Conceptual design of multipurpose ship and fleet accounting for SME shipyard building limitations

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ABSTRACT: This work deals with the design and optimization of a new multipurpose ship and fleet that will be built in a small and medium sized shipyard accounting for the constraints related to the shipbuilding limitations. The problem is solved in two stages, where in the first one, based on the cargo flows, the number of ships to be built and speed is defined. At the second stage, the completing of the fleet leads to defining the technical specification for the individual ship as a part of the fleet. A constraint associated to the maximum breadth of the ship is used as an additional limitation in defining the basic characteristics of the ship. The design solutions comply with the shipyard construction and navigation restrictions and the CAPEX and OPEX costs are used as a part of the optimization function employing the specialized software “Expert”. Based on the identified design solution several conclusions are derived.

1 INTRODUCTION

The technological development of the small and median enterprises, SMEs in Europe with respect to the economic growth and employment is of a great importance nowadays. According to LeaderSHIP strategy (ec.europe.eu/DocsRoom/ documents /10504/) the maritime technology industry is of strategic importance for the EU and in the RDI area one of the objectives is “encouraging open innovation in clusters to enhance participation of maritime technology SMEs in RDI projects and access to RDI results”.

In this respect, one of the main goals of the EU Project Shiplys is to respond to the needs of the SME shipyard designers, shipbuilders and shipowners (Bharadwaj et al., 2017) in the development of a ship risk-based design framework accounting for the life cycle cost assessments. The framework deals with the conceptual ship design, risk-based target structural reliability assessment, risk-based maintenance, and fast hull geometry prototyping and shipbuilding management (Garbatov et al., 2017b). This framework will enable the SMEs shipyards to make more reliable estimates, given the client requirements, in the early stages of the inquiry and the existing shipyard`s shipbuilding capacity.

The shipbuilding capacity of one specific SME ship repair yard with respect to building new ships was analysed by Atanasova et al. (2018). The main conclusion from the analysis is that it is possible to build new ships of different types with deadweight up to 7,000 tons with a limitation of the ship breadth due to the existing dock capacity. Considering the existing shipyard facilities and implemented shipbuilding technology and equipment, it was concluded that it is possible to build a new multipurpose ship in a shipbuilding period of eight months.

During the shipbuilding process, a limiting factor for the main dimensions of the ship is the width of the dock of 16 m and the docking weight capacity permits building of vessels with restricted breadth up to 6,800 tons.

The initial ship design is normally split into two stages - "Fleet Composition” and "Conceptual Design”, “external” and “internal” design tasks. The expedience of jointly tackling the two tasks was originally formulated by Gallin (1973) and Pashin (1983).

The main characteristics of the subsystem “fleet”, are the parameters that ensure the economic efficiency of a group of ships operating according to a predefined transportation scenario, where the most important output parameter the ship speed, load capacity (deadweight, number of containers, cargo volume etc.) and the number of ships.

The main task of the subsystem "ship" is defining the main dimensions of the ship, hull form coefficients, etc. that would provide the best economic performance during the ship operation. The design solution considers all conditions formulated by the “fleet” subsystem, which are part of the design specification.

In this respect, Wagner et al. (2014) presented a scenario-based optimization procedure of the KRISO container ship, using a statistically developed operational profile generated from an existing container vessel. The main conclusion was that the usage of scenarios within the optimization process has a strong impact on the hull form.

Ventura and Guedes Soares (2015) integrated a voyage model in to a ship design optimization procedure, where the voyage scenario allowed an estimation of the sailing and port times and operational costs. Two objective functions were established in minimizing of the required freight rate and attained EEDI.

The present work deals with the design and optimization of a new multipurpose ship and fleet that will be built in a small and medium sized shipyard accounting for the constraints related to the constructional limitations. The problem is solved in two stages, where in the first one, based on the cargo flows, the number of ships to be built and ship speed are defined. At the second stage, the completing of the fleet leads to defining the technical specification for the individual ship as a part of the fleet.

The design solution of the two tasks is performed by employing the software Expert (Damyanliev & Nikolov, 2002), which was recently used by Damyanliev et al. (2017) for designing new commercial ships. The fleet composition task considers a given distance between ports, total amount of transported cargo and Panama Canal restrictions.

Two transportation scenarios with a different total amount of cargo and distances between the ports are analysed. The second scenario is most suitable for a ship with deadweight up to 6,000 tons.

2 DESIGN DEFINITION

The "Fleet composition" and "Conceptual design" tasks are defined for a specific transportation conditions of a cargo flow, where the optimal design solution estimates the number of ships, speed and deadweight of required ships (external task) and the main dimensions and ship hull form coefficients (internal task).

The optimization of the object function, F(**X, Q**) is formulated as (Damyanliev et al., 2017):

$$F(\mathbf{X}^*) = minF(\mathbf{X},\mathbf{Q})\,,\ \mathbf{X}\ \in \mathbf{E}^n \qquad (1)$$

which is subjected to design constraints:

$$\mathbf{H}\{h_i(\mathbf{X},\mathbf{Q})\} > 0, i = 1,2,\dots,m \qquad (2)$$

where **X** is the vector of design variables x_1, x_2, …,x_n, $\mathbf{X}^*(x_1^*, x_2^*, \dots, x_n^*)$ is the vector optimum design solution, $\mathbf{h}_i(\mathbf{X}, \mathbf{Q})$ are the inequality constraints as a function of design variables **X** and uncontrollable parameters **Q**.

The components of the vectors of the design variables **X**, constraints, $\mathbf{h}_i$, and uncontrollable parameters, **Q** are part of the external and internal tasks.

The vector of design variables, **X** includes:

- number and speed of the ships, $\mathbf{X}_E$ (external task);
- main dimensions and ship hull form coefficients, $\mathbf{X}_I$.(internal task);

Uncontrollable parameters in most cases are input variables in the mathematical model and are defined as:

- descriptors of the transportation scenario and cargo flow (characteristics of the cargo, voyage distance, port performance, crew number, etc.);
- descriptors of the ship (coefficient of structures etc.);
- descriptors of the economic performance (normative and statistical coefficients etc.).

Similarly, the vector of constraints includes:

- constraints related to the external task, $\mathbf{H}_E$;
- constraints related to the internal task, $\mathbf{H}_I$.

The optimal solution is obtained by employing the Sequential Unconstrained Minimization Technique, SUMT as defined by Fiacco and McCormick (1968), Himmelblau (1972).

This algorithm is formulated in using nonlinear programming (1) and (2) without constraints by introducing a penalty parameter. The solution is based on a sequential unconstrained minimization of the transformed objective functions **P**(**X**, **Q**, r_k) in the following form:

$$\mathbf{P}(\mathbf{X},\mathbf{Q},r_k) = \mathbf{F}(\mathbf{X},\mathbf{Q}) + 1/r_k\sum\{min[0;\mathbf{H}(\mathbf{X},\mathbf{Q})]\}^2 \qquad (3)$$

$$\mathbf{F}(\mathbf{X}^*) = \lim\{min\,\mathbf{P}(\mathbf{X},\mathbf{Q},r_k\}, r_k \to 0 \qquad (4)$$

where r_k is the penalty parameter, $r_k > 0$.

This algorithm allows eliminating the intermediate checks for the compatibility of the design solution with the constraints. Employing this algorithm, a universal ship conceptual design framework was developed in (Damyanliev et al., 2017). The developed framework can solve the external and internal ship design tasks, subjected to different initial conditions and constraints and will be used in the present study.

3 BASE CASE STUDY

A case study in in defining a design solution of the “Fleet composition” and “Conceptual design” tasks is presented here.

3.1 *Transportation scenario*

The transportation scenario involves a transportation of cargo, mainly containers, from the terminal, T to Port 1, P1 and Port 2, P2 and return as can be seen in Figure 1.

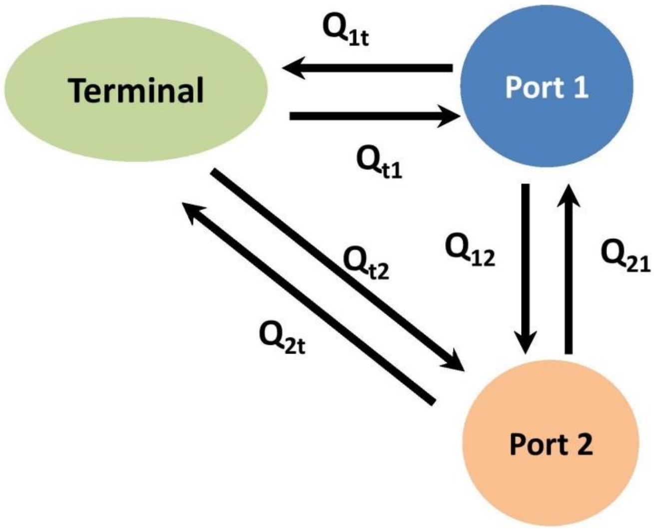

Figure 1 Transportation scenario

The amount of transported cargoes is as follows:

- Total amount of cargo from Terminal to Port 1 and Port 2 and vice versa per year is Q_{sum}=1,000,000 tons;
- Cargo from Terminal to Port 1 and vice versa is $Q_{t1} = Q_{1t} = k_{t1}.Q_{sum}$;
- Cargo from Terminal to Port 2 and vice versa is $Q_{t2} = Q_{2t} = k_{t2}. Q_{sum}$;
- Cargo from Port 1 to Port 2 and vice versa is $Q_{12} = Q_{21} = k_{12}.Q_{sum}$.

It is assumed that the cargo consists of 16-ton TEU. It is assumed 10% void space in the transported containers resulting in the average weight of one container of 14.65 tons.

The distances between the ports and terminal are:

- Terminal - Port 1 = 1161 nm;
- Port 1 - Port 2 = 339 nm.

The cargo handling time is:

Terminal	630 TEU/day;
Port 1	570 TEU/day;
Port 2	520 TEU/day;

The freight rate per ton of cargo is:

- Terminal - Port 1 = 30 USD/ton;
- Terminal - Port 2 = 40 USD/ton;
- Port 1 - Port 2 = 10 USD/ton;

3.2 *Ship definition*

The type of ships is multi-purpose, intended for transport of bulk and other dry cargoes. The ships are equipped with cranes for loading and loading of containers.

The ships are single-decked, with an engine room located aft, single propeller with a slow-speed diesel engine, and a superstructure located extremely aft. There is a bulb bow and transom stern.

3.3 *Design parameters*

The design parameters are defined as:

Number of ships	Ns;
Speed, kn	Vs;
Length between perpendiculars, m	L_{pp};
Breadth, m	B;
Draught, m	d;
Depth, m	D;
Block coefficient	C_B.

There are no formal constraints to the design variables. The design solution of the transportation of cargo is controlled by an indicator, P_{Qsum}, which is defined as:

$$P_{Qsum} = TC_{sum}/ Q_{sum} \tag{5}$$

where:

$$TC_{sum} = Ns\ Nv\ TCsv \tag{6}$$

where Nv is the number of voyages per year and TCsv is the transported cargo per ship per voyage.

The condition when P_{Qsum} =1 indicates that the total amount of cargo is transported during the year.

The required deadweight of the ships is provided by the condition when P_{Dw} =1 defined as:

$$P_{Dw} = DW/ DWr \tag{7}$$

where DW is the estimated deadweight and DWr is the required one.

In the cases where the deadweight is a resultant value, the buoyancy index, P_{FL} is defined as:

$$P_{FL}= \Delta/ (LW+DW) \tag{8}$$

where Δ is the weight displacement, tons, LW is the lightweight, tons and DW is the deadweight, tons.

The condition when P_{Qsum}=1 represent the case where the buoyancy equilibrium is satisfied.

Additionally, some functional constraints are also satisfied including:

- Summer free board, P_{FB};
- Minimum stability with containers, P_{GMc};
- Sufficient cargo volume, P_V.

The objective function may use one of the following economic indicators:

- Required Freight Rate, RFR;
- Profit, Pr;
- Profitability, Re.

The required freight rate is defined as:

$$RFR = (OPEX + CFR.CAPEX)/Q,\ USD/ton \tag{9}$$

where OPEX is the operational cost per year, USD, CFR is the capital recovery factor, CAPEX is the capital expenditure, USD and Q is the transported cargo per year, tons. A recent analysis about a CAPEX estimation in the condition of a SME shipyard was presented in (Garbatov et al., 2017a)

The profit is defined as:

$$Pr = (Rev - OPEX) / Q, \text{ USD/ton} \quad (10)$$

where Rev= Q.FR is the revenue per year, USD, FR is the market freight rate, USD/ton and Q is the amount of transported cargo, tons.

The profitability is defined by:

$$Re = (Rev - OPEX) / CAPEX, \% \quad (12)$$

The above economic indicators are of a universal nature and are often used in assessing the economic efficiency of complex technical systems.

The required freight rate assesses the rate of return of the initial investments; the profit includes only the revenues from the shipping activity.

Through the profitability, the effectiveness of the investments, accounting for the operating costs and revenues from the shipping may be controlled.

3.4 *Design solution*

The defined design tasks were solved by using the software Expert, considering the three economic indicators RFR, Pr and Re.

The design solution of the optimized design variables is presented in Table 1.

Table 1 Design parameters

	Indicators	RFR (min)	Pr (max)	Re (max)
	Design variables			
1	Ns	3.078	3.072	2.561
2	Vs, kn	10.411	11.549	10.592
3	L_{pp}, m	123.734	126.436	129.811
4	B, m	23.796	23.711	24.961
5	d, m	7.156	7.108	7.322
6	D, m	9.639	10.181	10.181
7	C_B	0.728	0.700	0.813
	„Active” constraints			
1	P_{Qsum}	1.00	1.00	1.00
2	P_{Fl}	1.00	1.00	1.00
3	P_{FB}	1.00	1.00	1.02
4	P_v	1.09	1.03	1.09
5	P_{GMc}	1.00	1.02	1.04
6	L_{pp}/B	5.20	5.33	5.20
	Output			
	DW, tons	11050	10500	14300
	L_{pp}/B	5.20	5.33	5.20
	B/d	3.33	3.34	3.41
	L_{pp}/D	12.84	12.42	12.75

Two of the economic indicators involved in the optimisation procedure, defining the design solution, RFR and Pr, lead to similar optimal ships with similar main dimensions and deadweight.

According to the profitability criterion, Re, the ship has a larger deadweight. For the three indicators, the L_{pp}/B ratio, which is associated with the ship propulsion and seakeeping performance, is close to the lover limit of 5.2. The ratio B/d is higher, which can be explained by the P_{GMc} limitation, which determines the minimum stability in the load cargo condition with containers.

For the assumed transportation scenario, the number of ships needed to transport the cargo in one year is tree units.

A more detailed analysis is needed to explain the relatively low optimum speed of the ship, which are close to the minimum one of 10 kn as a limit.

Figure 2 shows that the design speed for ships of deadweight between 8,000 and 12,000 tons is in the range of 15-17 kn for the analysed 32 multipurpose vessels. The reason for the lower speed can be related to the assumed economic conditions and transportation scenario.

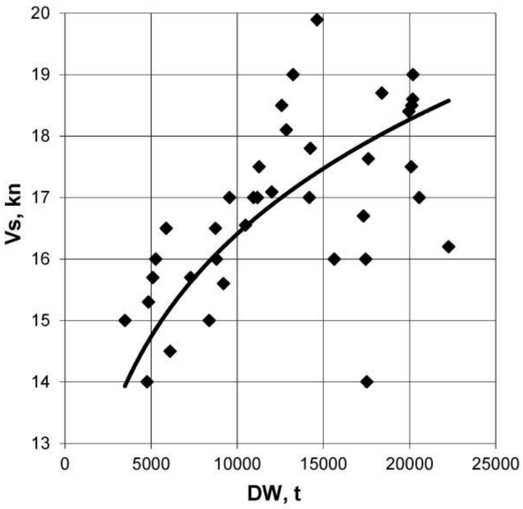

Figure 2 Speed as a function of DW.

In fact, it is a current practice to reduce the speed for relatively short voyages using so-called "economical speed". The reduction in the design speed results in a lowering in fuel and oil consumption, which may reduce the OPEX up to 30%.

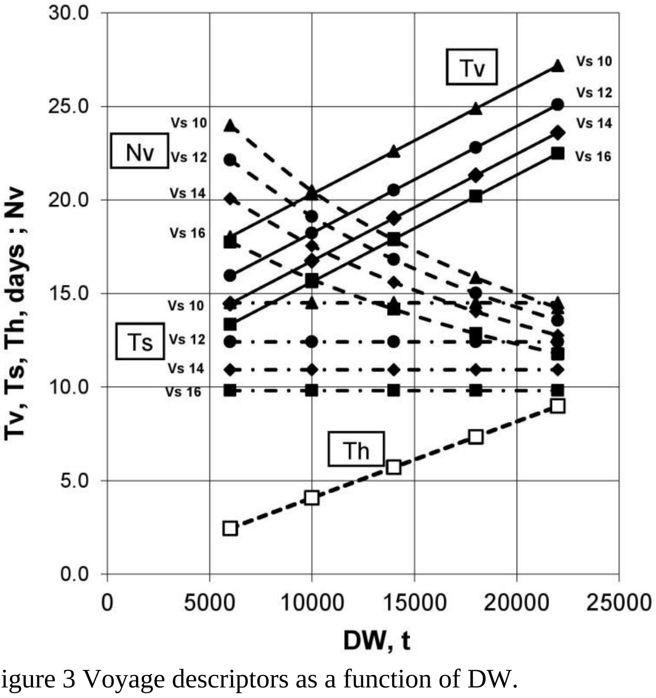

Figure 3 Voyage descriptors as a function of DW.

The optimum speed is influenced by the relation between the travel time and time for cargo handling. The change in the voyage descriptors: the voyage duration, Ts, cargo handling time, Th, the total time for one voyage operation, Tv and the number of voyages per year, Nv, for the assumed transportation scenario as a function of the deadweight and speed is presented in Figure 3.

As the speed of the ship increases, the voyage time decreases. For the ship with grater deadweight the time for handling the cargo also increases, which leads to an increase the total voyage time. In the case of a relatively short operational distance between the ports, the cargo handling time may be synchronised with the voyage time by reducing the higher ship speed.

In practice, the ship can operate in different operational conditions and to be effective the speed may need to be reduced. In this respect, a power margin that is related to the need to provide a higher speed to deliver the cargo on time and the use of controllable pitch propeller, CPP that may allow effective load of the main engine at speed different of the design one is analysed.

One can see from Table 1 that the design solution depends on the chosen criterion as an objective function. For the deadweight range from 6,000 to 22,000 tons with a fixed speed of 15 kn the normalized economic indicators R_{RFR}, R_{PR} and R_{RE} are presented in Figure 4.

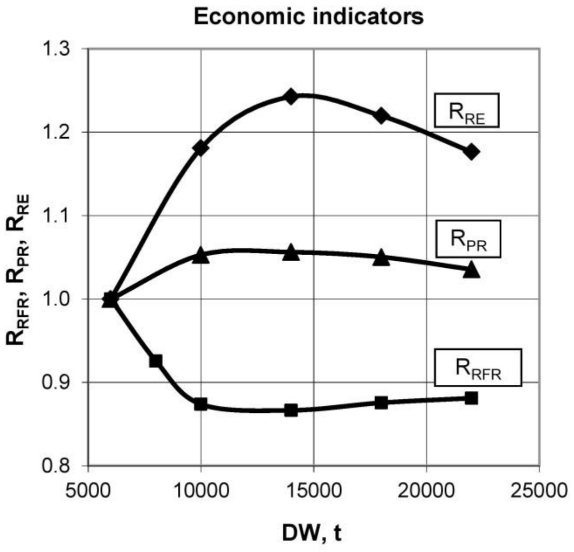

Figure 4 Relative economic indicators as a function of deadweight

It is commonly accepted that with increasing of the deadweight, the economic efficiency of the ship improves - initially sharply, and then smoothly to reach asymptotic (constant values).

In the case of RFR and Pr, the optimum ship deadweight is between 10,000 and 12,000 tons, and after that one can see a slight decrease in the efficiency. Profitability increases rapidly, reaching a clearly defined optimum of DW between 14,000 and 16,000 tons, followed by a decrease in the efficiency.

Figure 5 presents the required number of ships for transportation of total amount of cargo Q_{sum}=1,000,000 tons per year. For the deadweight in the range of 10,000 – 14,000 tons and speed Vs=15 kn, the number of ships is 2.5 – 3.

The optimal length between the perpendiculars does not differ significantly for the presented economic indicators as can be seen in Figure 6.

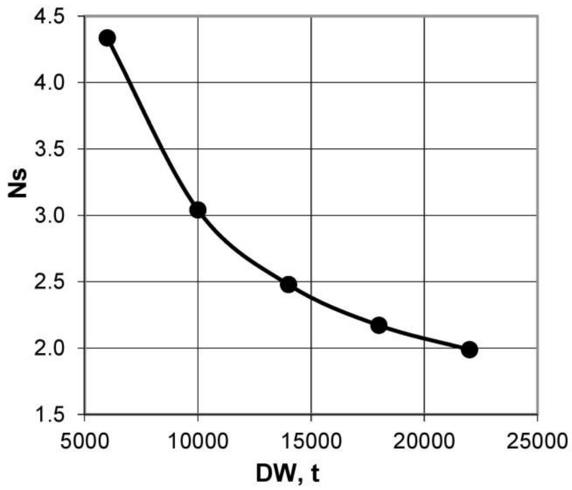

Figure 5 Number of ships, Ns as a function of DW

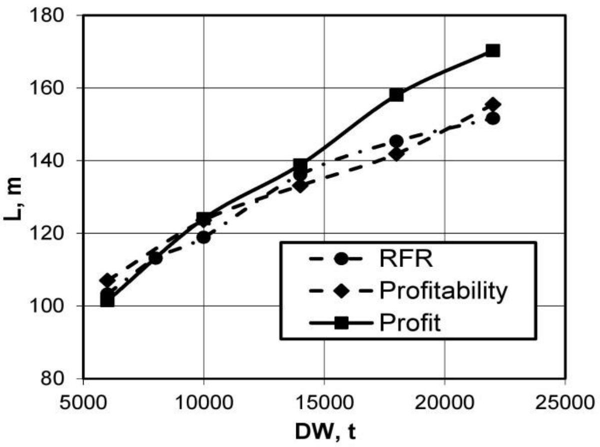

Figure 6. Ship length as a function of economic indicators

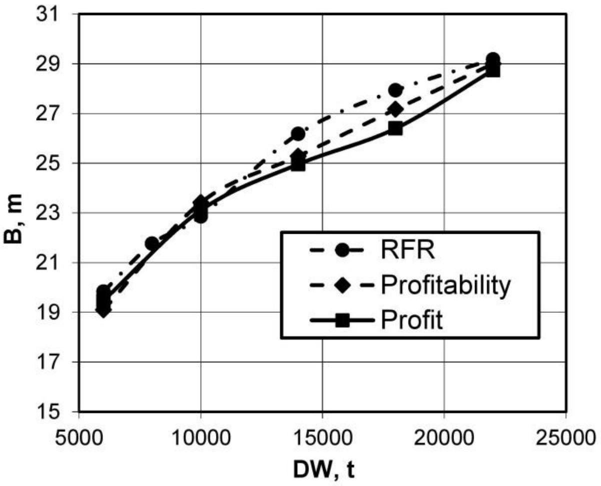

Figure 7 Ship breadth as a function of economic indicators

Table 2 Dimension ratios and economic indicators

Indicator	L_{pp}/B	B/d	L_{pp}/D
Statistical data			
min	5.10	2.42	11.25
max	6.30	3.12	15.32
Constraints			
min	5.20	2.00	8.00
max	12.00	4.00	18.00

In the case of the profit indicator, for deadweight bigger than 15,000 tons, there is a significant increase in the optimal length between the perpendiculars.

The reason for this is that the profit indicator does not consider the increasing of CAPEX due to increasing of the ship length.

The breadth of the vessel varies in narrow ranges for the three indicators as can be seen in Figure 7.

Table 2 presents some results of the analysed ship the main dimension ratios in the deadweight range of 14,000 to 16,000 tons.

The L_{pp}/B ratio, which is commonly referred to as an indicator of the ship propulsion and seakeeping is at or close to the minimum values, typical for wider ships. The B/d ratio, which influences the stability, is close to its upper limit. The L_{pp}/D ratio as an indirect indicator of the stiffness of the ship structure, takes values close to the average one.

4 SHIPS DESIGN OF DW UP TO 6000 TONS

To investigate the economic efficiency of cargo transportation with a ship built under the constraints of SME shipyard, ships with a DW range from 4,000 to 5,500 tons are analysed. Two case studies will be analysed accounting of the SME constraint. Case Study 1, CS1, the transportation scenario is the same as in the previous section and Case study 2, CS2, where the transportation scenario is defined as a cargo volume of Q_{sum} = 500,000 tons.

Distance b/w ports:

Terminal – Port 1:	340 nm
Port 1 – Port 2 :	420 nm

Freight rate:

Terminal - Port 1	10 USD/ton
Terminal – Port 2	10 USD/ton
Port 1 – Port 2	12 USD/ton

For both case studies, the constraints are related to the ship hull constructional capacity of the facilities of a SME shipyard (Garbatov et al., 2017a, Atanasova et al., 2018), where the breadth of the ships cannot be bigger than 16 m

The profitability, Re is considered as an objective function and a speed of 14 kn is adopted.

4.1 *Case study 1*

Table 3 and Table 4 present the output design parameters in the case of restriction and without restriction with respect to the breadth of the ships.

The constraints that set up the optimum solution are related to the requirements of transportation of the cargo volume, minimum intact stability and summer free board waterline

The imposed constraint in the breadth of the ship is active in the investigated range of the deadweight and leads to an increase of the length and block coefficient of the ship as can be seen in Table 4.

Table 3 Output design parameters, Case study 1, without restriction

DW, tons	4,000	4,500	5,000	5,500
Relative values of Re (RRe)				
RRe	1.000	1.058	1.107	1.168
Design variables				
Ns	5.841	5.295	4.869	4.520
L_{pp}, m	93.576	103.342	106.187	114.988
B, m	17.73	17.385	17.837	18.002
d, m	5.567	5.818	6.069	6.184
D, m	6.979	7.418	7.786	8.057
C_B	0.650	0.650	0.656	0.656
Main dimensions ratio				
L_{pp}/B	5.278	5.944	5.953	6.388
B/d	3.185	2.988	2.939	2.911
L_{pp}/D	13.408	13.931	13.638	14.272

Table 4 Output design parameters, Case study 1, with restriction

DW, tons	4,000	4,500	5,000	5,500
Relative values of Re (RRe)				
RRe	0.993	1.052	1.096	1.123
Design variables				
Ns	5.882	5.297	4.874	4.517
L_{pp}. m	96.49	105.923	113.199	119.477
B. m	16.001	16.005	16.001	16.001
d. m	5.662	5.716	5.553	5.406
D, m	7.171	7.392	7.423	7.564
C_B	0.678	0.695	0.743	0.792
Main dimensions ratio				
L_{pp}/B	6.030	6.618	7.074	7.467
B/d	2.826	2.800	2.882	2.960
L_{pp}/D	13.456	14.329	15.250	15.795

The relationship between the profitability, in the case of non-restricted design, and the deadweight is presented in Figure 8.

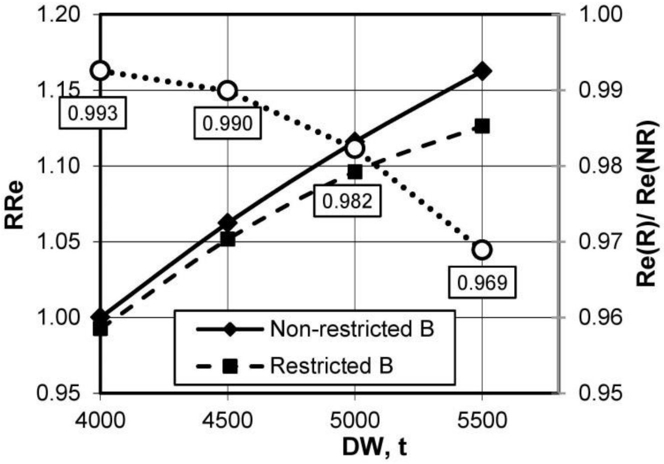

Figure 8 Relative profitability as a function of DW. CS1

The effectiveness of the ship with a restricted breadth decreases with increasing the length of the ship. The relation between the relative profitability for restricted Re(R) and non-restricted Re(NR) ships is presented in Figure 8 as a dotted line. The decreasing of Re due to the constraint related to the breadth varies from 0.7 – 3.1 %.

The profitability of ships with a deadweight in the range from 4,500 to 5,500 tons without restriction in the breadth is about 4 times lower than for the ships with deadweight around 14,000 tons. With a restriction of the breadth, the profitability additionally drops down by about 4%.

4.2 *Case Study 2*

The output design parameters for the Case study 2 are presented in Table 5 and Table 6.

The impact of the restricted breadth leads to a relative lengthening of the ship and increasing the block coefficient, which may explain the reduction of the efficiency (see Figure 9).

The relatively short voyages and associated lower freight rate, in a comparison to Case study 1, which reduces the profitability about two to three times.

Table 5 Output design parameters, Case study 2, without restriction

DW, tons	4,000	4,500	5,000	5,500
Relative values of Re (RRe)				
RRe	1.000	1.112	1.219	1.307
Design variables				
Ns	2.186	1.997	1.844	1.720
L_{pp}. m	98.809	101.332	104.215	109.985
B. m	16.145	16.878	17.229	18.075
d. m	5.74	5.859	5.861	5.858
D. m	7.258	7.461	7.551	7.633
C_B	0.65	0.662	0.693	0.695
Main dimensions ratio				
L_{pp}/B	6.120	6.004	6.049	6.085
B/d	2.813	2.881	2.940	3.086
L_{pp}/D	13.614	13.582	13.801	14.409

Table 6 Output design parameters, Case study 2, with restriction

DW. tons	4,000	4,500	5,000	5,500
Relative values of Re (RRe)				
RRe	0.983	1.094	1.188	1.220
Design variables				
Ns	2.193	2.002	1.854	1.737
L_{pp}. m	102.379	108.310	115.114	121.491
B. m	16.001	16.000	16.001	16.001
d. m	5.484	5.594	5.471	5.294
D, m	7.010	7.265	7.194	7.535
C_B	0.669	0.693	0.738	0.794
Main dimensions ratio				
L_{pp}/B	6.398	6.769	7.194	7.593
B/d	2.918	2.860	2.925	3.022
L_{pp}/D	14.605	14.908	16.001	16.124

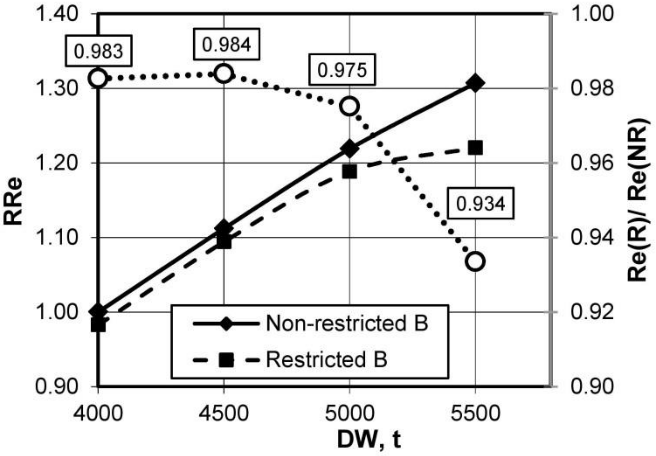

Figure 9 Relative profitability as a function of DW for restricted and non-restricted breadth, CS2

However, in the case of a ship with a design constraint due to the SME construction limitation and without shipbuilding restriction in the cargo transportation condition of Case study 2, the effectiveness of the two design ships is not very different, which is in the range of 2 % (see Figure 9).

5 CONCLUSIONS

This work performed a concept design and optimization of a new multipurpose ship and fleet that can be built in the condition of a small and medium sized shipyard accounting for the existing building limitations.

The analyses demonstrated that ships with a deadweight range of 4,000 to 5,500 tons can be built in the condition of SME and efficiently used for transportation of cargo with varying voyages specifications, especially in small consignments.

Even in a relatively short voyage, with an expected lower freight rate, the designed small ship with a maximum breadth of 16 m has a positive economic performance in transporting a cargo in both directions in absence of a ballast passage.

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