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EXPEDIENCY OF AN IMPROVEMENT FOR A DIESEL-GEARED PROPULSION WITH RESPECT TO SUBJECTIVELY PREFERRED OPERATIONAL FACTORS

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According to the technical data of the ship and her engine, the expediency of improving a two six-cylinder four-stroke reversible supercharged 36-centimeter bore 45-centimeter stroke diesel-geared engines propulsion system by way of changing both the reduction gear and the propeller with respect to subjectively preferred operational factors is considered.

Key words: diesel-geared engine, ship propulsion, propeller, operational strategy, subjective preferences, multi-alternative situations.

Introduction. The older fleet to be competitive to the newer one has to have reserves of potential for improvements. One of the possible ways of such an improvement is retrofitting the vessel's propulsion system in order to increase incomes from operation to compensate relatively higher operational costs because of higher fuel oil consumption.

Relatively older marine propulsion systems and engines, their representative is a two six-cylinder four-stroke reversible supercharged 36-centimeter bore 45-centimeter stroke (6 FRGS 36/45) diesel-geared engines propulsion system considered in this work, surrender to more modern leading to better economy diesel engines. They have reduced running costs comparatively to the older engines. The latter have got not just higher fuel oil consumptions. Generally they also have higher lubricating oil consumptions; in addition lower torques at part loads; shorter intervals between overhauls; shorter lifetimes of components; shrunk exchange part services; and more complicated maintenances.

All of that does not allow the older marine propulsion engines reducing their running costs.

Urgency of researches. The problem of monitoring and supporting the technical state of marine ship propulsions and power plants in multi-alternative operational situations is a complex and actual one.

The retrofitting of a vessel's propulsion system is dictated by subjective preferences of the ship-owner. He evaluates the feasibility of a possible modernization and economical issues of the improved propulsion system operation.

Thus this partial problem, for example, considered for the «Sergey Smirnov» vessel in this paper, becomes an urgent part of the general problem of monitoring and supporting the technical state of marine ship propulsions and power plants in multi-alternative operational situations.

Analysis of the latest researches and publications. Problems of project works for propulsion systems with the direct transmission of power from the ship's main engine to the propeller are considered in the book [1]. It deals just only with the comparatively more modern two stroke crosshead diesel engines built by «MAN Diesel» concern.

Methods for evaluation of a propeller geometrical and technical characteristics as well as kinematical, dynamical, and hydro-dynamical interrelations and interconnections between the propeller and hull developed in the books [2, 3]. Hereby we will make it applicable.

The optimal commercial speed of a transport vessel is considered in [4, 5]. There is a necessity to continue that kind of a research work and take into consideration incomes gained out of the operation.

Technical data are given in the ship's, engine's, and reduction gear documentation [6-10].

The theory of subjective analysis is developed in monographs [11, 12]. Criteria that make allowance for a subjective preferences influence are used in [4]. Hereby we will make it applicable.

Unsolved part of the general problem of monitoring and supporting the technical state of marine ship propulsion and power plants in multi-alternative operational situations is that for the optimization it is necessary to pay more attention to complex criteria that combine technical, economical, random, and subjective preferences factors.

Theoretical models of the preferred operational situations and strategies need mathematical researches.

The task setting. The object of this article is to research theoretically, including technical-economical parameters of operation, the expediency of a possible increase of the «Sergey Smirnov» ship's speed by the way of the reduction gears transmission ratio change for the main diesel-geared engines of 6 FRGS 36/45 with respect to a subjectively preferred feasible modernization.

The main content (material). Accordingly to technical data from [6-10] for the 6 FRGS 36/45 main engines, there is a possibility to install reduction gears with the transmission ratios of 1.5 or 1.98.

If the reduction gear with the transmission ratio of $i_{1.98}$ = 1.98 is installed on board ship and the engine speed is 500 rpm, the propeller speed is 252.5 rpm. If the reduction gear were changed for the one with the transmission ratio of $i_{1.5}$ = 1.5, then the propeller speed would be 333.3 rpm.

But, for the engine running by the propeller curve i.e. for a fixed pitch propeller, the relation will be the third power curve [3, p. 202, (3.107)]

$$N_e = c_n n^3, \tag{1}$$

where N_e – the engine power, c_n – the coefficient of proportionality between the engine power and the propeller speed, n – the propeller speed.

At the operational ship's speed of v_s = 13 knots [6, 10] and with the fact that it was experimentally determined that in a rather wide diapason of the operational rotational speeds the ship's speed is proportional to the rotational speed of the propeller [3, p. 202, (3.106)]

$$v_s \approx n, \quad (2)$$

i.e. between the vessel's speed and the propeller rotational speed there is an approximate linear dependence [1-3], it goes that

$$N_e = cv_s^3, \quad (3)$$

where c – the coefficient of proportionality between the engine power and the ship's speed.

From where at the 6 FRGS 36/45 main engine output of 1150 kW, the coefficient c will have the value of 0.5234.

This meant that with the new reduction gear and the old propeller it would have been possible to expect for the new speed of the vessel

$$v_s = \frac{n_{1,5}}{n_{1,98}} v_{s_{1,98}}, \quad (4)$$

where $n_{1,5}$ – the speed of the propeller rotation of 333.3 rpm with the new reduction gear with the transmission ratio of $i_{1.5}$= 1.5; $n_{1,98}$ – the speed of the propeller rotation of 252.5 rpm with the old reduction gear with the transmission ratio of $i_{1.}$ = 1.98; $v_{s_{1,98}}$ – the vessel's speed of 13 knots with the old reduction gear with the transmission ratio of $i_{1.}$ = 1.98.

Thus the expected ship's speed obtained form the equation (4) v_s would have been about of 17.16 knots. But unfortunately it is impossible on the reason of extremely high overloading of the main engine 6 FRGS 36/45 which necessary output would have been about of 2644 kW according to the cubic law (1, 3) and proportion (2).

Therefore it is necessary to select a more expedient propeller.

The problem formulation. On the basis of the theory of the ideal propeller, blade theory of propeller, and the Froude-Finsterwalder theorem the curves of the propeller action are built [3, p. 151, 171, 175, fig. 3.26].

In every specific case at the designed operational modes the propeller should work in the diapason of advance coefficients which correspond to high values of the efficiency, which is provided by the properly selected geometrical characteristics of propellers. As an illustration it is adduced in [2, p. 293, fig. 5.18] some curves of thrust coefficient $K_1 = f(\lambda_p)$ for propellers with fixed disc ratio at different pitch ratios.

Formulas for elementary thrust and torque of the propeller can be written in the view of [2, p. 291, (5.54, 5.55); 3]

$$dP = z\frac{\rho v_i^2}{2} bC_y \cos\beta_i (1 - \varepsilon \mathrm{tg}\beta_i) dr, \quad (5)$$

$$dM = z\frac{\rho v_i^2}{2} bC_y r \sin\beta_i (1 + \varepsilon \mathrm{ctg}\beta_i) dr, \quad (6)$$

where z – the number of blades; ρ – the density of water; v_i – the speed of the stream which is running upon the section of the propeller blade considered; b – chord line; C_y – lift coefficient; r – the radius; β_i – the angle of the inductive chord; ε – the coefficient of the inverse quality.

To determine the thrust and torque as a whole let us integrate expressions of (5, 6) in the limits from the radius of the propeller boss (hub) to the end of the blade [2, p. 292, (5.56, 5.57); 3]

$$P = \int_{r_0}^{R} z \frac{\rho v_i^2}{2} b C_y \cos \beta_i (1 - \varepsilon \mathrm{tg} \beta_i) dr , \quad (7)$$

$$M = \int_{r_0}^{R} z \frac{\rho v_i^2}{2} b C_y r \sin \beta_i (1 + \varepsilon \mathrm{ctg} \beta_i) dr . \quad (8)$$

To overcome the torque of resistance of the propeller there must be applied the equal and reversed torque to the propeller which is being created by the engine. The equality of these torques causes the rotation of the propeller with a constant speed.

When the propeller is rotating in addition to the torque there arises the force of thrust at its blades, as at the wings, which is applied alongside the shaft axis to the thrust bearing, which is in its turn rigidly connected to ship's hull. This force equalizing the force of ambient environment resistance makes the vessel move in the translational way.

The thrust and the torque are hydrodynamic characteristics of the propeller which are expressed in the measurement unit form. However in the theory and practice of projection and operation of propellers, as a rule, there used non-measurement hydrodynamic characteristics, for determination of which the integral expressions of (7, 8) are being represented in the non-measurement form, deducing to that form all the members of the under-integral expressions from the equations of (7, 8) [2, p. 292, (5.58, 5.59); 3]

$$P = \rho n^2 D^4 \int_{\bar{r}_0}^{1} \frac{z}{4} C_y \frac{b}{D} \left(\frac{v_i}{nD} \right)^2 \cos \beta_i (1 - \varepsilon \mathrm{tg} \beta_i) d\bar{r} , \quad (9)$$

$$M = \rho n^2 D^5 \int_{\bar{r}_0}^{1} \frac{z}{8} C_y \frac{b}{D} \left(\frac{v_i}{nD} \right)^2 \bar{r} \sin \beta_i (1 + \varepsilon \mathrm{ctg} \beta_i) d\bar{r} , \quad (10)$$

where n – the rotation speed of the propeller; D – the propeller diameter.

The integrals in the formulas of (9, 10) are depicted as K_1 which is called the thrust coefficient (thrust constant) of the propeller and K_2 – the torque coefficient.

Then the formulas of (9, 10) are getting the view of [2, p. 292, (5.60, 5.61); 3]

$$P = K_1 \rho n^2 D^4, \quad (11)$$

$$M = K_2 \rho n^2 D^5. \quad (12)$$

Here in (11, 12) [2 p. 292], analogous to [3, p. 175, (3.59, 3.60)]

$$K_1 = \int_{\bar{r}_0}^{1} \frac{z}{4} C_y \frac{b}{D} \left(\frac{v_i}{nD} \right)^2 \cos\beta_i \left(1 - \varepsilon \mathrm{tg}\beta_i\right) d\bar{r}, \quad (13)$$

$$K_2 = \int_{\bar{r}_0}^{1} \frac{z}{8} C_y \frac{b}{D} \left(\frac{v_i}{nD} \right)^2 \bar{r} \sin\beta_i \left(1 + \varepsilon \mathrm{ctg}\beta_i\right) d\bar{r}. \quad (14)$$

The problem solution. The propulsion qualities calculations [1, p. 101], aiming coefficients K_1, K_2 of the formulas (13, 14), with the $i_{1.98}$ = 1.98 and the old propeller give the towing (towrope) resistance

$$R = \frac{N_e \eta_r \eta_v \eta_p \eta_k}{v_s}, \quad (15)$$

where η_r – the efficiency of the reduction gear; η_v – the efficiency of the shaft line; η_p – the efficiency of the propeller; η_k – the coefficient of the hull's influence.

At the power at the engine driving end flange of 1,560 bhp, and at the reduction gear driving end flange of 1,500 bhp, η_r = 0.9615. Let us accept η_v = 0.98. From the presumed old propeller type calculation diagram in the Papmel form, shown in the fig. 1, we accept η_p in the fist iteration. In a few iterations the result converges to the solution of η_p = 0.6. For η_k determination we use

$$\eta_k = \frac{1-t}{1-\psi} i, \quad (16)$$

where t – the coefficient of the thrust deduction; ψ – the propeller wake coefficient; i – the coefficient of the wake non-uniformity influence upon the η_p.

Accepting form the book [3, p. 188] ψ = 0.15 and [3, p. 193]

$$t = 0{,}7\psi + 0{,}06, \quad (17)$$

we get t = 0.165. From [3, p. 189]

$$i = \frac{i_1}{i_2}, \quad (18)$$

where $i_1 = \dfrac{\overline{K}_1}{K_1}$ – the coefficient of the wake non-uniformity influence upon the thrust; $i_2 = \dfrac{\overline{K}_2}{K_2}$ – the coefficient of the wake non-uniformity influence upon the torque; $\overline{K}_1$, $\overline{K}_2$ – the coefficients of the working behind the ship's hull propeller thrust and torque respectively.

Accepting i= 0.9 we get η_k = 0.8841 and R = 85.86 kN.

The effective propeller thrust-loading coefficient at the propeller diameter of D = 2.56 m

$$K_1^R = 0{,}515 v_s D\sqrt{\frac{\rho}{R}}, \tag{19}$$

will be K_1^R = 1.872.

The translational speed of the propeller

$$v_p = 0{,}515 v_s \left(1-\psi\right), \tag{20}$$

will be v_p = 5.69 m/s.

The propeller's thrust

$$P = \frac{R}{1-t}, \tag{21}$$

will be P = 102.8 kN.

The propeller thrust-loading coefficient

$$K_1^P = v_p D\sqrt{\frac{\rho}{P}}, \tag{22}$$

will be K_1^P = 1.454.

From the presumed old propeller type calculation diagram in the Papmel form, fig. 1, we get in the fist iteration the values of K_1; pitch ratio $\dfrac{H}{D}$ at the geometrical pitch H = 1.82 m; advance ration (coefficient) λ_p.

Then we can calculate: the revolutions per minute n

$$n = \frac{v_p}{D\lambda_p}. \tag{23}$$

The effective output N_e

$$N_e = \frac{\rho K_1 n^2 D^4 v_p}{\eta_r \eta_v \eta_p}. \tag{24}$$

Finally, the ship's speed v_s

$$v_s = \sqrt[3]{\frac{N_e}{c}}. \qquad (25)$$

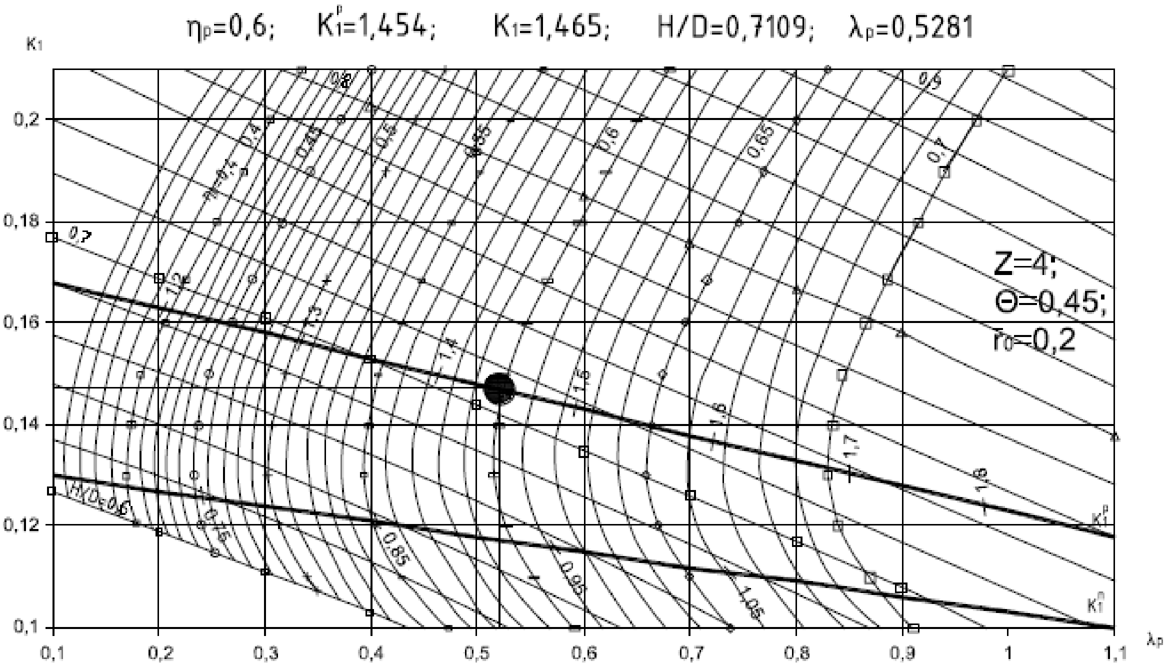

Figure 1 – The presumed old propeller type calculation diagram in the Papmel form

Then, doing next iterations, finally we get the converged to the solution results of $K_1 = 0.1465$; $\frac{H}{D} = 0.7109$; $\lambda_p = 0.5281$; $n = 252.5$ rpm; $N = 1150$ kW; $v_s = 13$ knots.

The propulsion qualities calculations by the formulas (15-25) with the $i_{1.5} = 1.5$ and the new propeller give in a few iterations the next results: $N = 1150$ kW; $v_s = 14$ knots; $\eta_r = 0.9615$; $\eta_v = 0.98$; $\eta_p = 0.74$, from the presumed new propeller type calculation diagram in the Papmel form, shown in the fig. 2; [3, p. 188] $\psi = 0.21$; [3, p. 193] $t = 0.207$; accepting $i = 0.9$ we get $\eta_k = 0.9034$ and $R = 100.4$ kN; $K_1 = 1.864$; $v_p = 5.695$ m/s; $P = 126.7$ kN; $K_1 = 1.311$.

From the presumed new propeller type calculation diagram in the Papmel form, fig. 2: $K_1 = 0.1036$; $H = 1.45$ m; $\frac{H}{D} = 0.5664$; $\lambda_p = 0.4004$; $n = 333.4$ rpm; $N = 1150$ kW; $v_s = 14$ knots.

Practical application of the problem solution. The proof of the economical expediency of the improvement for the diesel-geared propulsion complex by the way of changing the reduction gear with the transmission ratio of the $i_{1.98} = 1.98$ for the reduction gear with the transmission ratio of the $i_{1.} = 1.5$ and corresponding to that changing the replacement of the propeller will be deduced on the basis of some major operational economical indexes for two variants.

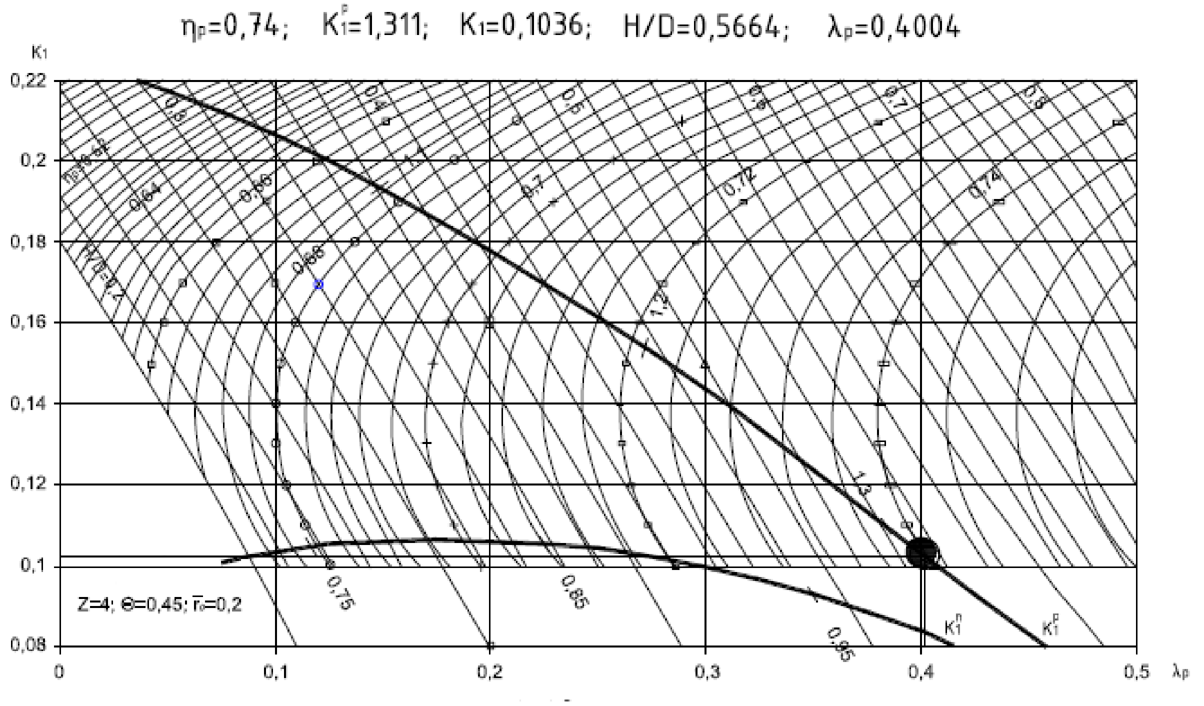

Figure 2 – The presumed new propeller type calculation diagram in the Papmel form

Variant 1. New-building

We choose the basis as the propulsion complex with the old reduction gear $i_{1.98}$ = 1.98, n = 252.5 rpm, old propeller, v_s = 13 knots.

The number of the engines equals the number of the propeller shaft lines k_e = 2. The accepted masses: of one engine is 33 t; a reduction gear – 4.5 t; two propeller shaft lines – 11.61 t; a propeller – 1.9 t. Then the mass of the propulsion installation will be summarized up to 90.41 t.

The cost for the engines with respect to the price of US 170 $/bhp will be up to US 0.53125 $ mil. If the price for a reduction gear were US 0.005 $ mil/t, the cost would be US 0.045 $ mil. For the propeller shaft lines accordingly to the same price it would be of US 0.05805 $ mil. And if the price for a propeller were US 0.05 $ mil/t, the cost would be US 0.19 $ mil. The summarized cost of the propulsion installation would be US 0.8243 $ mil.

Let us say assemblage of the installation costs up to 10 % of the installation cost.

Thus the capital investments would be up to US 0.90673 $ mil.

If we consider normative coefficient of the investments economical efficiency on the level of 0.15 which means that the capital investments are distributed into 6.667 years, the reduced capital investments will be US 0.13601 $ mil.

Duration of one route at the distance of 1500 km will constitute up to 2.595 days. Presume loading/unloading at a harbor would take for 4 days. Then the number of voyages per a year would be

$$N_p = \frac{365}{2.595 + 4} = 55.33 \text{ v/y}. \quad (26)$$

Corresponding running time – 143.6 days/year. Assume expenses for calling at ports – US 0.166011 $ mil/year. Maintenance – US 0.5 $ mil/year. Salaries and other – US 0.6 $ mil/year. For the average annual fuel oil prices of up to US 400 $/t the annual expenses of fuel oil would be of US 0.708271 $ mil/year and they would result in the operational costs: E of up to US 1.974282 $ mil/year.

For a yearly average incomes D we would have in the case of 6,000 t of load transported each time and the price of US 0.01 $/(t·mil) D = 2.689164 $ mil/year. Then the profit P_r = 0.578873 US $ mil/year. At taxes of up to 30 % the net profit P_n = 0.405211 US $ mil/year. It is for the recoupment period of 6.667 years. After that amortization time, the net profit P_n will be more because of the distributed into 6.667 years reduced capital investments of US 0.13601 $ mil.

Comparatively to the basis, let us consider the improved propulsion complex with the new reduction gear, i_1 = 1.5, n = 333.3 rpm and corresponding to that changing a lighter propeller shaft lines and the replaced new propeller, v = 14 knots.

The next parameters will change. Assume the new mass of the lighter propeller shaft lines would be 10 t instead of 11.61 t in the basis. The new mass of the propulsion – 88.8 t and the cost US 0.81625 $ mil. Finally, the capital investment would be – US 0.897875 $ mil, and distributed – US 0.134681 $ mil/year.

Duration of a route – 2.41 days. Accordingly to formula (26) N_p = 56.93 v/y. Running time – 137.2 days/year. Expenses for calling at ports – US 0.170813 $ mil/year. The annual expenses of fuel oil would be of US 0.676703 $ mil/year. E = 1.947516 US $ mil/year.

The new transported load capacity

$$D_w = 6000 - \Delta M_{pr} - 1{,}2\frac{\Delta M_f}{N_{p2}}, \quad (27)$$

where 6000 – the load capacity of the basis propulsion; ΔM_{pr} – the increase of the propulsion installation mass; 1.2 – the store of the fuel oil by the Register request; ΔM_f – the increase of the fuel oil consumption per a year; N_2 – the number of voyages per a year in the new case.

For the improved propulsion complex ΔM = – 1.61 t; ΔM_f = – 78.91 t; accordingly to the formula (27) D_w = 6003.273 t; D = 2.768458 US $ mil/year; P = 0.68626 US $ mil/year; P = 0.480382 US $ mil/year.

The comparison of the two cases is given in the table 1 for the conveniences of analyzing.

Table 1 – The comparison of the two cases parameters

Parameter	Value at the speed of	
	13 knots	14 knots
Cost of the engines, US $ mil	0.53125	
Cost of the reduction gears, US $ mil	0.045	
Cost of the shaft lines, US $ mil	0.05805	0.05
Cost of the propellers, US $ mil	0.19	
Cost of the propulsion installation, US $ mil	0.8243	0.81625
Cost of the installation assemblage, US $ mil	0.08243	0.081625
Capital investment, US $ mil	0.90673	0.897875
The reduced capital investment, US $ mil	0.13601	0.134681
Expenses for calling at ports, US $ mil/year	0.166011	0.170813
Maintenance, US $ mil/year	0.5	
Salaries and other, US $ mil/year	0.6	
Expenses of fuel oil, US $ mil/year	0.708271	0.676703
The operational costs, US $ mil/year	1.974282	1.947516
The reduced operational costs, US $ mil/year	2.110291	2.082198
Incomes, US $ mil/year	2.689164	2.768458
The profit, US $ mil/year	0.578873	0.68626
Taxes, US $ mil/year	0.173662	0.205878
The net profit, US $ mil/year	0.405211	0.480382

Variant 2. Modernization

In case of operation lasts longer than the recoupment time, let us say amortization period of about 10 years, we may recon that the capital investments have been already made back thus we can conduct calculations with respect to operational costs and additional capital investments into this modernization.

Without the modernization the profit would be P = 0.714882 US $ mil/year; P = 0.500418 US $ mil/year.

In order to carryout the modernization, it will take the additional capital investments for: dismantling US 5$ thousand; utilization (– US 0.146525$ mil); purchasing US 0.285$ mil; mantling US 10$ thousand. Thus the additional capital investments – US 0.153475$ mil.

With the modernization the profit would be P = 0.820941 US $ mil/year; P = 0.574659 US $ mil/year.

Thus the additional net profit would be ΔP_n = 0.074241 US $ mil/year. The time of recoupment 2.067 years.

The researches results. In addition, the influence of subjective preferences factors could be made allowance for by the use of the formula of the complete probability where hypotheses are considered preferences to accept the corresponding policy of the operation.

The responsible manager has to have got reliable information about the strategy situations in the corresponding operational conditions. If the set of possible alternatives forms a complete group of non-conjunctive events, the complete probability with respect to the subjective preferences

$$P(A) = \sum_{i=1}^{n} \pi_i P(A|\pi_i), \tag{28}$$

where A – the preferred alternative concerning the propulsion complex modernization; π_i – the subjective preferences of the possible alternatives; $P(A|\pi_i)$ – the conditional probability of the preferred alternative realization on the basis of that the corresponding operational mode has been preferred.

Then the expectation of the annual net profit would be

$$Exp[P_n] = \sum_{i=1}^{n} P_{n_i} p_i, \tag{29}$$

where P_{n_i} – the net profit from the table 1; p_i – the complete probability of the corresponding alternative in accordance with the formula (28).

In the case of the two variants we have the two alternatives: A – to except or B – to reject the possible modernization.

Conclusions. Accordingly to the given data and $\pi_A = 0.8$; $\pi_B = 0.2$; $P(A|\pi_A) = 0.85$; $P(B|\pi_A) = 0.15$; $P(A|\pi_B) = 0.15$; $P(B|\pi_B) = 0.85$; expectation referred to the formula (29) yields the result US 0.458582 $ mil/year.

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Гончаренко А.В. ДОЦІЛЬНІСТЬ УДОСКОНАЛЕННЯ ДИЗЕЛЬ-РЕДУКТОРНОЇ ПРОПУЛЬСИВНОЇ УСТАНОВКИ З УРАХУВАННЯМ СУБ'ЄКТИВНИХ ПЕРЕВАГ ЕКСПЛУАТАЦІЙНИХ ФАКТОРІВ

Відповідно до технічних даних на судно та його двигун розглянуто доцільніть удосконалення двохмашинної пропульсивної установки з дизель-редукторними агрегатами 6ЧРПН36/45 шляхом заміни редуктора разом із гвинтом з урахуванням суб'єктивних переваг експлуатаційних факторів.

Ключові слова: дизель-редукторний двигун, пропульсивна установка, гвинт, експлуатаційна стратегія, суб'єктивні переваги, багатоальтернативні ситуації.

Гончаренко А.В. ЦЕЛЕСООБРАЗНОСТЬ УСОВЕРШЕНСТВОВАНИЯ ДИЗЕЛЬ-РЕДУКТОРНОЙ ПРОПУЛЬСИВНОЙ УСТАНОВКИ С УЧЕТОМ СУБЪЕКТИВНЫХ ПРЕДПОЧТЕНИЙ ЭКСПЛУАТАЦИОННЫХ ФАКТОРОВ

Согласно техническим данным на судно и его двигатель рассмотрена целесообразность усовершенствования двухмашинной пропульсивной установки с дизель-редукторными агрегатами 6ЧРПН36/45 путем замены редуктора совместно с заменой винта с учетом субъективных предпочтений эксплуатационных факторов.

Ключевые слова: дизель-редукторный двигатель, пропульсивная установка, винт, эксплуатационная стратегия, субъективные предпочтения, многоальтернативные ситуации.