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A METHOD FOR PRELIMINARY OPTIMISATION OF THE SELECTION OF HIGH SPEED SHIP ENGINES

Abstract

A method for preliminary optimisation of the selection of high speed ship engines is presented using the example of MAN engines which form a part of Diesel-electric units of DEMP A/S.

After appropriate adaptation of the component functions of the objective function, i.e. of the cost of purchasing the engine and of the cost of consumed fuel, the presented method allows to make comparative calculations for other main engines and to take simultaneously into account a given structure of the propelling installation.

1. Functions of the research/prevention ship

The research/prevention ship (RPS) for the needs of the Maritime Institute is to fulfil the following functions:

a) research - investigations of sea bottom, water pollution, etc.,

b) prevention - passive protection of marine environment, i.e. minimising the effects of oil spills at sea.

The area of operation of the RPS shall be the economic zone of Poland on the Baltic Sea, and also other water areas - as need arises from contracts and international agreements and regulations (conventions) concerning sea areas.

2. Conditions and operational states of the RPS

It is planned that the RPS shall fulfil her functions at up to 4^{0}B sea state, outside the ice season.

The characteristic states of operation of the vessel will be:

— duty at a coastal port,

- approaching to a polygon,
- work on a polygon,
- approach to the port of duty.

All Baltic ports in which station vessels permitted to sail on the Baltic can be ports of duty for the RPS.

3. Structural and operational assumptions for the RPS

The basic structural and operational assumptions for the RPS are following:

- large volume of the hull, allowing fulfilment of the basic functions mentioned in p. 1,
- small draught ($T \leq 2.0$ m), allowing access to ports in acc. with p. 2,
- hull length $L_{PP} \leq 30$ m,
- appropriate trim,
- high transverse stability of the hull,
- high manoeuvrability and simultaneous high precision in maintaining course in respect to conditions of navigation.

The large volume of the hull is necessary to contain various laboratory, crew and research equipment storage and spill removal spaces. It is planned that the ship's hull will provide ample space on the deck for (besides the superstructure) 2 containers of 2x1C (2x1 TEU) size for the spill containment barrier. Besides, the open space of the hull will allow to station a pontoon (with own propulsion) for deploying the barrier. A davit with sufficiently long arm and sufficient hoisting power to lift on board the containers, lowering the pontoon and for boring in the sea bottom with vibration sounders will also have to be located on the deck. Working with a vibration sounder, which shall be boring 3 to 6 m into the sea bottom, requires high transverse stability of the RPS.

The demand for high manoeuvrability and good course maintenance for different conditions of navigation decides that the RPS engine room must fulfil the requirements of dynamic positioning.

3.1. Assumptions for the hull

The above basic assumptions lead to the conclusion that the displacement hull of the RPS will be a catamaran with large work deck, shape and block coefficient minimising resistance for $T \leq 2.0$ m and $L_{PP} \leq 30$ m.

In this place it should be stressed that the functions of the RPS shall not serve to generate profit from cargo carriage. The RPS will not perform cargo transportation functions. Rationale of the structure and operation of the RPS will be mainly based on the minimisation of costs of building the vessel and of costs of operation incurred to the ship owner (the Maritime Institute) during the ships life.

The preliminary design of the hull of the vessel, in the form of a catamaran, was developed earlier on order of the Department of Operational Oceanography of the Maritime Institute [9].

3.2. Assumptions for the engine room

The engine room (ER), a basic structural module of the vessel, has an overwhelming influence on the operational costs of the RPS. This influence results from the cost of building the engine room and from the costs of transforming the chemical energy of fuel into effective energy utilised on the ship in the period of ship operation.

Available literature does not provide technical descriptions of similar to the RPS vessels. In this situation, the basic problem of the design is the selection, on the basis of general qualitative analysis, of the type of ER for a hull fulfilling the above listed requirements, and then carrying out a preliminary optimisation of the selected type of ER.

Such an optimisation will be of preliminary character, since due to the lack of data from similar ships, obtained optimum parameters will be loaded with a certain error.

However, the basic advantage of such optimisation is that it allows to connect into one logical-numerical system all the parameters which describe and characterise the RPS, and to perform numerical analyses of the influence of these parameters on the optimum values of decision variables, describing with given accuracy the ER of the vessel of selected type, for various characteristics of operational states.

3.3. Qualitative analysis for ER type selection

Given the mentioned above functions of the RPS and limitations of hull structure, the following types of engine room can be considered:

A. piston combustion engine with mechanical transmission

B. combustion (piston) - electric engine

C. turbine combustion engine with mechanical transmission.

The above types of engine rooms are characterised by a sufficiently high concentration of power per unit of hull volume, small dimensions and high energy efficiency.

In Table 1 an assessment of the considered types of engine rooms is presented, using a 1 to 5 scale. The value “1" is given to the best solution, value "5" - to the worst from the point of view of a given criterion.

Analysis shows that the required type of engine room will be a combustion (piston) - electric ER. Though this type of engine requires high qualifications of the crew, its manoeuvrability, technical possibilities of realising dynamic positioning and easiness of repairs obtain the highest notes. Additionally, a combustion-electric ER allows to distribute mass symmetrically over both hulls of the catamaran and gives simultaneously a possibility of transferring in extreme states the power of one power unit, e.g. of the port side unit to the starboard propeller, or the reverse.

Inn such a situation, work of the RPS will be characterised by high operational reliability and the ability of the ER to work in extreme states, e.g. if one of the two power units is damaged.

Since the smallest modern medium speed piston combustion engines, i.e. the MAN - B&W engines type L 16/24 with minimum (due to number of cylinders) maximum continuous power ca. 450 kW, have an assembly height (for dismounting the piston-crankshaft system) of $H2 = 2930$ mm [8], and because the draught of the RPS should be $T \leq 2.0$ m., within the selected type of ER only combustion-electric units with high speed piston engines fit the requirements.

High speed piston combustion engines in the engine room of the RPS allow a proper arrangement of the spaces in the hulls, utilising their length and height, and providing every opportunity of fulfilling the basic limitation concerning draught ($T \leq 2.0$ m).

3.4. Model characteristics of the RPS engine room

A conceptual diagram of the combustion-electric ER of the vessel is shown in Fig. 1. Two main generating sets are designed. Energy from these sets will be directed to two main propellers, and also (in RPS work mode at speed below structural speed v), according to need, to two tubular rudders located one each at the bow of the catamaran. In accordance with [1], power demand for these rudders will not, at reduced ship speed (3÷4 knots), influence the power of main power units, ensuring structural speed of the vessel $v = 11$ knots.

Besides the two generating sets of the main power unit, one port generating set will be installed in the ER.

Each piston engine of the main power unit will develop the same equal power. The total power from both main engines will ensure that the speed v of the RPS is attained and that basic equipment of the ER and equipment guaranteeing safe navigation and proper realisation of research functions of the ship operate properly. Because of the doubled number of main power units, no additional emergency generating set is designed in the ER.

The presented above structure of RPS engine room, characterised by two identical power units, forms conditions for a symmetry of mass in the catamaran hulls, and also provides for:

- easier attainment of transverse stability,
- attaining the required trim of the hull in accordance with the permanent locations of hydro-acoustic measurement sounders,
- a smaller number of spare parts and simplification of service and repairs,
- good starting position for negotiating the price of the main engines (units).

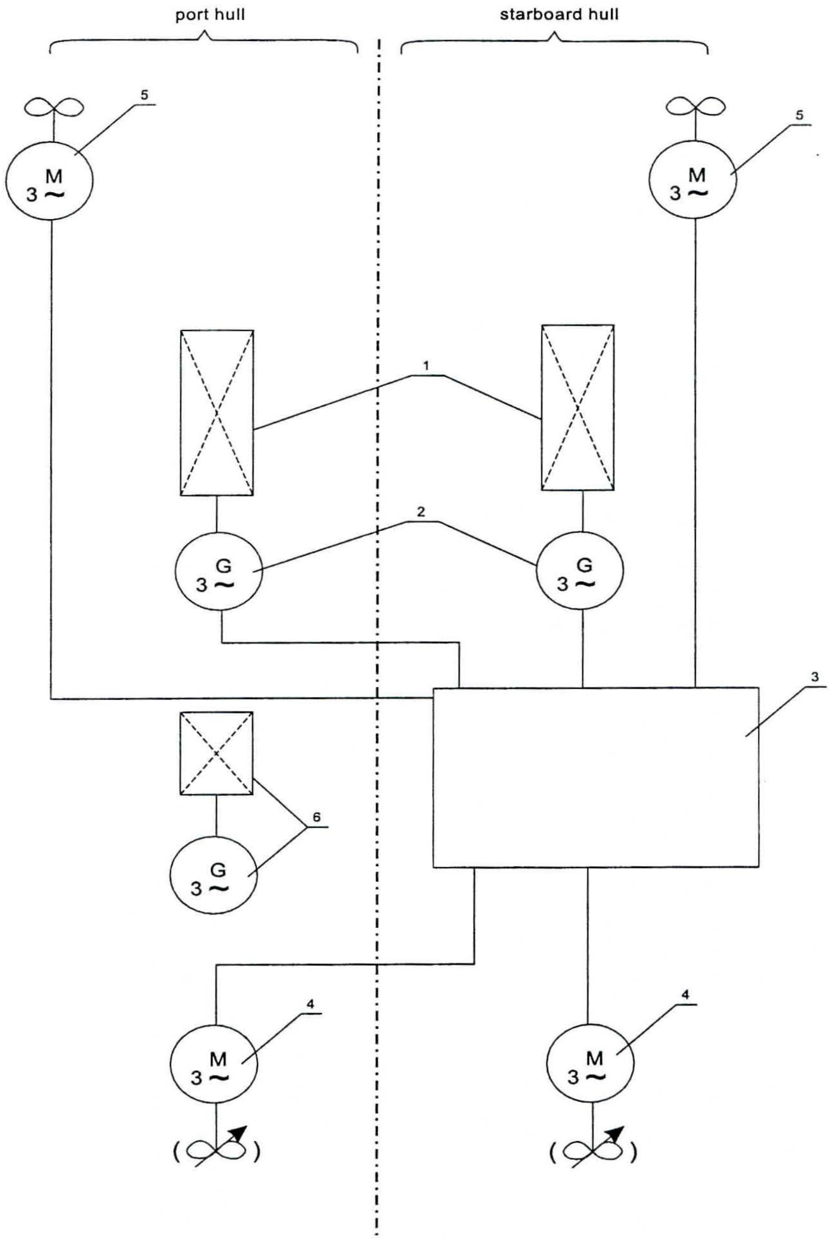
Table 1. Assessment of the type of RPS* engine room by adopted criteria

Type of ER	Cost of invest-ment	General efficiency	Life	Noise and vibrations	Cost of service	Easiness of repairs	Manoeuv-rability	Space require-ments	Easiness of locating**	Technical possibility of dynamic positio-ning	Total	General resultant asses-sment
A	2	1	2	5	1	2	3	2	5	3	26	1st place
B	3	2	2	3	5	1	1	2	1	1	21	2nd place
C	5	4	5	2	2	4	3	3	5	4	37	3rd place

A - piston combustion ER with mechanical transmission;
B - combustion (piston)- electric ER;
C - turbine combustion ER with mechanical transmission;

* Scale: "1" - highest ranking (best solution), "5" - lowest ranking (worst solution);

** This criterion allows to asses the planning of the hull space not only with respect to the function of the RPS, but also with respect to the interactions of vibrations of the engine-hull system.



1 - high speed piston combustion engine;
2 - generating set;
3 - control-switch-distributing system of main power unit;
4 - electric motor with main propeller;
5 - electric motor with tubular rudder;
6 - port generating set;

Fig. 1. Conceptual diagram of RPS engine room

4. Objective function and decision variables

The objective function is an indicator of quality for a given design solution. When it attains an extreme value, a design decision can be made at a given stage of designing. In mathematical terms, it is a function of parameters defining a certain design solution of the engine room. These parameters are often called the decision variables of the optimisation process.

4.1. Decision variables

The basic element of the considered combustion-electric engine room of the RPS is the high speed piston combustion engine. Since it is a heat engine with determined power, it can be defined by such parameters as:

- dry mass m,
- rated speed n.

The reason for selecting these parameters is that they are directly related with the heat capacity of the engine's structure. Heat capacity can be used for determining the energy efficiency and the cost of building the engine. The cost of building the engine is directly related with the price level of the engine, while energy efficiency is related with the amount of consumed fuel.

For a given total engines power N which ensures the design speed v, the pair of parameters (m, n) allows a preliminary selection of the engine.

4.2. The general form of the objective function

For the considered design solution, basing on the analysis of the physical sense of various forms of the objective function, it was assumed that the most appropriate will be the following general objective function Ω:

$$\Omega(\overline{X}, \overline{Y}) = \frac{\sum\limits_{i=1}^{i=k} K_i(\overline{X}, \overline{Y})}{M(\overline{X}, \overline{Y})} \quad \left[\frac{\text{c.u.}}{\text{kN}\cdot\text{m}}\right]^1 \tag{1}$$

where:

$\overline{X}$ - set of decision variables

$\overline{Y}$ - set of independent parameters

with:

$$(m,n) \in \overline{X}$$

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[1] c.u. - unit of currency, e.g. PLN, DM, USD.

$K_i(\overline{X}, \overline{Y})$ - type i costs carried during the ship's life T_L

i=1 - costs of construction carried during ship's life T_L

i=2 - costs of operation carried during ship's life T_L

$M(\overline{X}, \overline{Y})$ - torque of high speed piston engine.

The adopted form of the objective function Ω allows simultaneous testing of the influence of costs and torque on the value of the function. Torque $M(\overline{X}, \overline{Y})$ is the main parameter characterising the main ship propulsion, its maximum value has a deciding influence on the efficiency of the propulsion installation and on the value of the objective function $\Omega(\overline{X}, \overline{Y})$.

4.3. Criterion of preliminary optimisation

Due to the form of the objective function Ω, seeking the optimum values of structural parameters, i.e. of the dry mass of the engine m and rated speed n of RPS engines, will consist in finding such a value of the objective function Ω^* for which the condition

$$\Omega^* = MIN\,\Omega(\overline{X},\overline{Y}) \tag{2}$$

is fulfilled in the domain of determinancy of that function.

The domain of determinancy of the objective function Ω is defined by the following relationships

$$\overline{X}_{MIN} \leq \overline{X} \leq \overline{X}_{MAX} \tag{3}$$

$$F(\overline{X}) = 0 \tag{4}$$

for

Y_j = const

j - number of the set of independent parameters.

In the theory of optimisation, relationship (3) is called apparent constraint, and relationship (4) - functional constraint.

In practice, the apparent constraint is of decisive significance, especially in the preliminary stage of ship design. Use of the functional constraint is justified when there is a possibility, for a given optimisation problem, of forming the relationship $m= f(n)$ or $n= f(m)$ for the whole domain defined by relationship (3). However, construction of these relationships requires considering details of engine structure, which is inadequate for the present level of detail in the present optimisation problem. In the design of a ship, practically there is no possibility of influencing the detailed structural characteristics of the engine. Use can be made only of a ready made catalogue offer of the manufacturer of the engine, using optimum values of parameters (m, n) for a determined power.

5. Component functions of the objective function

The developed preliminary documentation [9] in the form of a general plan of the catamaran hull, does not give such quantities as: type of material for the hull, mass of the hull, gross hull capacity, etc. Besides, as it was already mentioned, the RPS is a prototype vessel, for which no set of similar ships exists. For these reasons there are no premises or sufficient data to calculate all the required components of the objective function, i.e. such costs incurred during ship operation as:

- amortisation and interest costs resulting from the cost of building the ship,
- cost of insurance,
- cost of repairs,
- crew cost,
- cost of scrapping the ship.

On the other hand, at this preliminary stage it is possible to determine the cost of purchasing the basic engines for the engine room, i.e. the main engines, and the fuel costs of main propulsion. In the present analysis the cost of generating sets and propellers is not taken into account, since it is impossible to determine what work frequency (and therefore what voltage frequency) will be optimal. The work frequency of the generating sets can be determined only when the optimum speed n of the main engines will be known, and this will be obtained in the framework of the discussed optimisation procedure.

In this situation, in accordance with (1), $k = 2$:

- $i = 1$; $K_1(\overline{X}, \overline{Y})$ - costs of purchasing the main engines carried during the ships life T_L
- $i = 2$; $K_2(\overline{X}, \overline{Y})$ - fuel costs carried during ships life T_L,

therefore:

$$\Omega(\overline{X}, \overline{Y}) = \frac{K_1(\overline{X},\overline{Y}) + K_2(\overline{X},\overline{Y})}{M(\overline{X},\overline{Y})} \qquad [\frac{\text{c.u.}}{\text{kN}\cdot\text{m}}] \tag{5}$$

Functions $K_1(\overline{X}, \overline{Y})$, $K_2(\overline{X}, \overline{Y})$, $M(\overline{X}, \overline{Y})$ are component functions of the objective function $\Omega(\overline{X}, \overline{Y})$.

5.1. Cost of purchasing the engines

The cost of purchasing the engines $K_1(\overline{X}, \overline{Y})$, [c.u.] carried during the whole life of the ship T_L [years] is formed by the value of invested capital[2]:

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[2] For determining the cost, the formula based on calculating the future value of invested capital was used, i.e. the law of continuous compound interest [5] for longer periods, was used.

$$K_1(\overline{X}, \overline{Y}) = (1 + 10^{-2} \cdot U_o)^{T_L} \cdot H_1 \cdot R_1 \cdot C_{ME} \cdot \mu_{ME} \tag{6}$$

where:

T_L [years] - total period of ship operation (integer)

U_o $[\frac{\%}{\text{year}}]$ - nominal annual rate of interest

H_1 $[\frac{\text{PLN}}{\text{c.u.}}]$ - currency rate for PLN

R_1 - function of the change of costs of purchase

C_{ME} [c.u.] - price at purchase of 2 main engines

μ_{ME} - coefficient increasing the cost of purchasing the engines due to indirect costs such as: necessary spare parts, custom dues, cost of middlemen, cost of transport to shipyard.

The price C_{ME} of purchasing 2 main engines is a function of the following decision variables: dry mass and speed obtained by least square method in accordance with data of the manufacturer DEMP A/S - Denmark.

The value of C_{ME} concerns MAN engines distributed by the above Danish company in Diesel-electric sets.

$$C_{ME} = 2 \cdot [9{,}733 \cdot 10^3 \cdot (\tfrac{N_1}{m \cdot n^2})^2 - 2{,}456 \cdot 10^3 \cdot \tfrac{N_1}{m \cdot n^2} + 426{,}2] \quad [\text{thous. DKK}] \tag{7}$$

N_1 [kW] - rated power of 1 combustion main engine

m [t] - dry mass of 1 combustion main engine

n $[\frac{\text{rev}}{\text{sec}}]$ - rated speed of the engine

N_1 in this formula is an independent parameter.

The relationship (7) is developed for the following ranges:

$N_1 \in \, < 79; 420 >$ [kW]

$m \in \, < 0{,}52; 1{,}55 >$ [t]

$n \in \, < 1500; 2600 >$ $[\frac{\text{rev}}{\text{min}}]$

$(n \in \, < 25; 43{,}3 >)$ $[\frac{\text{rev}}{\text{sec}}]$

Standarad deviation of engine price C_{ME} [thous. DKK] for sample size $l = 9$ is ±5.9%.

Table 2 presents the basic parameters of the analysed set of MAN engines used in DEMP A/S generating sets [7].

Table 2. Basic parameters of the analysed set of MAN engines in marine Diesel-electric units of DEMP A/S - Denmark

Model of engine	Number of cylinders, arrangement	Cylinder diameter D	Piston travel S	Unit fuel consumption g_e	Operational continuous power N_1	Speed n	Dry mass m
		mm	mm	$\frac{g}{kWh}$	kW	$\frac{rev}{min}$	t
D 0226 ME	6 L	102	116	226	79	2400	0.520
D 0226 MET	6 L	102	116	220	110	2600	0.530
D 0226 MLE	6 L	102	116	218	125	2600	0.545
D 2866 E	6 L	128	155	208	125	1500	0.985
D 2866 TE	6 L	128	155	210	190	1800	1.000
D 2866 LE	6 L	128	155	205	240	1800	1.035
D 2848 LE	8 V	128	142	205	280	1800	1.210
D 2840 LE	10 V	128	142	200	346	1800	1.340
D 2842 LE	12 V	128	142	200	420	1800	1.550

5.2. Fuel costs

Fuel costs $K_2(\overline{X}, \overline{Y})$ carried during period of ship operation T_L [years] is calculated from average annual fuel costs K_p in the following way[3]:

$$K_2\,(\overline{X}, \overline{Y}) = \frac{1-(1+10^{-2}\cdot U_o)^{-T_L}}{10^{-2}\cdot U_o}\cdot H_2\cdot R_2\cdot K_p \qquad (8)$$

where:

T_L [years] - total period of ship operation

U_o $[\frac{\%}{\text{year}}]$ - nominal annual rate of interest

H_2 $[\frac{\text{PLN}}{\text{c.u.}}]$ - rate of currency with respect to PLN

R_2 [-] - function for changes of fuel prices

K_p [c.u.] - mean annual fuel costs

The mean annual fuel cost K_p is calculated as the sum of costs for a range of modes of operation of the RPS during one average research round trip, taking into

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[3] Cost discount formula acc. to the principle of non-continuous rent [4] is used.

account the number of working engines, the price of fuel and the number of such voyages in a year.

$$K_p = f \cdot (K_{pp} + K_{pm} + K_{port}) \tag{9}$$

where:

K_{pp} [c.u.] - mean fuel cost on the way to and from a polygon during one research round trip

K_{pm} [c.u.] - mean fuel cost during work of RPS on polygon during one research round trip

K_{port} [c.u.] - mean fuel cost during stay in port of duty during one research round trip

f [-] - number of research round trips in 1 year

$$f = \frac{365 - T_R}{24^{-1} \cdot \frac{l_p}{v} + T_p + T_m + t_h} \tag{10}$$

where:

T_R [days] - mean inoperational time of the RPS in 1 year (for navigational, operational, repair reasons)

l_p [Nm] - distance to and from polygon during 1 research round trip

v [knots] - cruising (design) speed of the RPS

T_p [days] - time of work of RPS on polygon during 1 research round trip

T_m [days] - time of manoeuvres of the RPS when sailing out and entering port during 1 research round trip

t_h [days] - time of staying in port on duty during one research round trip.

The mentioned above fuel costs are calculated using the following formulas:

$$K_{pp} = 10^{-3} \cdot C_p \cdot g_e \cdot 2 \cdot N_1 \cdot \frac{l_p}{v} \qquad \text{[c.u.]} \tag{11}$$

$$K_{pm} = 10^{-3} \cdot C_p \cdot g_e \cdot 2 \cdot N_1 \cdot 24 \cdot T_p \qquad \text{[c.u.]} \tag{12}$$

$$K_{port} = \mu_p \cdot K_{pp} \qquad \text{[c.u.]} \tag{13}$$

where:

μ_p [-] - coefficient for the participation of cost of fuel used during duty in port with respect to K_{pp} ; $\mu_p \in (0; 0{,}4)$

C_p $[\frac{\text{c.u.}}{\text{kg}}]$ - price of fuel

g_e $[\frac{\text{g}}{\text{kWh}}]$ - unit effective fuel consumption of the main engine.

The remaining magnitudes appearing in formuklas (11), (12) (13) are the same as in (9) and (10).

For marine MAN high speed piston combustion engines of DEMP A/S units, the effective unit fuel consumption can be calculated using the relationship, derived in this work using the least squares method:

$$g_e = 3{,}81 \cdot \frac{m \cdot n^2}{N_1} + 192{,}0 \qquad [\tfrac{\mathrm{g}}{\mathrm{kWh}}] \tag{14}$$

where:

m [t] - dry mass of engine

$n\,[\frac{\mathrm{rev}}{\mathrm{sec}}]$ - engine speed

N_1[kW] - rated power of (one) engine

Standard deviation of g_e, for sample size $l = 9$ is $\pm 1\%$. Relationship (14) was determined using the set of engines shown in Table 2.

Finally, the fuel cost of the RPS, i.e. $K_2(\overline{X}, \overline{Y})$, is calculated from (8) after substituting the formulas given in p. 5.2.

5.4. Torque

The objective function Ω is an indicator of quality (suitability) to the RPS at the preliminary design assumption stage. The torque, which appears in the denominator, is the reference value for the sum of costs carried during the whole life of the vessel. Torque is calculated using the formula:

$$M(\overline{X}, \overline{Y}) = \frac{N_1}{2\pi \cdot n} \qquad [\mathrm{kNm}] \tag{15}$$

where:

N_1 [kW] - rated power of one main engine

$n\,[\frac{\mathrm{rev}}{\mathrm{sec}}]$ - main engine speed at power N_1

6. Procedure for determining rated power N_1 of a combustion engine

In the objective function Ω, power N_1 is an independent parameter appearing in each component function. The two combustion engines will attain power N

$$N = 2 \cdot N_1 \tag{16}$$

which will ensure that the ship sails with design speed v. The total power N of main propulsion results directly from the structural characteristics of the ship's hull, from the expected conditions of navigation and from the characteristics of the system of power transmission from the couplings of the combustion engines.

The determination of the total power rating N is a computational procedure, including the following steps:

I. determination of total resistance of the RPS catamaran hull and calculation of towrope power N_o using $\overline{Y}_1$ parameters,

II. determination of total thrust power N_T at main propellers, using $\overline{Y}_2$ parameters,

III. determination of power N_d delivered to main propellers , using $\overline{Y}_3$ parameters,

IV. determination of total power of electric motors of main propellers, using $\overline{Y}_4$ parameters,

V. determination of main generators power N_G (taking into account the additional power needed for auxiliary equipment), using Y_5 parameters,

VI. determination of rated power N (total, operational) of combustion enegines, using Y_6 parameters.

The procedure of determining the power N will be realised by hand since still no computer methods have been developed for catamarans which would take into account all parameters from the sets $\overline{Y}_i$ $(i = 1, 2, \dots 6)$.

Parameters belonging to the set $\overline{Y}_1$ provide a hydrodynamic and geometric description of the hull.

Parameters of the set $\overline{Y}_2$ allow to take into account the wake coefficient, the thrust deduction factor and the interactions of wakes behind both catamaran hulls. Parameters of set $\overline{Y}_3$ determine the type and efficiency of the open water propeller behind the hull. Set Y_4 includes the possible structural and operational parameters of electric motors transmitting torque to main propellers. In set Y_5 are parameters determining the type and structure of generators, the demand for additional energy in the engine room and additional energy for basic navigational and research functions of the RPS and for the safety of the vessel during its operation, as well as the transmission of energy between the generators and the electric motors of main propellers. Parameters of the set Y_6 result from catalogue data of the manufacturer of marine Diesel-electric units, and especially with respect to the flexibility of operation of the piston engine will concern its working point on the external characteristic of throttled power.

In general, due to the preliminary character of the optimisation procedure and to the cost of the calculations, the number of all the parameters from sets Y_i should be selected in such a way that these parameters cover the main structural and operational characteristics of the designed solution of the RPS engine room.

Former experience indicates that the cost of calculations increases nonlinearly with the number of considered parameters.

7. Description of the sets of parameters of objective function

The objective function Ω is defined by two basic sets:

$\overline{X}$ - set of decision variables

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

The set $\overline{X}$ was presented in p. 4.1. The set of independent parameter $\overline{Y}$ includes:

$$\overline{Y} \in (\overline{Y}_A, \overline{Y}_B) \tag{17}$$

where:

$\overline{Y}_A$ - set of parameters describing power N of the engines

$$\overline{Y}_A \in (\overline{Y}_1, \overline{Y}_2, \overline{Y}_3, \overline{Y}_4, \overline{Y}_5, \overline{Y}_6) \tag{18}$$

Set $\overline{Y}_A$ is described in p. 6 of this paper.

$\overline{Y}_B$ - set of independent technical and economical parameters.

In accordance with the developed objective function Ω, the following parameters belong to the set $\overline{Y}_B$:

T_L [years] - life of the vessel
U_o [$\frac{\%}{\text{year}}$] - nominal annual rate of interest
R_1 [-] - function of change of the cost of purchasing the engines
μ_{ME} [-] - coefficient of indirect costs of purchasing the engines
H_1 [$\frac{\text{PLN}}{\text{c.u.}}$] - rate of exchange of currency for engine costs
H_2 [$\frac{\text{PLN}}{\text{c.u.}}$] - rate of exchange of currency for fuel costs
R_2 [-] - function of change of fuel costs
T_R [days] - average stoppage time of the RPS during 1 year
l_p [Nm] - distance to and from polygon
v [knots] - design speed of the ship
T_p [days] - time of work on polygon during 1 research round trip
T_m [days] - time for manoeuvres when going out and entering port during 1 research round trip
t_h [days] - time in port during 1 research round trip
C_p [$\frac{\text{c.u.}}{\text{kg}}$] - price of fuel
μ_p [-] - coefficient of cost of fuel used in port
$N_1 = \frac{N}{2}$ - rated power of one main engine

where:

N [kW] - power of two main engines determined from parameters $\overline{Y}_A$ in accordance with the procedure presented in p. 6.

8. Flowchart for the procedure of calculating the value of objective function

The presented in Fig. 2 procedure of calculating the value of objective function Ω is open and linear. Therefore possible are modifications, which especially may consist in the reduction of the number of considered independent parameters, and in changing the formulas for calculating the component functions. Changing of formulas for component functions allows to take into consideration other piston main engines through appropriate adaptation of the basic functions, i.e. the functions for engine price and unit fuel consumption. Such other engines could then be e.g. Caterpilllar or Volvo engines.

Since the developed objective function Ω is provided with the possibility of reducing the number of parameters of the set Y_A and basic functions for other propulsion units can be introduced, it can be used in comparative design analyses for other engine room solutions, e.g. for an intermediate drive with mechanical transmission.

9. Method for minimising the objective function

Seeking of the optimum values of decision variables m^*, n^* for a given power N and $\overline{Y} = const$ consists in finding such coordinates of the objective function at which necessary condition (2) occurs.

This is a procedure of finding the extreme minimum of the function in the permissible domain. Since the quantityt of vector $\overline{Y}$ of independent parameters is sufficiently high, due to time and cost consumption methods of mathematical analysis cannot be used.

In case of objective function Ω, which is a function of two decision variables, seeking of the extreme minimum in the permissible domain should be realised by numerical methods on computers. In [4] an algorythm (flowchart and description) of a method for minimising a two-dimensional objective function based on Box algorythm [3] has been presented. Because of the wide range of uses (co-ordinates of the extremum can be found even at cros-section of limitations), this method can be used for the minimising of the objective function Ω dveveloped in the present work.

Because certain values controlling the calculations must be adopted, adaptation of the Box method to the discussed objective function Ω will require a numerical experiment of calculating the value of the objective function Ω. Such a numerical experiment will provide a picture of the function in space R^3, which significantly facilitates further minimisation calculations.

10. Geometrical interpretation of the objective function

In Fig. 3 the image of objective function Ω $(\overline{X}, \overline{Y})$ for the RPS is presented for defined vector $\overline{Y} = const$ and the following ranges of decision variables:

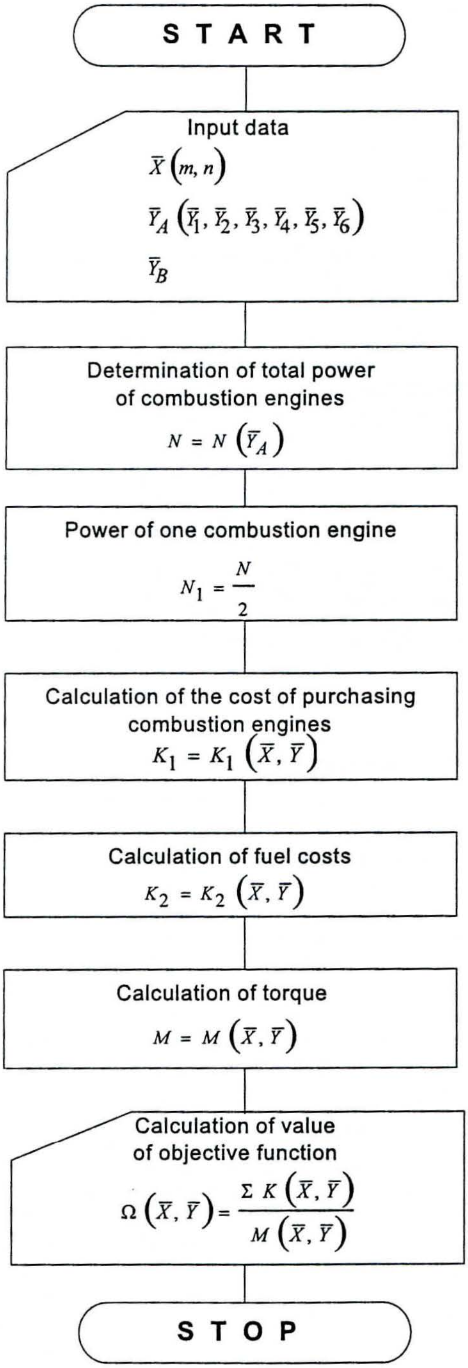

Fig. 2. Flow chart for calculating the values of objective function Ω

$$0{,}55 \le \mathrm{m} = X1 \le 1{,}55 \quad [\mathrm{t}]$$

$$30 \le \ \mathrm{n} = X2 \le 43{,}3 \quad [\tfrac{\mathrm{rev}}{\mathrm{sec}}]$$

In the realistic domain of objective function, its values fall within the interval $(4000 \cdot 10^3;\ 20000 \cdot 10^3)$ $[\frac{\mathrm{PLN}}{\mathrm{kNm}}]$.

The basic information obtain from 3D graphs of the objective function Ω is:

1. the objective function is a curvilinear function with values decreasing:
   - monotonously with the increase of variable $m=X1$
   - monotonously with decrease of varaible $n=X2$ for $m=m_{\max}$
2. its extreme minimum values belong to the neighbourhood of point

$$(m^* = m_{\max};\ n^* = n_{\min}),$$

i.e. from the point of view of optimisation of the main propulsion of the RPS for given power N, the best main engines among the Diesel-electric units will be Diesel piston engines with possibly large mass and possibly low rated speed.

In Table 3 are shown values of objective function from which graph 3 were formed.

Table 3. Example of values of objective function Ω in the domain of permissible solutions

n - speed $[\frac{\mathrm{rev}}{\mathrm{sec}}]$	Value of objective function Ω for RPS,for $\overline{Y} = \overline{Y}_{\mathrm{REPR}}$				
	m - dry mass [t]				
	0,52	0,80	1,10	1,40	1,55
	in thous. PLN/kNm				
30	19 328	8 699	5 600	4 529	4 274
33	14 642	7 202	5 162	4 531	4 403
36	11 661	6 395	5 077	4 744	4 704
39	9 763	6 031	5 214	5 092	5 114
42	8 577	5 951	5 498	5 530	5 560
43,3	8 223	5 980	5 654	5 740	5 826

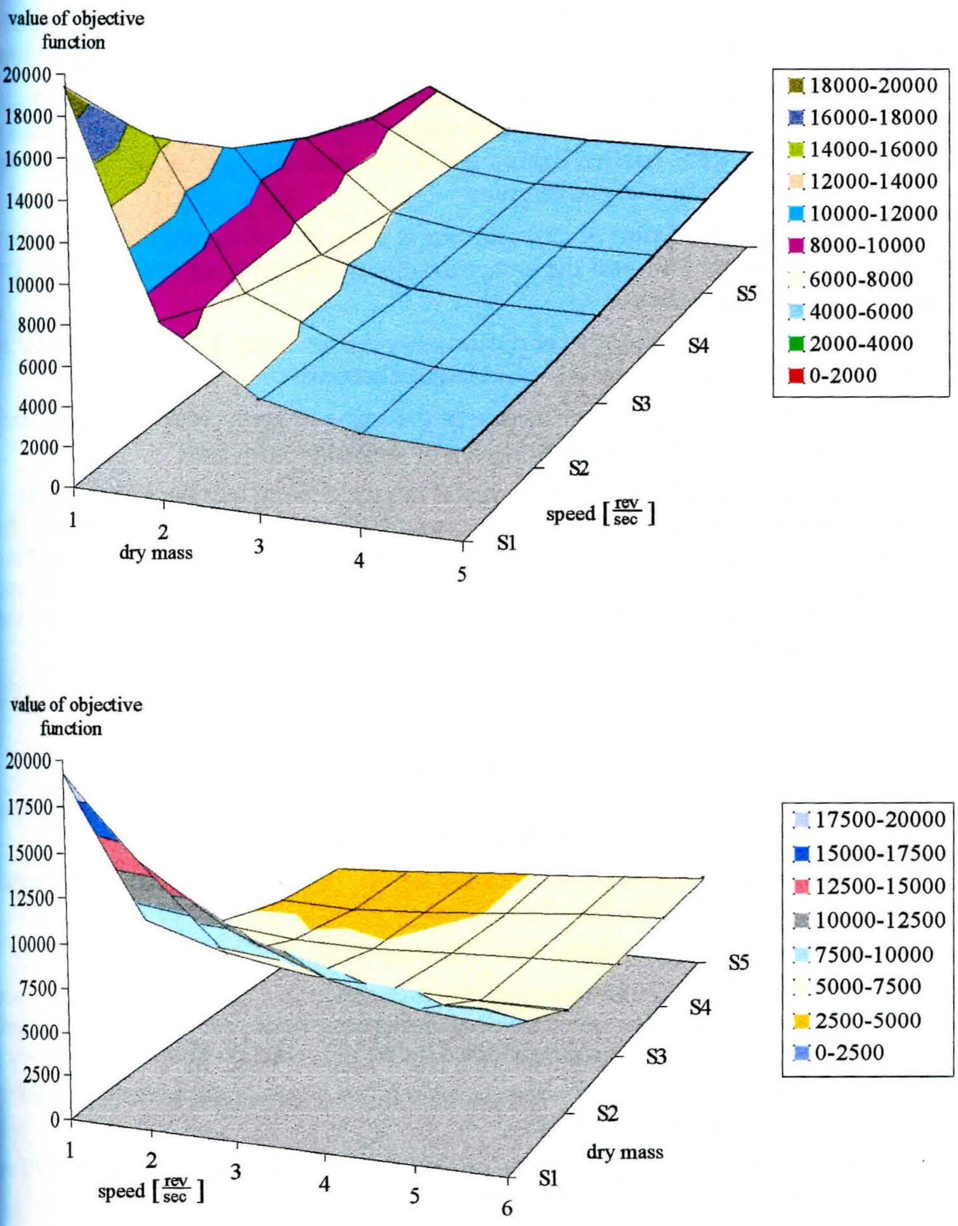

Fig. 3. Objective function $\Omega(\overline{X}, \overline{Y})$ for RPS, for $\overline{Y} = \overline{Y}_{REPR}$

11. Summary and conclusions

The analysis of values of engine room characteristics indicates that for the most appropriate for the RPS will be a Diesel-electric engine room.

At the preliminary design stage, selection of propelling combustion engines for a Diesel-electric engine room can be realised using an optimisation algorythm.

Preliminary selection of the main engine for the research/prevention ship can be made basing on an objective function describing the summary costs of building and operating the RPS, carried during the whole period of operation of the vessel and related to the torque of the engine.

The proposed algorythm of calculations is open to a wide range of parameters describing the ships hull and the transmission of energy from main combustion engines to main propellers.

The described methodology for preliminary design of the RPS can be the initial stage to further advanced design calculations because:

- it allows to determine the influence of the value of each independent parameter from set $\overline{Y}$ on the optimum values of decision variables,
- since, mainly because of the physical sense of decision variables (m, n), it concerns the properties of the process of driving power generation to the environment of the ship, it can be developed in the direction of investigating the process of energy transmission from main engines to main propellers, and later for the needs of investigating the process of energy utilisation by the main propellers.

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