Bulletin of the Maritime Institute

Gdańsk, 2001, 28, 1

DANIEL GADOMSKI
Department of Operational Oceanography
Maritime Institute, Gdańsk, Poland

EFFECTS OF PRELIMINARY OPTIMISATION OF OPERATION OF MAIN ENGINES OF THE RESEARCH AND PREVENTION VESSEL "IMOR II", FOR A REPRESENTATIVE RANGE OF SHIP SPEEDS

Abstract

In the paper, basing on developed computation programs, the optimum states of operation of a multi-engine ship propelling system are analysed for the research and prevention vessel "Imor II", for ship speeds v<4 knots.In the analyses, for the expected ranges of variability of technical and operational parameters of the ship, characteristics of the main engines are used, and their influence on possible fuel cost savings are determined.

1. Profits from optimisation of propulsion operation

1.1. Characteristic of propulsion

The diesel-electric propulsion system of the ship-catamaran "Imor II" consists of the following main blocks:

- generator system VOLVO PENTA TAMD 163A-A,
- two generator systems VOLVO PENTA TAMD102A-A,
- electrotechnical system of transmission and electric energy stream control,
- two auxiliary bow propellers SCHOTTEL SPJ 22,
- two main stern propellers SCHOTTEL STP 200.

Load characteristics of the combustion engines:

$g_e\,[\frac{\text{g}}{\text{kWh}}]$ – unit effective fuel consumption

N [kW] – main engine power

- TAMD 163 A:
  $g_e = 6{,}084 \cdot 10^{-4} \cdot N^2 - 0{,}3894 \cdot N + 265$ for $N \in <110; 370>$
- TAMD 102 A:
  $g_e = 10{,}215 \cdot 10^{-3} \cdot N^2 - 4{,}063 \cdot N + 618$ for $N \in <100; 201>$

1.2. General remarks concerning the optimisation

The synthetic quality indicator W [3] is a measure of the cost of operation of propulsion of the "Imor II" during one average research voyage. Since it is a mathematical model, in its structure it contains the parameters, which identify the prototype vessel (at a certain level of detail), and the decision variables (g_e, N), which by definition determine the intensity of flow of fuel supplied to the engine:

$$W = W(\overline{X},\ \overline{Y}) \tag{1}$$

where:

$\overline{X} = (g_e, N)$ – set of decision variables,

$\overline{Y}$ – set of independent parameters.

The intensity of fuel flow in time (fuel consumption per hour) G_h:

$$G_h = 10^{-3} * g_e * N \qquad [\frac{\text{kg}}{\text{h}}]. \tag{2}$$

The indicator W allows the ship operator to use it as a numerical decision model when supporting main engine operation by using optimisation methodology. In this methodology, the discussed indicator is an objective function, which attaining an extreme minimum W^{**}

$$W^{**} = \text{MIN}\ W(\overline{X}\ ,\ \overline{Y}) = W(\overline{X}^{**}, \overline{Y}) \tag{3}$$

within the range of permissible solutions:

$$\overline{X}_{\text{min}} \leq \overline{X}^{**} \leq \overline{X}_{\text{max}} \tag{4}$$

$$F(\overline{X}) = C \tag{5}$$

where:

$F(\overline{X})$ – functional limitation of the objective function in the form of a load characteristic of a given engine,

C – calculation constant,

allows to determine the optimum (most profitable) values of decision variables $\overline{X}^{**} = (g_e^{**}, N^{**})$, where:

g_e^{**} $[\frac{\text{g}}{\text{kWh}}]$ – optimum value of unit effective fuel consumption of engine attaining power N^{**}

N^{**} [kW] – optimum value of engine power.

The optimum values of $\overline{X}$ ensure minimum cost of operation of the vessel propelling system in the sense of the used objective function for the determined values of parameters of the set $\overline{Y}$.

Basing on the known optimum values (g_e^{**}, N^{**}), the optimum fuel cost during operation (in a research voyage) of the "Imor II" can be determined.

$$\overline{Y} = \overline{Y}_1 \cup \overline{Y}_2 \cup \overline{Y}_3 \tag{6}$$

where:

$\overline{Y}_1$ – set of operational parameters,

$\overline{Y}_2$ – set of strategic parameters,

$\overline{Y}_3$ – set of ship constants.

The following parameters belong to the set $\overline{Y}_1$:

$v\,[\frac{\mathrm{m}}{\mathrm{s}}]$ – ship speed,

T_{po} [h] – stoppage time in port during 1 round voyage,

T_{pl} [h] – sailing time of ship during 1 round voyage,

α – engine load coefficient ($\alpha < 1$).

The following parameters belong to the set $\overline{Y}_2$:

$f\,[\frac{1}{\mathrm{year}}]$ – number of round voyages per year

T_L [years] – life time of the ship,

$C_p\,[\frac{\mathrm{PLN}}{\mathrm{t}}]$ – fuel price,

κ – calculation coefficient for lubricating oil consumption,

$R1$ – coefficient of fuel price variability.

The following parameters belong to set $\overline{Y}_3$:

C_Σ [PLN] – cost of installed main propulsion units (constant value),

N_Σ [kW] – total mechanical power of installed main combustion engines (constant value).

For the various values of parameters of set $\overline{Y}$ of "Imor II", one may expect various optimum values of decision variables (g_e^{**}, N^{**}). In the work [3] a preliminary discussion of the detailed structure of the synthetic quality indicator W and the method of seeking the extreme minimum value are presented. Further in the present paper, the detailed forms of synthetic indicators of quality of operation of the ship propulsion for ship speeds $v \in <3; 4>$ knots shall be described.

The described above synthetic quality indicator W will allow to evaluate profitability in operational practice of "Imor II" with respect to:

- methodology, and
- finances.

1.3. Methodological profits from optimisation of ship propulsion

The quality indicator W is an algorithm of defined degree of detail, which aggregates the basic operational parameters of the "Imor II". It describes, in an orderly way, the process of fuel supply to the engine(s) in the environment of technical and operational parameters of the "Imor II". The mathematical model of the quality indicator W describes the cause-and-effect relationship between the intensity of flow of supplied fuel (cause) and the cost of operation of the ship propelling system (cause).

In this situation, the quality indicator W is of basic importance to the ship operator. It supports operational decision-making concerning the work of ship engines for the expected range of variability of the independent variables. The model of indicator W will become even more important when the relationships between the decision variables and each independent variable from the $\overline{Y}_1$ and $\overline{Y}_2$ sets will be investigated. Results of these investigations will allow to develop an operational strategy for the "Imor II".

1.4. Financial profits from optimisation of ship propulsion

In accordance with the concept of the objective function W, the optimum values of g_e^{**}, N^{**} determine the state of operation of the ship propelling system for a given sequence of the engine system, in which the cost of propulsion operation during one average voyage is smallest.

In relation to the nominal state of work of the engine, which is characterised by the nominal values of g_e, N, the following savings ΔK in fuel costs are obtained after optimisation:

$$\Delta K = K_{\text{nom}} - K^{*} \tag{7}$$

where:

– nominal fuel costs K_{nom}:

$$K_{\text{nom}} = g_e * N * C_p * T_p * \kappa * R1 * 10^{-6} \quad \text{[PLN]} \tag{8}$$

– fuel costs after optimisation K^{*}:

$$K^{*} = g_e^{**} * N^{**} * C_p * T_p * \kappa * R1 * 10^{-6} \quad \text{[PLN]} \tag{9}$$

g_e, g_e^{**} – nominal, optimum unit fuel consumption,
N, N^{**} – nominal, optimum propelling engine power,
T_p – time of operation of the propelling engine.

For $N^{**} < N$ i $g_e^{**} > g_e$ the effectiveness rate of savings on fuel cost is:

$$e_p = \left(1 - \frac{g_e^{**}}{g_e} * \frac{N^{**}}{N}\right) * 100\% \tag{10}$$

Because as a rule $N^{**} < N$, at optimum state of work of ship propulsion the vessel will be operated at the economical speed v_e, which is smaller than the speed v, attained for nominal power N.

Another possibility of saving on fuel costs will also result from the shape of the hyper-surface, which is the geometric spatial representation of the objective function W [3]. Quite important may be such a shape of this surface, in accordance with which the objective function W attains an extreme minimum not just at one point (with co-ordinates g_e^{**}, N^{**}), but in the range of values Δg_e^{**}, ΔN^{**}. For the discussed case, fuel cost savings will result from the possibility of selecting the time T_p of the ship propulsion system operation. Then it may be possible that fuel costs will be constant (the hyper-surface has a flat part) for such optimum powers that $N_1^{**} > N_2^{**}$ i $g_{e1}^{**} \cong g_{e2}^{**}$. This is the case of a flat extreme of objective function W. For selecting the time of operation T_p we have the relationship (resulting from the equation $K_1^{*} = K_2^{*}$):

$$1 < \frac{N_1^{**}}{N_2^{**}} = \frac{T_{p1} + \Delta T_p}{T_{p1}} \tag{11}$$

in which ΔT_p is the extension of ship sailing time (the time of additional work of the engine, resulting from the condition of constant fuel costs).

2. Characteristic of sequences of propelling engines

During a typical research voyage, “Imor II” will sail at speed $v \in \langle 3; 4 \rangle$ [knots]. Such speed is required during work with sounding equipment, which is the basic equipment of the vessel, in order to ensure proper resolution of oceanographic measurements.

At the present level of knowledge about the sailing properties of the "Imor II", it may be assumed that ship speed $v \leq 4$ [knots] will occur at the following sequences of propelling system operation [3]:

1) sequence I – only one TAMD 102A/HC propelling unit is working,
2) sequence II – only the TAMD 163A/HC propelling unit is working,
3) sequence III – two TAMD 102A/HC propelling units are working.

In general, the range of mechanical power obtained in the three sequences is 100 kW to 402 kW [3]. Taking into account that power losses during transmission propellers and for power consumption for other than propelling needs are about 70% (the so-called losses), the power at propellers will be 30 kW to 120 kW respectively. The obtained power range at the propellers ensure its supply with sufficient margin with respect to pulling power, taking into account propeller efficiency, bad sailing conditions and the inertia of the diesel-electric propelling system. The resulting power reserve is needed to ensure proper steering capacity and effectiveness of work of the ship's dynamic positioning system. For ship speed $v \leq 4$ knots, in accordance with the towrope curve [1, 4] towrope power is (20÷30) kW.

2.1. Sequence I of propelling system operation

In sequence I only one engine TAMD 102A is working. The remaining engines are stopped. The mechanical power at disposal is (100÷201) kW. At 70% loss level, the power at propellers is then (30÷60) kW. In sequence I, the propelling system can work continuously in good sailing conditions. In such a case, limitations on power consumption for non-propulsion needs will have to be imposed. There will be some limitation on the work of the dynamic positioning system, especially if sailing conditions would become worse. At low ship speed its steering capacity is low, and this increases the power demand for effective operation of the dynamic positioning system.

2.2. Sequence II of propelling system operation

In this sequence, only the TAMD 163A engine is working. The remaining two TAMD 102A engines are stopped. The power generated by the engine power is (110÷370) kW. At 70% losses this corresponds to power at propellers of (30÷110) kW.

This sequence is predisposed for continuous work in average sailing conditions with additionally operating auxiliary propellers. There is also a possibility of simultaneous work of other technological (research) apparatus installed on the ship. Consumption of non-propulsion power will be less limited than in sequence I. Good conditions for the work of the dynamic positioning system will be ensured.

2.3. Sequence III of propelling system operation

Two TAMD 102A engines work at the same time. The TAMD 163A engine is stopped. Mechanical power of 301 kW to 402 kW is produced. At 70% loss this means 90 kW to 120 kW at the propellers. This sequence is suitable for continuous operation in difficult sailing conditions, with all propellers working. No limitations are imposed on power consumption for non-propulsion needs. The dynamic positioning system can be fully operative without limiting the operation of the vessel.

3. Detailed forms of indicators of propulsion operation quality

Expression (1) is a general formula for the relationship:

$$W = (E_o + E_r) * (KJ_o + KJ_r) \qquad \text{[PLN]} \qquad (12)$$

where:

E_o [kWh] – mechanical energy freed in port,

E_r [kWh] – mechanical energy freed when the ship is sailing,

KJ_o $[\frac{\text{PLN}}{\text{kWh}}]$ – unit cost of reserve power (power remaining at disposal),

KJ_r $[\frac{\text{PLN}}{\text{kWh}}]$ – unit cost of developed power.

For the three sequences of propelling engine operation at ship speed $v \in <3; 4>$ knots, the above quantities are component functions of the indicator *W* of propulsion operation quality, and they have different mathematical relationships. The structure of these relationships depends on the method of calculating the so-called propulsion indicator *k* and on the formulation of component quantities, describing their physical sense.

3.1. The problem of the subjective range of quality indicator *W*

Generally, the quality indicator *W* described by expression (12), serves for selecting the optimum work parameters $\overline{X}^{**}$ of a given propelling engine in the case of an environment defined by the set of independent variables $\overline{Y}$. Its physical sense is connected with the absolute cost of propelling system operation **during one average research voyage of "Imor II"**. For a calculation period of one year or more, the objective function *W* must take into account additional costs of repairs of the propelling engine. These costs depend on the recommended scope of maintenance repairs, also on the way in which the engine is used.

Planned costs are a constant calculation item for the whole period of ship (propelling system) life, and are not dependent on the variability of decision variables $\overline{X}$. As a rule they are related with the nominal loading of the engine. Engine repair costs, resulting from the way the engine is used, depend especially on the way the engine is loaded, work regimes and effort of material of the structural elements. These costs vary in longer calculation periods, and therefore they are difficult to describe in a standard form within the deterministic model of the used objective function *W*. From the quality point of view, variable engine repair costs depend on its power loading, time of work under given loading, changes of loading and changes of time of operation, and on the consequences of the various states of work. These factors are difficult to plan or predict, especially when the propelling system of the "Imor II" and the ship itself are a prototype technical system. The determination of the relationship, describing with adequate to the needs of the optimisation problem detail and accuracy the magnitude of variable costs of engine repairs, will be possible only after at least one cycle of repairs. The deciding role will be played by the consequences of engine operation under other than nominal loading (appearing in the form of mechanical wear of cylinder liners, piston rings, development of carbon deposits) and by the number of work-hours. These parameters will form the measures of variable engine repair costs. Formulation of a relationship describing these costs will be possible on the basis of retrospective data obtained during operation of "Imor II".

3.2. Formulas for calculation of the propulsion indicator *k*

The propulsion indicator *k* is a non-dimensional calculation coefficient [3], which allows to form the algorithm of the quality indicator *W*. At the present level of knowledge about the operational properties of the "Imor II", it may be presented as the following function:

- for ship speed $v \in <3; 3{,}5>$ [knots]; $v \in <1{,}54; 1{,}80>$ $[\frac{\text{m}}{\text{s}}]$:

$$k(v) = 3{,}01 - 0{,}85 * v \tag{13}$$

- for ship speed $v \in (3{,}5; 4>$ [knots]; $v \in (1{,}80; 2{,}06>$ $[\frac{\text{m}}{\text{s}}]$:

$$k(v) = 8{,}26 - 3{,}77 * v \tag{14}$$

Basing on the expected operational properties of the "Imor II", expression (13) corresponds to work of the propelling system under sequence I or II. Expression (14) corresponds to sequence III of work of the propelling system.

3.3. Component functions of the indicator of quality of propelling system operation *W* for sequence I or II

Characteristic for these sequences is operation of only one type of engine, i.e TAMD 102A or TAMD 163A. Because of this the expressions for component functions are the same for both sequences.

The mechanical energy generated in port is calculated as:

$$E_o = \alpha * N(g_e) * T_{\text{po}} \qquad [\text{kWh}] \tag{15}$$

where:

$N(g_e)$ [kW] – characteristic of the engine.

Mechanical energy generated when the ship is sailing is calculated as:

$$E_r = g_e * N(g_e) * k(v) * v^2 * T_{\text{pł}} * 10^{-3} \qquad [\text{kWh}] \tag{16}$$

where:

$N(g_e)$ – as above,

$k(v)$ – propulsion indicator.

The unit cost of reserve power (power remaining at disposal) is calculated from:

$$KJ_o = C_\Sigma * \{f * T_L * [(T_{\text{po}} + T_{\text{pł}}) * N_\Sigma - N * (T_{\text{pł}} + \alpha * T_{\text{po}})]\}^{-1} \qquad [\frac{\text{PLN}}{\text{kWh}}] \tag{17}$$

The unit cost of running power is calculated from:

$$KJ_r = g_e(N) * C_p * \kappa * R1 * 10^{-6} \qquad [\frac{\text{PLN}}{\text{kWh}}] \tag{18}$$

where:

$g_e(N)$ $[\frac{\text{g}}{\text{kWh}}]$ – characteristic of the engine.

3.4. Component functions of the indicator of quality of propelling system operation *W* for sequence III (two TAMD 102A engines are working)

The mechanical energy generated in port is calculated depending on the number of engines working in port:

- when one TAMD 102A engine is working in port:

$$E_o = \alpha * N(g_e) * T_{\text{po}} \qquad [\text{kWh}] \tag{19}$$

- when two TAMD 102A engines are working in port (one engine partly loaded, the other at rated power 201 kW):

$$E_o = [\alpha * N(g_e) + 201] * T_{\text{po}} \qquad [\text{kWh}] \tag{20}$$

where:

$N(g_e)$ [kW] – characteristic of the engine.

Mechanical energy generated when the ship is sailing (two engines are working) is calculated as:

$$E_r = [g_e * N(g_e) + 216 * 201] * k(v) * v^2 * T_{\text{pł}} * 10^{-3} \qquad [\text{kWh}] \tag{21}$$

where:

$N(g_e)$ [kW] – characteristic of the engine,

$k(v)$ – propelling indicator of the ship,

T_{pl} [h] – sailing time of the ship during one round voyage.

The numbers in these relationships have the following meaning:

201 [kW] – rated power of TAMD 102A engine,

216 $[\frac{\text{g}}{\text{kWh}}]$ – unit rated fuel consumption of TAMD 102A engine.

The unit cost of reserve power is calculated as:

– when one TAMD 102A engine works in port:

$$KJ_o = C_\Sigma * \{f * T_L * [(T_{\text{po}} + T_{\text{pł}}) * N_\Sigma - \alpha * N * T_{\text{po}} - (N + 201) * T_{\text{pł}}]\}^{-1} \, [\frac{\text{PLN}}{\text{kWh}}] \tag{22}$$

– when two TAMD 102A engines work in port (one engine works at rated power 201 kW):

$$KJ_o = C_\Sigma * \{f * T_L * \{(T_{\text{po}} + T_{\text{pł}}) * N_\Sigma - (\alpha * N + 201) * T_{\text{po}} - (N + 201) * T_{\text{pł}}]^{-1} \, [\frac{\text{PLN}}{\text{kWh}}] \tag{23}$$

The numbers in expressions (22) and (23) have the same meaning as in expression (17).

For sequence III, the unit cost of generated running power is calculated from the relationship:

$$KJ_r = [g_e(N) + 216] * C_p * \kappa * R1 * 10^{-6} \qquad [\frac{\text{PLN}}{\text{kWh}}] \tag{24}$$

The appearing in (24) number 216 $[\frac{\text{g}}{\text{kWh}}]$ is the rated unit fuel consumption of the TAMD 102A engine. The remaining quantities have the same meaning as in expression (18).

4. Numerical experiments

Basing on the presented above assumptions and methods of calculation, the following numerical experiments were carried out:

a) preliminary searching for optimum values of g_e^{**}, N^{**} for sequences I, II and III,

b) determination of the so-called maximum fuel cost savings after optimisation.

For both experiments, appropriate programs were developed in TurboPascal 7.0. Programs for the first experiment are in files sekw (I).pas, sekw (II).pas and sekw (III).pas, which are installed in the computer IM 682/491 in directory C:\BP\NAPED.

The prototype for the program for the experiment of seeking the so-called maximum fuel cost savings for sequence I are the files: Boxww.dat and Boxww.pas installed in the computer IM 682/491 in directory C:\BOX. Similar programs for sequences II and III will have the same structure. The only difference will be that in separate blocks of these programs there will be some elements, which correspond to the various load characteristics, expressions for the propulsion indicator k and the presented expressions for calculating the component functions of the indicator W. The block for iterative searching for the absolute extremum of the quality indicator will remain unchanged.

4.1. Characteristic of results of the numerical experiment of searching for optimum values of g_e^{**}, N^{**} for selected engine operation sequences

Tables 1, 2 and 3 contain the preliminary results of optimisation calculations for the selected engine sequences. These are the costs of propelling system operation during one average voyage, calculated for the following values of independent parameters – set $\bar{Y}$:

$\alpha = 0,8$

$T_{\mathrm{po}} = 24$ h

$T_{\mathrm{pl}} = 240$ h

$v = 1,54\ [\frac{\mathrm{m}}{\mathrm{s}}]$ – for sequence I (Table 1)

$v = 1,80\ [\frac{\mathrm{m}}{\mathrm{s}}]$ – for sequence II (Table 2)

$v = 2,06\ [\frac{\mathrm{m}}{\mathrm{s}}]$ – for sequence III (Table 3)

$C_{\Sigma} = 800\,000$ PLN

$f = 20$

$T_L = 20$ year

$N_{\Sigma} = 772$ kW

$C_p = 1215\ [\frac{\mathrm{PLN}}{\mathrm{tonne}}]$

$\kappa = 1,03$

$R1 = 1$.

When in sequence II the range of loading of the TAMD 163A engine is limited to $N \in <130; 370>$ [kW], which is justified by the high risk of operation and the reduction of engine reliability for power $N < 130$ [kW], all results confirm the presence of an absolute minimum of costs of operation of the "Imor II" propelling system.

The following absolute extreme values were obtained:

- for sequence I:

$$g_o = 251\ \frac{\mathrm{g}}{\mathrm{kWh}};\ N_o = N_{\mathrm{nom}} = 201\ \mathrm{kW}$$

- for sequence II:

$$g_o = 219\ \frac{\mathrm{g}}{\mathrm{kWh}};\ N_o = 292\ \mathrm{kW}$$

- for sequence III:

$$g_o = 251\ \frac{\mathrm{g}}{\mathrm{kWh}};\ N_o = N_{\mathrm{nom}} = 201\ \mathrm{kW}.$$

Table 1. Numerical experiment: calculation of the value of quality indicator *W*(I) [PLN] (program “sekw(I). pas”)

Engine power [kW]	Unit effective fuel consumption $\left[\frac{g}{kWh}\right]$										
	216	221	226	231	236	241	246	251	256	261	265
100	18 302	17 124	16 101	15 246	14 574	14 097	13 829	13 783	13 973	14 412	14 952
110	17 222	16 114	15 151	14 347	13 714	13 265	13 013	12 970	13 149	13 562	14 070
120	16 259	15 212	14 303	13 544	12 947	12 523	12 285	12 244	12 413	12 803	13 283
130	15 411	14 419	13 557	12 838	12 272	11 870	11 644	11 606	11 766	12 136	12 590
140	14 680	13 734	12 914	12 229	11 689	11 307	11 092	11 055	11 207	11 560	11 993
150	14 064	13 159	12 372	11 716	11 199	10 833	10 627	10 591	10 737	11 075	11 490
160	13 565	12 691	11 933	11 300	10 801	10 448	10 249	10 215	10 356	10 682	11 082
170	13 181	12 333	11 596	10 981	10 496	10 153	9 960	9 927	10 064	10 380	10 769
180	12 914	12 083	11 361	10 758	10 283	9 947	9 758	9 725	9 860	10 170	10 550
190	12 763	11 942	11 228	10 632	10 163	9 831	9 644	9 612	9 744	10 051	10 427
201	12 731	11 912	11 200	10 606	10 138	9 806	9 619	9 588	9 720	10 025	10 401

Table 2. Numerical experiment: calculation of the value of quality indicator *W*(II) [PLN] (program "sekw(II). pas")

Engine power [kW]	Unit effective fuel consumption $\left[\frac{g}{kWh}\right]$						
	203	207	211	215	219	223	227
110	27 830	20 052	15 418	13 219	12 683	12 979	13 211
136	27 146	19 559	15 039	12 894	12 371	12 660	12 886
162	26 561	19 137	14 715	12 616	12 105	12 387	12 608
188	26 076	18 788	14 446	12 386	11 884	12 161	12 378
214	25 692	18 511	14 233	12 203	11 709	11 981	12 195
240	25 408	18 307	14 076	12 068	11 579	11 849	12 061
266	25 227	18 176	13 975	11 982	11 497	11 765	11 975
292	25 148	18 119	13 932	11 945	11 461	11 728	11 937
318	25 173	18 138	13 946	11 957	11 472	11 740	11 949
344	25 304	18 232	14 018	12 019	11 532	11 801	12 012
370	25 542	18 403	14 150	12 132	11 640	11 912	12 125

Table 3. Numerical experiment: calculation of the value of quality indicator *W*(III) [PLN] (program “sekw(III). pas”)

Engine power [kW]	Unit effective fuel consumption $\left[\frac{g}{kWh}\right]$										
	216	221	226	231	236	241	246	251	256	261	265
100	32 023	30 891	29 909	29 088	28 441	27 978	27 711	27 653	27 815	28 209	28 699
110	30 905	29 813	28 865	28 073	27 448	27 001	26 744	26 688	26 844	27 224	27 697
120	29 909	28 852	27 934	27 168	26 563	26 130	25 882	25 827	25 979	26 347	26 804
130	29 034	28 007	27 117	26 372	25 785	25 366	25 124	25 072	25 218	25 576	26 020
140	28 280	27 280	26 413	25 688	25 116	24 707	24 472	24 421	24 564	24 911	25 344
150	27 647	26 670	25 822	25 113	24 554	24 154	23 924	23 874	24 014	24 354	24 777
160	27 136	26 177	25 344	24 649	24 100	23 708	23 482	23 433	23 570	23 904	24 319
170	26 747	25 801	24 981	24 295	23 754	23 367	23 145	23 097	23 232	23 561	23 970
180	26 479	28 543	24 730	24 052	23 516	23 133	22 913	22 865	22 999	23 325	23 730
190	26 332	25 401	24 594	23 919	23 386	23 006	22 787	22 739	22 872	23 196	23 599
201	26 312	25 382	24 575	23 900	23 368	22 988	22 769	22 721	22 855	23 178	23 581

Taking into account the load characteristics of the engines, which form functional limitations of objective function W minimisation, the optimum decision variables g_e^{**}, N^{**} are the following[1]:

- for sequence I (propelling engine TAMD 102A):

$$g_e^{**} = g_o = 251 \ \frac{\text{g}}{\text{kWh}}$$

$$N^{**} = N(g_e^{**}) = 45{,}8*10^{-3}*251^2 - 23{,}34*251 + 3103 = 130 \text{ kW}$$

- for sequence II (propelling engine TAMD 163A):

$$g_e^{**} = g_o = 219 \ \frac{\text{g}}{\text{kWh}}$$

$$N^{**} = N(g_e^{**}) = -29{,}14*10^{-3}*219^3 + 19{,}47*219^2 - 4335{,}7*219 + 321945 = 157 \text{ kW}$$

- for sequence III (propelling engine TAMD 102A):

$$g_e^{**} = g_o = 251 \ \frac{\text{g}}{\text{kWh}}$$

$$N^{**} = N(g_e^{**} = 251) = 130 \text{ kW}$$

The minimum costs of operation of the propelling system, defined for one average voyage by means of the synthetic quality indicator W, are respectively:

- sequence I: W^{**} = 11 606 PLN
- sequence II: W^{**} = 12 153 PLN
- sequence III: W^{**} = 25 072 PLN

In these costs, the cost of fuel consumed by the engines at optimum operating conditions is:

- sequence I:

$$K_{\text{pal}} = 251*130*1215*(24 + 240)*10^{-6} = 10\,466 \text{ PLN}$$

- sequence II:

$$K_{\text{pal}} = 219*157*1215*(24 + 240)*10^{-6} = 11\,029 \text{ PLN}$$

- sequence III:

$$K_{\text{pal}} = (251*130 + 216*201)*1215*(24 + 240) = 24\,392 \text{ PLN}$$

For the obtained optimum values of g_e^{**}, N^{**}, the rate of effectiveness of saving on fuel cost (10) is:

- sequence I:

$$e_{p1} = (1 - \frac{251*130}{216*201}) * 100\% = 25\%$$

- sequence II:

$$e_{p2} = (1 - \frac{219*157}{203*370}) * 100\% = 54\%$$

- sequence III:

$$e_{p3} = \frac{2*g_e*N-(g_e^{**}*N^{**}+g_e*N)}{2*g_e*N} * 100\%$$

$$e_{p3} = (1 - \frac{251*130+216*201}{2*216*201}) * 100\% = 12{,}4\%$$

---

[1] The described calculations belong to the tasks of non-linear mathematical programming with functional limitation. Because of that, for preliminary interpretation, values presented in Tables 1-3 must be consistent with the values of the limiting function. At the same time these values must conform with the condition that the extreme minimum of the quality indicator W is reached.

The presented results show that savings on fuel costs during an average voyage grow with decreasing optimum power of operating engines. However, for longer periods of ship operation, the growing repair costs caused by operation of the engines at less than rated loading must be taken into account (p. 3.1 of this paper).

In operational practice the increasing cost of repairs will significantly reduce the possible fuel cost savings.

4.2. Description of program for calculating maximum fuel cost savings

The program Boxww.pas concerns a defined engine operation sequence, and contains three basic blocks:

No. 1 – for input of values of each independent parameter,
No. 2 – algorithm of objective function minimisation,
No. 3 – calculation of output values.

Block No. 1 is a data file with strict structure, named Boxww.dat and designed for the Boxww.pas program. It is in MS-DOS. Data input can be also carried out under Norton Commander.

Block No. 2 contains the iteration algorithm for finding the global (absolute) extreme of the objective function. The algorithm is based on the COMPLEX method and is written in TurboPascal 7.0. In this algorithm, the basics of which are due to Box [2], the concept of the so-called creeping simplex is used. Most important in this algorithm is the operation of comparing the values of the objective function. In result of this operation, the smaller value of the function is fed back into the next calculation step. Iterative searching for the co-ordinates of the global extreme ends when these co-ordinates differ less than the adopted at the start criterion of stopping computations. The program for the algorithm was developed basing on [5].

Block No. 3 concerns the specifics of the problem, and in this case allows obtaining such output values as the optimum unit fuel consumption g_e^{**}, optimum engine power N^{**} and maximum fuel cost savings for given sequence I of operating engines. The block is written in TurboPascal 7.0. The block takes into account simultaneously the optimum unit fuel consumption and the load characteristic of the working engine. The basis for the calculations is that the absolute extremum of engine power is as a rule equivalent with its rated power. For the criterion MIN W this forces searching for optimum decision variables along the direction of crossing of the absolute extremum of the unit effective fuel consumption and the functional limitation of objective function minimisation in the form of the load characteristic of given propelling engine.

4.3. Preliminary testing of variability of fuel cost savings

For needs of analysis, Table 4 gives the ranges of variability of each independent parameter of set $\overline{Y}$ and the representative vector $\overline{Y}_{\mathrm{REPR}}$ These ranges correspond to the planned variability of values of operational parameters of the "Imor II".

The carried out tests of the influence of the value of parameters $\overline{Y}$ on the optimum values g_e^{**}, N^{**} for sequence I have shown that practically there is no influence. Obtained results indicate that the range of change of g_e^{**}, N^{**} is less than 1%. Taking into account the relative error of g_e, which is 5%, and the standard relative error of N of 3%, changes of parameters $\overline{Y}$ do not result in changes of position of the minimum of quality indicator W(I) which could be of significance for the operation of the "Imor II".

Table 4. Ranges of variability of independent parameters of set $\overline{Y}$

Specification	Measure	Minimum value	Maximum value	$\overline{Y}_{REPR}$
α - coefficient of loading	-	0,6	1,0	0,8
T_{po} - stoppage time in port	h	12	36	24
T_{pl} - sailing time	h	120	312	216
v - ship speed;	$\frac{m}{s}$	1,54	2,06	.
C_{Σ} - cost of units	PLN	-	-	800 000
f_1 - number of voyages per year	$\frac{1}{year}$	20	40	30
T_L - ship's life	years	16	24	20
N_{Σ} - installed mechanical power	kW	-	-	772
C_p – price of fuel	PLN/tonne	1100	1500	1300
κ - coefficient of lubricating oil cost	-	1,02	1,04	1,03
$R1$ - coefficient of fuel price variability	-	1,0	1,4	1,2

However, this conclusion should not be extended to sequences II and III.

Table 5 shows the influence of appropriate independent parameters on the variability of fuel cost savings for set $\overline{Y}_{REPR}$ in sequence I.

Table 5. Variability of fuel cost savings for sequence I of propelling system

T_{pl}	ΔK	C_p	ΔK	$R1$	ΔK
[h]	[PLN]	[PLN/tonne]	[PLN]	[-]	[PLN]
120	2081,1	1100	3171,1	1,0	3123,0
168	2914,4	1200	3459,4	1,1	3435,3
216	3747,7	1300	3747,7	1,2	3747,7
264	4580,8	1400	4035,9	1,3	4060,0
312	5413,9	1500	4324,2	1,4	4372,3

Table 5 indicates that possible fuel cost savings for sequence I and determined set $\overline{Y}_{REPR}$ may vary from about 2000 PLN to 5400 PLN per voyage.

SUMMARY AND CONCLUSIONS

1) The optimisation of operation of the "Imor II" propelling system is based on a set of decision variables, which define in time the intensity of fuel flow to the engines, and allows to obtain financial and methodological advantages. The financial advantage consists in fuel cost savings. The methodological advantage is related to the possibility of obtaining a methodology for optimising recommendations for rational supporting the process of ship operation.

2) For "Imor II" speeds of $v < 4$ knots, sequence I of the propelling system is a variant, which after optimising ensures average fuel cost savings of the order of 25%. Sequence II allows to reach, after optimising, the highest fuel cost savings of the order of 50%. Sequence III results, after optimising, in the lowest fuel cost savings of the order of about 12%.

   Generally, resulting from optimisation fuel cost savings during one voyage increase with decreasing optimum engine power. The mentioned above values of fuel cost savings are of a preliminary character, since it is assumed that the supply of optimum propelling power from the operating engines is sufficient for ship operation. The preliminary character of the obtained results of computations is also due to the degree of detail of the computation algorithms.

3) In the long term balance of costs of propelling system operation, obtained from optimisation fuel cost savings will be reduced due to increasing costs of engine repair, caused by engine operation under partial optimal loading.

4) The developed pilot program for calculating maximum fuel cost savings for operation of the ship propelling system in sequence I shows, that the permissible ranges of technical and operational parameters of the "Imor II" do not have necessarily to decide about a significant for the ship operation variability of optimum values of decision parameters. Numerical experiments confirm that optimum decision variables in sequence I vary within the manufacturers tolerances for the propelling engines. In order to investigate these relations for ship speeds $v > 4$ knots, and for the remaining 6 sequences of propelling system operation [3], development of appropriate computation programs and further numerical experiments are needed

References

[1] *Model test of the research and prevention vessel RH/1443/99,* 1998, Centrum Techniki Okrętowej, Osrodek Hydromechaniki Okrętu, Gdańsk (in Polish).

[2] Findeisen W., Szymanowski J., Wierzbicki A., 1980, *Theory and calculation methods of optimisation.* PWN, Warszawa (in Polish).

[3] Gadomski D., 2000, *Optimisation of propelling system of a research and prevention vessel with dynamic positioning system; stage II, task 1: Assumptions and preliminary version of the algorithm for optimising the propelling system of the "Imor II" with dynamic positioning system.* WW IM No. 5654, Gdańsk (in Polish).

[4] Gadomski D., 1999, *Optimisation of propelling system of a research and prevention vessel with dynamic positioning system; stage I: Characteristics and scope of planned investigation of states of work of the special propelling system of a research and prevention vessel with dynamic positioning system.* WW IM No. 5549, Gdańsk (in Polish).

[5] Gadomski D., Kot A., 1997, *Programming of computations for the needs of preliminary designing of a research and prevention vessel.* WW IM No. 5286, Gdańsk (in Polish).