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EVALUATION OF A MARINE OBJECT PROPULSION SYSTEM PRELIMINARY DESIGN PROCESS USING AN ITERATION METHOD

Key words: preliminary design, iteration, evaluation, marine propulsion system.

Abstract: The article shows the complexity of a marine object generating the necessity of multi-criteria optimization. Due to a great number of criteria and complexity of structure, the design process was classified as hierarchic with a descending structure. A spatial design spiral has been suggested, through developing a two-dimensional Evans' spiral. Specifics of preliminary design have been discussed. A procedure of iteration calculations in designing propulsion systems of vessels resulting from the ship owner's design requirements has been presented. An evaluation of the process has been illustrated using as an example a local optimization of a one-dimension design problem of a propeller from a propulsion system of a Ro-Pax type vessel.

Ewaluacja procesu projektowania wstępnego układów ruchowych obiektów oceanotechnicznych z zastosowaniem metody iteracyjnej

Słowa kluczowe: obiekt oceanotechniczny, iteracja, ewaluacja, projektowanie, układ ruchowy.

Streszczenie: W artykule pokazano złożoność obiektów oceanotechnicznych generującą konieczność optymalizacji wielokryterialnej. Ze względu na mnogość kryteriów oraz złożoność budowy proces projektowania zakwalifikowano jako hierarchiczny o strukturze zstępującej. Zaproponowano przestrzenną spiralę projektową, rozwijając tym samym dwuwymiarową spiralę Evansa. Omówiono specyfikę projektowania wstępnego. Przedstawiono procedurę obliczeń iteracyjnych w projektowaniu układów ruchowych statków morskich wynikającą z założeń projektowych armatora. Ewaluację procesu zilustrowano na przykładzie optymalizacji lokalnej jednowymiarowego problemu projektowego śruby napędowej, układu ruchowego jednostki typu Ro-Pax.

Introduction

Designing marine engineering objects, e.g., vessel is a complex phenomenon, which is the result of the necessity to account for mutually connected interactions. Besides this, any intervention in a design process must have its economic justification. A complicated structure of functional systems of marine engineering objects is another aspect influencing the specific process of their design. Preliminary design is particularly complicated, because many technical, ecological, ship owners', and other criteria have to be accounted for while simultaneously ensuring proper realization of the operational function of the object.

In study [1], the authors presented calculations of the main parameters and the hydrodynamic resistance of a Ro-Pax type vessel as a stage of a multi-optional preliminary design. Complexity of this type of facilities generates the need to use an adequate design tool and design method or design methodology [3, 4].

Study [2] presents an analysis of contemporary conceptual and preliminary design methods of maritime facilities, dividing them into general ship design methodology and system based ship design. Evans, publishing in 1959, his design spiral is perceived as the origin of the general ship methodology considering a ship, in a global way, as a single technical object [2]. The other methodology is based on System Engineering, which was described in detail by Gaspar [6]. It uses the decomposition, hierarchy, and encapsulation of technical systems for solving complex design problems. The aim of this study is to evaluate the presented preliminary design methods and their usefulness.

1. Ship as a complex technical object

The degree of identification on the designed ship, even at initial stages, very high; however, the degree of physical identification requires going through stages where the structure and physical properties of its components become more and more detailed. Therefore, the process of designing is a multi-staged one. Irrespective of the matter, each stage of the design is realized for a defined superior purpose. Initial stages, from the acquisition design, through the offer, preliminary and conceptual contracts, and closing the contract by signing it with the object owner opens the beginning of developing the functional-spatial structure of a ship. That fact generates a problem of multi-criteria optimization, which, in practice, can be replaced by single problems of local optimization [7].

The solved problems of the local optimization comprise issues such as the following: the choice of underwater hull shape, choice of the type of thermal engine, and configuration of the power system, the geometry of the bow, parameters of the propulsion system, the choice of the main engines, etc. The change of the state of the multi-dimension design problem requires decomposition of the superior system into subordinate ones or into subsystems. Subordinate systems contain elements with certain attributes, and they remain in definite relations with each other.

Figure 1 shows the hierarchy of a complex marine system as cooperating with each subordinate subsystem of definite properties. Using the above model, the ship propulsion system was decomposed [2].

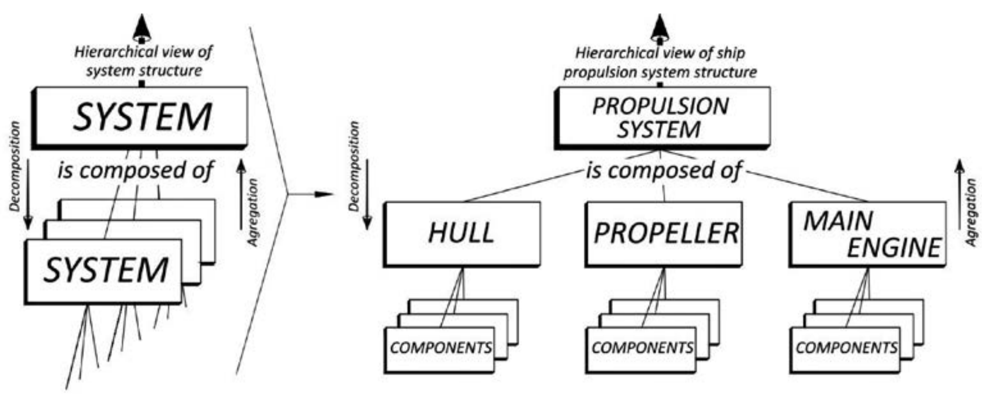

Fig. 1. An idea of hierarchy in a complex technical system [2]

Starting from the description of expected design properties, throughout multiple verification of assumptions and the gradual elimination of occurring contradictions, characteristics of the facility get evolutionally improved in a series of trials and errors until there is enough information to formulate a description of expected characteristics of the designed facility. To create complex marine objects, it is necessary to analyse the structure of the system and to identify the process and that is the basis to construct a mathematical model.

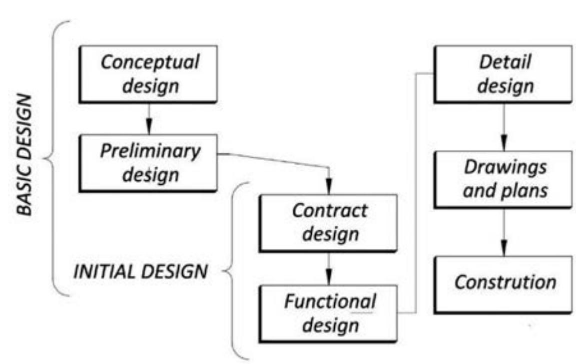

Fig. 2. Design stages [2]

2. Specifics of preliminary design

The process of design comprises stages that are dependent on the range of possessed information which is shown in Fig. 2. Conceptual and preliminary design as the first stages of the design process are characterized by the least quantity of data; whereas, the decisions taken there in the greatest degree affect the final form of the design [2].

The design stage takes place after the conceptual and preliminary stages, that is the contract, technical and detail design are based on the results of preliminary design using methods from other fields of technical sciences.

Figure 3 shows the relation between the quantity of data on the designed vessel, the costs of rectification of a misjudged decision, and the progress of the design process. Rectification costs of wrong decisions grow with the progress of the design process, which corresponds to the displacement between the levels of the spiral [7].

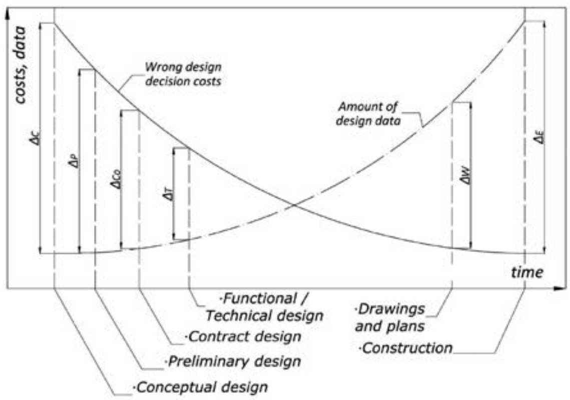

Fig. 3. Costs of the error rectification quantity of information versus the design process progress [7]

Differences designated in Figure 3 reflect the consequences resulting from misjudged decisions and difficulties in taking them based on a small pool of data on the facility. The biggest differences were observed for the initiation of conceptual and preliminary design, which illustrates the significant role of the discussed design stages, where the technical-operational properties of the designed vessel are assigned and from which depend the costs of design realization, construction, and its future operation.

The basic method utilized at the stage of initial design of vessels is parametric design, which relies on mathematical formulae relating facility properties with design parameters. Methodics of parametric design is based on known technical data of already built and operating vessels with similar functional parameters to those of the designed unit. Moreover, data from scientific publications are also used, i.e. empiric formulae, graphs, numeric ranges of characteristic parameters of various types of functional facilities, and others.

3. Design of maritime facilities/object as an iteration process

A maritime vessel, due to the number of criteria that should be met and the complexity of construction is characterized by a sequence-iteration design process. The beginning of design calculations requires taking initial assumptions, and the solution of subsequent design problems results in a more detailed description of the vessel- the hull and particular functional systems [3, 7].

Iteration here is a tool that is used to determine and verify the main characteristics of vessel, including the following: technical and economic at minimum financial investments in construction and operation, restrictive technical requirements of floating on water, which in the case of a displacement vessel, comes to fulfilling Archimedes' Law and the resulting conditions of stability. As Archimedes' Law combines the volume from the principal dimensions and its mass, their determination is connected with meeting a number of conditions and restrictions such as the main power, hull masses, as well as the characteristics of all of the subsystems determined during the iteration process.

The process was presented on a plane in the form of a design spiral by Evans in 1959 [3]. In 1981, Andrews showed the restrictions under which a designer operates changing Evans' flat spiral into the generatrix of a cylinder [2]. In [7], the process was described as hierarchic with a descending structure, which was an inspiration to construct a design spiral, presented in Fig. 4, as a development of the Evans-Andrews` concept.

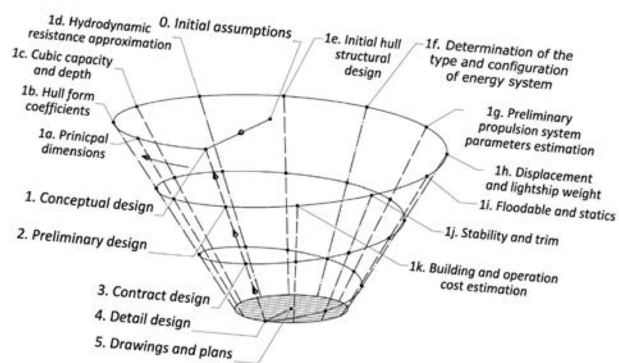

Fig. 4. Spatial design spiral as a development of Evans--Andrews` concept

Determination of main dimensions in preliminary design comes from solving non-linear equations combining the values given as design data, such as hold capacity V_H, deadweight m_{DWT}, and contractual speed v_s, with the unknown main dimensions of the vessel meeting these requirements. Their solution is obtained throughout iteration methods using the relations between main parameters of existing vessels (e.g., the assumed exemplary vessel [1]), such as the length between perpendiculars versus hold capacity $L_{PP} = f\left(V_H\right)$, the width versus the length between perpendiculars $B = f(L_{PP})$ and others. The procedure of determining the main dimensions throughout an iteration method, while simultaneous meeting the criterion of capacity, is shown in Fig 3.

The values implemented for calculations, e.g., the number of cars N_{cargo} and the stow coefficient for K which the hold capacity, was determined for the required cargo V_{H_1}. Using empiric formulae and approximate relations obtained as a result of analysis of similar

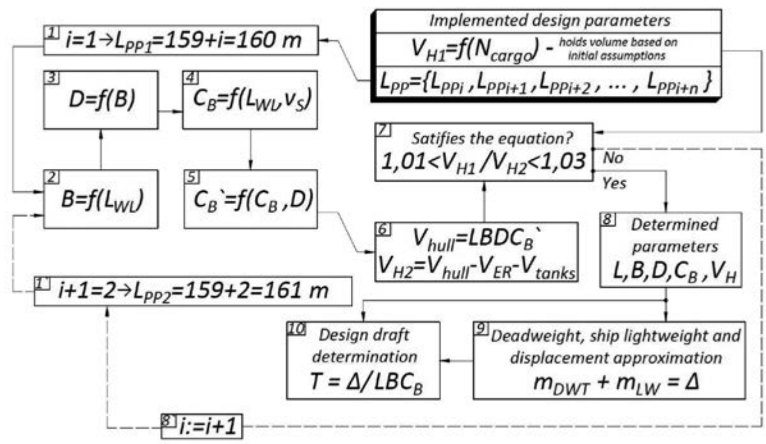

Fig. 5. An algorithm to determine ship parameters on the basis of the assumed cargo number

vessels, parameters $B, D, C_B, C_B`$, being the basis for hold capacity, are determined. The capacity of is described by Equation 6 (Fig. 5) as the difference of hull capacity, machine compartment, and tanks. Fulfilling inequality 7 in Fig. 5 is equivalent to meeting the capacity criterion.

The mass of the facility occurring in the buoyancy equation requires a possibly precise determination of masses of the systems and subsystems of the vessel. Balancing the displacement with the weight while meeting the owner's requirements is equivalent to the end of the iteration process determining the main dimensions, which are the bases for the next stage of the functional-spatial design process of a ship.

4. Procedure of iteration calculations in design propulsion systems on the example of a Ro-Pax vessel

Determination of searched parameters was realized using a Ro-Pax type vessel as an example. The design problem with this type of vessel is meeting the criterion of hold capacity when determining the proceedings of iterative determination of the principal parameters. For the studied vessel, the procedure from Fig. 5 was used. The determined main parameters took into consideration two options of hull construction, i.e. with the bulbous bow and with a conventional bow, both with a different block coefficient. The determined values were used as initial ones for determination of resistance characteristics. On their bases, the option meeting the criterion of minimum hydrodynamic resistance versus contractual speed was chosen. The ship principal parameters, resistance characteristics, and approximate relations were show in [1]. The described process corresponds to finding solutions to 1a-1d design problems on the spatial iteration spiral (Fig. 3), which was also shown in Fig. 6.

The obtained values (completed with information on the kind and configuration of the power system – point $1f_0$) were used as initial assumptions for designing the propulsion system – Fig. 6.

As a result of the identification of the parameters of particular elements (the hull, propeller, and main engine) (Point $1g_0$) and the construction of their mathematical models (Point $1g_1$) the following relation was obtained:

$$\sum_{j=1}^{2} P_{eMEj} = \sum_{j=1}^{2} Q_{eME_j}\,\omega_{n_j} = \frac{1}{\eta_T}\frac{1}{\eta_R}\varrho\left\{\sum_{j=1}^{2}\omega_{P_j}\left[K_{Qj}({n_P}_j{}^2 {D_P}_j{}^5)\right]\right\} = \frac{v_S(\sum_{j=1}^{2}\overline{T}_j)}{\eta_O\eta_H\eta_R\eta_T} \tag{1}$$

The designed propulsion system realizes the propulsion through two propellers, both of which generate the thrust T_j reaching together the value required by the ship, which is described by relation:

$$\sum_{j=1}^{2}\overline{T}_j = \sum_{j=1}^{2} T_j = \frac{R_T}{(1-t)} \tag{2}$$

The required thrust is determined in the process of modelling hydrodynamic resistance. The values taken for designing the propelling system were determined in [1]. Solving Equation (1) leads to finding propeller parameters for a given speed of the vessel, which is dependent on the required thrust.

Identification of parameters in preliminary design is mainly based on the results of model tests of propellers. Published researched results of models, e.g., [5] present dimensionless parameters. The description of the model of the studied propeller presents the following parameters in a dimensionless form: number of propeller plates z, pitch coefficient $P_{0,7R}/D$, ratio of

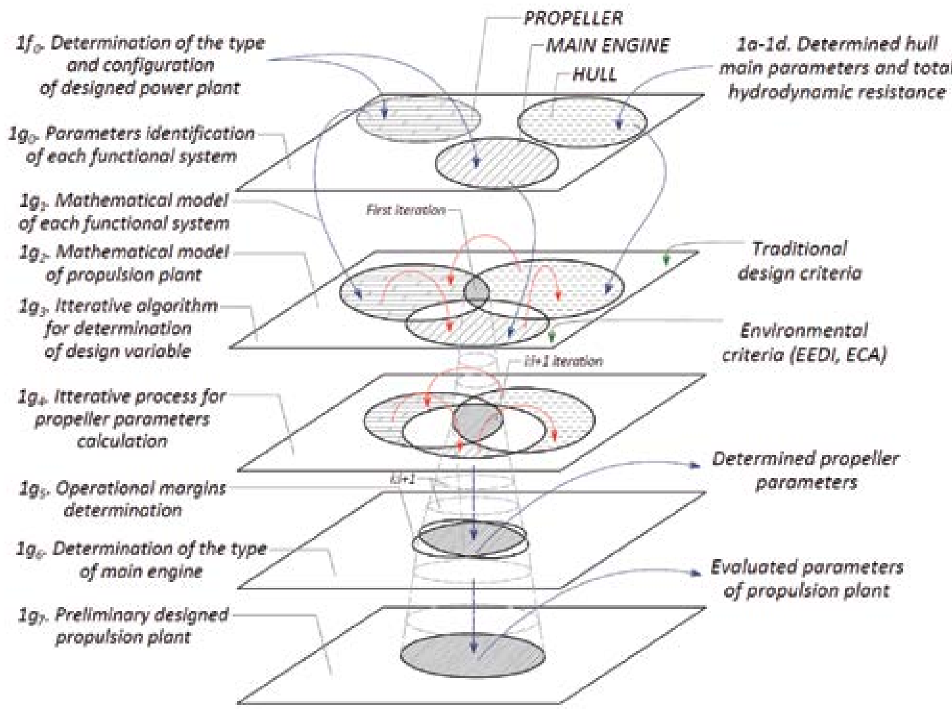

Fig. 6. A diagram of the initial design process of the propulsion system using an iterative method [5]

areas A_E / A_O, and the ratio of the plate thickness to the length of the chord versus relative thickness $(t/c)_{0,7R}$, (lower index denotes the radius of the section from the hub axis $-r = 0,7R + dr$) [6]).

Parameters important in design conditions, i.e. $\{(P_{0,7R}/D),(A_E/A_O),z,(t/c)_{0,7R}\} = idem$, do not change; whereas, advance coefficient *J* is a variable. According to (3), it is the function of the average speed of water v_A and the rotational speed of the propeller *n*.

$$J = \frac{v_A}{nD}\,, D = idem \rightarrow J = f(v_A, n) \tag{3}$$

To identify the unknown values, iteration calculations were suggested, and, for this reason, the algorithm shown in Fig. 7 was constructed.

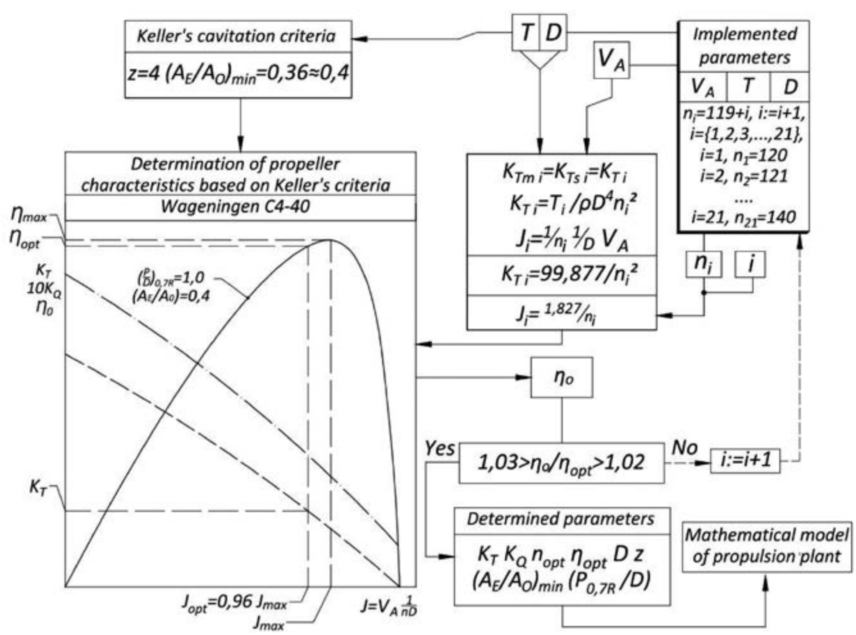

Fig. 7. An optimization algorithm for a one-dimensional propeller design problem

Determination of the searched parameter requires the assumption of a set of rotation speeds so as to solve the above relations. The diameter of the propeller D as a function of design draft was determined on the basis of an empiric relation obtained for Ro-Pax vessels. Determination of the ratio of expanded blade areas was based on *Keller's* cavitation criterion (4). The values of hydrostatic pressure in the hub axis p_0 and the pressure of water evaporation versus temperature $p_v = f(t)$ were determined. For a complex number of blades, the minimum value $\left(A_E / A_0\right)_{min}$ for which cavitation does not occur was determined [6].

$$\left(\frac{A_E}{A_0}\right)_{min} = \frac{1}{2}\sum_{j=1}^{2}\left(\frac{A_E}{A_0}\right)_j = \left(\frac{(1,3+0,3z)}{(p_0-p_v)D^2} + K\right)\sum_{j=1}^{2} T_j\ [-] \quad (4)$$

Using the above model, the minimum area was $\left(A_E / A_0\right)_{min} = 0.36$ determined for each propeller as for the blades number $z = 4$. By using the determined values, a series of propellers with controlled pitch were chosen – *Wageningen C4-40*, with open water characteristics shown in Fig. 6 [5].

Rotational speed of the propeller was determined from the aim function of the maximum efficiency taking into account the following restrictions:

$$\eta_{o_k} \rightarrow max = \eta_{o_{k\,opt}} \leftrightarrow \eta_{o_{k\,opt}} > \eta_{o_k}$$
$$\eta_{o\,jk} = f\left(K_{T_k}, K_{Q_k}, J_k\right)_j = f\left(K_{T_k}, K_{Q_k}, V_{Ak}, n_k\right)_j \quad (5)$$
$$j = \{1,2\}, k = \{1, 2, 3, \dots, 25\}, n_k = (119 + k)$$

The determined parameters of the *Wageningen C4-40* propeller were used to characterize the required effective power according to Equation (1) of a mathematical model of the propulsion system.

5. Results of using iteration procedure calculations on the example of a vessel of the Ro-Pax type

Based on the determined total resistance of a chosen hull shape [1] and the presented relations, the searched for design parameters were determined (Table 1).

For the assumed criteria and as the result of the suggested calculation procedure, design parameters of a *C4-40* propeller were determined and listed in Table 2; whereas, the design parameters of the propulsion system are listed in Table 3.

Table 1. Set design parameters [1]

v_S	R_T	t	w	η_H	$\sum_{j=1}^{2} T_j$	$T_1 = T_2$
$[m/s]$	$[kN]$	$[-]$	$[-]$	$[-]$	$[kN]$	$[kN]$
10.55	874.17	0.146	0.134	0.978	1023.74	511.87

Table 2. Parameters of the applied propeller

Z	A_E/A_O	$P_{0,7R}/D$	D	n_{opt}	J_{opt}	$K_{T_1} = K_{T_2}$	$K_{Q_1} = K_{Q_2}$	η_O
$[-]$	$[-]$	$[kN/m]$	$[m]$	$[min^{-1}]$	$[-]$	$[-]$	$[-]$	$[-]$
4.00	0.40	1.00	5.02	134.00	0.82	0.156	0.0285	0.724

Table 3. Parameters of the designed propulsion system

v_S	R_T	P_E	$T.$	η_D	P_D	ω_{opt}	Q_D	η_R	P_{eME}
$[m/s]$	$[kN]$	$[kW]$	$[kN]$	$[-]$	$[kW]$	$[rad/s]$	$[kN]$	$[-]$	$[kW]$
10.55	874.17	9218.34	511.87	0.706	6529.46	14.02	465.73	0.986	6662.5

Conclusions

The aim of the evaluation was to supply information that helps designers to take proper and justified decisions based on data, while diminishing the error of a sometimes inappropriate decision. The described evaluation confirmed the agreement of the design with the actual requirements concerning functionality. Using the iterative proceedings as an example of a realized design and the obtained results of calculations proved that, in order to design functional, operational complex marine systems, both design methods are necessary: the global system based ship design and the systematic one – the system based ship design. They should always be applied together.

The presented evaluation of the design process gives an outlook on the quality of designing a marine propulsion system and the adequacy of its functional values. At the design process, decisions and recommendations were made to decrease the development of the iteration spiral and reduce the work of the designer. Thus, the evaluation becomes a necessary element of any design, in particular, a conceptual and preliminary one.

References

1. Adamkiewicz A., Przybyła M.: Determination of Hull Parameters and Total Resistance of Ro-Pax Vessel at the Preliminary Design Stage. *SGEM Conference Proceedings*, 2017, 17(31), pp. 847––854.
2. Bruinessen T.M.: *Towards controlled innovation of complex objects: a social-technological approach to describing ship design*. Delft University of Technology, 2016.
3. Evans H.J.: Basic Design Concepts. *Journal of the American Society for Naval Engineers*, 1959, 4(71), pp. 67–678.
4. Gaspar H.M., Rhodes D.H., Ross A.M., Erikstad S.O.: Adressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach. *Journal of Ship Production and Design*, 2012, 28(4), pp. 145–159.
5. Dang. J., Ligteljn J.T., van den Boom H.J.J.: The Wageningen C- and D-Series Propellers. In: *12th International Conference on Fast Sea Transportation (FAST), Amsterdam, 2013*. FAST Conference 2013 Paper ID 61.
6. Molland A.F., Turnock S.R., Hudson D.A.: *Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power*. New York: Cambridge University Press, 2011.
7. Sekulski Z.: *Wybrane problemy optymalizacji wielokryterialnej we wstępnym projektowaniu konstrukcji kadłuba statków morskich.* Szczecin: Wydawnictwo Uczelniane Zachodniopomorskiego Uniwersytetu Technologi-cznego, 2012 (in Polish).