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A MULTICRITERIA REDESIGN OF THE MIDSHIP SECTION OF AN INTERMODAL RO-RO SHIP

Summary

Intermodal RO-RO ship, 83 m in length had been designed initially with a lightweight and VCG exceeding the demanded level by approximately 20% due to the service requirements. The ship's intended service includes transportation of trailers. In order to meet the wintertime navigation in intended route ship is designed in accordance with the Finnish-Swedish Ice Class 1B. Two concepts have been investigated in order to meet the demand, and compared with the initial design: first, having a traditionally paneled structure and second, which uses laser welded steel sandwich panels for decking. Problem is approached by multicriterion optimization with genetic algorithm as optimizer. 11 different Pareto-optima solutions have been calculated. Among them was suggested the most efficient design for each concept. Noticeable improvements in weight and VCG have been achieved.

Key words: Intermodal ship, multicriterion optimization, genetic algorithm, steel sandwich panels

VIŠE-KRITERIJALNO RJEŠENJE PARALELNOG SREDNJAKA INTERMODALNOG RO-RO BRODA

Sažetak

Inicijalni projekt intermodalnog RO-RO broda dugog 83 m rezultirao je, zbog potreba u službi, sa 20%-tnim prekoračenjem potrebne mase praznog opremljenog broda i VCG-a. Brod je namijenjen za transport tegljača. Zbog područja djelovanja brod je konstruiran prema Finsko-Švedskoj klasi za led 1B. Dva su koncepta istražena i uspoređena sa inicijalnim rješenjem: prvi, koji ima tradicionalno ukrepljenje panele i drugi koji koristi laserski zavarene čelične sendvič panele za strukturu vremenske palube čvrstoće. Problemu je pristupljeno više-kriterijalnom optimizacijom sa genetskim algoritmom kao optimizatorom. Izvedeno je 11 različitih Pareto-optimalnih konstrukcijskih rješenja. Među njima predložena su najefektivnija rješenja za svaki koncept. Ostvarena su primjetna smanjenja u masi i VCG-u.

Ključne riječi: Intermodalni brod, više-kriterijalna optimizacija, genetski algoritam, čelični sendvič paneli

1. Introduction

An intermodal RO-RO ship for inland/short-sea operations, seen on Fig. 1, with the main particulars given in Table 1, had been initially designed to transport trailers between Lake Vänern in Sweden and Duisburg in Germany, passing through the Trollhätte Canal locks, North Atlantic and River Rhine between Rotterdam to Duisburg. Main frame is given in Fig. 2. Trailers are carried on the weather deck and on the hoistable-rotating cardeck, which does not contribute to longitudinal strength and is not accounted for in this study.

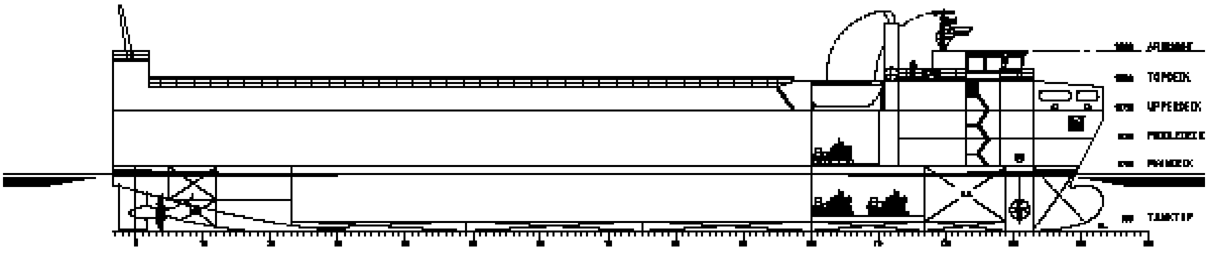

Fig. 1. General arrangement of an intermodal RO-RO ship [1]

Slika 1. Opći plan intermodularnog RO-RO broda [1]

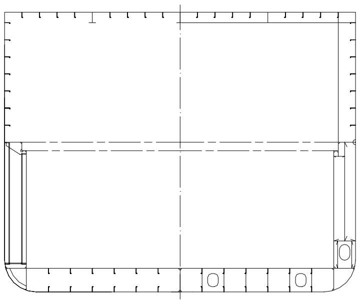

Fig. 2. Main frame [1]

Slika 2. Glavno rebro [1]

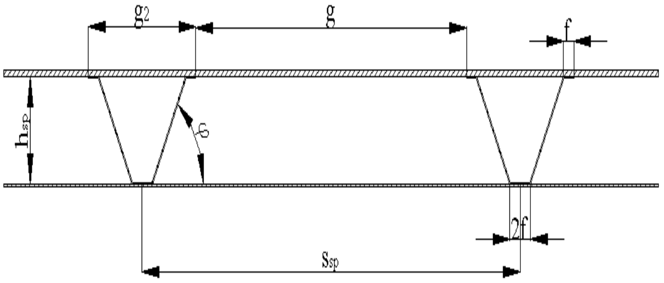

Fig. 3. Cross section of the applied sandwich panel

Slika. 3. Poprečni presjek primjenjenog sendvič panela

Lightweight of the initial design is exceeding planned weight by 300 t, while the vertical center of gravity (VCG) is 1 m too high. Due to this reason a minimum weight/minimum VCG optimization of the hull structure is performed. Two structural concepts are investigated. Concept I embeds optimization of traditional paneled structure, made up of steel plating with bulb flat stiffening. In Concept II, idea is to substitute traditional paneling of the weather deck with a corrugated steel sandwich panel, seen on Fig. 3, to offer further possibility of weight reduction in a top part of the ship. This problem is approached with the multicriterion optimization procedure.

Table 1. Main particulars

Tablica 1. Glavne značajke

Length between pp, L_{pp} [m]	83,00
Rule length, L [m]	80,51
Breadth moulded, B [m]	13,35
Depth moulded, D [m]	10,65
Drought in summer, T [m]	5
Displacement, Δ [t]	4354
Block coefficient C_b	0,79

2. Multicriteria redesign

Ship is designed to carry a cargo of 48 loaded trailers. In its service it will have to pass through the locks, sail in shallow waters and under low bridges, navigate in ice. Due to these reasons an initial design is already tightly constrained, limiting the possibilities for major improvement. This especially reflects to the geometry and topology of the main frame. Accent is then given to the sizing optimization where thicknesses of plates and sizes of profiles are redesigned. However, some elements of geometrical optimization are performed as well in changing the number of longitudinals. Variables of number of longitudinals are specifically considered as integers through the longitudinal spacing, while all the other design variables are continuous. After the optimization, fractional results are rounded to the nearest integer. A novel design that offers reduction of weight and VCG is found by means of multicriterion optimization [2]. A structural multicriterion optimization problem is defined as a problem of a vector of objective functions (criteria), being here the weight of the midship section per meter length $\mathrm{W_o}(\mathbf{x})$, and its vertical centre of gravity $\mathrm{VCG}(\mathbf{x})$, $\mathbf{f}(\mathbf{x}) = [\mathrm{W_o}(\mathbf{x}) \quad \mathrm{VCG}(\mathbf{x})]^{\mathrm{T}}$, under the design constraints $\mathbf{g}(\mathbf{x})$

$$\min_{\mathbf{x}\in\Re^n} \{\mathbf{f}(\mathbf{x}):\ \mathbf{g}(\mathbf{x}) \le 0\}, \tag{1}$$

where $\mathbf{x}$ is a vector of n design variables.

However, instead of identifying the single optimum design $\mathbf{x}^*$, the solution of this minimization problem is a set of non-dominated designs called Pareto-optimums $\mathbf{X}^*$. By mapping the feasible set $\mathrm{X} \subset \Re^n$ of a design space into a criterion space $\mathrm{Y} \subset \Re^2$, Pareto-optimum set in a design space results in an efficient boundary $\partial\mathrm{Y}^*$ of objective conflict in a criterion space, where a simultaneous minimization of objective functions $\mathrm{W_o}(\mathbf{x})$ and $\mathrm{VCG_o}(\mathbf{x})$ is impossible. Therefore, reduction of one function causes increase of another.

Each k point $\mathbf{y}^{*,k} = \left[\mathrm{W_o}\left(\mathbf{x}^{*,k}\right) \quad \mathrm{VCG_o}\left(\mathbf{x}^{*,k}\right)\right]^{\mathrm{T}}$ on an efficient boundary $\partial\mathrm{Y}^*$ is a non-dominated design solution, if it is valid that

$$\mathrm{W_o}\left(\mathbf{x}^{*,k}\right) \le \mathrm{W_o}(\mathbf{x}) \text{ and/or } \mathrm{VCG_o}\left(\mathbf{x}^{*,k}\right) \le \mathrm{VCG_o}(\mathbf{x}) \quad \forall\ \mathbf{f}(\mathbf{x}) \in \mathrm{Y}. \tag{3}$$

These are found by scalar optimization of weight, with transforming a VCG into an inequality constraint by setting

$$\mathrm{VCG_o}(\mathbf{x}) \le C, \tag{4}$$

where C is an arbitrary constant. One non-dominated solution is then found by solving the following scalar optimization problem

$$\min_{\mathbf{x}\in\Re^n} \{\mathrm{W_o}(\mathbf{x}):\ \mathbf{g}(\mathbf{x}) \le 0,\ \mathrm{VCG_o}(\mathbf{x}) \le C\}. \tag{5}$$

This problem is solved by using genetic algorithm optimizer *Gallops* [3] with the set up of parameters, presented in Table 2.

Table 2. Applied parameters of genetic algorithm **Tablica 3.** Primjenjeni parametri genetskog algoritma

Min-max partitioning coefficient, α	100
Number of generations	20000
Population size	30
Probability of cross over	0,92
Probability of mutation	0,33

Weight per meter and VCG are defined descriptively with

$$\mathrm{W_0}(\mathbf{x}) = 1.5 \cdot \rho_s \cdot \left(\sum_{q=1}^{Q} \mathrm{A}_{1,q}(\mathbf{x}) + \frac{1}{S} \cdot \sum_{r=1}^{R} \mathrm{V}_{\mathrm{t},r}(\mathbf{x}) \right), \tag{6}$$

$$\mathrm{VCG_0}(\mathbf{x}) = \frac{\sum_{q=1}^{Q} \mathrm{A}_{1,q}(\mathbf{x}) \cdot \mathrm{e}_{1,q}(\mathbf{x}) + \frac{1}{S} \cdot \sum_{r=1}^{R} \mathrm{V}_{\mathrm{t},r}(\mathbf{x}) \cdot \mathrm{e}_{\mathrm{t},r}(\mathbf{x})}{\sum_{q=1}^{Q} \mathrm{A}_{1,q}(\mathbf{x}) + \frac{1}{S} \cdot \sum_{r=1}^{R} \mathrm{V}_{\mathrm{t},r}(\mathbf{x})}, \tag{7}$$

where ρ_s is the steel density taken as 8.0 $\mathrm{t/m^3}$, $\mathrm{A}_{1,q}(\mathbf{x})$ area of any longitudinal element, $\mathrm{V}_{\mathrm{t},r}(\mathbf{x})$ volume of any transverse element, $\mathrm{e}_{1,q}(\mathbf{x})$ distance of neutral axis of any longitudinal element from base line (BL), $\mathrm{e}_{\mathrm{t},r}(\mathbf{x})$ distance of neutral axis of any transverse element from BL, Q total number of longitudinal elements, R total number of transverse elements, and factor of 1.5 accounts as the approximate value for the additional local structural elements (brackets, bulkhead stiffeners, floor stiffeners...) not originally considered in calculations.

Table 4. Design variables and min-max constraints **Tablica 4.** Projektne varijable i min. i maks. ograničenja

Design variable x_i	**Min**	**Max**	**Material**[1]
Thickness of weather deck, t_d [mm]	6	15	NV 40
Size and section modulus of deck longitudinals, Z_{dl} [cm^3]	50	500	NV 40
Spacing of deck longitudinals, s_{dl} [mm]	500	1000	-
Thickness of sandwich top plate, t_{tsp} [mm]	5	10	NV 40
Thickness of sandwich bottom plate, t_{bsp} [mm]	2	10	NV 40
Thickness of sandwich core plate, t_{csp} [mm]	2	10	NV 40
Height of sandwich core, h_{sp} [mm]	25	400	-
Spacing of sandwich core, s_{sp} [mm]	60	550	-
Size and section modulus of deck transverses, Z_{dt} [cm^3]	2000	4000	NV 40
Thickness of side sheerstrake, t_{ss} [mm]	6	30	NV 40
Thickness of side shell above ice region, t_{sa} [mm]	6	30	NV 40
Size and section modulus of side longitudinals, Z_{sl} [cm^3]	30	500	NV 40
Spacing of side longitudinals [mm]	500	1000	-
Size and section modulus of side webframe, Z_{st} [cm^3]	500	4000	NV 40
Thickness of side shell in ice belt, t_{si} [mm]	6	30	NV 40
Thickness of inner hull, t_{ih} [mm]	6	30	NS
Size and section modulus of frames in ice belt, Z_{fi} [cm^3]	50	1000	NV 40
Thickness of deep tank bulkhead, t_{dtb} [mm]	6	30	NS

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[1] Material is denoted according to DNV Rules and Regulations for Design of Ships [9], where NS stands for standard shipbuilding steel (σ_y = 235 MPa) and NV 40 stands for high tensile steel (σ_y = 390 MPa)

Thickness of keel, t_k [mm]	10	10	NS
Thickness of centre girder, t_{cg} [mm]	6	30	NS
Thickness of bottom shell, t_b [mm]	6	30	NS
Size and section modulus of bottom longitudinals, Z_{bl} [cm^3]	30	500	NS
Thickness of watertight girder, t_{wg} [mm]	6	30	NS
Spacing of bottom longitudinals [mm]	500	1000	-
Thickness of inner bottom, t_{ib} [mm]	6	30	NS
Size and section modulus of inner bottom longitudinals, Z_{ibl} [cm^3]	30	500	NS
Thickness of watertight floor, t_{wf} [mm]	6	30	NS

Since *Gallops* cannot handle constrained minimization problems minimum weight optimization problem is transformed into an unconstrained maximization problem. The weight function $\mathrm{W}_0(\mathbf{x})$ is transformed into a fitness function $\mathrm{Fit}(\mathbf{x})$ by making two changes to Eq. (6). First, a constant *Big* is added to transform the minimization problem into a maximization problem. *Big* has to be of proper size. Too big values reduce sensitivity of the fitness function, resulting in a large offset from the maximum, while too small values, close to maximum, return negative values of fitness function, which *Gallops* cannot properly evaluate. Value of $Big = 20\ \mathrm{t/m}$ is used here. Second change is the conversion of the Eq. (6) into a piecewise function to account for constraints in terms of the penalty approach. If any of the constraints is broken, fitness function returns the value of a penalty constant *P*, which is small enough to result in a solution far from the maximum. Summarizing this, the optimization problem inputted to optimizer is the following

$$\min_{\mathbf{x}\in\Re^n} \{\mathrm{Fit}(\mathbf{x})\}, \text{ where}$$

$$\mathrm{Fit}(\mathbf{x}) = \begin{cases} Big - 1.5\rho_s\left(\sum\limits_{p=1}^{P}\mathrm{A}_{1,p}(\mathbf{x}) + \dfrac{1}{S}\sum\limits_{q=1}^{Q}\mathrm{V}_{\mathrm{t},q}(\mathbf{x})\right) & \text{if } \mathbf{g}(\mathbf{x}) \le 0 \text{ and } \mathrm{VCG}_0(\mathbf{x}) \le C \\ P, & \text{otherwise} \end{cases} \cdot \tag{8}$$

Design variables **x** are given in Table 3, which also shows the applied min-max constraints. These are chosen in accordance with the good practice and specific design requirements, e.g. sandwich core spacing was limited to 550 mm in order to avoid more than two trailer tires supported by one sandwich segment, which would additionally complicate the calculations. Steel material is not changed from the initial design with the intention to keep the cost of production approximately the same. Primary and secondary stiffeners' sizes are considered through their section modulus in order to decrease the number of design variables. Multiple numbers of standard HP profiles and custom built T-girders were preliminary investigated to obtain the relationships between section modulus and area of profile's cross section. The following was obtained

$$A_{HP} = 0.73 \cdot Z_{HP}^{0.65}, \tag{9}$$

$$A_T = 0.77 \cdot Z_T^{0.63}. \tag{10}$$

A_{HP} is the area of a bulb flat, Z_{HP} its section modulus. A_T is the area of a T-girder, Z_T its section modulus.

Transverse frame spacing *s* is kept constant at $s = 600\,\mathrm{mm}$ and was not altered from the initial design. The same applies to deck girders with $Z_{dg} = 1744\,\mathrm{cm}^3$, in order to simplify the calculations, particularly calculation of grillage deck structure. However, in ice belt the frame spacing was halved to $s_i = 300\,\mathrm{mm}$.

Table 5. Specification of wheel loading **Tablica 5.** Specifikacija opterećenja kotača

Load on tire print, P_w [t]		7
Tire print	Longitudinal, u [mm]	500
	Transverse, v [mm]	250
Tire correction factor, n[2]		0.6
Dynamic magnification factor, λ[3]		1.42

Weather deck is loaded laterally by wheel load [11], given in Table 4, and by in-plane load due to the sagging of hull beam in waves, calculated from the LR Pt.3 Ch.4.5.2. [4]. For traditionally built weather deck in concept I worst case loading is assumed so that the two trailer tires, each with load of 3.5 t, lie between one webframe spacing S. Due to this reason original tire print longitudinal dimension u and load are doubled.

Table 6. List of constraints g(x) **Tablica 6.** Popis ograničenja g(x)

Minimum allowable scantlings	**Calculated according to**
Weather deck minimum allowable thickness, $t_{d,\min}$	LR Pt.3 Ch.9.3.4
Section modulus of deck longitudinals, $Z_{dl,\min}$	LR Pt.3 Ch.9.3.5
Thickness of sheerstrake, $t_{ss,\min}$ Thickness of side shell above neutral axis $t_{sa,\min}$	LR Pt.4 Ch.1. Table 1.5.3
Section modulus of the side longitudinals $Z_{sl,\min}$	LR Pt.4 Ch.1. Table 1.6.1
Section modulus of side transverse $Z_{st,\min}$	LR Pt.4 Ch.1. Table 1.6.3
Thickness of plating in ice belt $t_{i,min}$ Section modulus of frames in ice belt $Z_{fi,\min}$	Finnish-Swedish Ice Class Rules
Thickness of bottom shell $t_{b,\min}$	LR Pt.4 Ch.1. Table 1.5.2
Thickness of keel $t_{k,\min}$	LR Pt.4 Ch.1. Table 1.5.1
Section modulus of bottom longitudinals $Z_{bl,\min}$	LR Pt.4 Ch.1. Table 1.6.1
Thickness of center girder $t_{cg,\min}$	LR Pt.4 Ch.1.8.3
Thickness of watertight double bottom girder $t_{wg,\min}$	
Thickness of inner bottom $t_{ib,\min}$	LR Pt.4 Ch.1.8.4
Thickness of watertight floors, $t_{wf,\min}$	LR Pt.4 Ch.1.8.3
Thickness of inner hull, $t_{ih,\min}$	LR Pt.4 Ch.1 Table 1.9.1

Applied design constraints are calculated according to the *Lloyds Register of Shipping rules and regulations for the classification of ships* [4] and *Finnish-Swedish Ice Class Rules* [5] as identified in Table 5. Constraints for sandwich panel decking in concept II, for thickness of faces, top t_{tsp} and bottom t_{bsp}, core t_{csp}, its height h_{sp} and spacing of core elements s_{sp} are determined by direct calculations of:

- global deflection under the wheel loading,
- local deflection of sandwich top face,
- plastic collapse of core,
- buckling and yielding of sandwich faces,

according to the analytical formulations in [6]. For the rest of the main frame structure in concept II constraints from Table 5 are applied. Sandwich panel is analyzed as a beam supported by webframes with cross section given in Fig. 3 [6], [10]. This assumption is valid since the span of the sandwich panel is rather short, being the webframe spacing, comparing to the panel's breadth, being the breadth of a ship B. If again the worst case is assumed, that

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[2] Cf. [4] – LR Pt.3 Table 9.3.3

[3] Cf. [4] – LR Pt.3 Table 9.3.1

the two tires are positioned between the webframes, then the panel's segment is a beam in four point bending. This differs from the assumption of wheel loading for concept I, but it is more conservative. For the midship section in concept II ultimate strength was calculated after the optimized design was obtained to verify the stability of sandwich decking. It was calculated for the sagging condition only.[4] Vertical hull girder stress distribution was calculated according to the method of Paik & Mansour [7], with formulations for ultimate load of sandwich deck from [8]. All the presented designs offer substantial reserve to critical level. By solving the scalar problem in Eq. (6) one non-dominated design point is obtained. Others are found by repeating this approach and by changing the values of VCG constraint constant *C*. All together 11 different minimum weight designs are defined, five for concept I and six for concept II. After mapping these results from a design space into a criterion space, seen in Fig. 4, as ratios of weight and VCG over weight and VCG of initial design respectively, a functional relationship between objective functions is established. This is done by fitting a polynomial function through the non-dominated designs. This function then defines the complete Pareto-optimal set or the efficient boundary. Two linear Pareto-optimal sets are found, one for each concept, described as

$$\mathrm{VCG}_{\mathrm{o,I}}(\mathbf{x}) = -0.95 \cdot \mathrm{W}_{\mathrm{o}}(\mathbf{x}) + 1.86\,, \tag{11}$$

$$\mathrm{VCG}_{\mathrm{o,II}}(\mathbf{x}) = -0.95 \cdot \mathrm{W}_{\mathrm{o}}(\mathbf{x}) + 1.73\,. \tag{12}$$

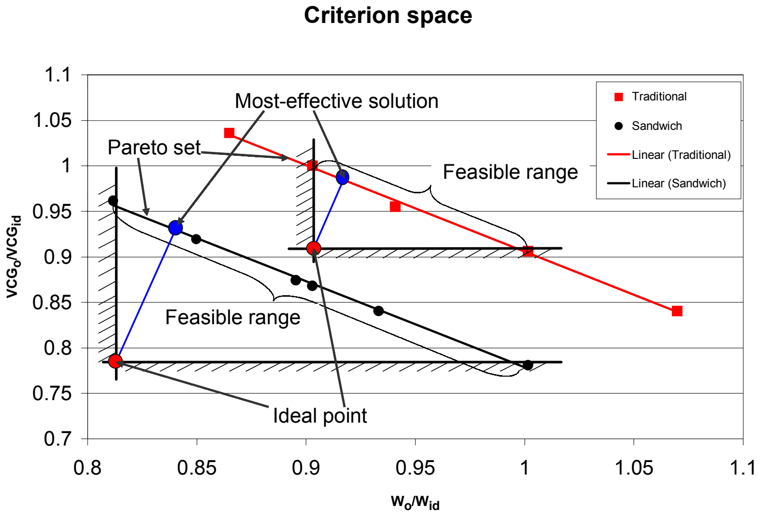

Fig. 4. Optimal and Paretto-optimal designs **Slika 4.** Optimalni i Paretto-optimalna rješenja

The most-efficient solutions $\tilde{\mathbf{x}}_{\mathbf{I}}$ and $\tilde{\mathbf{x}}_{\mathbf{II}}$, for each concept, lie somewhere on them. The question now is how to decide on point from a Pareto-optimal set as the most-efficient solution. A very simple approach is applied. Most-efficient design is established as a point $\tilde{\mathbf{y}}$ in a criterion space closest to the ideal point $\mathbf{y}_{\mathbf{ID}}$, which is a vector consisting of individual minima of objective functions, found from the non-dominated solutions under the necessary condition that the side objective does not result in a value worse off than in initial design

$$\mathbf{y}_{\mathbf{ID}} = \begin{pmatrix} \min\left\{\mathrm{W}_{\mathrm{o}}\left(\mathbf{x}^{*}\right):\ \mathrm{VCG}_{\mathrm{o}}\left(\mathbf{x}^{*}\right) \le VCG_{id}\right\} \\ \min\left\{\mathrm{VCG}_{\mathrm{o}}\left(\mathbf{x}^{*}\right):\ \mathrm{W}_{\mathrm{o}}\left(\mathbf{x}^{*}\right) \le VCG_{id}\right\} \end{pmatrix}. \tag{13}$$

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[4] In still water the ship is in hogging, so the value of still water bending moment was taken as $M_S = 0$

The minimum distance is defined from the Euclidean metric distance function as the following line search problem

$$\min\left\{\sqrt{\left(\mathrm{W_o}\left(\mathbf{x}^*\right)-\mathbf{y}_{\mathbf{ID}1}\right)^2+\left(\mathrm{VCG_o}\left(\mathbf{x}^*\right)-\mathbf{y}_{\mathbf{ID}2}\right)^2}\right\}. \tag{14}$$

The most-efficient design $\tilde{\mathbf{y}}$ is identified in a criteria space. However, in order to find the most-efficient design in a design space $\tilde{\mathbf{x}}$, a scalar optimization of the main objective is performed again, where the side objective VCG is accounted as constraint by setting

$$\mathrm{VCG_o}(\mathbf{x}) \le \mathrm{VCG_o}(\tilde{\mathbf{x}}). \tag{15}$$

$\tilde{\mathbf{x}}$ is then found from the following

$$\min_{\mathbf{x}\in\Re^n}\left\{\mathrm{W_o}(\mathbf{x}):\ \mathbf{g}(\mathbf{x})\le 0,\ \mathrm{VCG_o}(\mathbf{x})\le \mathrm{VCG_o}(\tilde{\mathbf{x}})\right\}. \tag{16}$$

Table 7. Results of optimization with the values of design and slack variables

Tablica 7. Rezultati optimizacije s vrijednostima projekta i slack varijabli

DESIGN	**No.**	**0**	**1**	**2**	**3^***	**4**	**5**	**6**	**7**	**8^***	**9**	**10**	**11**
	Concept	**ID**	**I – Traditional**					**II – Sandwich**					
No	**VCG [m]**	**4,70**	**4,87**	**4,70**	**4,49**	**4,27**	**3,96**	**4,52**	**4,32**	**4,11**	**4,08**	**3,95**	**3,67**
	VCG diff. to ID [%]	**0**	**-3.6**	**0.0**	**4.5**	**9.1**	**15.7**	**3.8**	**8.1**	**12.6**	**13.2**	**16.0**	**21.9**
	Weight [t/m]	**13,2**	**11,4**	**11,9**	**12,4**	**13,2**	**14,1**	**10,7**	**11,2**	**11,8**	**11,9**	**12,3**	**13,2**
	Weight diff. to ID [%]	**0**	**13.5**	**9.7**	**5.9**	**-0.2**	**-7.0**	**18.8**	**15.0**	**10.5**	**9.7**	**6.7**	**-0.2**
1	t_d [mm]	12	11,5					-					
2	Z_{dl} [cm^3]	235	131										
3	s_{dl} [mm]	750	670										
4	t_t [mm]	-						7					
5	t_b [mm]							2					
6	t_c [mm]							2					
7	h_{sp} [mm]							100					
8	s_{sp} [mm]							750					
9	Z_{dg} [cm^3]	1744											
10	Z_{dt} [cm^3]	3289	3452										
11	t_{ss} [mm]	11,0	7,5	7,5	8,0	7,5	7,5	8	7,5	7,5	7,5	7,5	7,5
12	t_{sa} [mm]	7,0	7,5										
13	Z_{sl} [cm^3]	42,8	60,5										
14	s_{sl} [mm]	665	650										
15	Z_{st} [cm^3]	2509	1269										
16	t_{si} [mm]	14,0	7,5	8,5	7,5			7,5					
17	t_{ih} [mm]	7,0	6,5										
18	Z_{fi} [cm^3]	223	163										
19	t_{dtb} [mm]	10,0	7,5	7,0	7,5	7,0		7					
20	t_k [mm]	13,0	10	10	14,5	16,5	23	10	11	14,5	17	21,5	27
21	t_{cg} [mm]	12,0	12	12	11,5	11,5	11,5	12	13	20,5	11,5	13	12
22	t_b [mm]	10,0	8	8	12,5	14,5	21	8	9	11,5	12	13,5	21
23	Z_{bl} [cm^3]	163	42,8	84	42,8	65,7	163	42,8	131	42,8	261	163	60,5
24	t_{wg} [mm]	10,0	9	9,5	9,5	9	9	9	13,5	15,2	13	13,5	10,5
25	s_{bl} [mm]	730	650	650	835	835	835	650	650	650	730	835	835
26	t_{ib} [mm]	9,0	8	9	10,5	13	9	8	8	8,5	9	10	9,5
27	Z_{ibl} [cm^3]	163	42,8	131	42,8	65,7	60,5	42,8	84	42,8	42,8	65,7	60,5
28	t_{wf} [mm]	10,0	10,5	11	10,5	10,5	12	10,5	10,5	14,5	11	12,5	11,5

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[*] Most-efficient design

3. Results and discussion

Noticeable improvements in weight and VCG of the midship region have been achieved, absolute weight minimum being about 19 % lighter than in initial design, and absolute VCG minimum 22 % lower that in the initial design. Implementation of steel sandwich panels in weather deck in concept II has further decreased the weight and the VCG for additional 5%. Substantial weight savings have been achieved by reduction of frame spacing by half in ice belt resulting in major reduction of plating thickness.

By analyzing Table 6 we can notice that the optimization has resulted in most of the design cases with reduction of spacing of longitudinals, which reduces their size and enables application of thinner plates. For the weather deck spacing of longitudinals s_{dl} is reduced from 750 mm to 670 mm. For the concept II the spacing of sandwich core s_{sp} is the same as in the initial design, but with the reduced width of the unsupported top face to 550 mm. In the side shell region above the neutral axis (NA) the spacing of side longitudinals s_{sl} is reduced only marginally for 15 mm. In the double bottom the spacing is varying for all designs. It can be concluded that the spacing depends more on thickness of bottom shell, which is increased for some designs drastically in order to lower the VCG, thus relaxing the need for smaller spacing. Thickness of plates t_{si} and frame size Z_{fi} in ice belt are basically halved from the initial values due to the reduction of frame spacing by half to 300 mm. This considerably reduces the weight of the midship section, and does not negatively influence on lowering of VCG, since their position is in the region close to the NA.

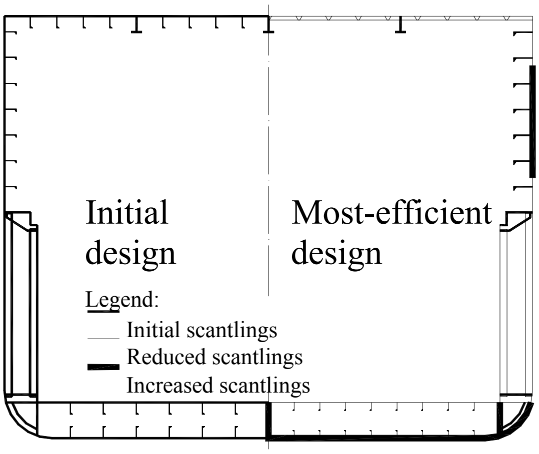

Fig. 5. Comparison between the initial design ID and the overall most-efficient design (design no. 8) by graphic interpretation of change in scantlings of structural elements

Slika. 5. Usporedba početnog projekta ID i cjelokupni najkorisniji projekt (projekt br. 8) prema grafičkom tumačenju promjena dimenzija strukturnih elemenata

Fig. 5 summarizes previously said by comparing the initial and the overall most-efficient design (design no. 8 from Table 6). It presents all the longitudinal elements of the main frame and in addition the frames of ice belt. Using appropriate thickness of lines and sizes of bulb flats, we can visualize the results of optimization. Very thin lines and small bulbs stand for reduction of scantlings, while very thick lines present increased scantling. However, the thickness of lines does not truly present the size of scantlings, but it is a mere symbolic representation. For the exact scantling reader is referred to Table 5. From this, we can then conclude that the most-efficient design is reached by reduction of strake thickness and bulb flats size in all regions except for strakes of bottom shell, double bottom girders and side shell strakes and bulbs above the NA. Explanation for such a solution can be found in fine balancing between the reduction of weight and VCG, which mutually correspond non-proportionally.

4. Conclusion

Multicriterion optimization approach for redesign has shown improvements when compared to initial design. Percentage wise, newly developed designs have managed to reduce either the weight or VCG up to 22 % when compared to the initial design. The aim was to reduce the total light ship weight by 300 t and VCG by about 1 m. However, this was not reached since the task included the investigations of the midship region only. One could raise a question on selection of most-efficient solution. Why the minimum distance to an ideal point was used, when it could have been the demand point? Of course, there is no strong reason for one or another – it is a conflict situation. Even though, the first method was chosen due to the sheer approach to the problem, and that was to minimize the weight and the VCG of the midship section, and not of the whole hull. Thus, it is then better to aim for the individual minimum of weight and VCG simultaneously. Much better results have been achieved with application of steel sandwich panel in weather deck. Even though the high local loading of trailer wheels diminishes this advantage, still the savings in weight and VCG are considerable when compared to the traditional decking. It is understandable that this kind of a solution might prove to be a bit more complicated when it comes to detail structural design and production. Recent research has come up however with the solutions to most of these problems.

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