Optimisation of the container ship hull structure

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ABSTRACT: Results of investigation of influence of spatial arrangement of the structural elements of a 3200 TEU container ship on building cost and strength of the ship hull are presented in the paper. The problem was investigated applying parametric analysis of a number of variants of the spatial arrangement of structural elements of a section of the ship hull amidships. An optimisation model was developed composed of set of design variables, scalar objective function, optimisation parameters and constraints. Quantities defining spatial arrangement of transverse and longitudinal girders and stiffeners of the investigated section were taken as the design variables. Four optimisation criteria were assumed: structural mass, weld length, area of elements for maintenance and bending moment. Using these criteria preference objective function was formulated, replacing a problem of multi-objective optimisation with single-objective. Constant values in the optimisation process: main particulars of the ship, structural characteristics (material, arrangement of structural elements). Constraints were formulated using the rules of the classification society. As a result the most advantageous variants of the structural arrangement with respect to the values of the optimisation criteria were indicated. The variants were compared to the actual ship. The variants developed in the present investigation are a premise for changes of the design of the actual ship to reduce the structural weight and building cost of the investigated as well as similar ships.

1 INTRODUCTION

During the conventional designing process a number of structural variants is usually limited to a few while, theoretically, the structure can be designed in arbitrary number of variants and practically in a large number. Optimisation methods for optimal structural design of ship hulls have been developed by many researchers. Examples include Augusto & Kawano (1998), Hughes et al. (1980), Jendo (1979), Jang & Seo (1996), Konieczny et al. (1994), Liang et al. (1997), Rahman (1992), Rahman & Caldwell (1995), Sekulski & Jastrzebski (1999a), (1999b).

An objective of the investigation presented in the paper was to estimate the influence of longitudinal and transversal spacing of stiffeners and girders on ship structural strength and labour consumption of a container ship 3200 TEU. The problem was investigated employing the parametric optimisation. A number of variants of spatial arrangement of structural elements of the ship hull was developed and values of criteria were calculated for each structural variant. It was then possible to select the variant with the least values of the optimisation criteria. This variant was compared with the actual ship.

Investigated variants indicated tendencies towards minimization of structural weight. The paper is concluded with recommendations concerning influence of various modifications on the structural weight and labour consumption of the investigated ship.

2 DESCRIPTION OF ACTUAL SHIP

Actual ship is presented in Figure 1.

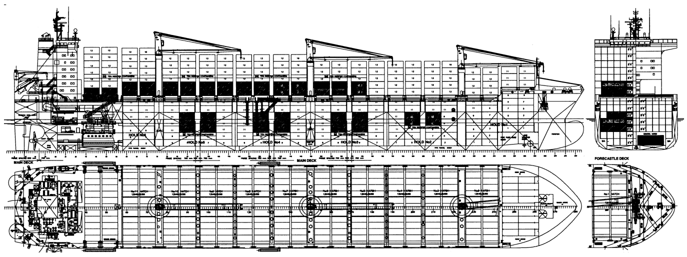


Figure 1. General arrangement of actual ship.

Actual ship is a container ship for transport of TEU and FEU 8’6” high containers in six holds and on the deck, and 45- and 49-foot 9’6” high containers on the deck. Some of the holds are also adjusted for carrying containers with dangerous cargo, refrigerated containers and general cargo stored in boxes, pallets and bales. Container guides with stoppers above tank top allow to store containers above the general cargo. Main particulars and other data of the ship are given in Table 1.

3 SPATIAL ARRANGEMENT OF STRUCTURAL ELEMENTS OF ACTUAL SHIP

Actual ship hull is a typical structure of a container ship with longitudinal stiffening system, frame spacing 790 mm in the middle part of the ship. Floors are web frames positioned at every fourth frame spacing close to the positions of container seats. Cross sections of the actual ship hull including scantlings are presented in Figures 2 and 3. Positions of the transverse bulkheads are presented in Figure 1.

Table 1. Main particulars and other data of the ship.

Item	Value
General data	
Class of ship	GL +100 A5 Container Ship IW, NAV-0, SOLAS II-2 Reg.54, RSD, +MC AUT
Main particulars	
Length overall, L_c	200.00 m
Length between perpendiculars, L_{pp}	210.20 m
Breadth, B	32.24 m
Depth, H	18.70 m
Design draught, T	10.50 m
Maximum draught, T_{MAX}	12.10 m
Speed at design draught, v	22.30 m
Speed at maximum draught, v_{MAX}	20.70 m
Tonnage	
Gross register	34836 GT
Net register	14882 NT
Deadweight at design draught	32500 t
Deadweight at maximum draught	42200 t
Capacity in TEU	
Total	3091
On deck	1683
In holds	1408

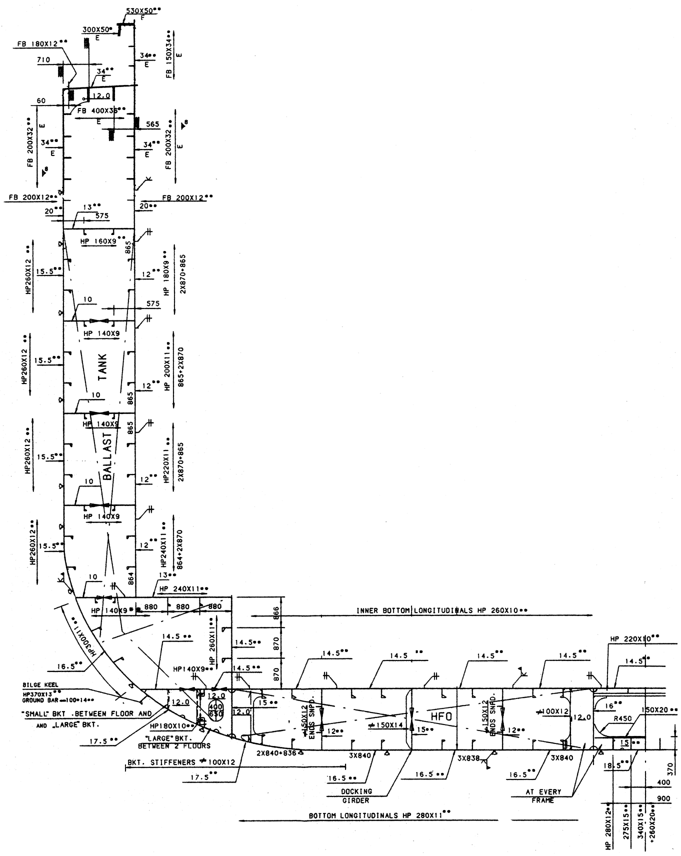


Figure 2. Cross section of actual ship at ordinary frame.

4 STRUCTURAL MODEL

4.1 *Geometrical model of structure*

A section of the ship hull situated between frames 132 and 148 was analysed. Numbers of web frames, girders and longitudinals were optimized variables. Span of longitudinals is equal to spacing of web frames.

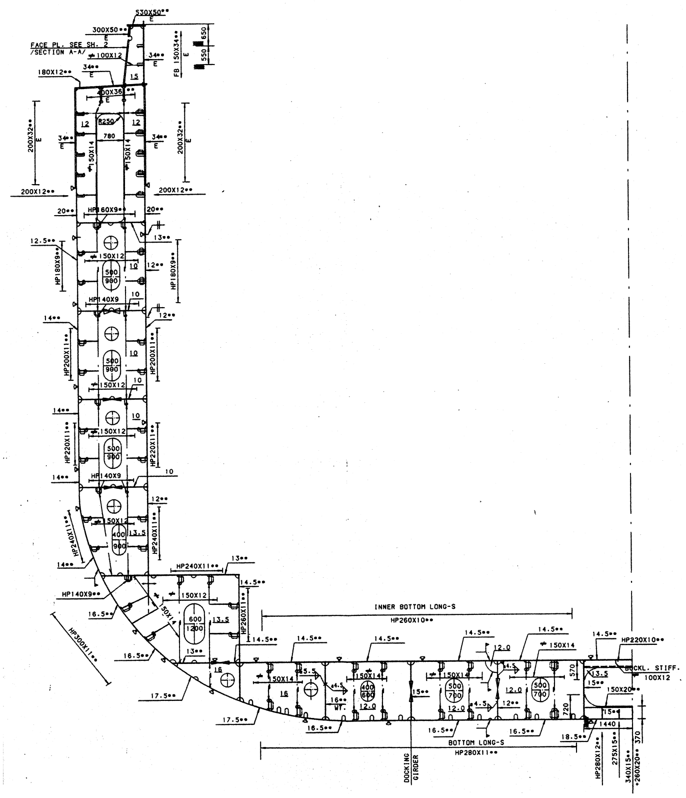


Figure 3. Cross section of actual ship at web frame.

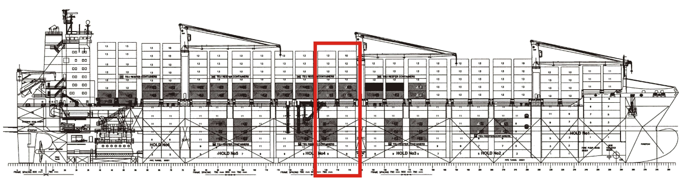


Figure 4. Analysed section of actual ship.

Simplified drawings of cross-sections and profile plan are presented in Figures 5 and 6.

4.2 *Material model of structure*

According to documentation material for the ship hull is mild steel and higher tensile steel. Properties of materials are given in Table 2.

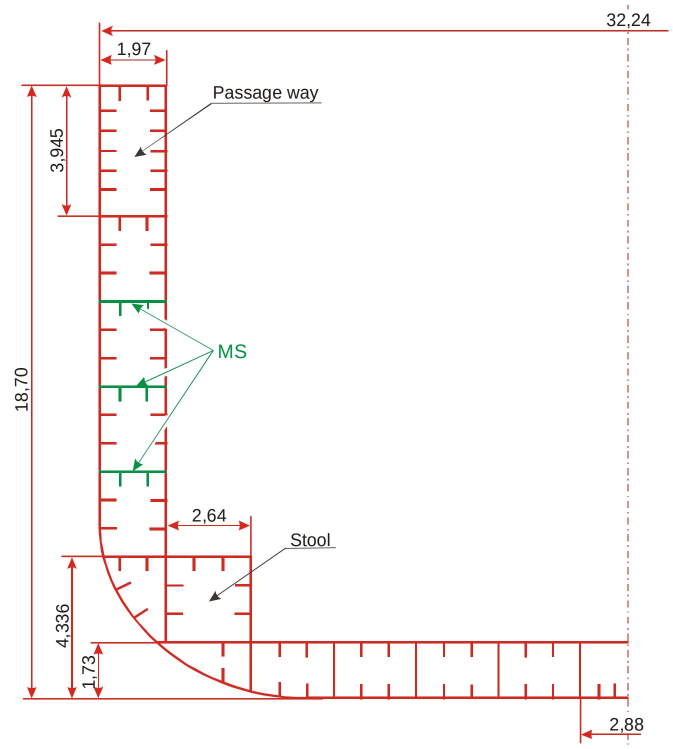


Figure 5. Geometrical model of ship structure, cross-section.

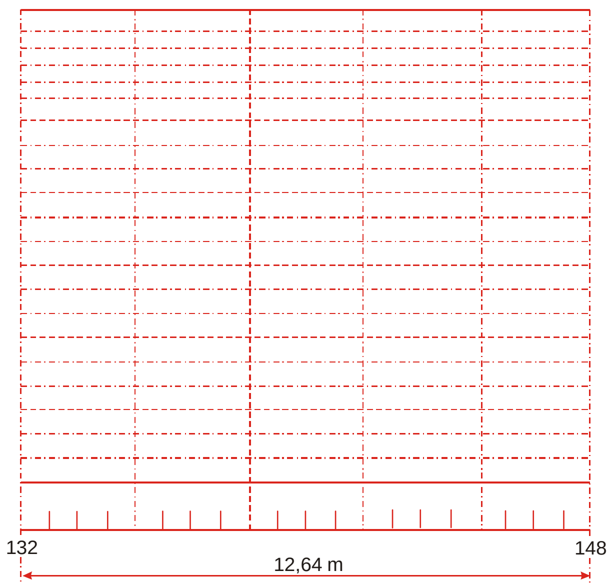


Figure 6. Geometrical model of ship structure, profile plan.

Table 2. Properties of materials.

Property	Symbol	Value	Unit
Yield stress	R_e	235 (for MS) 355 (for HTS)	N/mm^2
Young modulus	E	206000	N/mm^2
Poisson ratio	ν	0.3	-
Density	ρ	78.5	kN/m^3

Except for a few minor elements mild steel was applied for transverse elements while higher tensile steel was applied. Higher tensile steel was applied for longitudinal structural elements except for plates and stiffeners of side girders below the side passage way and above the stool on the actual ship which were built in mild steel, Figure 5.

5 FORMULATION OF OPTIMISATION MODEL

5.1 *General form of optimisation problem*

A general definition of the optimisation problem consists of:

– vector of variables **x** which components define an optimised structure and are searched throughout the optimisation process,
– scalar $f(\mathbf{x})$ or vector $\mathbf{f}(\mathbf{x})$ objective function which is a measure of meeting the optimisation criteria,
– parameter set p_k, containing quantities defining an optimised structure remaining constant throughout the optimisation process,
– constraints $x_{i,min} \le x_i \le x_{i,max}$, $h_j(\mathbf{x}) = 0$, $g_j(\mathbf{x}) \ge 0$ referring to design variables.

In the case of vector objective function $\mathbf{f}(\mathbf{x})$ with components being scalar objective functions $f_c(\mathbf{x})$, a problem of multi-objective optimisation is to be solved having the following form:

$$\text{find } \mathbf{x} = [x_1, \ldots, x_i, \ldots, x_n]^T,\ i = 1, 2, \ldots, n,$$

$$\text{optimising } \mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), \ldots, f_c(\mathbf{x}), \ldots, f_s(\mathbf{x})]^T,\ c = 1, 2, \ldots, s,$$

subject to set of parameters p_k = const., $k = 1, 2, \ldots, l$,

$$\text{and constraints } x_{i,min} \le x_i \le x_{i,max},$$

$$h_j(\mathbf{x}) = 0,\ j = 1, 2, \ldots, m',$$

$$g_j(\mathbf{x}) \ge 0,\ j = m'+1, \ldots, m.$$

In such a case a concept of optimum solution maximising or minimising scalar objective function $f(\mathbf{x})$ should be extended onto a concept of a set of multi-objective optimal solutions (Pareto-optimal) with respect to vector objective function $\mathbf{f}(\mathbf{x})$. To solve such a problem special, non-classical method of multi-objective optimisation are employed.

5.2 *Design variables*

Quantities defining spatial arrangement of web frames and girders and longitudinals in the analysed section are taken as design variables, c.f. Table 3.

Table 3. Simplified specification of design variables.

Symbol	Description	$x_{i,min}$	$x_{i.max}$
x_1	number of web frames	5	11
x_2	number of frame spacings between web frames	1	4
x_3	number of bottom girders	2	4
x_4	number of bottom longitudinals between girders	1	5
x_5	number of side girders	3	7
x_6	number of side longitudinals between side girders	1	4
x_7	number of deck longitudinals	1	3
x_8	number of longitudinals in side passage way	1	5

Structural variants formed within the accepted model belong to subset S of cartesian products of the set of structural variants:

$$S \subset (x_1 \otimes x_2 \otimes x_3 \otimes x_4 \otimes x_5 \otimes x_6 \otimes x_7 \otimes x_8) = (x_1 \otimes \ldots \otimes x_i \otimes \ldots \otimes x_8)$$

where $\otimes$ - symbol of cartesian product.

Thus there are $d = 8$ design variables in the problem of ship hull optimisation. Each structural variant can be interpreted as a point in the $D = 8$ – dimensional space having coordinates $(x_1, ..., x_i, ..., x_d)$. The accepted set of design variables contains 126,000 design variants of the spatial arrangement of structural elements in the analysed section.

5.3 *Objective function*

By specification of the optimisation criteria and formulation of the objective function it is possible to estimate the quality of the structural variant. Practically optimisation consists in comparison of admissible structural variants for select the variant best suited to requirements. Optimisation criteria should include not only technical but also economical aspects. Criteria can be categorised in either of the three following groups:

– technical and operational criteria K_1,
– strength criteria K_2,
– fabrication criteria K_3.

It was assumed in the present analysis that structural weight of the hull, K_{11}, total length of welds, K_{12} and total area of structural elements subject to maintenance K_{13} can be taken as well-defined quantities which can be expressed as a function of the design variables:

$$K_{11} = K_{11}(x_1, x_2, ..., x_d) \rightarrow \text{min!},$$
$$K_{12} = K_{12}(x_1, x_2, ..., x_d) \rightarrow \text{min!},$$
$$K_{13} = K_{13}(x_1, x_2, ..., x_d) \rightarrow \text{min!},$$

and appropriate for quantitative estimation in arbitrary design stage.

Structural weight K_{11} was evaluated as a sum of structural weights of all elements. It is generally accepted that the structural weight is a good index for estimation of a building cost.

Weld length K_{12} and area of structural elements for maintenance K_{13} are measures of labour consumption at all stages of fabrication.

Considering overall strength of a ship hull, bending moment is one of the essential design criteria K_{21}:

$$K_{21} = K_{21}(x_1, x_2, ..., x_d) \rightarrow \text{min!}.$$

Decreasing the bending moment it is possible to reduce scantlings of the longitudinal elements thus reducing the structural weight.

Formulation of four optimisation criteria required solving a multi-objective optimisation problem.

A method of weighted objectives from the group of classical methods of multi-objective optimization methods was employed in the present analysis. A linear combination with arbitrarily selected weighting factors w_i was constructed using the estimation criteria K_i. The combination was a scalar preference function $f_p(\mathbf{x})$. The quality of a variant was then evaluated quantitatively in the form of a single real number greater then zero. It was obtained using relative measures of component criteria represented by weighting factors w_i. Estimation criteria K_i thus become partial estimation criteria of preference function $f_p(\mathbf{x})$.

To include also subjective attractiveness of the criteria in the analysis, preference function $f_p(\mathbf{x})$ was formulated in the form of a function of utility introducing functions of partial utility u_i instead of estimation criteria K_i. Value of the partial utility function u_i is a measure of attractiveness of respective estimation criterion K_i.

Employing partial utility functions u_i, and weighting factors w_i, preference function $f_p(\mathbf{x})$ is expressed in the form of utility function:

$$f_p(K_{11}, K_{12}, K_{13}, K_{21}) = w_{11}u_{11} + w_{12}u_{12} + w_{13}u_{13} + w_{21}u_{21} \rightarrow \text{max!}$$

Values of weighting factors w_i:

$$w_i \in [0, 1] \text{ and } \sum_{i=1}^{4} w_i = 1$$

were assumed applying the results of test computations and own experience: w_1=0.5, w_2=0.2, w_3=0.2 and w_4=0.1.

5.4 *Optimisation parameters*

Optimisation parameters are constant values in the optimisation process. They can be divided into two categories:

– main particulars and other principal data of the actual ship, c.f. Table 1,
– specific features of the ship structure:
  – properties of structural materials, c.f. Table 2,
  – spatial arrangement of structural elements, c.f. Table 4 and Figure 7.

Table 4. Parameters of optimisation defining spatial arrangement of structural elements.

Symbol	Description	Value
p_1	length of investigated section	12.64 m
p_2	breadth of double side	1.97 m
p_3	height of side passage way	3.957 m
p_4	depth of double bottom	1.73 m
p_5	depth of stool	4.336 m
p_6	breadth of stool	2.64 m
p_7	distance between central girder plates	2.88 m

5.5 *Constraints*

Constraints were formulated using the rules of the classification society Germanischer Lloyd (2004). They can be categorised in two groups: (i) requirements concerning the distance between specific structural elements, e.g. the distance between two bottom side girders cannot be greater than 3.5 m or distance between two floor should not be greater than 5 frame spacings, and (ii) constraints related directly to strength and given in the form of equations, e.g. requirement on the section modulus of inner bottom longitudinal. Yet some most significant features of the actual ship were reproduced in the investigated variants, e.g. position of the side girder which was supposed to be in-line with the upper plate of the stool – Figure 7.

Ranges of variation of design variables are given in Table 3.

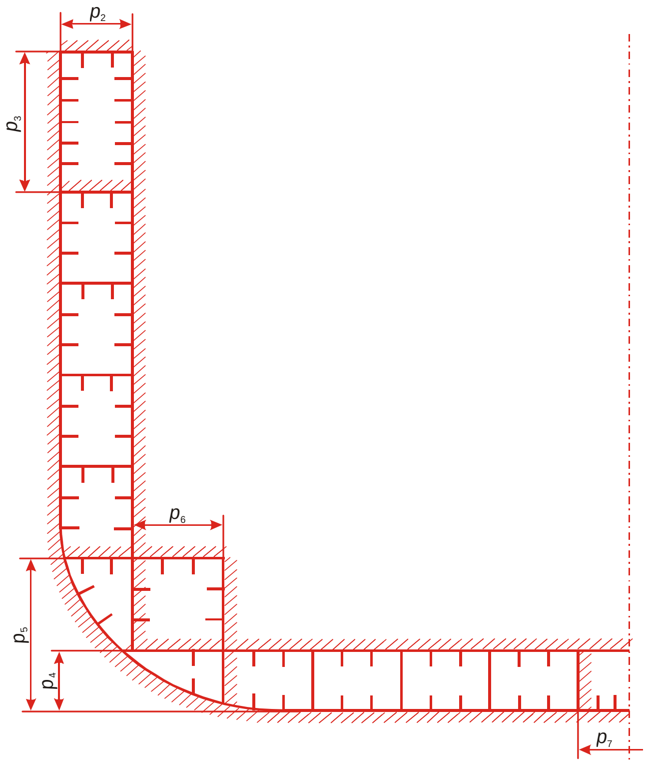


Figure 7. Ship structural model for optimisation.

6 PARAMETRIC OPTIMISATION ANALYSIS

The optimisation model developed in the present analysis generates as many as 126,000 variants of spatial arrangement of web frames, girders and longitudinals which should be carefully examined and estimated with respect to the optimisation criterion. Practically, such a numerous set of variants could not be investigated. The set had to be limited to eleven structural variants – c.f. Table 5. The variants were selected after preliminary computations had been done with representative changes of spatial arrangement and exhibiting significant changes of accepted optimisation criteria K_i and preference function $f_p(\mathbf{x})$.

For selected variants longitudinal strength was calculated using Maxsurf-Hydromax computer codes. Hull shape and loading cases were taken as for the actual ship, Figures 8 and 9. Bending moment K_{21} was the greatest value of the values obtained for all the loading cases.

To verify the structural variants against the requirements of Germanisher Lloyd they were modelled in the PoseidonND computer code using the ship hull data from Maxsurf on the base of standard variant W_0. Model W_0 is based on the actual ship design, however, the scantling surpluses required by the owner are excluded. The model is presented in Figures 10 and 11. Standard model W_0 was modified to obtain structural variants W_1-W_{11}, Figure 2. Scantlings were taken as the minimum required by the rules.

Table 5. Specification of structural variants W_i.

Variable	Structural variant W_i								
	W_0	W_1	W_2	W_3	W_4	…	W_8	W_9	W_{10}	W_{11}
x_1	5	5	5	5	5	…	5	5	5	7
x_2	4	4	4	4	4	…	4	4	3	3
x_3	4	4	4	3	3	…	4	4	4	4
x_4	2	3	4	3	4	…	2	2	2	2
x_5	5	5	5	5	5	…	4	5	5	5
x_6	2	2	2	2	2	…	4	2	2	2
x_7	2	2	2	2	2	…	2	3	2	2
x_8	5	5	5	5	5	…	5	5	5	5

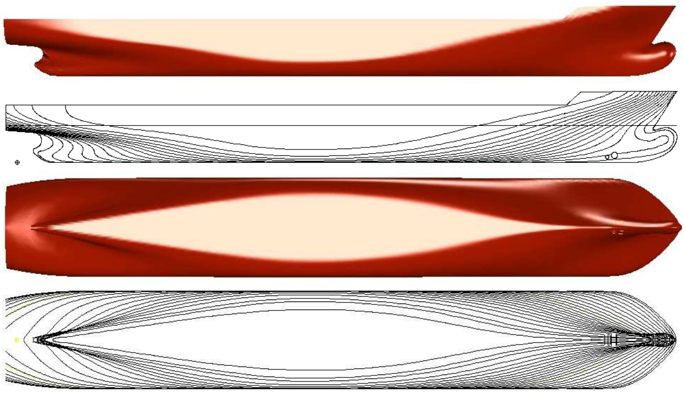


Figure 8. Mapping of actual ship hull shape in Maxsurf: buttocks and waterlines.

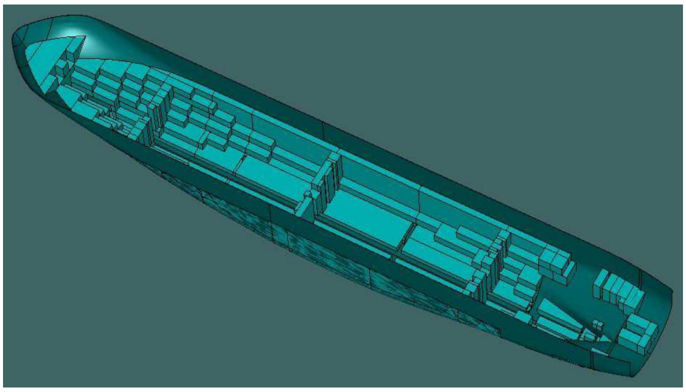


Figure 9. Mapping of actual ship tanks in Maxsurf.

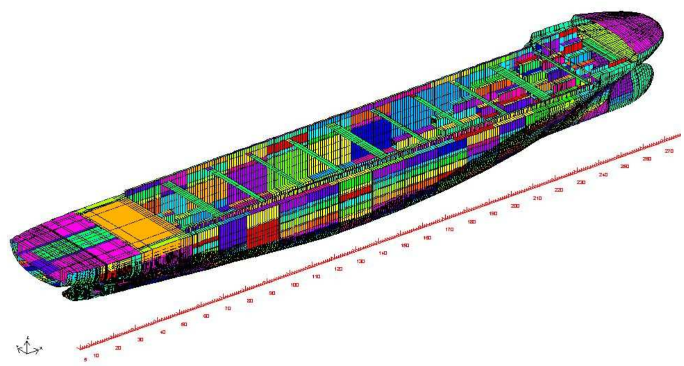


Figure 10. Axonometric view of actual ship hull model in PoseidonND.

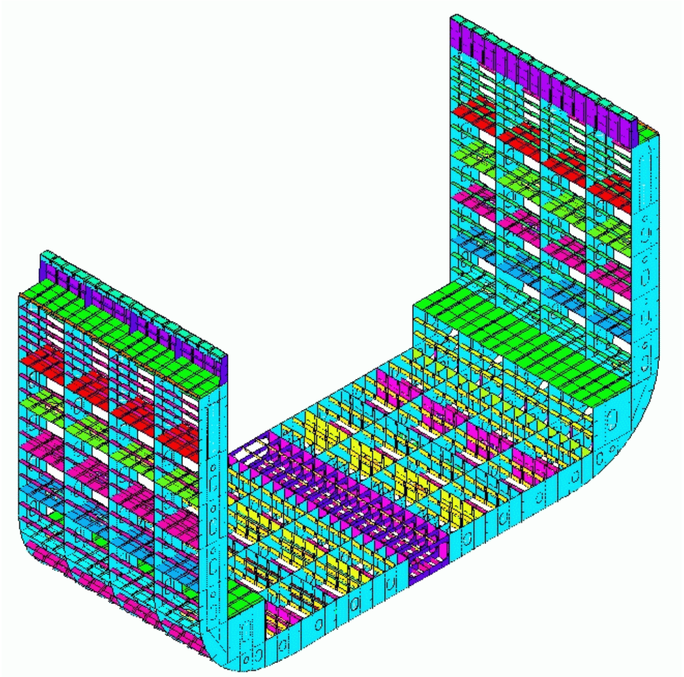


Figure 11. Axonometric view of actual ship hull model in PoseidonND; view of structural elements in hold.

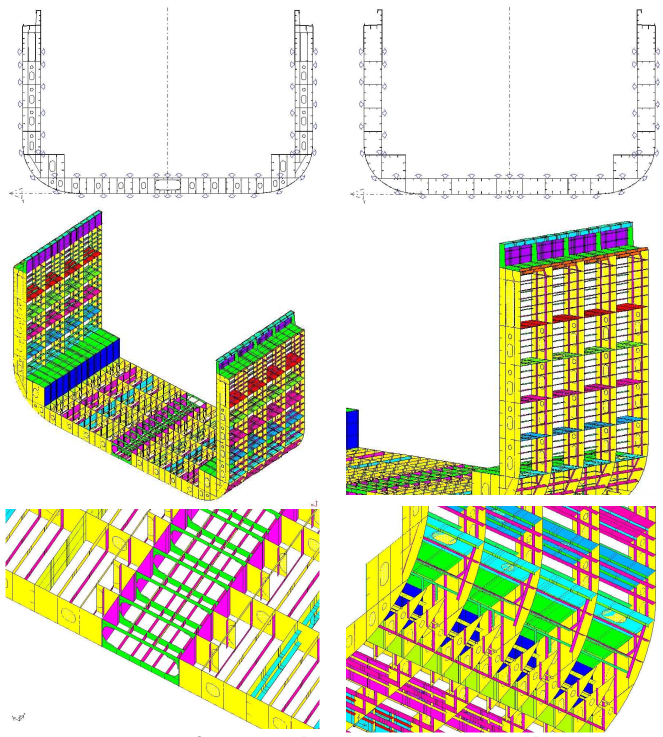


Figure 12. View of structural variant W_{10} in PoseidonND.

For structural variants W_i optimisation criteria K_i, were calculated, c.f. Table 6, and preference function $f_p(\mathbf{x})$, c.f. Table 7.

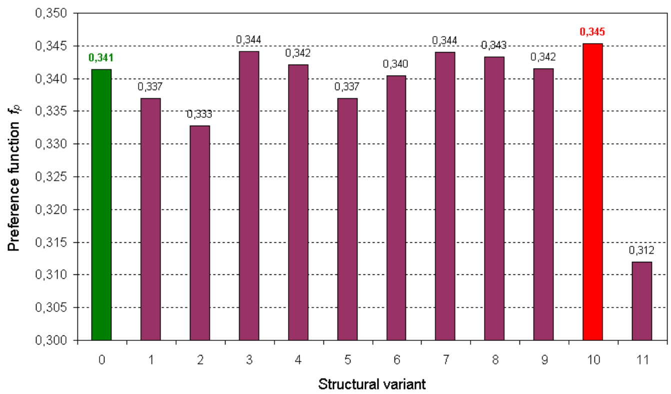
Results of the investigation indicate that the most advantageous variant regarding scalar objective function was W_{10} where the number of frame spacings was reduced keeping the number of web frames. Criteria K_i as well as their absolute and relative changes are given in Table 8. Unit values are also given in the table which can be found useful for design purpose.

Table 6. Optimisation criteria K_i.

W_i	Optimisation criteria			
	K_{11}, kN	K_{12}, m	K_{13}, m^2	K_{21}, MNm
W_0	**3789.31**	**11886.13**	**7214.72**	**1791.57**
W_1	3771.75	12413.01	7316.63	1791.80
W_2	3770.08	12867.89	7394.97	1791.82
W_3	3775.08	11737.53	7146.37	1791.76
W_4	3756.84	11996.61	7229.03	1791.99
W_5	3758.31	12559.05	7288.67	1791.97
W_6	3790.54	11987.25	7219.61	1791.56
W_7	3776.46	11761.43	7140.53	1791.75
W_8	3777.54	11826.99	7153.99	1791.73
W_9	3762.33	12010.37	7239.98	1791.92
W_{10}	**3766.26**	**11675.65**	**7132.33**	**1791.88**
W_{11}	3980.02	13617.04	7769.25	1789.03

Table 7. Preference function $f_p(\mathbf{x})$.

W_i	$f_p(\mathbf{x})$
W_0	**0.34139**
W_1	0.33701
W_2	0.33277
W_3	0.34419
W_4	0.34209
W_5	0.33700
W_6	0.34047
W_7	0.34401
W_8	0.34326
W_9	0.34155
W_{10}	**0.34535**
W_{11}	0.31195



Modifications of the selected eleven variants influence most significantly the weld length which ranged as much as 14.26% with respect to the maximum value. On the other hand the influence on the bending moment was practically unimportant yielding the change equal to 0.16%. The results for the structural weight and maintenance area were intermediate; 5.61% and 8.20%, respectively.

The results indicate that the following variants W_{10}, W_3, W_7, W_8, W_4 i W_9 turned to be more advantageous than the standard model W_0 based on the actual ship. The most advantageous changes are as follows:

– decreasing the number of frame spacings keeping the number of floors,
– decreasing the number of double bottom girders increasing the number of bottom longitudinals,
– decreasing the number of side girders possibly decreasing spacing of side longitudinals,

– increasing the number of deck longitudinals.

Table 8. Absolute and relative values of criteria K_i and preference function f_p.

Value	W_0	W_{10}
Structural weight K_{11}, kN	3789.31	3766.26 ↓
Change of K_{11}, kN	23.15	
Change of K_{11}, %	0.61	
Change of K_{11}, kN/m	1.83	
Weld length K_{12}, m	11886.13	11675.65 ↓
Change of K_{12}, m	210.48	
Change of K_{12}, %	1.77	
Change of K_{12}, m/m	16.65	
Area of elements K_{13}, m^2	7214.72	7132.33 ↓
Change of K_{13}, m^2	82.39	
Change of K_{13}, %	1.14	
Change of K_{13}, m^2/m	6.52	
Bending moment K_{21}, MNm	1791.58	1791.87 ↑
Change of K_{21}, MNm	-0.304 [1)]	
Change of K_{21}, %	-0.017 [1)]	
Preference function $f_p(\mathbf{x})$	0.34139	0.34535 ↑
Change of $f_p(\mathbf{x})$	-0.00396 [1)]	
Change of $f_p(\mathbf{x})$, %	-1.16 [1)]	

[1)] minus sign denotes increase of specific value with respect to standard model

Variants W_6, W_1, W_5, W_2 and W_{11} turned to be less advantageous than the actual ship. Analysing the results obtained for these variants the following changes can be specified as yielding disadvantageous effects:
– increasing the number of longitudinals in the region of side passage way,
– increasing the number of longitudinals keeping the same number of girders,
– increasing the number of web frames decreasing the frame spacing.

7 SUMMARY AND CONCLUSIONS

Ship structural design was optimised with respect to the following selected criteria: structural weight, weld length, maintenance area and bending moment to investigate the effects of spacing of web frames, girders and longitudinals on structural strength and labour consumption of the container ship 3200 TEU. The first three criteria can be treated as measures of building cost in preliminary design. Optimisation criteria were then reformulated yielding the scalar preference function thus replacing multi-objective optimisation with the equivalent single-objective optimisation. It was then possible, having defined the scalar preference function, to estimate and compare selected structural variants comparing single real values.

The results of the investigation prove that the most advantageous variant is the variant where the number of frame spacings is decreased keeping the number of web frame spacing.

Concerning the labour consumption issue weighting coefficients were selected to represent the dependencies between weight and manufacturing indices.

The results of the investigation can be a premise for redesigning the actual ship to reduce the structural weight and decrease cost measured by labour consumption.

8 ACKNOWLEDGEMENT

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