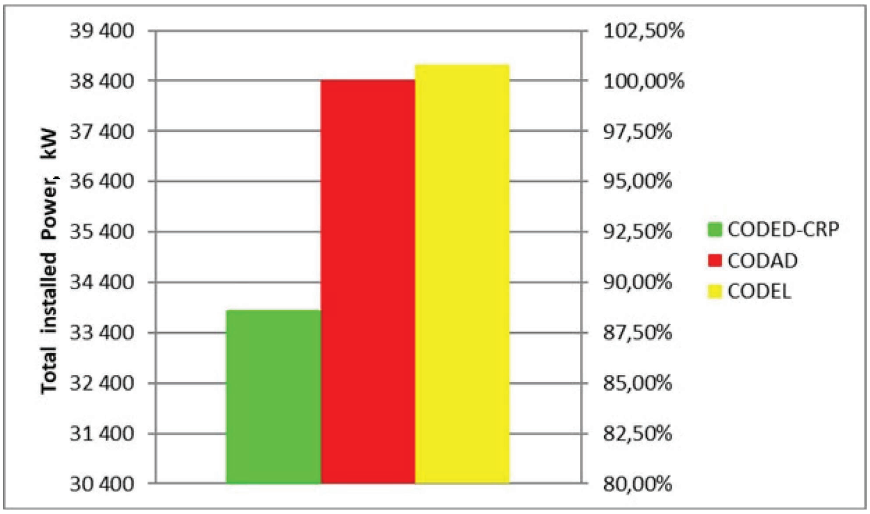

Figure 14 Total installed power of analysed propulsion systems compared to CODAD. Its total installed power 38,400 kW is a 100% reference point to others

Slika 14. Ukupna ugrađena snaga analiziranih porivnih sustava u usporedbi s CODAD. Njihova ugrađena snaga 38,400 kW JE 100 % referentna točka drugima

Source: Own study

Total installed power is the sum of the rated powers of all engines driving the propellers and generators producing electrical energy for propulsive purposes. On the basis of a comparison of the data given in Table 6 (in accordance with Table 5) and in Figure 14, it was concluded that CODED-CRP requires lower installed power than CODAD by 4,560 kW (11.88%) for operation under service load while maintaining the engine margin. CODEL requires diesel generating sets with a sum of rated powers equal to 38,720 kW, exceeding the CODAD system's power by 320 kW (0.83%).

CODEL has the lowest specific fuel oil consumption for MGO (Marine Gas Oil) in ISO ambient conditions, amounting to 170.05 g/kWh, which is lower by 3.9 g/kWh (2.24%) than the CODAD system's consumption (Figure 15). Such a low value was obtained using Wärtsilä V31 engines (Table 5) powering a synchronous generator. Their record-breaking minimum specific fuel oil consumption is equal to 167.7 g/kWh at a rated load of 85%. A pair of engines of this series is used similarly in the CODED-CRP system, for which this parameter, being the weighted average of the values for the diesel-mechanical and diesel-electric sections, amounts to 171.47 g/kWh. This ensures savings up to 2.48 g/kWh (1.63%) relative to the CODAD system, which is based entirely on Wärtsilä 8L46F engines with lower energy efficiency.

Daily and annual fuel oil consumption are the products of the specific fuel oil consumption and attained brake power with time, expressed as a number of hours or days. In the case of the second indicator it was assumed that the vessel is used for 2/3 of the year under service load. The CODED-CRP system consumes 124.73 t/day (Figure 16) and 30,350.9 t/year of fuel, which allows 17.45 t/day and 4,246.2 t/year (12.27%) to be saved relative to the CODAD system. These differences arise from lower values of specific fuel oil consumption and service brake power. In the CODEL system the savings result only from

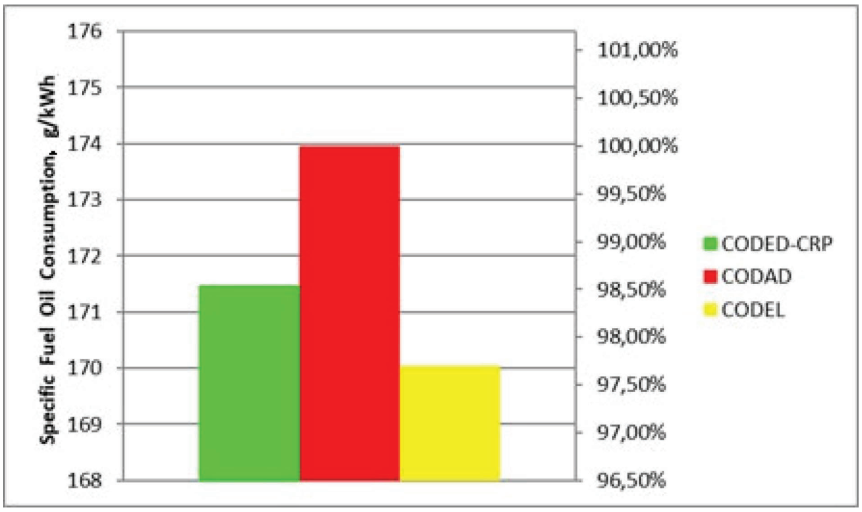

Figure 15 Specific fuel oil consumption of analysed propulsion systems compared to CODAD. Its specific fuel oil consumption 173.95 g/kWh is a 100% reference point to others

Slika 15. Specifična potrošnja goriva analiziranih porivnih sustava u usporedbi s CODAD. Njihova specifična potrošnja goriva 173.95 g/kWh je 100 % referentna točka drugima

Source: Own study

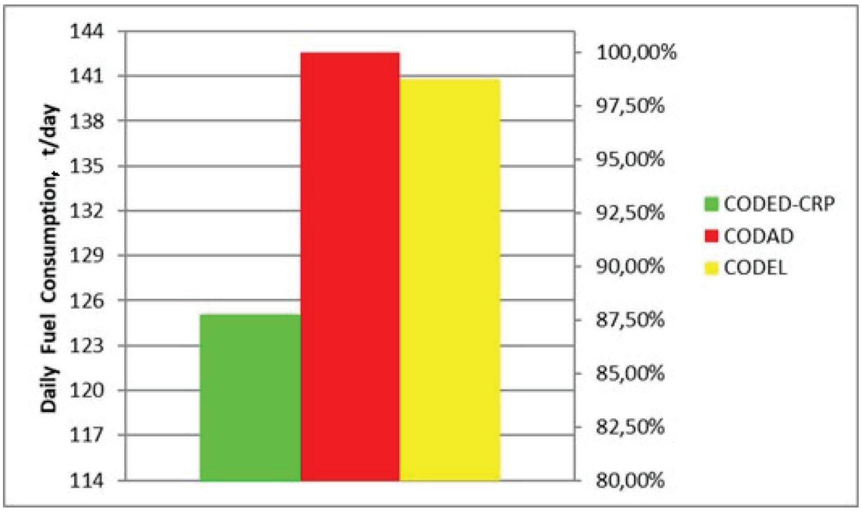

Figure 16 Daily fuel oil consumption of analysed propulsion systems compared to CODAD. Its daily fuel oil consumption 142.18 t/day is a 100% reference point to others

Slika 16. Dnevna potrošnja goriva analiziranih porivnih sustava u usporedbi s CODAD. Njihova dnevna potrošnja goriva 142.18 t/day je 100 % referentna točka drugima

Source: Own study

the first of the aforementioned indicators, which causes the system to consume 1.81 t/day and 440.4 t/year (1.27%) less fuel oil than CODAD.

The average price of MGO (Marine Gas Oil) on European markets in 2019, amounting to 550 USD/t [25] was used to compare costs of fuel oil consumption. Both alternative propulsion systems allow the saving of some part of the amount corresponding to CODAD's fuel oil consumption per hour, which results from the fact that they are its multiples. The CODED-CRP system generates savings up to 9,597.5 USD/day and 2,335,391 USD/year. The CODEL system's savings are nearly tenfold lower, at 995.5 USD/day and 242,238 USD/year.

5. CONCLUSIONS / *Zaključci*

The calculation results presented in Table 7 indicate that the brake power of a large RoPax with CODED-CRP required for operation at service speed will be lower by 11% than for the same vessel equipped with CODAD, due to lower total resistance (by 2.7%) and higher total propulsive efficiency of the propulsion system (by 9.73%). Therefore, total installed power will also be lower (by 11.88%), as will the consumption and costs of fuel oil (by 12.27%).

What is more, a large RoPax vessel equipped with CODED-CRP also offers better manoeuvrability (the entire Azipod thruster power may be used for steering) and greater capacity to maintain higher efficiencies of the propulsion system in the part-load range (the electric propulsion is better adapted to load variation, and generators producing electrical energy for the Azipod may also replace the auxiliary propulsion to avoid inefficient operation in a low load range).

Nevertheless, the costs of construction of a ferry equipped with the CODED-CRP system are significantly higher (especially due to the purchase and installation of the Azipod thruster) than the costs of the standard CODAD system, but this type of main propulsion system entails a series of benefits, presented in Table 1, which enable investment expenditure to be recovered in the course of long-term service. On this basis it is concluded that the CODED-CRP system, which combines the advantages of CODAD and CODEL, may be the best solution both for ferries serving long routes with a large proportion of operation time under service load, and for ferries serving short routes with a negligible proportion of operation time under service load.

The CODEL propulsion system is selected only for ferries serving short routes running mainly under reduced load. Generating low savings under service load, it cannot enable increased investment expenditure to be recovered over a standard 20-year ferry service period on the long routes dominated by CODAD vessels, which still prevail in current order portfolios. It should be expected, however, that the use of CODED-CRP in newly built vessels will become more frequent with the development and growing popularity of hybrid propulsion systems as a consequence of increasingly restrictive emission limits for harmful substances.

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