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NEW INNOVATIVE DESIGN OF ROPAX SHIP

Summary

The objective of the paper is to present the main outcome regarding design of the new innovative Ro-Pax vessel developed through EU FP6 project IMPROVE. The main characteristics of the ship, based upon ship owner design requirements and shipyard preferences are presented. The primary focus was on the general ship design (Naval Architecture calculations: speed, power, damage stability, etc.) performed at ULJANIK shipyard. Different propulsion variants were compared and evaluated. Additional benefits can be achieved by structural optimization of deck transverses web height and superstructure topology, specially for multi-deck ships, in order to obtain lower Equipment Number and smaller Gross Tonnage reducing additionally vessel's price and port fees. Various structural arrangements of midship and superstructure were analyzed as a multi-objective design problem. Approach that combined ship general and ship structural design has been suggested for early design stage.

Key words: *Ro-Pax vessel, propulsion concept, ship structural optimization, early design phase.*

NOVI INOVATIVNI PROJEKT ROPAX BRODA

Sažetak

Cilj rada je prikazati glavne karakteristike projekta novog Ro-Pax broda razvijenog kroz EU FP6 projekt IMPROVE. Prikazane su glavne karakteristike projekta, temeljene na projektnim zahtjevima brodovlasnika i preferencijama brodogradilišta. Primarni fokus bio generalni projekt broda (različite brodograđevne kalkulacije: snaga, stabilitet, brzina, itd.) koje su provedene u brodogradilištu ULJANIK. Predloženi su i evaluirani različiti propulzijski koncepti. Dodatna uštede mogu se postići primjenom strukturne optimizacije visine poprečnih elemenata i topologije nadgrađa s ciljem smanjenja težine broda i prelaska u niži razred opremnog broja, što u konačnici dovodi do smanjenja cijene plovila i lučkih pristojbi. Različite topološke varijante glavnog rebra i nadgrađa su analizirane kao više-ciljni projektni problem. Za ranu fazu projekta predložen je postupak koji istovremeno razmatra generalno projektiranje broda i projektiranje strukture.

Ključne riječi: *RoPax brod, propulzijski koncepti, strukturna optimizacija trupa, rana projektna faza*

1. Introduction

The main objective of the EU FP6 IMPROVE project was to design 3 different types of a next generation vessels by integrating different aspects of ship structural design into one formal framework and applying it [1]. The nature of shipbuilding in Europe is to build small series of very specialized ships (the opposite of the Korean and Chinese shipyards). Thus, the IMPROVE project has addressed ships which, with their complex structures and design criteria, are at the top of the list for customization. The IMPROVE consortium has identified the next generation of Large ROPAX ship, Product/chemical carrier and LNG gas carrier as the vessels the most suitable for European yards to focus their energies on [2] and [3].

ULJANIK Shipyard in the last 10 years has designed several car-carriers, ConRo and ROPAX vessels for different ship-owners [4]. For a long period ULJANIK has strong cooperation with GRIMALDI GROUP as respectable ship owner regarding market needs and trends.

In Owner definition: RoPax Vessels are built to combine two genres of transport: the roll on roll of services (as trailer, semi trailers, cars and special cargo) and the passenger transfer, and of course to take profit out it. A close cooperation between the Shipyard and the Owner during the design phase and during the preparation of the technical specification is a key point to achieve above results. The development of the new products required a concurrent design, where new product design generations have to be developed in a multiple criteria decision making environment including multiple objective design and multiple attribute design evaluation stages. Overall goal is to increase the ship-owner's profit while at the same time to reduce shipyard production cost. To maximize the key performance indicators (KPI) for a multi-deck RoPax ship, various aspects of ship structural design were integrated into the multi-criteria (MC) optimization process. It is using, besides existing methods and tools, a number of new tools developed within IMPROVE project. The procedure was mainly split into two interconnected levels:

(1) general ship design (GD) – optimization and selection.

(2) ship structural design (SD) – optimization, selection and analysis.

Regarding general ship design the targets were:

Selection of resistance friendly hull form,
Smaller propulsion engine for the same speed,
Reduced fuel oil consumption,
Selection of a hull form in order to reduce a length of the engine room (increased length of cargo space).

Regarding ship structural design the targets were:

Lower VCG (better stability).
Reduced light ship weight (reduced displacement and propulsion power)
Reduced maintenance cost

To achieve defined objectives an existing line of vessels, as designed by ULJANIK shipyard and GRIMALDI GROUP, was re-assessed (structural limit states, production cost, maintenance assessment).

2. General ship design

The primary focus was on the general ship design (Naval Architecture calculations: speed, power, damage stability, etc.) performed at ULJANIK and corresponding comparisons of selected propulsion variants. Within set requirements, the design considered large variations in seasonal trade (summer 1600pax, winter 100pax). The design was based on a successful existing contemporary ship, used as a prototype (Level 1).

The design methodology in the IMPROVE project defines three design levels:

I. *STANDARD SHIP* is the existing ship or Yard prototype,

II. *NEW SHIP* was designed during the first period of the project. The design was realized using mainly the existing methodology and will include improvements to the main dimensions, general arrangement, hydrodynamics and propulsion,

III. *IMPROVEd SHIP* was obtained starting from the Level II design and using results from multi-criteria structural optimization.

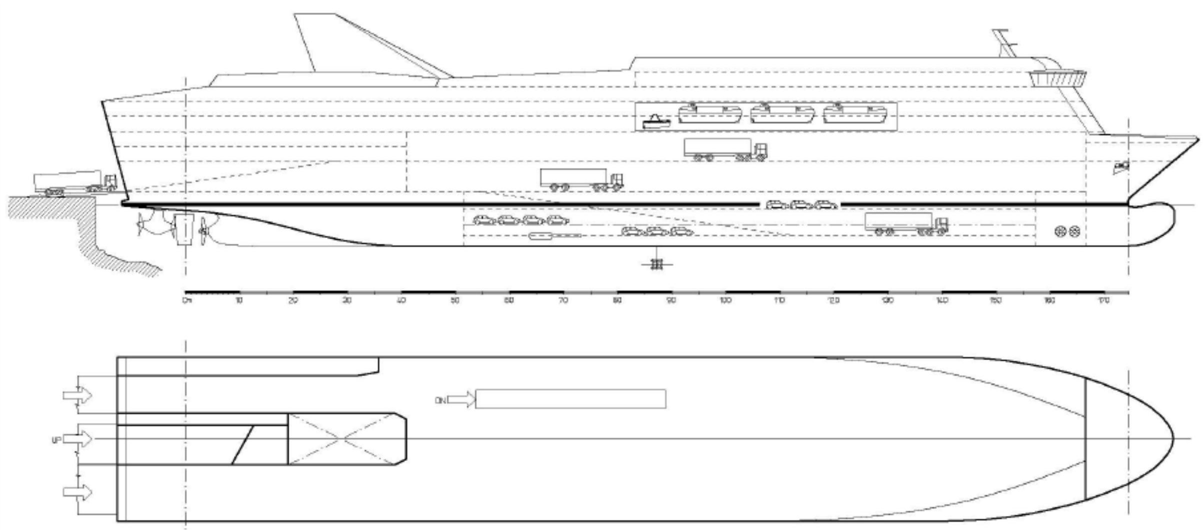


Fig. 1 Standard Ro-Pax Ship-Level I

Slika 1. Standardni projekt Ro-Pax broda-Nivo I

The project of Ro-Pax, developed before ten years by ULJANIK, has been considered as standard ship, Fig.1. The main characteristics of this ship are given below.

Main dimensions: Length overall – 193 + 4 m, Breadth – 29.0 m, Draft design – 6.7 m
Trial speed – 24.5 knots
Cargo capacities – Trailers 3000 lane meters + 300 cars
Capacities: HFO – 1400 m^3, DO – 250 t, FW – 1200 m^3, SW – 600 m^3
Passengers: 166 cabins + 400 aircraft seats
Crew 74 cabins
The designed ship had to be propelled by two pods behind two skegs.

The optimized design (Level II), see Fig.2, has significant advantages as compared with reference RoPax ship(Level I), such as improved redundancy and simplicity of systems, improved manoeuvrability, optimized seakeeping and maximized comfort.

Fig. 2 New Ro-Pax ship design-Level II

Slika 2. Novi projekt Ro-Pax broda-Nivo II

Main dimensions of ROPAX concept design are optimized using TRIDENT/SEAKING software (ULJANIK/USCS software [5]) in order to obtain minimal main engine power and sufficient stability. The cargo capacities, restrictions of main dimensions, trial speed etc. are defined by ship-owner request. A new application was developed, which finds a best combination of main dimensions in order of minimize resistance. Original hull form was Uljanik's biggest PCTC, which was then transformed into new (Level II) form with smaller resistance, see Fig. 3.

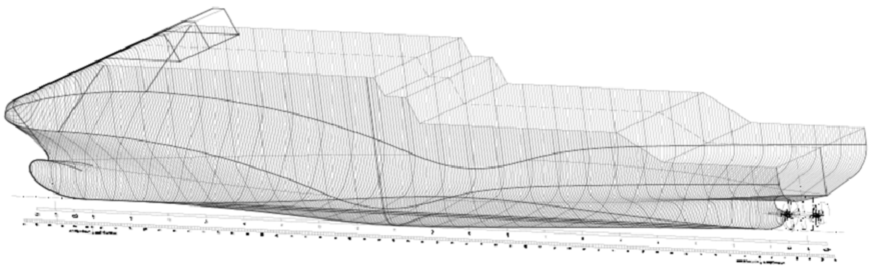


Fig.3 Body Lines of RoPax (Level II)

Slika 3. Brodske linije Ro-Pax broda-Nivo II

In comparison with standard ship, optimized design needs 2900 kW (abt. 11 %) less power due to different main particulars and hull form.

The main characteristics of a new ship:

- Length overall abt 193 m
- Length between perpendiculars: 180 m
- Breadth: 29.8 m
- Design draft: 7.5 m
- Block coefficient: 0.53
- Trial speed: 24.5 knots
- Main engine power (MCR): 14940 kW
- Active rudder output: 5000 kW
- Capacities: HFO – 860 m^3, DO – 440 t, FW – 1000 m^3, SW – 600 m^3
- Passengers: 350 cabins + 200 aircraft seats
- Crew 85 cabins

Loading/unloading of vehicles is done via stern ramp over four decks. Trucks and trailers are parked on tank top, freeboard deck and upper deck, while cars and smaller vehicles are located on second deck. The total lane length is 3000 m plus 300 cars. There are two fixed ramp ways for transport connection between decks, one going from tank top to main deck with bridge extension to second deck and the other from main to upper deck. Passenger embarkment is done also via stern ramp over elevators to accommodation decks.

After the optimization of main particulars, two propulsion design alternatives were investigated, see Fig.4:

Variant I: One slow speed main engine directly coupled to fix pitch propeller with one active rudder with propulsion bulb to increase main propeller efficiency. Auxiliary propeller is driven by direct electric drive of 5000 kW using bevel gears at the top and the bottom of the leg (inside circular torpedo body). Planetary gears for steering are driven by frequency controlled electric motors. Engine room space is divided into three parts: main engine room with main engine with power of 14900 kW, auxiliary engine room with 4 engines with total power of about 9000 kW and electric converters room for driving active rudder propeller.

Variant II: Two medium speed main engines coupled via gearbox to CP-propeller with two retractable side thrusters. Engine room space is divided into four parts: main engine room with main two engines of 8400 kW each, auxiliary engine room with 4 engines with total power of about 8000 kW, bow retractable thruster room and electric stern retractable thruster room. Retractable thrusters will operate in port only.

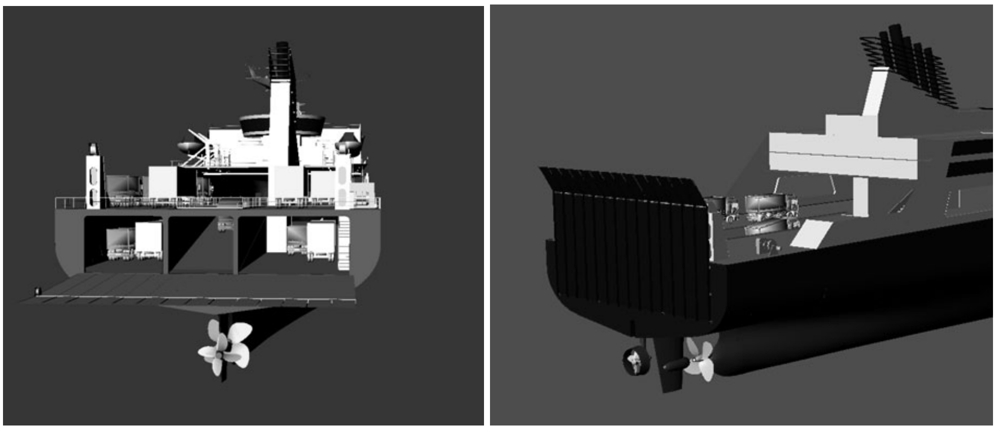


Fig. 4 Different propulsion solutions-Level II

Slika 4. Različita propulzijska rješenja-Nivo II

The main idea of novel propulsion concept is to avoid as much as possible the running of electrically driven thrusters in seagoing condition, i.e. to use it only during manoeuvring in harbour (no tugs) and to have two independent sources of propulsion in order to obtain 100% redundancy notation. The owner requirement was that ship must never stop and requested selection of two main engines coupled via gearbox to one CP-propeller (Variant II). This arrangement gives the possibility to operate vessel with one main engine running and carry out maintenance on the other main engine. The selected Variant II arrangement shows 9% smaller efficiency compared to Variant I.

Goals regarding achievement in fuel oil consumptions and increased lane meter on tank top (cargo capacity) have been achieved. In comparison with *Standard* ship, *New* design (Level II) needs almost 7900 kW less power, weight of machinery is reduced by 450 t, fuel oil consumption is 28% less and finally, propulsion system is more reliable. Index of redundancy is 100% (2 independent engine rooms and 2 independent propulsion systems).

Final *IMPROVEd* ship (Level III) has been obtained using multi-criteria structure/general design optimization results given in Ch.3.

3. Multi-criteria structural design optimization

The main idea of Level III is to further increased savings obtained on the Level II design by implemented structural design optimization in connection with general ship calculations.

3.1. Structural optimization

On the general ship level, several topological/geometrical concepts have been proposed and evaluated based on new ship design (Level II) which served as prototype. Two different concepts of superstructure were attached to each of three midship section variants proposed by ULJANIK. In that way a total number of six different model variants were formulated in order to perform structural optimization for each of them, Fig. 5:

1. Number of superstructure decks. Two variants of superstructure ($\mathbf{x}^T$: two and three tiers), but with the same total area of accommodation decks.
2. Transverse position of longitudinal bulkhead between deck 1 and deck 3 ($\mathbf{x}^G$). Three different positions have been examined.

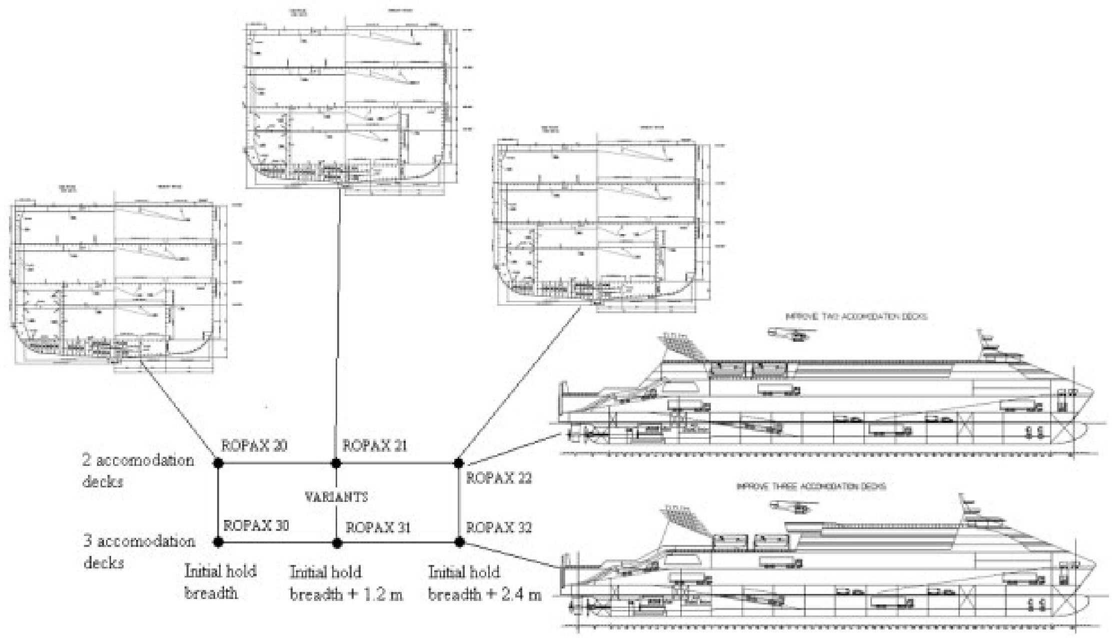


Fig. 5 RoPax Topological/geometrical design variants

Slika 5. RoPax topološke/geometrijske projektne varijable

For a concept structural design of multi-deck ships (such as Ro-Pax) an efficient multi step procedure have been established to solve topology (and interwoven scantling/geometry) optimization via two main tasks [6] and [7]:

(A) topology / geometry optimization

(B) scantling / material optimization of the preferred variants from task (A)

Generic tapered ship 3D FEM models based on gross-elements/surrogates [8] according to class Rules, was selected as the appropriate model for structural optimization of both task. Each of the six extruded generic 3D FEM models were generated in MAESTRO structural design software [9], see Fig. 6.

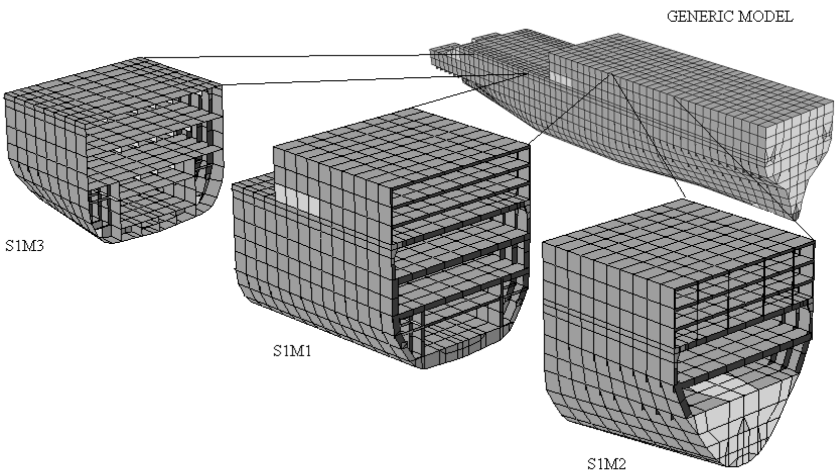


Fig. 6 MAESTRO 3D generic model of RoPax ship

Slika 6. MAESTRO 3D generički MKE model RoPax broda

The design variables used are divided into topological, geometrical and scantling variables, see Table 1. The topological variable was the number of superstructure decks ($\mathbf{x}^T$: two and three tiers). The geometrical variable was the breadth of lower hold ($\mathbf{x}^G$: three different position of longitudinal bulkhead in cargo space). The scantling variables were scantlings of structural elements ($\mathbf{x}^S$: 14 scantling variables per stiffened panel). $\mathbf{x}^T$ and $\mathbf{x}^G$ are very important on the general ship level because their reduction could possibly reduce equipment number (cost of equipment). Shipyard supplied constraint function for equipment number based upon geometrical design variables used in optimization process. Also, by increasing the lower hold breadth, a total gross tonnage also increases.

Table 1. Design variables

Tablica1. Projektne varijable

Design variables type	DESIGN VARIABLES PROPERTIES				
	Name	Min	Max	Step	Comment
$\mathbf{x}^T$	Number of SS decks	2	3	1	Booth version have the same area of accommodation decks
$\mathbf{x}^G$	Lower hold breadth	15360 mm	17760 mm	1200 mm	One or more car lane (height of deck 3 is function of this variable)
$\mathbf{x}^S$	Structural elements				Min/Max values based on class. rules, technology demands, experience, etc.

Structural optimization of different design concepts for given objectives (cost, mass, VCG, safety, etc.) w.r.t. the topological, geometrical and scantling variables enables their fair comparison. In the context of general design, designer's selection should be performed as second design task, using the global design quality measures on the grid of optimized variants. In parallel with the structural part, ULJANIK performed general naval architecture calculations (damage stability, power, resistance, cargo capacity, etc.) for each of three midship section variants. Also, for each variant the damage stability calculations have been performed to achieve minimal depth of freeboard deck (height of Deck 3) which satisfies damage stability criteria.

Each panel can contain plating, stiffeners, transverse frames and longitudinal girder). Design constraints and requirements were:

(a) Minimum and maximum values for the height of frame web of deck transverses specified by shipyard;

(b) Minimum values for the thickness of plating and stiffener section modulus determined according to the requirements of BV, as minimum allowable thickness of plating and section modulus that can support wheel loads [10];

(c) To satisfy structural strength, the adapted set of MAESTRO adequacy parameters was used [11].

The design objectives used for optimization of all six structural variants were: structural weight, cost of material and position of vertical centre of gravity (VCG). All variants were optimized using MAESTRO SLP optimization algorithm during 10 design cycles. Mass, cost and VCG of each model were calculated using MAESTRO inbuilt functions. Safety measures were determined using normalized adequacy criteria. Relative adequacy index [11], has been calculated for all three modules used in optimization (S1M1, S1M2 and S1M3). Height of ship for proposed models was determined after the optimization was performed. Based on the comparison between all six models (initial and proposed) the following results have been achieved:

Total mass of each model was successfully decreased by approximately 200 to 300 t for all variants (depending on a model).

Production cost and VCG were successfully decreased.

Safety was increased due to smaller number of unsatisfied constraints and greater relative adequacy index.

Height of all models was slightly increased due to greater height of transverse beams of decks 2 and 3.

Fig. 7 shows the structural mass cycle-history as well as the changes in total number of unsatisfied constraints with respect to the cycle number for design RoPax 22.

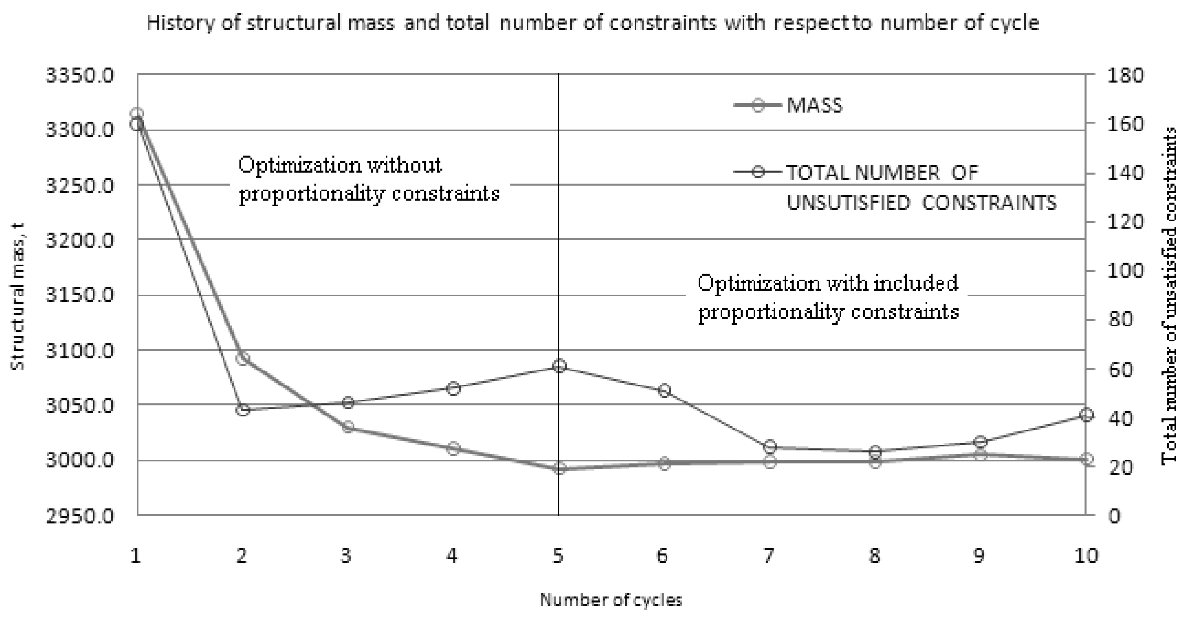


Fig. 7 Design history of mass and safety for RoPax 22

Slika 7. Promjena mase i sigurnosti po projektnim ciklusima za projekt RoPax 22

Influences of $\mathbf{x}^T$ and $\mathbf{x}^G$ on the structural design are briefly summarized:

The main differences between two superstructure concepts ($\mathbf{x}^T$), one with two tiers (RoPax 20, 21 and 22) and those with three superstructure decks (RoPax 30, 31 and 32), is in longitudinal (hull girder) stress distribution along the ship height/length. Due to the fact that superstructure with two decks is very long, about 80-90% of ship length, it participates in the hull global bending with more efficiency then variants with much shorter superstructure with three decks. Comparison of longitudinal stresses for LC2 is given for two variants RoPax 22 and RoPax 30, see Fig.8.

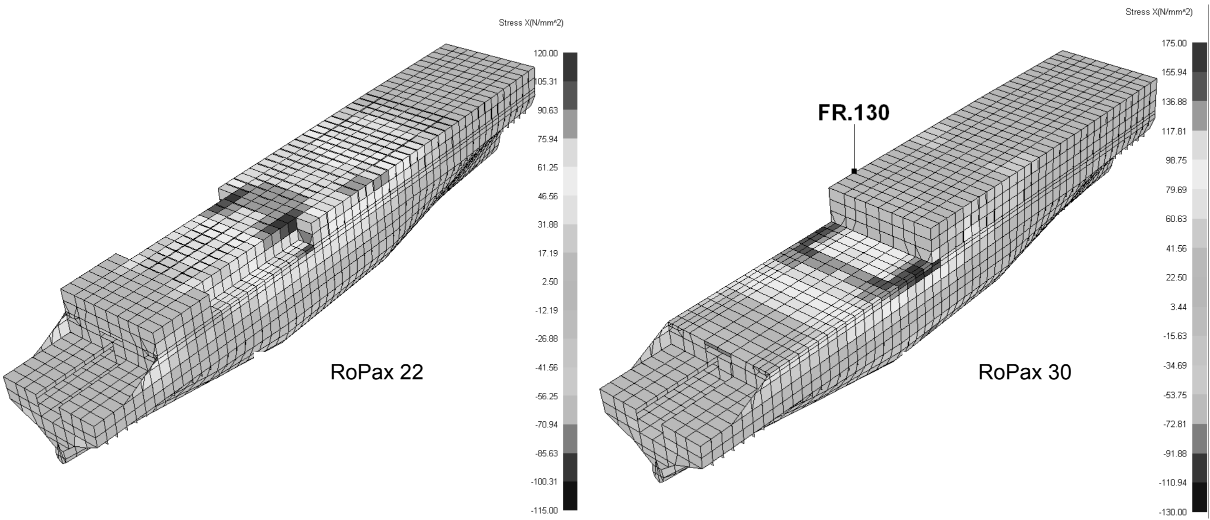


Fig. 8 Longitudinal primary stresses distribution for two variants RoPax 22 and RoPax 30

Slika 8. Uzdužna primarna naprezanja za dvije varijante RoPax 22 i RoPax 30

The contribution of superstructure decks to the primary strength for RoPax 30 is low. This variant is also characterized with the stress concentration areas at the position of the connection of the superstructure end with the upper hull deck (Deck 6). It affects stress distributions over cross section height and causes higher stresses in Deck 6 (highest lower hull deck) and increases compression stresses in the bottom plating, compared to RoPax 22 variant. Higher compression stresses lead to thicker bottom plating to prevent the buckling problems. The reduction in mass of RoPax 22 for about 60t is achieved compared to RoPax 30.

Transverse position of longitudinal bulkhead between Deck 1 and Deck 3 ($\mathbf{x}^G$) has an influence mainly on the transverse beams scantlings on Deck 2 and 3. Its influence is relatively low with respect to the completely structural mass. As it was expected, the variants RoPax- 20 and RoPax-30 resulted in the smallest scantlings of transverse beams for both decks due to smaller unsupported beam length.

3.2. Design selection

Structural optimization of a real ship can offer a significant help to the ship designer because it can optimally redistribute material, reducing weight of initial model and increasing its safety. Also, a total number of six RoPax ship model variants were investigated in order to determine the best variant with respect to multiple objectives (lowering of ship height, minimization of total mass, cost and position of vertical centre of gravity, safety criteria). Based on structural optimization results and additional general naval architecture calculation of ship damage stability and cargo handling for all variants, designer has specified six criteria for the final selection:

- Parking Area,
- Production measure,
- Ship stability,
- Passenger comfort
- Air draught,
- Structural Safety

Values of six design attributes are summarized in Fig. 9 for all six examined RoPax variants (6 generic FEM models for: 2 variants of superstructure x 3 variants of LBHD-Fig. 5.

Nondominated Designs

VARIANT NAME	No	PARK_AR	STABILITY	AIR_DRAUG	PRODUCTIO	PASS_COMF	SAFETY
RoPax 30	1	10150	13376	32250	2991	36765	0.9599
RoPax 31	2	10360	13405	32400	3038	35964	0.9497
RoPax 32	3	10570	13450	32550	3058	35479	0.9519
RoPax 20	4	10150	12797	29250	2930	33345	0.9469
RoPax 21	5	10360	12870	29400	2958	32634	0.9415
RoPax 22	6	10570	12906	29550	3000	32209	0.9451

Fig. 9 Values of design attributes for different variants

Slika 9. Vrijednost projektnih atributa za različite projektne varijante

Designer's and Owner's subjective intra-attribute and inter-attribute preferences were revealed. Novak's fuzzy functions were used to model intra-attribute preferences, Fig.10, while Saaty's AHP method was used for inter-attribute preferences [12].

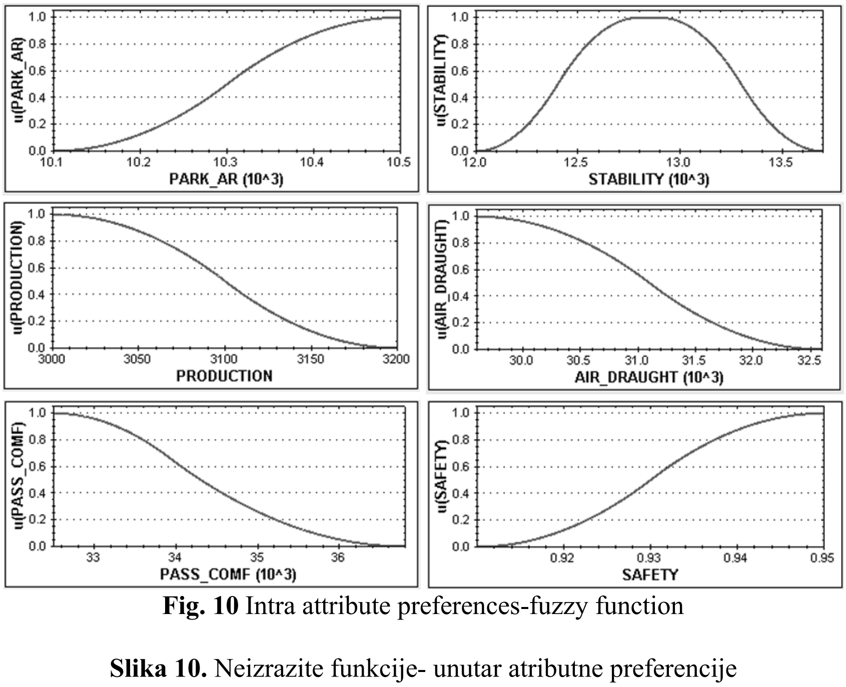
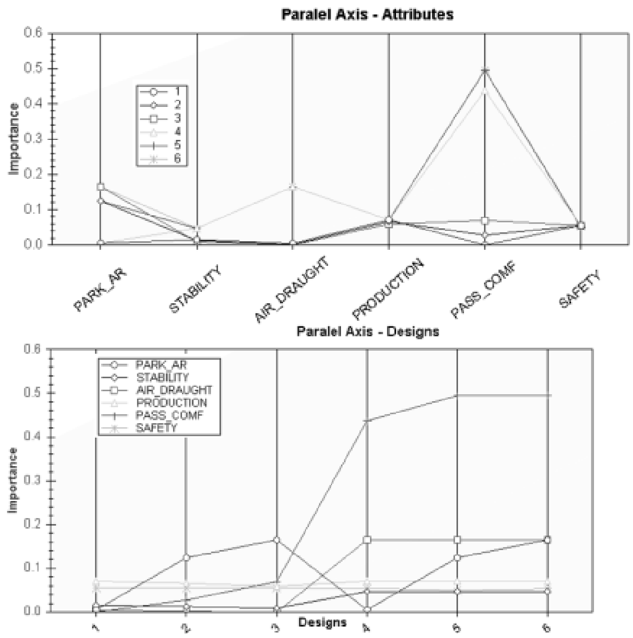


Fig. 10 Intra attribute preferences-fuzzy function

Slika 10. Neizrazite funkcije- unutar atributne preferencije

Final selection of the preferred variants was performed by ULJANIK shipyard head designer on the *Parallel axis plot* of selected criteria's in OCTOPUS Designer DeView Tool (see Fig.11) based on Designer's and Ship Owner's subjective intra-attribute and inter-attribute preferences.



Legend: Design 1 - RoPax 30; D2 - RoPax 31; D3 - RoPax 32; D4 - RoPax 20; D5 - RoPax 21; D6 - RoPax 22

Fig. 11 Parallel axis plot of criteria for all six variants

Slika 11. Prikaz svih šest projektnih varijanti pomoću paralelnih osi

The variant ***RoPax 22*** has been chosen as preferred solution. Some of the highlights of the preferred *RoPax 22* variant are:

(1) Additional 403.2 m^2 of parking area with respect to the starting variant RoPax 30.

Parking area Deck 2 = +201.6 m^2 × 3000 Euro/m^2	= + 604800 euro
Parking area Deck 1 = +201.6 m^2 × 5000 Euro/m^2	= +1008000 euro
Total parking area = +403.2 m^2	= +1612800 euro

(2) No additional ballasting – the vessel will sail at smaller draught in arrival condition,

(3) 2.5 m smaller air draught with respect to *RoPax 32*,

(4) Reduced weight of wing tank blocks and smaller distance to water line, which directly improves passenger comfort.

(5) Structure inside wing tanks is modified in a way that three stringers are added P/S in order to avoid erection of scaffoldings for inspection of Voids P/S. It will make easier Class inspection.

Selection performed presents the interaction of General Design (GD) procedure and Structural Design (SD) procedure in the first design cycle.

Final *IMPROVEd* ship (Level III) has 4 % less lightship weight in comparison with *New* IMPROVE ship (Level 2) and because of this, the required propulsion power and fuel oil consumption are 5 % less (19560 kW instead of 20500 kW). The gain of 5% more trailer lanes (cargo capacity) on tank top is achieved by investigating different positions of longitudinal ballast tank bulkhead and at the same time ballast volume is minimized.

4. Conclusions

An innovative RoPax design has resulted following a multi-stakeholder approach where shipyards and ship-operators were involved. To maximize the key performance indicators (KPI) for a RoPax product various aspects of ship structural design were integrated into the multi-criteria optimization process.

IMPROVE goals regarding achievement in fuel oil consumptions (12%) and increased cargo capacity of about 5% more trailer lanes on tank top has been achieved. Ship-owner profit has been significantly increased due to reduction in fuel consumption (better propulsion and ship hull form, reduced weight, etc.), increase in payload (increased parking area).

Various structural arrangements were analyzed by ULJANIK and UZ as a multi-objective design problem. Structural optimization obtained savings in cargo space weight of approx. 300 tons in which influenced general ship design (Level III) in terms of additional reduction of required propulsion power for 5% compared to the same propulsion system implementer in new ship (Level II). Also, the preferred topological/geometrical concept (RoPax 22) has been chosen and served as the starting point for the more detailed structural optimization.

Presented approach gives Yards and Owners a possibility to select competitive design solutions by following the basic IMPROVE paradigm: better ship for the Yard production and more profitable ship for Owner regarding maintenance and operational aspects within LCC.

Presented work represents the successful cooperation and joint work of Yard and Faculty design teams as an example of modern design approach in very early design phase.

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