Investment cost estimate accounting for shipbuilding constraints

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ABSTRACT: The objective of this work is to propose a methodology for a fast estimate of the initial investment cost, CAPEX for the building of multi-purpose ships. A historical experience of building of similar ships is analysed and the estimates of the weight of ship groups: steel, superstructure, outfitting, machinery and equipment are performed. The existing empirical equations, with respect to the weight estimates are calibrated and new relationships of labour hours in ship building are proposed. The uncertainties raised from the price escalation of steel market and labour cost are accounted for and the sensitivities of different parameters involved in the analysis are performed. The cumulative distribution function, S-curve is defined, which may be used to estimate the probability of the overrunning of the point estimate or a specified initial investment cost during the construction process.

1 INTRODUCTION

A fast estimate of the initial investment cost, CAPEX, for the building of multi-purpose ships is performed here. The costs related to the life-cycle phases may be categorized into three groups related to the capital costs, CAPEX) operational cost, OPEX and decommissioning cost, DECEX.

The life cycle cost, CAPEX+OPEX+DECEX is normally used in the design process of all engineering systems, including ships (Damyanliev et al., 2017, Garbatov and Georgiev, 2017, Garbatov et al., 2017) and offshore structures (Yeter et al., 2016a, Yeter et al., 2016b, Yeter et al., 2017) among many others.

A data management system is normally used to collect and analyse historical up-to-date data and applying quantitative models (estimating relationships) to perform a forecasting. With this respect, the existing challenges are related to the lack of data and model uncertainties as well as to the inter-dependability of different factors. Examples are the cost of steel, equipment, machinery and outfitting; the labour cost that depends on the technological profile of the shipyard and respective overheads.

Another key parameter of this analysis is the profitability rate accounted in the so-called discounted average annual rate. The price escalation will also need to be accounted for. This is because most of related costs are time varying. When estimating the costs based on data, collected from different countries or shipyards, the difference in the productivity as the average labour rate also needs to be considered (Eurostat, 2017, SBB, 2017).

One possible solution is to use economic indicators like gross domestic product (GDP) per employee or GDP per hour worked. A database about these parameters needs to be developed or linked so as to provide a forecast.

The aim of this work is to find the correlation between the labour load for construction and the basic technical, economic and constructive characteristics of the vessel using the multi-factorial (multi-correlation) analysis of the mathematical statistics.

For the purpose of the present study, the production information of five consecutively built multi-purpose ships is used. For the determination of the regression dependencies, a variety of parameters and their combinations are taken into account, namely the major ship dimensions and their ratios, weights, total coefficient of completeness, and the relative cylindrical part of the ship´s hull.

The output of this study will be the CAPEX that needs to be defined as a part of a multi-objective (CAPEX, OPEX, etc.) optimized ship, including a cost S-curve, representing the probability of overrunning the point estimate of a specific budget, for a new shipbuilding project that will be managed by a shipyard or explored by a new ship owner.

2 LIGHTSHIP ESTIMATION

The lightship weight is split into subsystems such as: hull structure, equipment and outfitting and machinery. The hull structure weight includes the main hull structure, superstructure and deck houses.

The equipment and outfitting category includes pipes, deck outfitting, anchors, rudder, non-propulsion mechanical equipment such as deck machinery, steering engine, generators, ventilation systems, refrigeration systems, hull piping systems and pumps, and the electrical systems. The total machinery weight includes the main engine, auxiliary machinery, propeller, propeller shaft, engine spares, controls, and liquids in machinery.

To estimate the structural weight, regression equations based on statistical analysis of existing ships can be used (Benford, 1967, Cudina et al., 2010). To calibrate the regression equations that will be employed to estimate the weight of different subsystems, information taken from four recently built similar ships are used (Lee et al., 2007).

A multi-purpose ship, suitable for container transport with a single deck, stern engine compartment, single wheel power unit, slow-moving main engine with cargo cranes is analysed.

The weights of the vessel are estimated using the regression equations developed by Damyanliev (2001, 2002) and used in a conceptual design by Damyanliev et al. (2017) are re-calibrated here to real data of five recently built multi-purpose ships of similar dimensions. The regression equations are as a function of the ship main characteristics, where L is the length between the perpendiculars, m; B is the breadth, m; T is the draught, m; D is the depth, m; Cb is the block coefficient, Vs is the speed, kn; Pw is the effective propulsive power, kW, NE is the number of crew members and NJ is the number of superstructure decks. In the present study, L=115.1m, B=20.0m, T=8.3m, D=10.4m, Cb=0.7, vs=14.0 knots, Pw=5400.kW, NE=20 crew members and NJ=6 decks.

The weight of ship hull, t is defined as:

$$W_{11} = 0.00072\cdot CB^{1/3}\, L^{2.5}\cdot T/D\cdot B \tag{1}$$

where W_{11} is the weight of the main hull, t:

$$W_{12}=0.011\cdot L\cdot B\cdot D \tag{2}$$

where W_{12} is the weight of bulkheads in the main hull, t:

$$W_{13}=0.0198\cdot L\cdot B\cdot D \tag{3}$$

where W_{13} is the weight of decks and platforms, t:

$$W_{14} = 0.0388\cdot L\cdot B\cdot NJ \tag{4}$$

where W_{14} is the weight of the superstructure, t:

$$W_{15} = 0.00275\cdot L\cdot B\cdot D \tag{5}$$

where W_{15} is the weight of the foundation and other, t:

$$W_1 = (W_{11}+W_{12}+W_{13}+W_{14}+W_{15}) \tag{6}$$

where W_1 is the weight of ship hull, t.

The weight of ship equipment, t is defined as:

$$NCo= (L\cdot B\cdot T)^{2/3}+2\cdot B\cdot[D-T+(NJ-1)\ 2.8] \tag{7}$$

$$NC=NCo+0.1\cdot[D-T+0.588\cdot(NJ-1)]\ L \tag{8}$$

$$W_{21}=0.0475\cdot NC \tag{9}$$

where W_{21} the weight of the anchor equipment, t,

$$W_{22}=0.0216\cdot NC \tag{10}$$

where W_{22} is the weight of the mooring & towing arrangements, t,

$$W_{23}=0.0001185\cdot L\cdot T\cdot\sqrt{(Vs)} \tag{11}$$

where W_{23} is the weight of the rudder equipment, t,

$$W_{241}=0.00883\cdot L\cdot B\cdot D \tag{12}$$

where W_{241} is the weight of the loading equipment, t

$$W_{24}=P_{241}+0.002029\cdot L\cdot B\cdot D \tag{13}$$

where W_{24} is the weight of the loading equipment & mast, t,

$$W_{25}=0.002325\cdot(L\cdot B\cdot D) \tag{14}$$

where W_{25} is the weight of the outfit, t,

$$W_{26}=0.116\cdot(L\cdot B) \tag{15}$$

where W_{26} is the weight of the hatch covers, t,

$$W_{27}=0.871\cdot NE \tag{16}$$

where W_{27} is the weight of life boat & other arrangements, t,

$$W_{29}=0.0000845\cdot L\cdot B\cdot D \tag{17}$$

where W_{29} is the weight of other equipment, t,

$$W_2=W_{21}+W_{22}+W_{23}+W_{24}+W_{25}+W_{26}+W_{27}+W_{29} \tag{18}$$

where W_2 is the weight of the ship equipment, t.

The weights of the accommodation, t are defined as:

$$W_1=L\cdot B\cdot D/1000; \tag{19}$$

$$W_2=0.22\cdot L\cdot B\cdot NJ/100; \tag{20}$$

$$W_{31}=1.0182\cdot M_2 \tag{21}$$

where W_{31} is the weight of the compartment equipment, t,

$$W_{32}=0.3854\cdot M_1 \tag{22}$$

where W_{32} is the weight of the stories accommodation, t,

$$W_{34}=0.3504\cdot M_2 \tag{23}$$

where W_{34} is the weight of the office accommodation, t,

$$W_{36}=0.8030\cdot M_1 \tag{24}$$

where W_{36} is the weight of painting, t

W_{38}=2.3772·M_1 (25)

where W_{38} is the weight of other`s accommodation, t,

W_{39}=5.782·M_1 (26)

where W_{39} is the weight of isolation & other, t

W_3=W_{31}+W_{32}+W_{34}+W_{36}+W_{38}+W_{39} (27)

where W_3 is the weight of the accommodation, t,

The weight of the propulsion machinery is estimated as:

W_{41}= 0.00017·Pw (28)

where W_{41} is the weight of the boilers, t,

W_{42}=0.0657·Pw (29)

where W_{42} is the weight of the main engine, t,

W_{43}=0.017066·Pw (30)

where W_{43} is the weight of the auxiliary machinery in ER, t,

W_{44}=0.000666·Pw (31)

where W_{44} is the weight of the control systems in ER, t,

W_{46}=0.0002666·Pw (32)

where W_{46} is the weight of the systems & pipes in ER, t,

W_{48}=0.0002666·Pw (33)

where W_{46} is the weight of pipes and other equipment in ER, t

W_{49}=0.0105·Pw (34)

where W_{49} is the weight of other equipment in ER, t,

W_4=W_{41}+W_{42}+W_{43}+W_{44}+W_{46}+W_{48}+W_{49} (35)

where W_4 is the weight of propulsion machinery, t.

The weight of ship`s systems is estimated as:

W_{51}=1.0761·M_1 (36)

where W_{51} is the weight of the hull`s systems, t,

W_{52}=1.2528·M_1 (37)

where W_{52} is the weight of the fire-protection systems, t,

W_{53}=0.8031·M_1 (38)

where W_{53} is the weight of the sanitary systems, t,

W_{54}=1.4134·M_1 (39)

where W_{54} is the weight of the ventilation systems, t,

W_{58}=0.8031·M_1 (40)

where W_{58} is the weight of other hull systems, t,

W_{59}=0.0964·M_1 (41)

where W_{59} is the weight of other systems, t,

W_5=W_{51}+W_{52}+W_{53}+W_{54}+W_{58}+W_{59} (42)

where W_5 is the weight of the ship`s systems, t.

The weight of the electric equipment & control system is defined as:

W_6=3.276·M_1 (43)

where W_6 is the weight of electrical equipment and control system, t.

The weights of the general ship equipment & arrangement are defined as:

PI =0.759·M_1 (44)

where PI is the weight of inventory, t,

PTT =0.85·M_1 (45)

where PTT is the weight of the residue liquid cargo, t,

W_{91} = 5·M_1 (46)

where W_{91} is the weight of the reserve displacement, t

W_9 = PI+PTT+W_{91} (47)

where W_9 is the weight of the general ship equipment and arrangement, t.

The weight of light ship is estimated as:

LW = W_1+W_2+W_3+W_4+W_5+W_6+W_9 (48)

In the cost assessment analysis, the MARAD (2017) system is used in breaking down the weight groups, where W_A =W_1 is the weight of the ship hull, W_B = W_2+W_3+W_5+W_6+W_9 is the weight of equipment and outfitting and W_C=W_4 is the weight of the propulsion machinery system.

3 COST DESCRIPTION

Parameter estimates of the initial investment cost, CAPEX is based on design parameters such as ship size, weight, propulsion power, etc. This analysis uses a mathematical relationship between the input parameter and the cost that is historically determined through the regression analysis.

A cost breakdown divides the costs into material, labour, overheads, and profit. Material involves all shipyard purchases: materials, equipment, subcontracted work, outside engineering services, etc. The labour includes wages and benefits paid to shipyard employees whose work is directly connected with the ship building. Overhead is the sum of all internal shipyard costs that cannot be directly attributed to any given individual contract (Benford, 1967, Erichsen, 1971).

Steel material costs on average per ton net weight are considered here, which includes transportation and covers special shapes, welding rods, castings, forgings, and a nominal quantity of different steel. The variation of the net price of steel (SBB, 2017, Steelbenchmarker, 2017) is shown in Figure 1.

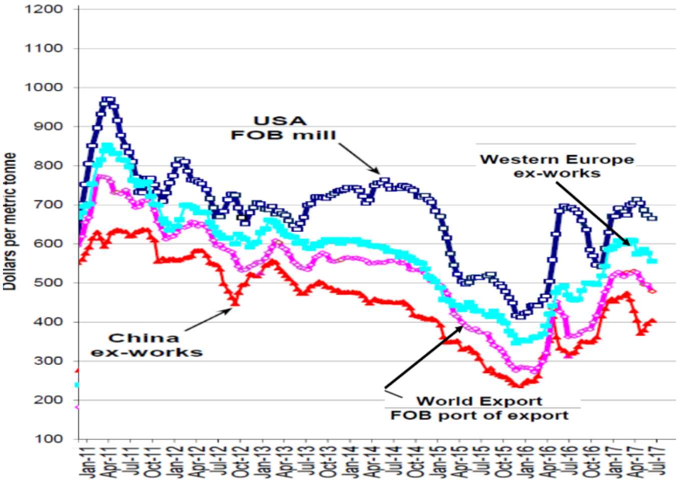

Figure 1 – Cost of ton steel (Steelbenchmarker, 2017)

For a small shipyard, a considerable amount of work is subcontracted. The subcontracted work may be included in the labour cost instead of to be a part of the shipyard purchase. The total labour cost depends on the percentage of subcontracted work, and this percentage could be included as a separate variable.

The labour cost in different European country based on Eurostat (2017) are shown in Figure 2.

In the present study, the estimated hourly labour cost of 10 €/hour is used.

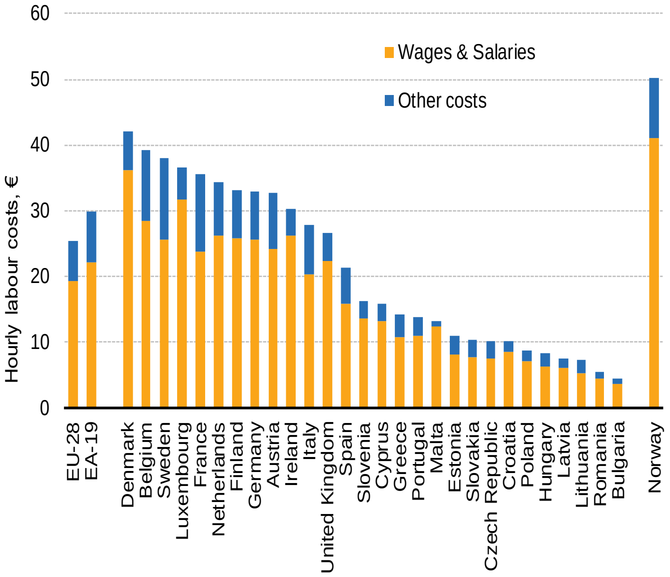

Figure 2 – Estimated hourly labour costs for the whole economy in euros, 2016 (Eurostat, 2017)

The hull structure material costs are assumed here as € per ton weight and may be estimated as:

$$C_A = k_A \cdot W_A, € \qquad (49)$$

and the labour cost in man-hours can be estimated based on the new developed here regression equation:

$$MH_A = W_A^{0.281} \cdot L^{1.347} \cdot B^{1.412} / (D^{0.274} \cdot Cb^{0.487} \cdot i^{0.102}) \qquad (50)$$

where MH_A, man-hours is fitted with R^2 very close to 1 and i is the series number of the ship.

The labour cost of the equipment and outfitting in man-hours are calculated based on the new developed regression equation:

$$MH_B = W_B^{0.287} \cdot L^{1.377} \cdot B^{1.452} / (D^{0.272} \cdot Cb^{0.488} \cdot i^{0.137}) \qquad (51)$$

where MH_B, man-hours, is fitted with R^2 very close to 1.

The material costs of the equipment and outfitting may be estimated as:

$$C_B = k_B \cdot W_B, € \qquad (52)$$

The coefficients k_A and k_B are assumed here as 580 €/ton and 1500 €/ton respectively.

The labour cost of the installation of the propulsion machinery system in man-hours is calculated based on the new developed regression equation here as:

$$MH_C = W_C^{0.292} \cdot L^{1.224} \cdot B^{1.417} / (D^{0.267} \cdot Cb^{0.490} \cdot i^{0.138}) \qquad (53)$$

where MH_C, man-hours, is fitted with R^2 very close to 1 and the material costs of the propulsion machinery system may be estimated as:

$$C_C = 850{,}000 \cdot (Pw/1{,}000)^{0.7} € \qquad (54)$$

where Pw is the propulsion power in kW.

Estimating the cost of the overhead, O is generally approximated as a percentage of the labour cost. The profit, P_r is calculated as a percentage of the summation of all the material, labour, and overhead costs. The overheads and profit are assumed here as 25% and 5% respectively.

The CAPEX cost is estimated as:

$$CAPEX = [1+Pr] \cdot [1+O] \cdot [\Sigma(W_i \cdot C_i) + C_C + \Sigma(MH_i \cdot C_{mi})] \qquad (55)$$

where W_i is and C_i are the weight and cost estimation of the ship where i=A is for the hull, i=B is for the equipment and outfitting and i=C and for the machinery. The material cost is estimated as a function of the propulsive power as C_C. MH_i and C_{mi} are the man-hour estimation and the cost of the man-hour of the hull, equipment and outfitting and propulsion machinery.

4 COST ESTIMATE UNCERTAINTIES

There are some difficulties in defining CAPEX and this is explained by the fact that is necessary to account for the factors that could result in the cost changes in order to enhance the forecast. This becomes a very important issue mainly due to the quite a long-time in-service of ships and the variation of prices in such a long period.

Time series analysis may be used in the economic forecasting. In order to analyse and forecast prices an average, naive, random walk or decomposition, exponential smoothing, autoregressive integrated moving average, ARIMA (Asteriou and Hall, 2011) processes can be chosen. A single exponential smoothing (Brown, 1963) assumes that the data fluctuate around a reasonable stable mean.

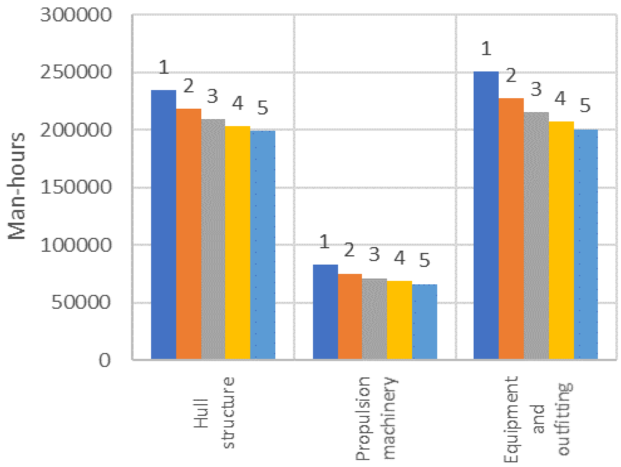

Figure 3 – Labour cost of different ship weight groups

The choice of the method is heavily dependent on the price index to be analysed. Usually, there have been a need to build an escalator clause for each field as for example material, labour, personnel, maintenance and fuel costs etc.

Several issues are seeing here related to the technology change (new processes, new materials), social, economic, and political situation (changing workforce, economic downturn and unrest), shipyard backlog (heavy backlog causes confusion and few orders results in loss of learning), labour rates (different for each shipyard and unpredictable changes), material costs (vendor base changes and delayed shipments), regulatory structure (new rules), inflation (fluctuates unpredictably, different rate for each item).

This will provide cost estimates with a certain range of uncertainty, which needs to be accounted for. An important capability of the cost forecast is to specify a range of possible costs for the shipbuilding processes.

The cost estimation relationships depend from one or more independent cost-driving variables, which can be the main dimensions of the ship, performance characteristics or others. The data collected over the time may be treated by the regression analysis to identify the most suitable function for the purpose. The output of this analysis is the most expected trend.

The driving variable may change and the estimated trend also. Both variations may be presented by a suitable probability density function. If the input uncertainties associated with the driving variable may vary in the interval A to B, then the cost estimation will also vary in the interval C to D (see Figure 4). The correlation between different cost estimates needs also to be accounted for.

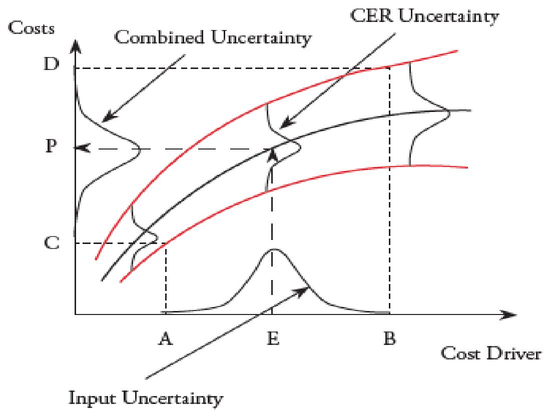

Figure 4 – Cost estimation relationships uncertainties

The weight, cost and model descriptors are assumed to follow the Log-normal distribution with COV between 0.05 and 0.1.

CAPEX can be expanded using the Taylor series, and if only the first order terms are kept and if the correlations between the involved random variable are neglected, the mean value may be estimated as:

$$E[CAPEX(\mathbf{x})] = [1 + E(\gamma^{pr})\cdot E(Pr)] \cdot [1 + E(\gamma^{o})\cdot E(O)] \cdot [\Sigma E(\gamma_i^{w})\cdot E(W_i)\cdot E(\gamma_i^{c})\cdot E(C_i) + E(\gamma_3^{c})\cdot E[f(\gamma_{pw}\cdot Pw)] + \Sigma E(\gamma_i^{m})\cdot E(MH_i) \cdot E(\gamma_i^{cm})\cdot E(C_{mi})]] \quad (56)$$

where γ_i^w is the uncertainty in the model of the weight estimation of the hull structure, i=A, equipment and outfitting, i =B, and γ_3^c is the uncertainty in the cost model of the propulsion machinery, γ_{pw} is the uncertainty in the model of the propulsive power estimation, γ_i^m is the uncertainty in the model of the man-hours estimations and γ_i^{cm} is the uncertainty in the model of the man-hours cost estimations. γ^{pr} and γ^o is the uncertainty in the model of the profit and overheads respectively.

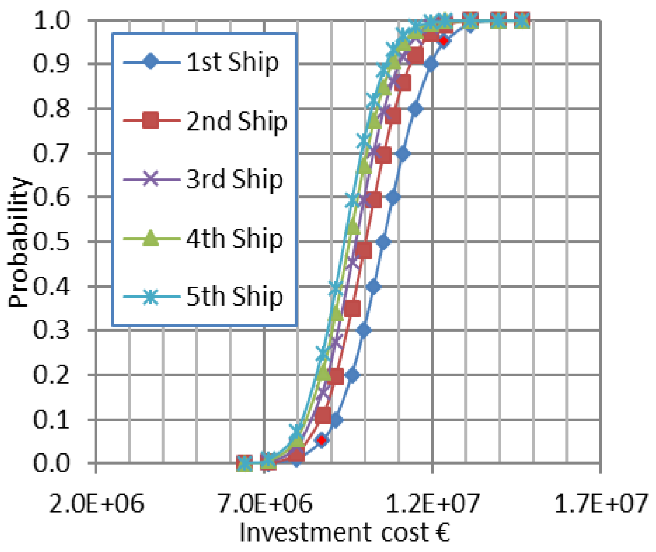

Figure 5 - S-curve as a function of cost progress

The standard deviation of the CAPEX cost, if the correlation between involved variable is not accounted for, is estimated as:

$$\sigma[\mathrm{CAPEX}(\mathbf{x})]=\sqrt{[\Sigma[\partial \mathrm{CAPEX}(x_i)/\partial x_i]\cdot\sigma^2(x_i)]} \quad (57)$$

where E(…) and σ(…) represent the mean value and standard deviation. The accuracy of the mean value and standard deviations depends of neglecting the higher order terms in the CAPEX estimation.

A truncated normal cumulative distribution function, S-curve, may be used to estimate the probability of overrunning the point estimate or a specified budget as can be seen in Figure 5, where the five analysed multi-purpose ships are also included.

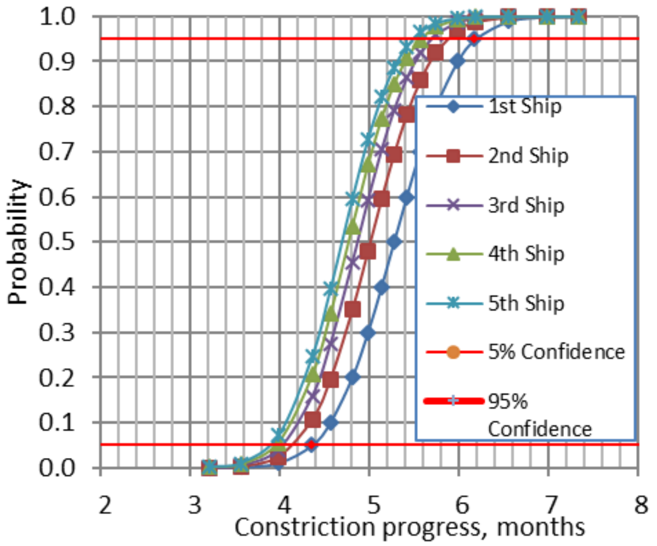

Figure 6 - S-curve as a function of construction progress

The greater the risk, the greater is the probability that the cost estimate is not realistic. To define the confidence levels, indicating the probability that the cost estimate will be wrong, and what the range of the possible cost will be about the expected prediction, the cumulative distribution function of the cost estimate is needed.

If the construction of the ship is assumed to progress regularly by 2.0E6 € per month, the probability of the construction progress is presented in Figure 6. The lower horizontal line represents the lower confidence level of 5% and the upper one represents 95% respectively.

Figure 6 also shows the difference in the constructional progress and the associated risk in building of five consecutive multi-purpose ships. It is clear that as the constructional experience is improved, the risk of not following the planed constructional schedule is reduced.

Cost risk drivers are those parameters that produce the highest variability in the risk associated cost estimate. The sensitivity of the parameters involved in the CAPEX estimate is shown in Figure 7 where 1 is the model of profit and overhead, 2 is the estimated profit and overhead, %, 3 is the model of labour cost, 4 is the estimated labour cost, €, 5 is the model of hull structure weight, 6 is the estimated the hull structure weight, ton, 7 is the model of the hull structure cost, 8 is the estimated hull structure cost, €, 9 is the model of the hull structure labour, 10 is the estimated hull structure labour, man-hours, 11 is the model of the equipment and outfitting weight, 12 is the estimated equipment and outfitting weight, ton, 13 is the model of the equipment and outfitting cost, 14 is the estimated equipment and outfitting cost, €, 15 is the model of the equipment and outfitting labour, 16 is the estimated equipment and outfitting labour, man-hour, 17 is the model of the propulsion machinery cost, 18 is the estimated propulsion machinery cost, €, 19 is the model of propulsion machinery labour, and 20 is the estimated propulsion machinery labour, man-hour.

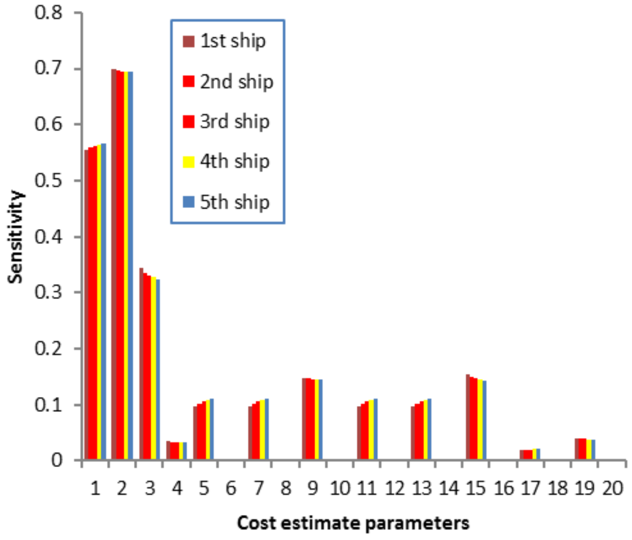

Figure 7 – Sensitivity of cost estimate

The sensitivities of the cost estimate with respect to the changes in the involved parameters show that the estimated profit and overhead (2), model of the profit and overhead (1) and model of the labour cost (3) are the most important, followed by the model of hull labour cost (9) and equipment and outfitting labour (15). It can be noticed that the importance of the different factors changes as the building experience is collected and in some cases, it may rise up to 10-20%.

5 CONCLUSIONS

A very fast estimate of the initial investment cost, CAPEX for building of multi-purpose ships has been performed. Empirical equations, with respect to the weight estimates were calibrated and new relationships of labour hours in ship building process are proposed. The uncertainties raised from the price escalation of the steel market and labour cost were accounted for and the sensitivities of different parameters involved in the analysis are performed.

The cumulative distribution function, S-curve, was defined, which can be used to estimate the probability of overrunning of the point estimate or a specified initial investment cost during the construction process.

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