Conceptual ship design framework for designing new commercial ships

T. Damyanliev and P. Georgiev

Technical University of Varna, 1, Studentska Str. UPB, 201, Varna, Bulgaria

Y. Garbatov

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: The objective of this work is to employ a conceptual design framework in designing a new bulk carrier vessel by satisfying all constraints related to the shipyard constructional limitation and service life exploration factors in minimizing the cost or other design or operational factors. A developed interactive intelligent conceptual design framework "*Expert*", which can be applied in designing commercial ships is employed here. To support the conceptual design environment, the framework accommodates the existing design experience and knowledge into mathematical tools that can be operated by computer systems. Different mathematical models are used in identifying the main dimensions of ship, ship hull form, mass and volume distributions, general arrangement, ship hull structures and equipment; propulsion complex; freeboard requirements; stability; sea-keeping; manoeuvrability etc. These models are operating in compliment of the requirements of the Classification Societies, including the shipyard construction and navigation restrictions and cost models for a ship construction and operation during the service life.

1 INTRODUCTION

Nova days, the conceptual ship design is performed by computerized systems that incorporate intelligent design frameworks. These frameworks initially proposed to be used in the initial stage of the design process lately were completed and transformed into a tool that can be employed through the entire design process.

Based on the current development of the computer aided design methodology, a multi objective and multi criteria optimization has been explored in ship design. This is explained by the fact that the ship design is a compromise between different designs constraints and limitations in satisfying the most contradictory characteristics, complexity and the uniqueness of the ship as a system.

There are many new concepts after the well-known "design spiral" from the 1959s. The Pugh controlled convergence approach developed in 1981 (Frey & al., 2009) promoted that the early stage design should be an iterative process of cooling down and adding to a set of concepts under consideration. There are two goals in this approach: 1) a "controlled convergence" on a strong concept that will be competitive in the current market; and 2) a common understanding of the reasons for this choice.

Parsons & al. (1999) proposed a set-based conceptual ship design to analogy with the method proposed by Alan Ward for the Toyota Company.

Bole & Forrest, 2005 discussed an integrated ship design environment that is based on an object-oriented framework. The system includes a creation of a product model and performs the analysis together.

The core of the system is an Early Stage Design module, based on the Functional Building Block methodology (University College London – Andrews, 1998). The latter permits the establishing of the complete design requirements for the hull surface and give the opportunity to integrate parametric hull form generation techniques in the concept design process.

Today, the computer aided design, CAD revolutionised the shipbuilding. It accelerates the design process and assisted the improvements in the accuracy at the design stage. Examples of such integrated computer design systems are AVEVA Marine (http://www.aveva.com) and Foran (http://www.marine.sener/), through, which is possible to design a comprehensive ship system and to be followed through the service life operation up to the end, including dismantling. However, every integrated design computer system starts after exploring a framework for a conceptual ship design.

The objective of this work is to employ a conceptual design framework in designing a new bulk carrier vessel by satisfying all constraints related to the shipyard constructional limitation and service life exploration factors in optimizing the cost or other design or operational factors using a home-made conceptual ship design framework "*Expert*" (Damynliev, 2001, 2002).

2 CONCEPTUAL SHIP DESIGN METHODOLOGY

Once the owner requirements are defined, including ship type, deadweight, speed, distance range, etc., the first step in the conceptual design is to generate the basic characteristics of the ship employing a mathematical model, taking into account all imposed requirements and constraints.

From mathematical point of view the conceptual ship design is considered as a solving of a system of equations that describe the ship performance. The mathematical model includes more unknowns than available equations, some of relationships related to the ship performance are inequalities and the equations are too complex to be analytically solved.

The model requires using consistent approximations as can be seen in Fig.1.

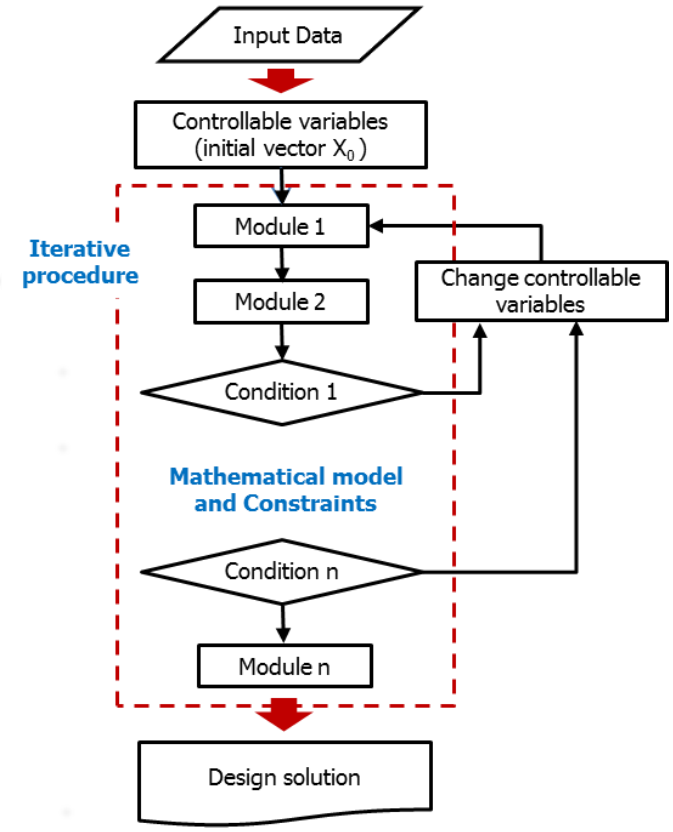

Fig.1 Concept design methodology.

The vector of the design variables $\mathbf{X}^o$ (x_1^o, x_2^o, ... , x_n^o) is defined based on a statistical data regression analysis or preliminary calculations. Most frequently, this vector includes the main dimensions, (or their relations) and hull form coefficients.

The design solution $\mathbf{X}^c$ (x_1^c, x_2^c, ... , x_n^c) is obtained by consecutively satisfying a set of design constraints and requirements and modifying the controllable variables. The design solution is feasible, but in the absence of an evaluation criterion this is just one of the possible solutions.

The logic of the optimization methods is primarily an analysis of the objective function to find the vector of controllable variables at which they reach the optimum design solution. Gallin (1973) suggested that it is possible to implement an algorithm, wherein the automated optimization procedure to find the optimum design solution, taking into account the constraints. This idea is purely procedural in nature, since nothing in the mathematical model does not change, but makes it possible to formulate a new methodology for building up a mathematical model of the ship design, including all restrictions (see Fig. 2).

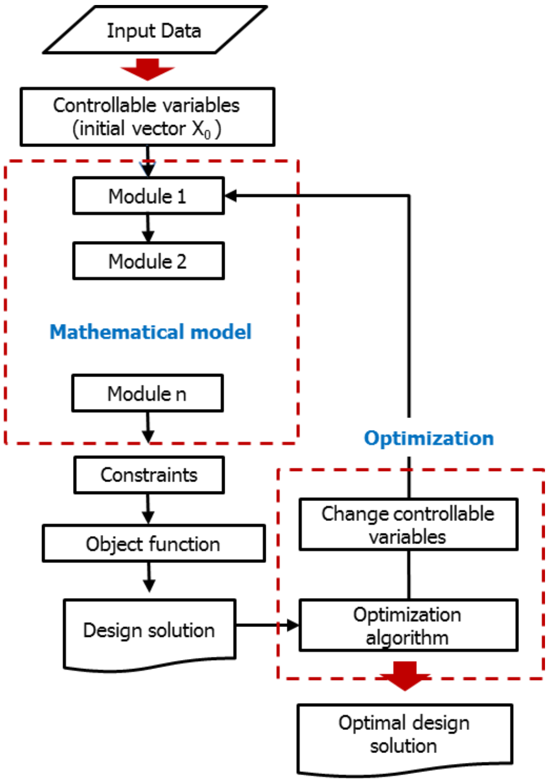

Fig.2 Design optimization methodology

The scheme of the optimization design methodology used in the "*Expert*" differs from the traditional one as presented in Fig. 1. The mathematical model and constraints are divided into two independent linear executed blocks. The current value vector $\mathbf{X}$ (x_1, x_2, ..., x_n) could not be feasible, but the optimization procedure automatically will find the vector $\mathbf{X}^*$ (x_1^*, x_2^*, ... , x_n^*), to achieve an optimum design solution that meets all the design constraints.

This approach removes the need of a consecutive check in satisfying the design constraints and requirements by modifying the controllable variables, which leads to a substantial simplification of optimization algorithms. In another case such check operations shall be developed for each type of ship or design task separately.

The optimization algorithm is based on the Sequential Unconstrained Minimization Techniques – SUMT (Fiacco & McCormick, 1972). The described approach is included in the conceptual ship design framework "*Expert*" (Damyanliev, 2002)

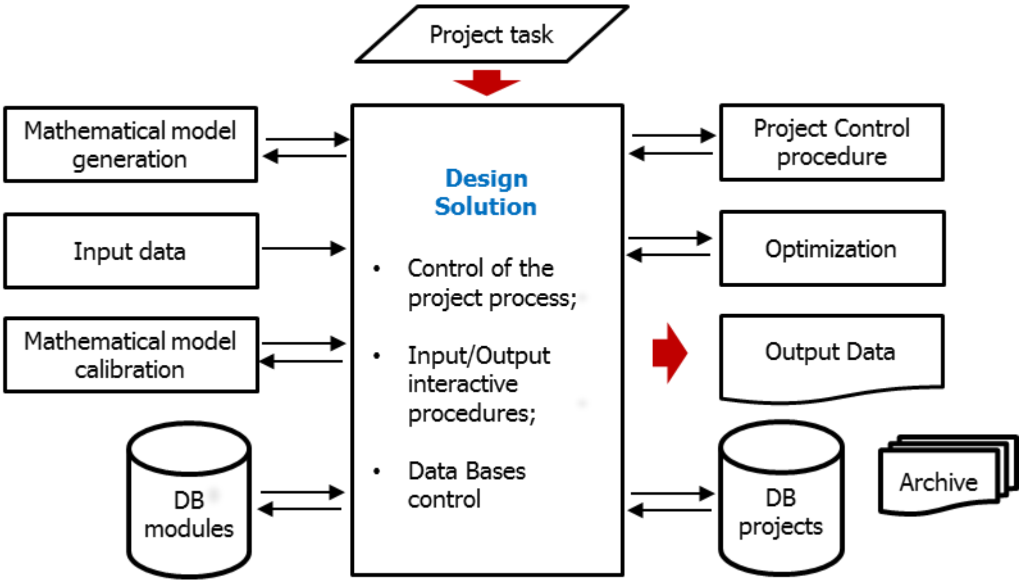

Fig. 3. Framework “*Expert*”

3 CONCEPTUAL SHIP DESIGN FRAMEWORK “*EXPERT*”

The principal scheme of the *Expert* system is presented in Fig. 3. The system is composed of two main functions: system analysis, which covers the optimization procedure and the identification of the optimal ship design solution, where the naval architecture and marine systems are defined.

DB “*Modules*” (library) is composed of 30 subsystem modules. Each subsystem is developing a specific part of the ship and can integrate several modules. The modules are structured as unified program units. The system database is generated by the modules of the mathematical model. The database is connected to a dictionary of terms.

Depending of the type of the ship to be designed and the ship design requirements, the active modules are selected from DB “Modules” defining the mathematical model of the project object.

Different mathematical models are employed in identifying the main dimensions of ship, ship hull form, mass and cargo capacity, general arrangement, ship hull structures and equipment; propulsion complex; free-board; initial stability; sea keeping; manoeuvrability, CAPEX, OPEX etc.

For any mathematical model, a database automatically is generated, including the input and output characteristics and constraints to guarantee the correctness of the design solution.

The decision variables, constraints and object function are defined in an interactive manner following the logic of the design problem.

For dry cargo ships and bulk carriers, the decision variables in the conceptual design are the length, L, breadth, B, depth, D, draught, d and block coefficient, Cb.

The boundary conditions are imposed to the generated ship model to guarantee that the initial requirements of the project are satisfied and the ship descriptors met the operational profile of the ship. However, the boundary conditions related to the functionality of the ship are defined by the requirements of the requested DW, minimum depth in accordance with the Load Line Regulations, cargo capacity, initial stability of the ship, etc. This can be achieved by imposing lower and upper bounds of the estimated variables as a part of the mathematical model as:

The control parameter of DW is defined as:

$$P_{DW} = Dw^{C} / Dw^{R} \quad (1)$$

where Dw^C is the defined DW and Dw^R is the required one, which is an input variable. In the case when:

$$1.0 \leq P_{DW} \leq 1.00 \quad (2)$$

then the defined deadweight is satisfying the required one.

The control parameter of the minimum freeboard is defined as:

$$P_{FB} = FB / (D-d) \quad (3)$$

where D and d are the currently defined depth and draught respectively and FB is the required freeboard. The limitation related to the minimum freeboard is defined as:

$1.0 \le P_{FB} \le A_{FB}$ (4)

where A_{FB} is the relative abundance of the free-board.

The control parameter of the cargo capacity, P_W is defined as:

$P_W = W/ (Q*SF)$ (5)

where W is the estimated cargo capacity, Q is the weight of the estimated cargo and SF is the stowage factor (input constant). The limitation related to the cargo capacity is defined as:

$1.0 \le P_W \le A_W$ (6)

where A_W is the relative abundant cargo capacity.

The control parameter of the minimum initial stability, P_{GM} is defined by:

$P_{GM} = GM/(0.04*B)$ (7)

where GM is the transverse metacentric height, B is the breadth of the ship. The limitations related to the initial stability are defined as:

$1.0 \le P_{GM} \le A_{GM}$ (8)

where A_{GM} is a factor defining the relative abundant initial stability. The maximum of the initial stability, P_{KA} is defined by:

$P_{KA} = 0.30/Ac$ (9)

where Ac is the relative rolling acceleration

$1.0 \le P_{KA} \le A_{KA}$ (10)

where A_{KA} is the relative minimum initial stability.

Additionally, additional limitations are imposed with respect to the main dimensions of the ship as $L/B \ge 5.2$ and $L/D \le 15$. The first relation takes into account the stability of ship heading and the second one satisfy the strength of the ship hull as given by DnV (2010).

The limitations related to the operational profile, for passing through the narrow canals and regions of shallow water result in particular limitation of the main characteristics of the ship related to the breadth, draught and length of the ship.

The design solution is also evaluated based on the defined technical and economic criterion. The economic criteria may be defined based on the required freight rate, R_{RFR} as:

$R_{RFR} = (S + CRF*K)/Q$ (11)

where S is the operational cost, K is the capital cost; Q is the annual transported cargo for one year and CRF is the Capital Recovery Factor.

The income, related to the transported cargo may be estimated by introducing the profit, PR and profitability, RE as:

$PR = (D – S) / Q$ (12)

$RE = (D – S) / K$ (13)

$D= Ø*Q$ (14)

where D is the annual income and Ø – freight.

During the formulation of the design task about 200 – 400 variables are generated on DB of the project. These variables define the ship as a mathematical model / object and may be included in the following groups:

- main dimensions and hull coefficients;
- principal hydrostatic particulars;
- general arrangement and volume of main compartments;
- resistance and propulsion, propeller and required power;
- weight of steel, machinery and outfitting;
- deadweight components.

The obtained ship characteristics as cargo capacity, minimum freeboard, initial stability, see keeping, manoeuvrability are used to define the operational constraints for the ship.

Another group of data is related to the economic characteristics of the ship, especial related to capital cost - CAPEX and operating cost- OPEX related to one specific shipyard technological profile and one specific maritime transportation company, including the current market price of steel, machinery, outfitting, equipment etc. The results are presented in a normalized format.

4 IMPACT OF LIMITED DRAUGHT

For ships designed to operate at limited draught, as the deadweight is increasing their efficiency in transporting cargo is increasing.

Table 1. Optimal design solution for limited draught

Dw, t	30,800		61,500		87,900		65,600
	d = 8 m	no limits	d = 10 m	no limits	d = 12.04	no limits	Panamax
R_{RFR}	0.758	0.664	0.584	0.560	0.558	0.538	0.564
L, m	181.89	166.00	229.94	228.68	234.99	267.92	242.25
B, m	30.86	27.88	38.67	30.62	39.11	36.24	32.31
d, m	8.00	10.48	10.00	12.66	12.00	13.96	12.04
D, m	12.14	14.81	15.33	18.33	17.54	19.67	17.58
Cb	0.859	0.784	0.81	0.807	0.82	0.738	0.81
L/B	5.89	5.95	5.95	7.47	6.01	7.39	7.50
B/d	3.86	2.66	3.87	2.42	3.26	2.60	2.68
D/d	1.52	1.41	1.53	1.45	1.46	1.41	1.46

Table 2. Optimal design solution for different values of SF [m^3/t]

SF,m^3/t	1.20	1.30	1.40	1.50	1.60
L, m	161.88	167.17	185.74	194.01	214.17
B, m	31.13	32.09	29.46	28.48	27.98
d, m	11.86	11.74	11.73	11.88	11.25
D, m	16.76	16.54	16.70	17.42	17.01
Cb	0.847	0.803	0.786	0.771	0.756
L/B	5.20	5.21	6.30	6.81	7.65
B/d	2.63	2.73	2.51	2.40	2.49
D/d	1.41	1.41	1.42	1.47	1.51
W, m^3	48317	52908	57314	61515	65664
W/Dw	1.150	1.260	1.365	1.465	1.563
$1 \leq P_{Dw} \leq 1$	1.000	1.000	1.000	1.000	1.000
$1 \leq P_W \leq 1$	1.000	1.000	1.000	1.000	1.000
$1 \leq P_{FB} \leq 2$	1.000	1.000	1.000	1.017	1.029
$1 \leq P_{GM} \leq 2$	2.208	2.512	1.219	1.147	1.157

This can be seen in Figure 4, where with increasing of the deadweight and the efficiency sharply increases (decreasing of RRFR) in the interval between 10 and 50,000 tons and it is stable above 50,000 tons. The results marked as „no limits" are obtained without limitations of the main dimensions.

In fact, when the ship will have navigational constraints (passing through canals and narrow waters: limits on the maximum draught and beam, seldom on the length; approaching harbours: limits mainly on the draft, seldom on the length) the ship will obey different economic efficiency. The impact of these restrictions, in the case of RRFR for draught of 8, 10 and 12.04 m to the optimal DW is shown in Figure 4 and Table 1. The optimal DW is estimated at 30,800, 61,500 and 87,900 tons

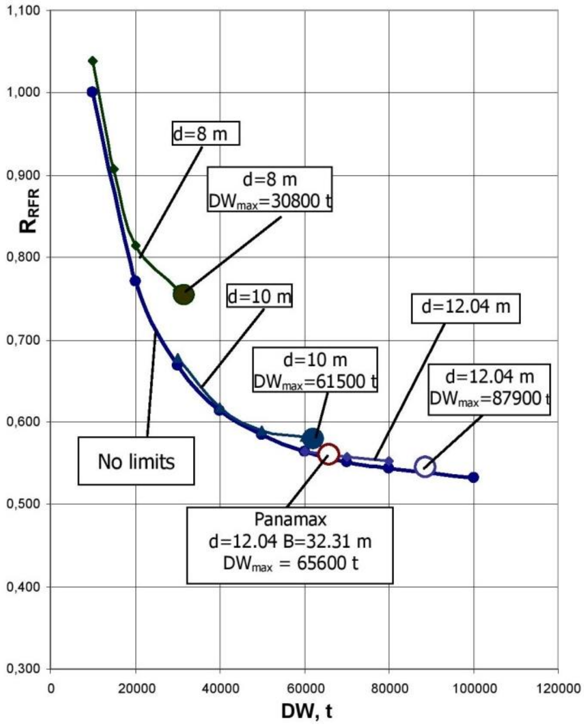

Fig. 4 Required Fright Rate (R_{RFR}) as a function of DW

Constraining the draught, the economic efficiency increases DW, which is supported by increasing of the breadth and block coefficient by reducing the length of the ship. This is also leading to a minimum value of L/B and maximum value of B/d. The design solutions with a limited draught have demonstrated a low efficiency in transporting cargo with respect to those without any limitation of the draught. This conclusion may be confirmed for ships up to 10,000 DWT and for Handy size (10,000 – 35,000 DWT) and not that much for Handymax (35,000 – 50,000 DWT) and much less for DWT > 50,000tons.

If, additionally to the draught limitation, other limitations are included, such as limitations about the main characteristics of the ship crossing the canal of Panama, the design solutions have a longer length as can be seen from Table 1.

5 DETERMINATION OF STOWAGE FACTOR

The capacity coefficient is defined as the ratio of the holds' volume to the deadweight of the ship (Papanikolaou, 2014). The capacity coefficient is an attribute of the ship. The stowage factor (SF), corresponds to the required hold volume per ton of cargo, and is an attribute of the cargo.

The SF relates to a potential capacity of transporting cargo in short and long-term distances during the service life of the ship and is defined during the early stage of the design of the ship.

From the design point of view, for a given DW this factor relates to two fundamental characteristics of the ship: cargo capacity (maximum value of SF – light cargoes) and strength (minimum value of SF- heavy cargoes), which define the main dimensions and shape of ship hull. An analysis of the impact of values greater than 1.20 (semi-heavy cargoes) is presented here.

As can be seen from Table 2, varying SF (input variable for the system "*Expert*") from 1.20 to 1.60

m^3/t, conditional to DW = 42,000 tons, the cargo capacity of the hull increases, which can be explained with the variation of the main dimensions and block coefficient of the design solution.

The design solution is defined by the limitations with respect to P_{DW}, P_W, P_{FB} and P_{GM}. The first two factors influence the DW and cargo capacity and the third and fourth ones control the lower bound of the freeboard and initial stability (minimum metacentric height).

The lower value of SF defines the optimal design solutions with a minimum freeboard and ratio L/B. As may be expected, in case of heavier cargo, the capacity is satisfied by relatively reduced main dimensions and the requested displacement is achieved by a bigger draught and block coefficient.

For the given initial requirements and chosen design criteria the required cargo capacity, in the case of increasing of SF, is achieved by increasing of the draught, breadth of the ship and the freeboard stays close to its minimum required value (P_{FB} = 1). However, the variation of SF may result in an essential difference in the main dimensions and shape of the ship hull.

As a rule, the dominant design variable for so called deadweight carriers (bulk carriers and tankers) is DW. In the case of tankers, the capacity coefficient is not varying significantly and it is constant. Using DW as an input variable, the main dimensions of the tanker may be correctly defined.

This is not the case for bulk cargoes. As can be seen from Table 2, for relatively small variation of SF (about 33%) the capacity coefficient varies about 36%, which leads to a large variation in the main dimensions of the ship. In this case the dominant design variable is the maximum value of SF, additionally to DW.

6 OPTIMIZATION OF FLEET COMPOSITION

The optimization of fleet composition or completing the fleet is conventionally called "external" to the conceptual ship design task. The results of this task govern the design project phase and where the main optimal dimensions of the ship ("internal" task) are defined.

Analysing the diversity and complexity of the "external" task, Pashin (1983) resolved the problem in two stages. In the first stage, after analysing the possible cargo flows, available financial resources, the number and type of existing ships and other data determines the amount of ships to be built in a period of time. In fact, this type of problems was solved by Gallin (1973) in the optimization of the fleet composition of tankers and dry cargo ships. At the second stage, the task of completing the fleet leads to defining the technical specification for the designed ship.

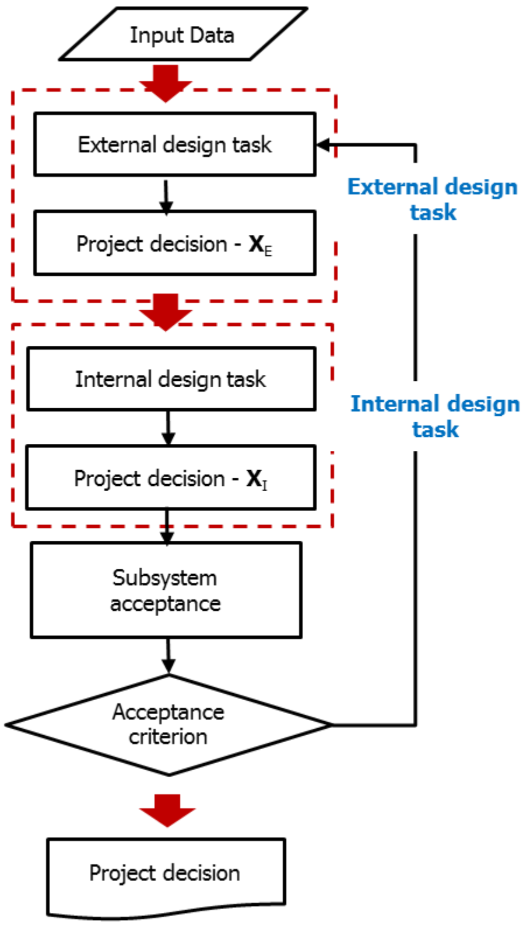

Fig.5. Joint solution of internal and external problem, "Expert" system

The conceptual ship design framework "*Expert*" allows a joint solution of both tasks; the "external" and "internal" ones (see Figure 5). The application of this approach is easier since the framework lets to apply the same mathematical models and objective functions in the two phase solution. Otherwise, the "external" task is understood as the conceptual design of the ship and the "internal" task is the optimization of the elements of the ship.

A case study is presented here, where the "*Expert*" system provides a joint solution of the number of ships needed, i.e. the principal characteristic of the technical specification (external task) and identification of the optimal solution (internal task).

The problem is defined as follows:

- for a given speed and cargo type (SF) define the number of ships (N_S) with optimal DW, capable of transporting for one year a defined total cargo volume (Q_{SUM}), conditional of the distance between two ports;
- for any possible design solution, define the optimal main dimensions of the ship.

A simplified logistic scheme of bulk cargo transport between two ports, including cargo loaded-ballast transition is considered.

The developed mathematical model, connected to the "external" task defines: the necessary time for cargo handling, time for the voyage and CAPEX and OPEX costs.

Following the logic of the design task, the external (E) and internal (I) decision variables include: $\mathbf{X}_E(N_S)$ and $\mathbf{X}_I$ (L, B, d, D and C_B). Additionally to the boundary conditions P_{DW}, P_W, P_{FB} and P_{GM}, the limitation of the external task related to the transported annual cargo P_{QSUM} is defined as:

$$P_{QSUM} = Q_{SUM} / (Q_T . N_S . N_R) \quad (15)$$

where Q_T is the cargo capacity of the design solution, N_R is the number of voyages per year leading to:

$$1.00 \leq P_{QSUM} \leq 1.00 \quad (16)$$

representing the fact that the entire planed cargo, Q_{SUM} will be transported.

The criterion for the optimum solution is assumed RFR. Table 3 and Fig. 6 present the obtained results for the initial conditions as follows:

- distance range – from 1,000 to 9,000 nautical miles;
- cargo - Q_{SUM} = 5,000,000 tons;
- stowage factor - SF = 1.40 m^3/t;
- limitations of the main dimensions of the ship: Panama Canal (B ≤ 32.31 m, d ≤ 12.04 m).

Table 3. Fleet composition

R, nm	1,000	3,000	5,000	7,000	9,000
Dw, t	32129	58714	68714	73482	74794
Ns	6.1	6.9	8.3	10.8	13.3
L. m	177.49	214.01	258.57	258.37	258.14
B. m	30.34	31.09	32.31	32.31	32.31
d. m	9.21	12.04	12.04	12.04	12.04
D. m	13.39	18.39	17.68	17.75	17.84
Cb	0.792	0.848	0.82	0.834	0.848
Vs,kn	14.2	14.2	14.2	14.2	14.2
L/B	5.850	6.884	8.003	7.997	7.989
B/d	3.296	2.582	2.683	2.684	2.684
D/d	1.455	1.528	1.468	1.474	1.482

With increasing the distance range, the optimal DW and the number of ships needed is also increasing. The optimal design solutions are bounded by the limitations related to P_{QSUM}, P_W and P_{FB}.

As can be seen from Table 3, with increasing of DW, the navigational constraints of the breadth and draught lead to a relatively increase of L/B (up to the upper bound of L/B ≤ 8.00) and block coefficient.

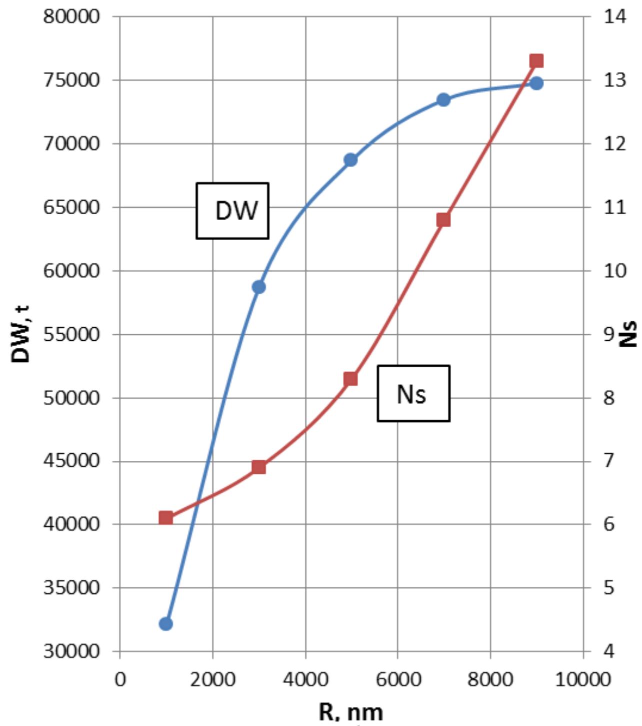

Fig.6. Optimal DW and number of ships, Ns vs. R

7 CONCEPTUAL DESIGN OF A BULK CARRIER

In the conceptual ship design, the mathematical model of the ship is traditionally built based on the statistical analyses, developing regression equations to describe the ship as a physical object with predefined properties. The mathematical model has to achieve a good consistency and correlation between the obtained design solution and controllable variables for each subsystem and the ship as a whole. In a statistical analysis of the data, the prototype conditions are relatively easily achieved by a rational choice of the functional relationship between the available data and decision variables and the regression equations.

An important issue is the accuracy of the model. The rational approach is to reconcile the results with data from similar prototype. The system "*Expert*" execute, in an interactive mode, an option "Agreement". Each output value, W from the database of the system may be enhanced by:

$$W = N{*}W + M \quad (17)$$

where the factors N and M are 1 and 0 respectively by default.

If necessary, N or M or both factors can be assigned corrective values determined after an analysis of the performance of the prototype, through a similar adjustment and this enhancement may increase the accuracy of the mathematical model.

On the other hand, at N = 0 and M ≠ 0 may be introduced a constant value of the parameter or by N = 0 and M = 0, to "turn off" the model.

This approach is applied to design a bulk carrier with deadweight of 42,000 tons in the presence of a close prototype build in a Bulgarian shipyard. Here, by appropriately defining the factor values of N and M an increase in the mass of the ship hull (M_{mh}) due to the ice reinforcement and the correction of the weight of the cargo loading equipment (M_{le}) due to the absence of cranes, compared to the prototype is taken into account.

M_{mh}'=N.M_{mh} + M where N= 1.08; M=0 (18)

M_{le}' =N.M_{le} + M where N= 1.00; M= -62.0 (19)

The new ship type is defined as follows:

- single deck, single-screw with aft located ER, with hatch covers and without deck cranes;
- U- shape bow frames with bulb and with transom and aft bulb;
- the superstructure is separated from the funnel and it is located over ER;
- cargo space is formed by a double bottom and hopper tanks, single board and topside ballast tanks.

The mathematical model includes 23 subsystems and generates about 200 variables.

The inputs to the system include:

- deadweight – 42, 000 t;
- speed - 14.2 kn;
- sailing distance – 5,000 miles
- datasets to assess the CAPEX and OPEX of the vessel;
- other data

The decision variables are the length, breadth, depth, draught and block coefficient.

Table 4 Conceptual design of 42,000 tDW bulk carrier

	Prototype	Case 1	Case 2
SF,m^3/t	1.307	1.307	1.333
L, m	177.00	164.48	165.67
B, m	30.00	31.63	31.86
d, m	11.80	11.96	11.98
D, m	16.20	16.82	16.82
Cb	0.819	0.812	0.799
L/B	5.900	5.201	5.200
B/d	2.543	2.644	2.660
D/d	1.373	1.406	1.404
LW, t	9648	9813	9815
W, m^3	52669	51944	53024
LW/(LBD),t/m^3	0.112	0.112	0.111
W/DW,m^3/t	1.254	1.237	1.262

Table 4 shows the main features of the three design solutions. The first is the ship prototype, the second is with SF=1.307 m^3/t (Case 1) and SF=1.33 m^3/t (Case 2). For accepted criterion the calculated optimal solution is for relatively short ships. The ratio L/B is close to the lower boundary (L/B ≥ 5.2)

CONCLUSIONS

The conceptual ship design framework "*Expert*", which was explored in this study, is structured as an open system allowing the search design solution for different types of ships for which a suitable mathematical model can be generated.

The conceptual framework is capable of accounting for series of constraints. Different mathematical models can be employed in identifying the main dimensions of ship, ship hull form, mass and volume distributions, general arrangement, ship hull structures and equipment; propulsion complex; freeboard requirements; stability; seakeeping; manoeuvrability etc.

The developed interactive intelligent conceptual design framework "*Expert*" can be applied in designing different types of commercial ships.

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