Parametric method of preliminary prediction of the ship building costs

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ABSTRACT

Paper presents results of studies on a parametric method of predicting ship building costs – – useful in the preliminary design. Conception and theoretical basis of the method are presented, devised are also approximation formulae for estimating the building costs of the ship hull, ship equipment and the power plant with propulsion system. Factors of importance for the ship building costs are identified and a computational algorithm formulated. The useful character of the method is illustrated by examples of building cost predictions for four different ship types designed in the Eureka project E!2772, i.e.: SINE 202 universal container carrier, SINE 203 oil product tanker, SINE 204 ro-ro ship and SINE 205 river-sea ship.

Keywords: ships design theory, ship building costs

INTRODUCTION

At the initial stages of designing a ship, its parameters are determined by the ship design theory methods allowing to find design solutions fulfilling the owner design requirements as well as the valid international conventions, e.g. freeboard rules or the ship damage stability requirements. In the optimum design methodology it is also necessary to formulate the designed ship evaluation criterion.

The criterion measure should be a ship property – of a measurable economic effectiveness character – important for the owner's operations on the market and containing, in a direct or indirect form, ship investment costs, predicted operating costs, evaluation of the ship transporting and money earning capability as well as the investment and acting capital costs. The ship evaluation criterion measure must be expressible by a set of ship technical parameters $\bar{\mathbf{x}}$ determined in the ship design process - decision variables of the design optimization mathematical model. Optimization models in the methods of ship design theory may be particularly useful in the work of ship design offices at the time of stronger competition on the world shipbuilding and shipping markets.

This paper contains results of research studies on a parametric method of preliminary prediction of the ship building costs, based on a small set of its main design parameters. The developed method of ship building cost prediction (a top-down method) may be used as an evaluation criterion in the preliminary ship design optimization models. The presented method is a contribution to the development of ship design theory as well as a tool to be applied in practical ship design.

The problem of methodology of ship building cost prediction at the preliminary design stage has been a subject of many publications, both those already classic, like the works of Benford [1, 2, 3], Sójka [4], Buxton [5], Fetchko [6], Dart [7] and Fisher [8] and the more recent items, e.g. [9, 10, 11, 12, 13].

AIM AND SCOPE OF THE WORK

Collecting data on **real costs** of building ships is a difficult task – in particular in relation to the ships currently under construction – as the data are treated as confidential business information of shipyards and owners. For evaluation of the economic value of a designed ship important are, apart from the production costs, also the predicted future operating costs, availability of cargoes, freight rates etc. in an appropriate time period, e.g. 15 to 30 years of the expected ship operation. Acquiring a reliable prediction tool is a significant difficulty in the research work on the development of preliminary ship design optimization methods.

The ship building and operating cost data are scarce in the literature, usually they are related to different time periods and are presented in a form of diagrams or tables of little use to the optimization method computational algorithms.

The presented research was initially aimed at results consisting in the development of ship design theory through devising an original parametric method of ship building cost evaluation at the preliminary design stage, a method of a mathematical structure appropriate for the computer optimization algorithms.

A useful effect of the research was demonstrated by using the method to perform the building and operating cost predictions for ships designed in the EUREKA project E!2772.

REQUIREMENTS OF THE METHOD

In the early phases of preliminary ship design the building cost may be predicted by means of parametric relations corresponding with the level of the identified technical parameters. At that stage no data are available to predict the cost from the equipment and material pricelists or from the maker's proposals. The parameters in question are main dimensions, component weight estimates, speed, propulsion power etc.. The method is based on the available data related to ship parameters and building costs as well as information on the cost structure.

In view of the non-homogeneity of data, as they come from different sources and are differentiated as regards :

- territory – they pertain to shipyards in different countries, operating in different economic systems
- monetary system – they are expressed in different currencies
- time – they pertain to different periods in the past.

The costs have been reduced to comparable values – different currencies were converted to US dollars at the rates valid in the respective periods and then updated to the current value using an average US inflation rate (in the years 1990÷2003) of 3% (according to the Bank of America indices).

It has been assumed that the total ship building cost including :

- material cost
- labour cost
- other shipyard costs

consists of :

- hull construction
- ship equipment
- power plant and propulsion system.

It has been also assumed that costs of each of these groups are related to the weight of a respective group. Approximating functions were determined from the collected data to express the unit cost in US dollars per ton of a group weight. The power plant horse-power was converted to an equivalent power plant weight. An advantage of such approach is balancing the designed ship displacement with the sum of component weights, e.g. by the Normand method, already in the preliminary stages of the design process.

Depending on a functional type of the ship, the hull cost is considered for two cases, as in [11] :

- single-deck hulls, e.g. tankers or bulk carriers
- multi-deck hulls, with well developed internal volume subdivision, e.g. passenger ships, car carriers or ro-ro ships.

The ship equipment cost is considered in three classes, differing in respect of the equipment quality and of saturation of the ship with equipment. The equipment unit prices and the assembly labour cost may differ considerably. The equipment class variant depends on the owner requirements as well as on :

- functional type of the ship (e.g. classic general cargo ships usually have low equipment class whereas passenger ships have high equipment class, etc.)
- necessity of installing special equipment, e.g. refrigerating or air conditioning plant, according to owner's requirements.

The power plant cost predicting formulae are related to diesel engine plants, where :

- lower range of the main engine weight (power) corresponds to medium-speed engine power plants
- upper range of the main engine weight (power) corresponds to low-speed engine power plants.

Cost shares of the individual ship building stages in the total cost, according to an empirical estimation quoted in [14], are the following:

Building stage	Cost of the stage	Impact on total building costs
Preliminary design	3%	60%
Other design stages	7%	25%
Ship production	90%	15%

The estimation shows that the design stage, having itself approx. 10% share in the total ship building costs, determines 85% of those costs. Expenses on the design quality – proper choice of the ship main parameters, production technology, structural materials, equipment types etc. – have a significant impact both on the shipyard's and owner's economic effects.

UNIT COSTS

Preliminary studies have shown that analytical relations between a unit cost q_j of a ship technological group and its weight m_j may be approximated with sufficient accuracy by means of power functions containing four constant structural coefficients $c_{i,j}$ determined by the least squares method. An identical structure of the unit cost and weight binding formula has been assumed for all the technological groups :

$$q_j = c_{0,j} + c_{1,j} \cdot m_j + c_{2,j} \cdot m_j^{c_{3,j}} \quad (1)$$

The unit cost determined by this formula comprises:

- material costs
- labour costs
- other shipyard costs.

Structure of the formula was determined from tests performed with different test functions, using the following selection criteria:

- good approximation quality in the considered range of design parameters
- easy determination of numerical values of the formula as well as derivative relations, which is an important advantage when manual calculations have to be performed, e.g. with a calculator, and also when an optimum design mathematical model is formulated (a problem of accurate determination of the Jacobian or Hessian determinant).

The structural coefficients of approximation formulae, given in Table 1, have been determined by means of the regression analysis.

Table 1. *Values of structural coefficients of the ship building cost predicting formulae*

j	Weight group	Symbol	Unit cost	$c_{0,j}$	$c_{1,j}$	$c_{2,j}$	$c_{3,j}$
		[t]	[$/t]	[-]	[-]	[-]	[-]
1	Single deck hull	m_h	q_s	8056.4	0.031	-936.42	0.1949
2	Multi deck hull	m_h	q_m	16023.8	0.053	-4927.0	0.1084
3	Low standard equipment	m_e	q_l	35512.9	-1.175	-12957.0	0.0518
4	Average standard equipment	m_e	q_a	23196.6	61.590	-69.62	0.9903
5	High standard equipment	m_e	q_h	29751.0	33.006	-63.37	0.9344
6	Power plant	m_p	q_p	25230.2	2.928	-161.66	0.63435

The preliminary ship building cost predictions, confronted with actual market prices (as published by the Centromor foreign trade agency in the „Budownictwo Okrętowe" monthly), were evidently on the high side. That may be attributed to the fact that prices for some types of ships have decreased during the last decade not only in a relative sense (allowing for inflation) but also in an absolute sense, as an effect of sharp competition on the shipbuilding market and dumping prices quoted by the Far East shipyards.

Correction of the predictions was performed by calibration of the formulae with the use of the mentioned published actual prices. New corrected structural constants of the approximation formulae are given in Table 2.

Table 2. *Corrected structural coefficients of the ship building cost predicting formulae*

j	Weight group	Symbol	Unit cost	$c_{0,j}$	$c_{1,j}$	$c_{2,j}$	$c_{3,j}$
		[t]	[$/t]	[-]	[-]	[-]	[-]
1	Single deck hull	m_h	q_s	1994.663	0.015549	-154.0222	0.2471932
2	Multi deck hull	m_h	q_m	3241.7105	0.0194715	-592.6707	0.1637139
3	Low standard equipment	m_e	q_l	6528.5325	9.6026706	-12.56288	0.979517
4	Average standard equipment	m_e	q_a	-2599.825	-1.395667	9146.288	0.0213938
5	High standard eqipment	m_e	q_h	9749.0427	14.66748	-16.71265	0.9963722
6	Power plant	m_p	q_p	16720.374	0.7839685	-221.3641	0.510682

The unit construction cost q_s [$/t] of a single-deck hull of weight $m_h \in (1000 \div 30000)$ [t] is the following :

$$q_s = c_{0,1} + c_{1,1} \cdot m_h + c_{2,1} \cdot m_h^{c_{3,1}} \tag{2}$$

and that of a multi-deck hull of weight $m_h \in (1000 \div 30000)$ [t] :

$$q_m = c_{0,2} + c_{1,2} \cdot m_h + c_{2,2} \cdot m_h^{c_{3,2}} \tag{3}$$

The unit cost q_e [$/t] of ship equipment of weight $m_e \in (100 \div 3000)$ [t], depending on the equipment standard :

low standard equipment :

$$q_l = c_{0,3} + c_{1,3} \cdot m_e + c_{2,3} \cdot m_e^{c_{3,3}} \tag{4}$$

average standard equipment :

$$q_a = c_{0,4} + c_{1,4} \cdot m_e + c_{2,4} \cdot m_e^{c_{3,4}} \tag{5}$$

high standard equipment :

$$q_h = c_{0,5} + c_{1,5} \cdot m_e + c_{2,5} \cdot m_e^{c_{3,5}} \tag{6}$$

The unit cost q_p [$/t] of the power plant of weight $m_p \in (100 \div 2500)$ [t] :

$$q_p = c_{0,6} + c_{1,6} \cdot m_p + c_{2,6} \cdot m_p^{c_{3,6}} \tag{7}$$

The formula validity ranges correspond to the statistical samples used for their approximation. As the unit cost functions are smooth, a moderate extrapolation is admissible.

THE SHIP BUILDING COST PREDICTION ALGORITHM

In the preliminary ship design stages, the component weight groups are usually determined by methods based on the

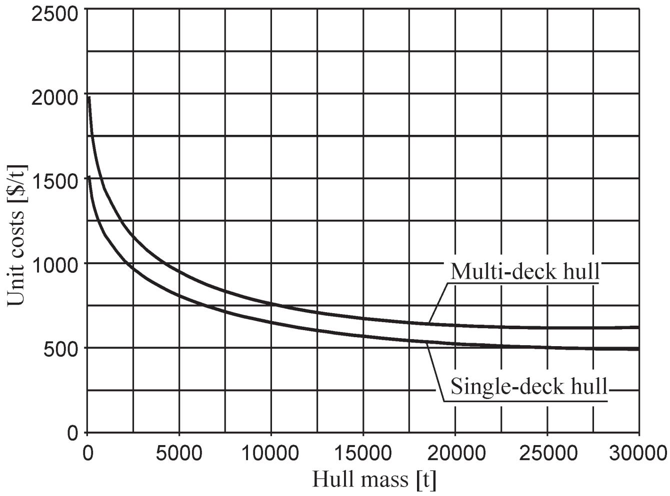

Fig. 1. *Ship hull construction costs*

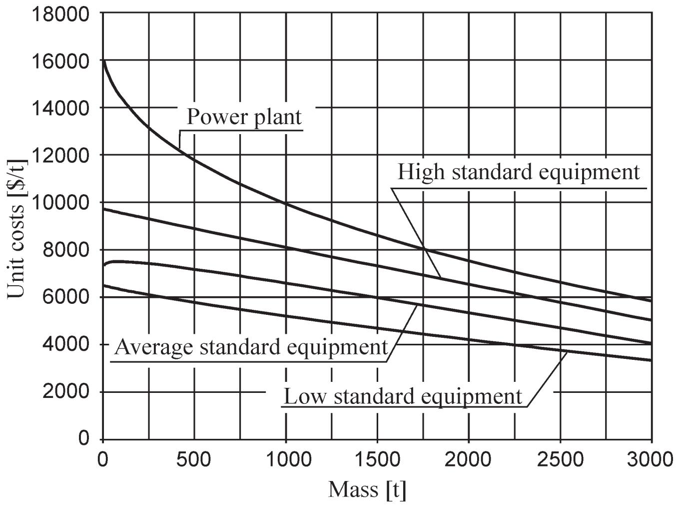

Fig. 2. *Ship equipment and power plant costs*

parent ship data, e.g. by the Normand or Bubnov method or from the empirical and statistical relations, e.g. those given by Watson [11]. In both cases the component weights are expressed by main parameters $\overline{x} = (x_1, x_2, ..., x_n)$ of the designed ship in functional analytical (modular) formulae :

$$m_h = m_h(\overline{x}) \;;\; m_e = m_e(\overline{x}) \;;\; m_p = m_p(\overline{x}) \tag{8}$$

so selected that they approximate the actual relations in the best possible way. The modular formulae determine the weight increases due to the changes of main design parameters of the ship, described by the $\overline{x} = (x_1, x_2, ..., x_n)$ vector, in relation to the parent ship parameters $\overline{x}_0 = (x_{01}, x_{02}, ..., x_{0n})$, which in the domain of linear relations, for the $\mathbf{m_j}$ weight group, is described by the expression :

$$m_j(\overline{x}) = m_j(\overline{x}_0) + \Delta m_j(\overline{x}) = m_j(\overline{x}_0) + + \sum_{i=1}^{n} \frac{\partial m_j(\overline{x})}{\partial x_i} \Bigg|_{\overline{x}=\overline{x}_0} \left(x_i - x_{0i}\right) \tag{9}$$

The individual group costs are described by an expression of the following structure :

$$Q_j(\overline{x}) = q_j(\overline{x}) \cdot m_j(\overline{x}) \tag{10}$$

The total ship building cost $\mathbf{Q_t}$, depending on the functional type, saturation with equipment and equipment quality, may be expressed as a sum of respective components :

$$Q_t(\overline{x}) = Q_{s,m}(\overline{x}) + Q_{l,a,h}(\overline{x}) + Q_p(\overline{x}) \tag{11}$$

Table 3. *Main design parameters of ships and predicted building costs in US dollars*

Building cost prediction simulation parameters for the baltecologicalships project ships	Unit	SINE 202 Container carrier	SINE 203 Product tanker	SINE 204 Ro-ro ship	SINE 205 River-sea ship
Deadweight	[t]	8 550	14 300	7 400	2 950
Displacement	[t]	15 600	19 922	15 850	3 938
Length over all	[m]	138.70	138.10	156.70	89.45
Length between pp	[m]	132.00	132.00	147.75	87.47
Breadth moulded	[m]	22.50	22.50	24.80	11.40
Depth to maindeck	[m]	11.20	12.80	19.60	5.45
Design draught	[m]	7.60	8.00	6.00	4.40
Scantling draught	[m]	8.55	8.70	6.50	2.80
Speed at design draught	[kn]	18.5	14.0	20.00	12.00
Power at 1800 rpm	[kW]	11 200	10 000	19 520	3 640
Range of operation	[nm]	10 000	6 000	8 000	4 000
Number of decks : 1 − single-deck ; 2 − multi-deck	[-]	1	1	2	1
Equipment standard : (1 − low, 2 − average, 3 − high)	[-]	1	1	2	1
Hull weight	[t]	2 855	3 530	6 050	710
Equipment weight	[t]	900	877	1 760	198
Power plant weight	[t]	430	343	697	100
Predicted ship building cost	[$]	**~12 700 000**	**~12 200 000**	**~23 100 000**	**~3 544 373**
Hull cost	[$]	**~2 678 160**	**~3 139 070**	**~5 407 590**	**~869 866**
Equipment cost	[$]	**~4 801 380**	**~4 700 970**	**~9 989 330**	**~1 227 157**
Power plant cost	[$]	**~5 228 790**	**~4 330 630**	**~7 666 480**	**~1 447 350**

BUILDING COST PREDICTIONS FOR SHIPS DESIGNED IN THE EUREKA PROJECT E!2772

The table above contains design parameters of the analysed ships, used for predictions of building costs. The total building cost of a ship consists of the hull construction cost, equipment cost and the cost of power plant with propulsion system.

SUMMARY AND CONCLUSIONS

- A parametric (top-down) method has been presented of predicting the building costs of ships, to be used at the preliminary design stages. The method may be used to determine a ship evaluation criterion measure in the design methodology based on formal mathematical optimization models. The optimum design models may prove useful in the work of ship design offices, particularly at the time of strong competition on the world shipbuilding and shipping markets.
- The presented original parametric method of the estimation of ship building costs, with a mathematical structure applicable to computer optimization algorithms, is a contribution to the development of ship design theory.
- It is also a tool for practical ship design and was used for performing predictions of the building and operating costs of ships designed in the EUREKA project E!2772.
- It is expected that empirical verification of the prediction results will be the cost estimations prepared in the respective shipyards constructing the analysed ships.

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