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Generation of Optimal Vessel's Production Cost Structure

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Establishing ship newbuilding production costs structure represents a fundamental management activity, concerning materials and fabrication in shipbuilding. Shipyards are competing in world market niches, regarding vessel types and dimensions. Therefore, a vessel's market price has a tremendous influence at shipyard's determination of vessel price offered to buyers. For this reason shipyard management is forced to concentrate its effort to act upon new building production costs structure optimisation as to achieve the goal of profitable shipyard enterprise. In this paper a computer integrated mathematical model of engineering cost of vessel production generated by authors is presented. Proposed cost structure configuration is based on both functional and technological vessel breakdown structures. Statistical analysis of data was performed for a sample of tankers population, built in Croatian shipyards. Probabilistic theory was applied and several results such as the expected values for aggregate figures are presented. Such developed tool for obtaining an optimal production costs structure enables shipyard management besides more successful managing and decision making, also latter, through the process a better costs control within model parameters. Dynamic control is needed of costing figures within optimised structure of production costs that for assigned conditions, for the whole shipbuilding process and product, have significant influence upon performance final results. Mathematical model for achieving optimal structure of production costs was verified and tested against real sample of new tankers built, not previously included in cost structure generation.

Generiranje optimalne strukture troškova gradnje broda

Izvornoznanstveni članak

Utvrđivanje strukture troškova gradnje plovnog objekta s obzirom na materijale i proizvodnju, predstavlja temeljnu aktivnost menadžmenta u brodogradnji. Budući da se brodogradilišta natječu na svjetskom tržištu novogradnji, tržišna cijena plovnog objekta ima presudan utjecaj na definiranje prodajne cijene koju brodogradilište nudi kupcu. Kako menadžment ne može bitno utjecati na tržišnu cijenu, prisiljen je djelovati na strukturu internih troškova gradnje broda kako bi brodogradilište poslovalo kao profitabilna industrija. Za podršku realizaciji tog cilja generirana je konfiguracija strukture troškova gradnje broda kao kompjutorski integrirani matematički model s funkcijom mogućnosti optimizacije. Predložena konfiguracija strukture troškova temelji se na funkcionalnoj i tehnološkoj raščlambi gradnje broda. Za potrebe osnivanja modela statistički je analiziran niz novogradnji tankera izgrađenih u hrvatskim brodogradilištima. S obzirom na stohastičnost procesa proizvodnje, za osnivanje modela primijenjeno je matematičko programiranje uz teoriju vjerojatnosti, te su prikazane očekivane vrijednosti grupiranih glavnih troškova. Prikazani model za definiranje optimalne strukture troškova omogućuje menadžmentu brodogradilišta kvalitetnije upravljanje i donošenje odluka, kao i bolju kontrolu troškova za vrijeme izvođenja proizvodnog procesa. Modelom je također omogućena kontinuirana kontrola onih troškovnih varijabli, unutar optimirane strukture, za koje je utvrđeno da imaju najznačajniji utjecaj na konačnu razinu troškova cjelokupnog proizvodnog procesa gradnje broda. Model je provjeren i potvrđen na realnom uzorku izgrađenih tankera koji prethodno nisu bili uključeni u generiranje strukture troškova.

Keywords

Production costs analysis
Ship building industry
Stochastic processes

Ključne riječi

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Symbols/Oznake

T_{GB}	- vessel production costs - troškovi gradnje broda	θ	- normal distribution - normalna distribucija
t_i^j	- production costs of i^{th} part of vessel's costs spent for building j^{th} vessel - troškovi i-tog resursa utrošenog u gradnji j-tog broda	f_i^μ	- basic statistical set - temeljni statistički skup
f_i^j	- cost variable as percentage in vessel's production costs - troškovna stavka kao postotni udjel u troškovima gradnje broda	$T(f_i^\mu)$	- Student's distribution - Studentova distribucija
$\hat{f}_i$	- sample expected value - očekivana vrijednost uzorka	m-1	- degree of freedom - stupanj slobode
$E\,[f_i^j]$	- sample expected value - očekivana vrijednost uzorka	1 - α	- degree of reliability - stupanj pouzdanosti
$V\,[f_i^j]$	- sample variance - varijanca uzorka	α	- degree of unreliability - stupanj nepouzdanosti
$\sigma\,[f_i^j]$	- standard deviation - standardna devijacija	$t_\alpha^{(m-1)}$	- Student's distribution coefficient - koeficijent Studentove distribucije
		f^*_i	- optimised production cost structure - optimizirana struktura troškova
		$E\,[f_i]$	- expected aggregate cost structure - očekivana struktura troškova

1. Introduction

Generation of optimal vessel's production costs structure for preliminary production costs estimation is based on linkage among vessel project, production process and costs [1]. Actual shipbuilding production costs estimations are based on using conventional functional dependencies between costs and masses, and functional product breakdown structure against vessels systems. In such manner production process characteristics and its costs are insufficiently included. A functional vessel breakdown structure is based upon systems spreading all over the product. Such structure does not include divisions among spaces, but it reflects functional project characteristics, that enable adequate information quantity for preliminary estimations in early project stages. Nevertheless, the vessel is built against spaces, or zones, i.e. against wholes determined by volume. New shipbuilding technologies include modular, process oriented approach, which intersects the elements of the functional breakdown structure [2]. Therefore, the structure of conventional approach for preliminary shipbuilding production cost estimation, which includes several independent wholes for cost estimation, is insufficient [3]. Furthermore, conventional approach is not founded upon systematically collected data. This approach is not encircled within the model, which systematically includes all building costs, and therefore it cannot be, nor defended, neither reproduced. The reality denied its precision already confirmed on previous newbuildings. Such approach does not breakdown costs of the procedure with which the vessels are built. It is not suitable for project decision making as it is not linked with vessel project characteristics, neither it reflects the technology of process impacts upon other costs, and does not give feedback information for project design and production process [4].

2. Problem approach

The need for preliminary newbuilding costs estimation improvement is evident. Therefore, on basis of analysed data, preliminary calculations' analysis, reviewing of employed production working hours, the new production costs structure was developed. Such generated costs structure consists of all newbuilding costs data within the group level against functional breakdown structure as one whole, with costs variables mutually interdependent [5], [6]. Besides functional product breakdown, the product work breakdown structure was employed by which production costs were disassembled against process phases. As newbuilding price is market determined, as already stated, it is an imperative to act with the objective of newbuilding production cost optimisation [7]. It is possible to influence on larger part of these costs within context of the whole newbuilding production process cycle [8]. Therefore it is important to optimise every such segment with the objective of building costs minimisation. Therefore, authors' research is aimed to develop an optimal newbuilding production costs structure. With such objective a relevant mathematical model is developed, using methods of mathematical programming [9], [10]. Knowing the structure, it is also possible in latter stages of the shipbuilding process, to recognise if the process generation is within limits defined by the model, or what are their eventual deferring, and by what mechanisms management can act upon shipyard's performance. Therefore, for preliminary newbuilding costs estimation is significant to take care of shipbuilding costs structure, upon which the shipyard management can influence, monitor, and maintain them within predicted constraints intervals [11]. The preliminary calculation objective for the model is, therefore, vessel newbuilding, for which the shipyard is involved in bidding process. For model development, historical data from Croatian shipyards for tanker standard newbuilding type of deadweight capacity within range from 80000 t to 110000 t were used. Such data contains uncertainties within production process. Risks were included in the model and analysed by means of statistical method and probability theory, what offers to model user, greater costs estimation reliability.

The main objective of generating an optimal vessel's production costs structure is to provide management with one vehicle for costs estimation offering the possibility to envisage the profit realisation in cases when the bid offer being accepted by the buyer [12]. Performed research included collection and analysis of realised data and their systematisation and verification. Criteria for cost structure development were established [13].

The generated stochastic model gives description of real system functioning in more qualitative and quantitative manner, in regards to the conventional deterministic approach [14]. After statistically analysed data of particular cost variables, various investigations and simulations with regards to newbuilding production costs structure can be performed depending upon changes of the objective function and constraints for the optimisation procedure, viewed as problem of mathematical linear and/or non-linear programming, [15]. Within the model, data of already built vessels are stored, and therefore by knowing the newbuilding project configuration it is possible to determine differing of particular cost variable in relation to the expected average and variance interval. The model contains 73 cost variables. To achieve mentioned criteria within functional model characteristics, it was concluded that the model has to employ functions for treatment of these criteria, and thus fulfil shipyard needs. As to realise such functions, model development was performed through data analysis of already built newbuildings of certain type, and for previously determined production process technological level. Model development is based on following functional modules:

- Modulus of realised costs, which ensures the mechanism for electronically input and storage of realised data of costs variables regarding particular newbuilding;
- Modulus for statistical analysis, as modulus for relating to realised data;
- Probability modulus, which enables probability data analysis for several vessels of the same type and determination of distribution interval within which costs estimation of each particular variable will be located;
- Model with 73 variables as central modulus for newbuilding of certain type production costs structure optimisation.

3. Mathematical model definition for optimal production cost structure generation

Population of m vessels of certain type is observed. Production costs of each vessel from the given population are divided in n parts. Production costs of j^{th} vessel are denominated as:

$$T_{\text{GB}}{}^{j},\ j = 1, 2, \ldots, m, \tag{1}$$

and production costs of i^{th} part of vessel's costs spent for building the j^{th} vessel as

$$t_i^j;\quad i = 1,2, \ldots, n, j = 1,2, \ldots, m. \tag{2}$$

Therefore it applies:

$$T_{\text{GB}}{}^{j} = \sum_{i=1}^{n} t_i^j;\quad j = 1,2,\ldots,m. \tag{3}$$

It is introduced:

$$f_i^j = \frac{t_i^j}{T_{GB}^j}100\,. \tag{4}$$

For the given i, the population:

$$\left\{ f_i^1, f_i^2, \ldots, f_i^m \right\}, \tag{5}$$

is defined as a discrete random variable of the share of i^{th} part of ship production costs from the given population.

Standard pointers of statistical set, such as mathematical expectation $E[f_i^j]$, variance $V[f_i^j]$ and standard deviation $\sigma[f_i^j]$ are defined [16].

By that on each particular i^{th} part of vessel's cost the pair $\left(\hat{f}_i, \hat{\sigma}_i\right)$ is defined. Therefore, within the model and random variables f_i is observed. It is assumed that random variables f_i, $i = 1, 2, \ldots, n$, within the basic population have normal distributions, $q\ (f_i^\mu; \sigma_i)$. As the observed specimen have a small dimension (m<30), Student distribution, $T(f_i^\mu)$, will be used to obtain interval estimation within which the expected value of basic statistical population f_i^μ, [17], will be located with reliability 1-α, i.e. i.e. with probability 1-α. With these assumptions, random variables have Student's distribution with degree of freedom (m – 1), and interval estimation is obtained from the relation:

$$P\left(\begin{array}{l} E\left[f_i^j\right] - t_\alpha^{(m-1)} \dfrac{\sqrt{V\left[f_i^j\right]}}{\sqrt{m-1}} < f_i^\mu < \\ E\left[f_i^j\right] + t_\alpha^{(m-1)} \dfrac{\sqrt{V\left[f_i^j\right]}}{\sqrt{m-1}} \end{array} \right) = 1 - \alpha, \tag{6}$$

i=1, 2,…, n.

Relation (6) gives the possibility for stochastic definition of expected average differing interval $E[f_i^j]$, i.e. f_i^μ, with probability 1 - α, where $t_\alpha^{(m-1)}$ is a Student distribution coefficient. In such manner upper and lower limit for the management variable f_i, is obtained. Relation (4), due to stochastic nature implies that random variables f_i^j are mutually dependent, which does not apply for expected averages, so:

$$\sum_{i=1}^{n} E\left[f_i^j\right] \neq 100 \,. \tag{7}$$

The objective function is the sum of all random variables. Mathematical criterion imposes that this sum equals 100. As management variables are stochastic, the problem of searching an optimal solution is to minimise

$$\min_j \sum_{i=1}^{n} f_i^j \,, \tag{8}$$

with constraints:

$$P\left(\begin{array}{l} E\left[f_i^j\right] - t_\alpha^{(m-1)} \dfrac{\sqrt{V\left[f_i^j\right]}}{\sqrt{m-1}} < f_i < \\ E\left[f_i^j\right] + t_\alpha^{(m-1)} \dfrac{\sqrt{V\left[f_i^j\right]}}{\sqrt{m-1}} \end{array} \right) = 1 - \alpha \,, \tag{9}$$

i=1, 2,…, n,

while:

$$\sum_{i=1}^{n} f_i^j \geq 100 \,. \tag{10}$$

Minimisation process (8) with relation (9) will have as a final result the fulfilment of relation (10) as equations, which here represents the objective. During the calculation procedure, optimal solutions fi* as optimal newbuilding production costs structure, will be produced respecting all of m equalities within relation (9). The existence of at least one allowable solution is unquestionable, and theoretical investigation of optimal problem solution equation existence (8, 10) here is not a research objective. The objective is to construct the solution upon real problem application by means of computer integrated mathematical procedure. Solution of the problem of stochastic optimisation is located in rather demanding class of problems within operations research and its theoretical apparatus have been developed in recent twenty years [18]. To escape theoretical difficulties within the process, solving of stochastic optimisation models, often is aimed towards restriction and approximation to array of optimisation problems of deterministic type within mathematical non-linear, and eventually linear programming.

4. Validation of generated costs structure

Stochastic optimisation model (8, 10) is applied for tanker newbuildings built in Croatian shipyards in period from 1996 to 2005. Selected tanker costs variables are presented in Table 1, where also expected costs average percentage, explained in previous chapter is presented in column 14. Due to simplifications reason only most significant 20 of 73 variables are presented, but all 73 were taken into account in following optimisation procedure.

Expected cost variables $E[f_i]$ are also presented graphically in Figure 1, where T_{GB} represent vessel production cost.

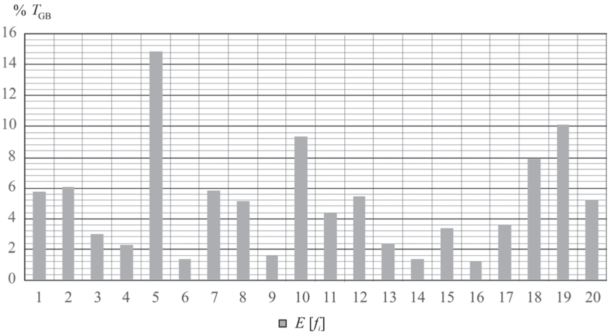


Figure 1. Cost variable expected average $E[f_i]$
Slika 1. Očekivani prosječni troškovi $E[f_i]$

A further procedure is related to defining constraints for each expected cost variable $E[f_i]$ according to eqn 6. Within such defined design limits, cost variable will be optimised to achieve optimal vessel production cost structure. For that purpose, the model will be transformed within real application in deterministic optimisation model by specialising parameter α = 0,01. In such manner probability of 0,99 is defined, meaning that the expected value of random variable f_i^j will be located within an interval defined by relation (6).

$$t_{0,01}^{9} = 3{,}25; \tag{11}$$

where a degree of freedom is:

$$m - 1 = 9 \tag{12}$$

and a degree of reliability is:

$$1 - \alpha = 0{,}99. \tag{13}$$

By detailed data analysis a model was generated containing 73 management variables:

$$f_i \,;\; i = 1, 2, ..., 73. \tag{14}$$

Probability relations (6) are transformed in 73 inequalities of type "≤" and additional same number of inequalities of type "≥". Therefore, if inequalities (24) are added, to those inequalities, in total the model contains 147 inequalities and one objective function. The

Table 1. Cost variables as percentage of tanker production costs and expected cost average $E[f_i]$

Tablica 1. Iznosi troškovnih stavki za tankere izraženi u postocima troškova gradnje broda te očekivani prosječni troškovi $E[f_i]$

1	2	3	4	5	6	7	8	9	10	11	12	13	14
No/Red.br	Variable/ Varijabla	Costing variable/Troškovna varijabla	% $T_{GB}1$	% $T_{GB}2$	% $T_{GB}3$	% $T_{GB}4$	% $T_{GB}5$	% $T_{GB}6$	% $T_{GB}7$	% $T_{GB}8$	% $T_{GB}9$	% $T_{GB}10$	$E[f_i]$
1	f_1	General costs/Opći troškovi	4.828	6.114	5.482	5.820	6.265	5.758	5.458	6.431	5.551	5.803	5.751
2	f_2	Financing costs/Troškovi financiranja	4.314	6.831	7.410	6.399	6.051	5.227	6.551	7.347	5.104	5.210	6.044
3	f_3	Undesignated mater./Nenamj. mater.	2.218	2.420	3.141	2.552	3.932	3.433	3.654	2.598	3.430	2.480	2.986
4	f_4	Paints/Boje	2.999	2.025	2.240	4.326	1.623	2.015	1.549	1.715	2.157	1.990	2.264
5	f_5	Steel material/Čelični materijal	17.164	13.924	14.714	9.575	18.081	14.519	17.144	10.297	18.737	14.116	14.827
6	f_6	Other steel mat./Ostali čelični mater.	1.199	1.173	1.353	1.258	1.678	1.516	1.396	1.239	1.517	1.156	1.348
7	f_7	Cargo equipment/Oprema za teret	4.273	4.238	5.260	8.814	5.755	6.137	6.615	4.733	4.985	7.429	5.824
8	f_8	Hull equipment/Oprema trupa	3.352	4.506	5.421	5.566	4.601	6.448	5.603	4.854	5.621	5.157	5.113
9	f_9	Crew&passg. equ./Opr. za pos. i put.	1.013	1.292	1.687	1.341	1.727	1.821	1.600	1.835	1.969	1.542	1.583
10	f_{10}	Main prop. System/Glavni prop. sist.	7.108	10.000	9.210	9.662	9.666	9.940	9.347	10.479	8.977	9.137	9.353
11	f_{11}	Auxi. engine syst./Pomoćni strojevi	3.242	3.038	4.702	4.773	5.331	5.075	4.648	3.945	4.853	3.814	4.342
12	f_{12}	Engine room syst./Sistemi strojarnice	5.118	4.025	4.840	6.590	5.702	5.284	5.448	6.826	4.880	5.622	5.433
13	f_{13}	Vessel systems/Brodski sistemi	1.532	2.025	2.490	1.961	2.782	2.687	3.098	2.504	2.427	1.857	2.336
14	f_{14}	Other equip. mat./Ostali mater. opr.	1.199	1.173	1.353	1.258	1.678	1.516	1.396	1.239	1.517	1.156	1.348
15	f_{15}	Design costs/Troškovi projektiranja	4.004	3.797	3.319	4.153	1.391	3.582	2.479	4.116	3.235	3.980	3.406
16	f_{16}	Pre.&fabric.mat./Predob. i obr. mater.	1.563	1.434	1.174	1.114	1.018	1.074	1.030	1.280	1.074	1.268	1.203
17	f_{17}	Preassembly/Predmontaža	4.686	4.298	3.521	3.338	3.053	3.221	3.089	3.838	3.220	3.800	3.606
18	f_{18}	Hull assembly/Montaža trupa	10.281	9.422	7.718	7.317	6.692	7.060	6.771	8.413	7.059	8.330	7.906
19	f_{19}	Met. eq. outfit./Opr. s met. opr.	13.128	12.043	9.864	9.352	8.553	9.023	8.654	10.753	9.022	10.647	10.104
20	f_{20}	Nonmet. eq. outfit./Opr. s nemet. opr.	6.784	6.224	5.098	4.833	4.420	4.663	4.472	5.557	4.662	5.502	5.222
21	T_{GB}	Ves. product. costs/Trošk. grad. broda	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	

mathematical condition of non-negativity upon variables is not necessary to introduce, because the model is formulated with a non-negative lower limit to variables. For example, for random variable f_1 the constraints were calculated in the following manner, so that the lower limit is (Table 3, column 7):

$$E\left[f_1\right]-t_{\alpha}^{(m-1)}\frac{\sqrt{V\left[f_1\right]}}{\sqrt{m-1}}= \\ =0,065645286-3,25\frac{\sqrt{0,0006035}}{\sqrt{10-1}}= \\ =0,03903259 \tag{15}$$

and upper limit is (Table 3, column 9):

$$E\left[f_1\right]-t_{0,001}^{9}\frac{\sqrt{V\left[f_1\right]}}{\sqrt{10-1}}=0,09225798 \tag{16}$$

and, therefore, in the model inequalities enter as inputs enter the:

$$f_1 \leq 0,09225798 \tag{17}$$

and

$$f_1 \geq 0,03903259. \tag{18}$$

The analogy is valid also for all other variables as presented in Table 2. Therefore, finding an optimal production cost structure for tanker newbuilding can be defined as a problem of linear programming, where:

- (8) defines the objective function;
- (9) defines 73 inequality relations where each consists of two relations of the type including (17) and (18); and
- (10) which defines 73 more inequalities.

Problem (8, 10) is resolved within specialised statistical software, where the optimal solution has to satisfy the following condition:

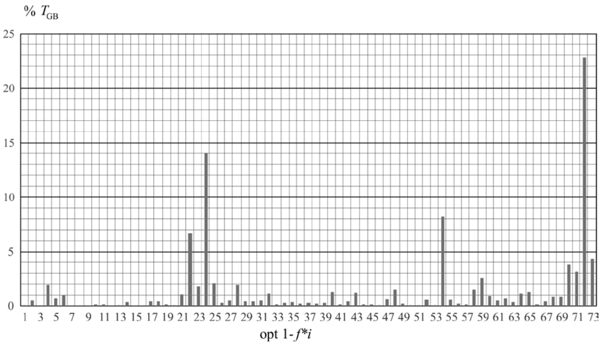
$$\sum_{i=1}^{73} f_i = 100\,. \tag{19}$$

Each of the optimal random variables is presented in Table 3 within column 8, and graphically in Figure 2.

Table 2. Calculated constraints for 73 cost variables

Tablica 2. Izračunata ograničenja za 73 troškovne varijable

$0{,}0390 \leq f_1 \leq 0{,}0923$	$0{,}1572 \leq f_{26} \leq 0{,}4834$	
$0{,}4176 \leq f_2 \leq 0{,}6855$	$0{,}2962 \leq f_{27} \leq 0{,}8107$	$0{,}0390 \leq f_{51} \leq 0{,}0900$
$0{,}0016 \leq f_3 \leq 0{,}0102$	$1{,}1501 \leq f_{28} \leq 3{,}3076$	$0{,}4900 \leq f_{52} \leq 0{,}7721$
$0{,}0000 \leq f_4 \leq 5{,}2720$	$0{,}0886 \leq f_{29} \leq 1{,}0564$	$0{,}0061 \leq f_{53} \leq 0{,}1284$
$0{,}4405 \leq f_5 \leq 1{,}2514$	$0{,}1398 \leq f_{30} \leq 0{,}9521$	$7{,}5382 \leq f_{54} \leq 9{,}2904$
$0{,}9541 \leq f_6 \leq 1{,}0119$	$0{,}0188 \leq f_{31} \leq 1{,}2661$	$0{,}4534 \leq f_{55} \leq 0{,}6974$
$0{,}0060 \leq f_7 \leq 0{,}0299$	$0{,}9403 \leq f_{32} \leq 1{,}4986$	$0{,}1691 \leq f_{56} \leq 0{,}2790$
$0{,}0000 \leq f_8 \leq 0{,}0470$	$0{,}0235 \leq f_{33} \leq 0{,}2734$	$0{,}0900 \leq f_{57} \leq 0{,}1879$
$0{,}0025 \leq f_9 \leq 0{,}0176$	$0{,}1685 \leq f_{34} \leq 0{,}4260$	$1{,}0455 \leq f_{58} \leq 2{,}2784$
$0{,}0485 \leq f_{10} \leq 0{,}2366$	$0{,}2745 \leq f_{35} \leq 0{,}5862$	$2{,}2050 \leq f_{59} \leq 3{,}1551$
$0{,}0153 \leq f_{11} \leq 0{,}4329$	$0{,}0000 \leq f_{36} \leq 0{,}6199$	$0{,}7711 \leq f_{60} \leq 1{,}1955$
$0{,}0052 \leq f_{12} \leq 0{,}0386$	$0{,}2079 \leq f_{37} \leq 0{,}3282$	$0{,}4172 \leq f_{61} \leq 0{,}6968$
$0{,}0258 \leq f_{13} \leq 0{,}0940$	$0{,}1649 \leq f_{38} \leq 0{,}2633$	$0{,}6207 \leq f_{62} \leq 0{,}8854$
$0{,}2806 \leq f_{14} \leq 0{,}4785$	$0{,}1931 \leq f_{39} \leq 0{,}3877$	$0{,}2499 \leq f_{63} \leq 0{,}4734$
$0{,}0091 \leq f_{15} \leq 0{,}0378$	$1{,}0142 \leq f_{40} \leq 1{,}6904$	$0{,}9212 \leq f_{64} \leq 1{,}6118$
$0{,}0095 \leq f_{16} \leq 0{,}0365$	$0{,}1080 \leq f_{41} \leq 0{,}1797$	$1{,}0521 \leq f_{65} \leq 1{,}7064$
$0{,}3590 \leq f_{17} \leq 0{,}4897$	$0{,}3768 \leq f_{42} \leq 0{,}5587$	$0{,}1103 \leq f_{66} \leq 0{,}1550$
$0{,}0000 \leq f_{18} \leq 1{,}0760$	$0{,}9811 \leq f_{43} \leq 1{,}6640$	$0{,}3653 \leq f_{67} \leq 0{,}6218$
$0{,}0598 \leq f_{19} \leq 0{,}2602$	$0{,}0993 \leq f_{44} \leq 0{,}1677$	$0{,}6686 \leq f_{68} \leq 1{,}2256$
$0{,}0192 \leq f_{20} \leq 0{,}1419$	$0{,}0918 \leq f_{45} \leq 0{,}1446$	$0{,}7210 \leq f_{69} \leq 1{,}070$
$0{,}9710 \leq f_{21} \leq 1{,}2127$	$0{,}0000 \leq f_{46} \leq 0{,}2690$	$2{,}9761 \leq f_{70} \leq 5{,}2295$
$4{,}6084 \leq f_{22} \leq 10{,}0491$	$0{,}5652 \leq f_{47} \leq 0{,}8245$	$2{,}5063 \leq f_{71} \leq 4{,}3050$
$1{,}4574 \leq f_{23} \leq 2{,}4426$	$0{,}0000 \leq f_{48} \leq 4{,}0352$	$20{,}1920 \leq f_{72} \leq 27{,}1079$
$11{,}6459 \leq f_{24} \leq 18{,}0084$	$0{,}0096 \leq f_{49} \leq 0{,}6152$	$3{,}2259 \leq f_{73} \leq 6{,}0320$
$1{,}4094 \leq f_{25} \leq 3{,}1185$	$0{,}0803 \leq f_{50} \leq 0{,}1388$	



Legend / Legenda: T_{GB} = Vessel production costs / Troškovi gradnje broda;
opt1-f^*i = Optimised cost variable / Optimirana troškovna varijabla

Figure 2. Optimal structure of newbuilding production costs

Slika 2. Optimalna struktura troškova gradnje plovnog objekta

5. Conclusion

Shipyard management is forced to concentrate its effort to act upon newbuilding production costs structure as to achieve the goal of profitable shipyard enterprise. With this objective an optimal vessel's production cost structure was generated. On basis of analysed previous newbuilding data, for a given standard type vessel, and for a given shipyard technological level, a particular cost structure configuration was developed. It is integrating the data of functional and product work breakdown structures. Further, based on statistical analysis and probability theory, a mathematical model of optimal newbuilding production cost structure is defined. Optimal structure is obtained through optimisation procedure as a mathematical programming problem. This structure defers from the stochastically expected cost variable averages. Generated structure enables shipyard management to determine production costs structure in preliminary design stage for contract bidding purposes, regarding vessels price and profit determination. Also, later during the production process, the model enables better control of those costing figures that for assigned conditions and restrictions have significant influence upon shipyard final performance results. Mathematical model for achieving optimal structure of production costs was verified and tested against real example of tanker newbuilding. Authors propose further research in integrating product and process breakdown structures, as to achieve unique

Table 3. Optimal structure of vessel's production costs

Tablica 3. Optimalna struktura troškova gradnje plovnog objekta

1	2	3	4	5	6	7	8	9	10
No/Red. Br.	Cost variable/Troškovna varijabla	$E[f_i]$	$V[f_i]$	$(V[f_i])^{1/2}$	variance coef./koef. odstup.	$E[f_i] - t^*(V[f_i]/(m-1))^{1/2}$	opt-1 f^*_i	$E[f_i] + t^*(V[f_i]/(m-1))^{1/2}$	$((f^*_i - E[f_i])^2)/(V[f_i])^{1/2}$
1	Model testing/Ispitivanje modela	0.066	0.0006	0.025	0.3742	0.0390	0.0592	0.0923	0.0017
2	Classif. society/Klasifikacijsko društvo	0.552	0.01528	0.124	0.2241	0.4176	0.5191	0.6855	0.0085
3	Maritime well fare/Pomorsko dobro	0.006	0.00002	0.004	0.6683	0.0016	0.0049	0.0102	0.0003
4	Interests on credit/Kamate na kredit	2.600	6.0836	2.466	0.9487	0.0000	1.9531	5.2720	0.1696
5	Bank commissions/Bankarske provizije	0.846	0.1401	0.374	0.4424	0.4405	0.7478	1.2514	0.0257
6	Brokers commissions/Provizije posrednika	0.983	0.0007	0.027	0.0271	0.9541	0.9760	1.0119	0.0018
7	Travel expenses/Putni troškovi	0.018	0.0001	0.011	0.6127	0.0060	0.0151	0.0299	0.0008
8	Representation/Reprezentacija	0.023	0.0005	0.022	0.9487	0.0000	0.0174	0.0470	0.0015
9	Repr.at launc.&deliv./Repre.na porin. i ispor.	0.010	0.00005	0.007	0.6961	0.0025	0.0082	0.0176	0.0005
10	Transport services/Transportne usluge	0.143	0.0075	0.087	0.6088	0.0485	0.1198	0.2366	0.0060
11	Forward.&ext. serv./Vanjskotr. i šped. usluge	0.224	0.0371	0.193	0.8600	0.0153	0.1736	0.4329	0.0132
12	Launching activities/Radovi u vezi porinuća	0.022	0.0002	0.015	0.7042	0.0052	0.0178	0.0386	0.0011
13	Tug services/Usluge remorkera	0.060	0.0010	0.031	0.5254	0.0258	0.0517	0.0940	0.0022
14	Docking/Dokovanje	0.380	0.0083	0.091	0.2406	0.2806	0.3556	0.4785	0.0063
15	Moving and towing/Pomicanje i tegljenje	0.023	0.0002	0.013	0.5639	0.0091	0.0200	0.0378	0.0009
16	Testing/Ispitivanja	0.023	0.0002	0.012	0.5419	0.0095	0.0197	0.0365	0.0009
17	Warranty works/Garantni radovi	0.424	0.0036	0.060	0.1421	0.3590	0.4086	0.4897	0.0041
18	Other expenses/Ostali troškovi	0.531	0.2534	0.503	0.9487	0.0000	0.3986	1.0760	0.0346
19	Cooperation-material/Kooperacija-meterijal	0.160	0.0086	0.092	0.5780	0.0598	0.1358	0.2602	0.0064
20	Basic resources rental/Najam osnovnih sredst.	0.081	0.0032	0.057	0.7029	0.0192	0.0657	0.1419	0.0039
21	Vessel insurance/Premija osiguranja broda	1.092	0.0125	0.112	0.1022	0.9710	1.0626	1.2127	0.0077
22	Holding expenses/Troškovi holdinga	7.329	6.3057	2.511	0.3426	4.6084	6.6702	10.0491	0.1727
23	Welding material/Materijal za zavarivanje	1.950	0.2068	0.455	0.2332	1.4574	1.8308	2.4426	0.0313
24	Steel material/Čelični materijal	14.827	8.6235	2.937	0.1981	11.6459	14.0573	18.0084	0.2018
25	Paints/Boje	2.264	0.6222	0.789	0.3484	1.4094	2.0571	3.1185	0.0542
26	Hatch covers/Poklopci grotala	0.320	0.0227	0.151	0.4701	0.1572	0.2808	0.4834	0.0103
27	Deck cranes with equip./Palub. diz. s oprem.	0.553	0.0564	0.237	0.4291	0.2962	0.4912	0.8107	0.0163
28	Cargo pumps/Pumpe tereta	2.229	0.9916	0.996	0.4468	1.1501	1.9678	3.3076	0.0684
29	Cargo pipeline/Cjevovod tereta	0.572	0.1995	0.447	0.7802	0.0886	0.4554	1.0564	0.0307
30	Cargo heating system/Sistem grijanja tereta	0.546	0.1406	0.375	0.6867	0.1398	0.4476	0.9521	0.0258
31	Inert gas system/Sistem inertnog plina	0.642	0.3314	0.576	0.8961	0.0188	0.4914	1.2661	0.0396
32	Aux. & cargo equip./Pom. sist. i opr. za ter.	1.219	0.0664	0.258	0.2113	0.9403	1.1519	1.4986	0.0177
33	Cargo vent. syst./ Sist. vent. tankova tereta	0.148	0.0133	0.115	0.7770	0.0235	0.1182	0.2734	0.0079
34	Rudder/Sklop kormila	0.297	0.0141	0.119	0.3998	0.1685	0.2661	0.4260	0.0082
35	Steering device/Kormilarski stroj	0.430	0.0207	0.144	0.3343	0.2745	0.3926	0.5862	0.0099
36	Bow thrust/Bočni propeler	0.307	0.0834	0.289	0.9403	0.0000	0.2314	0.6199	0.0198
37	Radar & satellite nav./Rad. uređ. i sat. nav.	0.268	0.0031	0.056	0.2072	0.2079	0.2535	0.3282	0.0038
38	Autopilot, compass/Autopilot, kompas	0.214	0.0021	0.045	0.2121	0.1649	0.2022	0.2633	0.0031
39	Communication equipment/Oprema za vezu	0.290	0.0081	0.090	0.3094	0.1931	0.2668	0.3877	0.0062
40	Other electr. Equip./Ostala elektr. oprema	1.352	0.0974	0.312	0.2308	1.0142	1.2705	1.6904	0.0214
41	Anchors/Sidra	0.144	0.0011	0.033	0.2302	0.1080	0.1352	0.1797	0.0023
42	Anchors chains/Sidreni lanci	0.468	0.0070	0.084	0.1794	0.3768	0.4457	0.5587	0.0058
43	Deck winches/Palubna vitla	1.323	0.0993	0.315	0.2383	0.9811	1.2399	1.6640	0.0217
44	Workshops machines/Strojevi u radionicama	0.134	0.0010	0.032	0.2364	0.0993	0.1252	0.1677	0.0022
45	Crane engine room/Dizalica strojarnice	0.118	0.0006	0.024	0.2060	0.0918	0.1118	0.1446	0.0017
46	Incinerators/Spaljivači otpadaka	0.133	0.0158	0.126	0.9487	0.0000	0.0997	0.2690	0.0087
47	Life boat with equipment/Brodica za spašav.	0.695	0.0143	0.120	0.1723	0.5652	0.6634	0.8245	0.0082
48	Accommodation equip./Oprema nastambi	1.990	3.5640	1.888	0.9487	0.0000	1.4951	4.0352	0.1297
49	Crew lifts/Liftovi za posadu	0.312	0.0781	0.279	0.8946	0.0096	0.2392	0.6152	0.0192
50	Kitchen equipment/Oprema za kuhinju	0.110	0.0007	0.027	0.2463	0.0803	0.1025	0.1388	0.0019
51	Laundry equipment/Oprema za praonicu	0.064	0.0006	0.024	0.3648	0.0390	0.0583	0.0900	0.0016
52	Vent., heat. & cool./ Vent., klimat. i grijanje	0.631	0.0170	0.130	0.2063	0.4900	0.5970	0.7721	0.0090
53	Sanitary systems/Sanitarni sistem	0.067	0.0032	0.056	0.8392	0.0061	0.0525	0.1284	0.0039
54	Main engine/Glavni motor	8.414	0.6540	0.809	0.0961	7.5382	8.2022	9.2904	0.0556
55	Screw/Propeler	0.575	0.0127	0.113	0.1957	0.4534	0.5459	0.6974	0.0077
56	Shafting/Osovinski vod	0.224	0.0026	0.051	0.2263	0.1691	0.2108	0.2790	0.0035
57	Stern tube/Statvena cijev	0.139	0.0020	0.045	0.3252	0.0900	0.1271	0.1879	0.0031
58	Auxiliary boilers/Pomoćni kotlovi	1.662	0.3238	0.569	0.3424	1.0455	1.5128	2.2784	0.0391
59	Auxiliary engines/Pomoćni motori	2.680	0.1923	0.439	0.1636	2.2050	2.5651	3.1551	0.0301
60	Separators and filters/Separatori i filteri	0.983	0.0384	0.196	0.1992	0.7711	0.9319	1.1955	0.0135
61	Coolers and heaters/Rashladnici i zagrijači	0.557	0.0166	0.129	0.2316	0.4172	0.5232	0.6968	0.0089
62	Pumps/Pumpe sistema	0.753	0.0149	0.122	0.1622	0.6207	0.7210	0.8854	0.0084
63	Comp. & air contain./Kompr. i sprem. zraka	0.362	0.0106	0.103	0.2852	0.2499	0.3346	0.4734	0.0071
64	Steel pipes/Čelične cijevi	1.267	0.1016	0.319	0.2516	0.9212	1.1830	1.6118	0.0219
65	Pipeline armature/Armatura cjevovoda	1.379	0.0912	0.302	0.2189	1.0521	1.3001	1.7064	0.0208
66	Fresh water generator/Generator slatke vode	0.133	0.0004	0.021	0.1557	0.1103	0.1273	0.1550	0.0014
67	Ballast & bilge syst./Sistemi kaljuže i balasta	0.494	0.0140	0.118	0.2398	0.3653	0.4625	0.6218	0.0081
68	Fire fighting systems/Protupožarni sistemi	0.947	0.0661	0.257	0.2714	0.6686	0.8797	1.2256	0.0177
69	Common el. systems/Zajednički el. sist.	0.896	0.0259	0.161	0.1798	0.7210	0.8533	1.0700	0.0111
70	Other material/Ostali materijal	4.103	1.0817	1.040	0.2535	2.9761	3.8301	5.2295	0.0715
71	Technical affairs/Tehnički poslovi	3.406	0.6891	0.830	0.2438	2.5063	3.1880	4.3050	0.0571
72	Man labour-shipyard/Radna snaga-vlastita	23.650	10.1886	3.192	0.1350	20.1920	22.8131	27.1079	0.2194
73	Man labour-cooper./Radna snaga-kooper.	4.629	1.6773	1.295	0.2798	3.2259	4.2894	6.0320	0.0890
	Vessel product. costs/Trošk. grad. broda, % →						100.0		1.9574

data values. Also, for change of technological level inclusion, special method for weighting these changes should be generated.

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