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Philippe RIGO[1]
Vedran ŽANIĆ[2]
Sören EHLERS[3]
Jerolim ANDRIĆ[2]

Design of Innovative Ship Concepts Using an Integrated Decision Support System for Ship Production and Operation

Review paper

The paper describes a concept of integrated decision support system for a methodological assessment of ship designs that provide a rational basic for making decisions pertaining to the design, production and operation. Main objectives of this research was to develop an integrated multiple criteria decision making environment by using the advanced design synthesis and analysis techniques at the earliest stage of the design process, which innovatively considers structure, production, operational aspects, performance, and safety criteria on a concurrent basis. Such support can be used to make more informed decisions, which in turn will contribute to reducing the life-cycle costs and improving the performance of those ships. The work has been realized through EU FP6 project IMPROVE and tested in through design of three ship of new generations. The product types focused are new generations and innovative concepts of LNG gas carrier, a large Ro-Pax vessel and chemical tanker.

Keywords: *multiple criteria mathematical models, LNG ship, Ro-Pax ship, chemical tanker, structural optimization, EU FP6 project IMPROVE.*

Osnivanje inovativnoga koncepta broda uporabom integriranoga sustava za donošenje odluka za proizvodnju i službu broda

Pregledni rad

U radu je ukratko prikazan koncept integriranoga sustava za metodološko ocjenjivanje uspješnosti pojedinih projekata broda, unutar kojega se stvara racionalna osnova za donošenje odluka vezanih uz projektiranje, proizvodnju i korištenje brodova. Glavni cilj istraživanja bio je razviti integrirani višekriterijski projektni okoliš unutar kojega se korištenjem suvremenih metode analize i sinteze, u najranijoj projektnoj fazi, istodobno razmatraju struktura broda, proizvodni proces, eksploatacija, performanse i sigurnosni kriteriji. Takav se sustav može iskoristiti za donošenje kvalitetnijih odluka, što pak dovodi do smanjenja troškova kroz životni vijek broda nove generacije i poboljšanja njegovih svojstava. Rad je na razvoju i praktičnoj aplikaciji realiziran kroz EU FP6 projekt IMPROVE i testiran u projektiranju tri broda nove generacije. Fokusom projekta bili su nova generacija broda za prijevoz ukapljenoga prirodnog plina (LNG), inovativni koncept broda za prijevoz tereta na kotačima i putnika (*Ro-Pax*), te unaprijeđeni brod za prijevoz kemikalija.

Ključne riječi: *višekriterijski projektni modeli, brod za prijevoz ukapljenoga plina-LNG,* Ro-Pax *brod, tanker za prijevoz kemikalija, strukturna optimizacija, EU FP6 projekt IMPROVE.*

Authors' Addresses (Adrese autora):
1 *University of Liege, ANAST, Naval Architecture, Institut du Genie Civil,* Bat. B52/3, Chemin des Chevreuils 1, 4000 Liege 1, Belgium.
2 *University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture,* Ivana Lucica 5, 10 000 Zagreb.
3 *Aalto University - School of Science and Technology Department of Applied Mechanics / Marine Technology* P.O.Box 15300, FIN-00076 Aalto.

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1 Introduction

IMPROVE is a three-year research project (2006-2009) supported by the European Commission under the 6th Framework Programme (see Annex 1). IMPROVE aimed at using advanced synthesis and analysis techniques at the earliest stage of the design process, concurrently considering the structure, production, operational performance, and safety criteria.

The nature of shipbuilding in Europe is to build small series of specialized ships. Thus, the project addressed ships which, with their complex structures and design criteria, are at the top of the list for customization. Specific objectives of the project are:

a) to develop improved generic ship designs based on multiple criteria mathematical models,

b) to improve and apply rational models for the estimation of the design characteristics (capacity, production costs, maintenance costs, availability, safety, reliability and robustness of ship structure) in the early design stage,

c) to use and reformulate basic models of multiple criteria ship design and include them into an integrated decision support system for ship production and operation.

Operators buying specialized ships generally plan to operate them for the majority of their design lives. This means that the maintenance characteristics of the design are very important and for this reason IMPROVE was focused on designing for a reduction in operating costs. Designing ship structures in such a way as to reduce the problems of structural fatigue, for instance, can help to achieve this reduction. In addition, designing for minimal operating costs can help to increase the structural reliability and to reduce failures, thus increasing safety.

The targets were to increase shipyard competitiveness by 10% to 20% and reduce manufacturing costs by 8%-15%, production lead-times by 10%-15%, and to find a way to make savings of 5%-10% in maintenance costs related to the structure (painting, corrosion, and plate replacement induced by fatigue). Three specific ship types (here called products) were selected for the study:

1) LNG Carrier (see Figure 1). STX Europe has designed and built 17 LNG carriers (from 50 000 m^3 to 154 500 m^3). In the framework of IMPROVE, a 220 000 m^3 unit with free ballast tanks was designed. The shipowner's requirements were fulfilled and reduction in life-cycle costs was achieved.

2) Large Ro-Pax ship (see Figure 2). *ULJANIK Shipyard* has designed several car-carriers, Con-Ro and Ro-Pax vessels in the past 5 years. *ULJANIK* is in close cooperation with the *GRIMALDI GROUP*, as a respectable shipowner, regarding market needs, trends and product improvements. In the framework of IMPROVE, a new innovative concept of Ro-Pax was proposed.

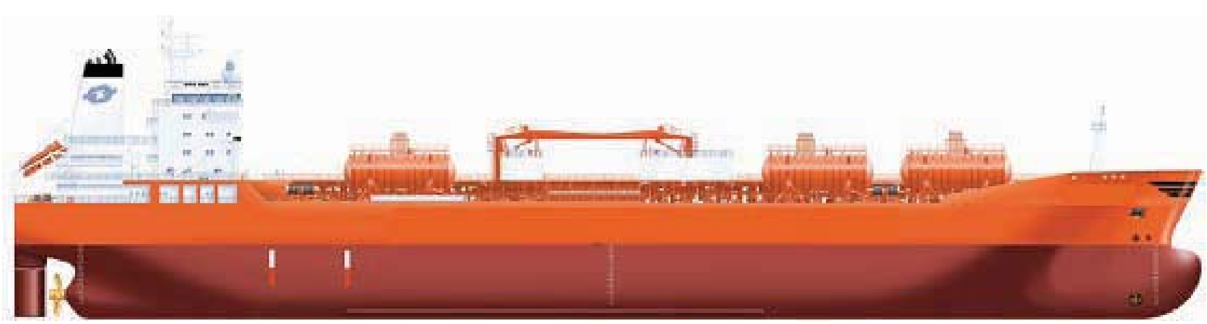
3) Chemical tanker (see Figure 3). *SZCZECIN shipyard* (*SSN*, Poland) has recently built several chemical tankers (40 000 DWT). In the framework of IMPROVE, new concepts of general arrangement, savings in production cost by reducing the amount of duplex steel and by using extensively corrugated bulkheads were investigated.

Since the proposed methodology is based on the multi-criteria structural optimization, not only designers but also shipyards and shipowners / operators (one per product) have to work together in close cooperation. The research activity was divided into three main stages:

Figure 1 **A 220 000 m³ LNG carrier designed by *STX-France***
Slika 1 **220 000 m³ LNG (brod za prijevoz ukapljenog plina), projekt brodogradilišta *STX France***

Figure 2 **A Ro-Pax vessel designed by *ULJANIK Shipyard***
Slika 2 **Ro-Pax brod, projekt brodogradilišta *ULJANIK***

Figure 3 **A 40 000 DWT chemical tanker designed by *Szczecin shipyard (SSN)***
Slika 3 **40 000 DWT tanker za kemikalije, projekt brodogradilišta *Szczecin (SSN)***



(1) Definition of stakeholders' requirements and specification of optimization targets and key performance indicators. In addition, the project partners (particularly the shipyards) designed the reference or prototype ships, one per each ship type, in the "first design loop".

(2) Technical and R&D developments related to the selected structural optimization tools. Several modules, such as fatigue assessment, vibration, ultimate strength, sloshing load assessment, production and maintenance costs, optimization robustness, were delivered and most of them integrated into the existing and improved tools (LBR5, OCTOPUS, and CONSTRUCT).

(3) Application of the developed optimization platforms for the three target products.

Applications are described in detail for the LNG Carrier in [1] and [2], the Ro-Pax ship in [3] and [4], and the chemical tanker in [5].

2 Project objectives

2.1 The background

The IMPROVE project focuses on developing and promoting concepts for one-off, small series and mass customization production environments specific to European surface transport, based on the innovative use of advanced design and manufacturing. A general objective is to increase the shipyard competitiveness through improved product quality and performance based on cost-effective and environmentally-friendly production systems on a life-cycle basis. The research seeks to reduce manufacturing costs, production lead-times, and maintenance costs of the ship structure.

The main objective is to design three different types of new generation vessels by integrating different aspects of ship structural design into one formal framework. The nature of shipbuilding in Europe is to build small series of very specialized ships. Following this, the IMPROVE consortium, (see Appendix), identified next-generation prototypes of an LNG carrier with reduced ballast tanks, a large Ro-Pax ship and a product/chemical carrier as the most suitable vessels to study. Operators using these ships generally operate them for the most of the ship life, making maintenance characteristics of the design very important. Therefore, IMPROVE aimed at designing for lower operating costs. Designing a ship structure in such a way as to reduce problems such as fatigue can help in achieving this aim. In addition, the designing for minimal operating costs helps to increase the structural reliability and to reduce failures, thus increasing safety.

The full life-cycle design approach is the key issue in the future design of ship structures. Therefore, IMPROVE proposes the coupling of decision-support problem (DSP) environments (multi-attribute and multi-stakeholder concurrent design problem) with the life-cycle analysis, while employing modern advanced assessment and design approaches. Shipowners want to minimize short-term investments and, above all, to maximize their long-term benefits. The formal integration of the life-cycle cost into the design procedure and the creation of a long-term competitive ship could be also used as a valid argument in selling.

An integrated decision support system (DSS) for the design of ship structures can assist the designer in this challenging task. This novel design approach considers the usual technical requirements, but also producibility, production cost, risk, performance, customer requirements, operating costs, environmental concerns, maintenance and the life-cycle issues. IMPROVE developed this new design environment. The purpose was not to replace the designer but to provide experienced designers with a better insight into the design problem by means of advanced techniques and tools, which give a quantitative and qualitative assessment of how the current design satisfies the stakeholders' goals and requirements. The developed design approach is focused on the concept/preliminary design stage since the main functional and technological parameters are defined in that stage.

2.2 Scientific and technological objectives

In order to improve their competitiveness, the European shipbuilding industry and shipowners/operators need new generations of ships (products) to be developed for the most valuable and significant transportation needs:

- multimodal transport of goods (advanced generic Ro-Pax),
- transport of gas, oil, and chemicals (advanced gas carriers and chemical tankers).

This should be achieved through the application of:

- multi-stakeholder and multi-attribute design optimization
- risk-based maintenance procedures,
- manufacturing simulation,

in the ship design, production and operation.

Motivation was also generated by the fact that the IMPROVE members were surprised by a constant quest for revolutionary products, while the wisdom of quality product improvement based on the mature design procedures was not properly harvested. For example, by using advanced optimization techniques, significant improvements in the design and production are made available but are still not used.

The feasibility of such potential improvements was proved and confirmed owing to the three practical ship designs done by IMPROVE, i.e:

- early definition of requirements and measures of design quality;
- generation of sets of efficient competitive designs and their presentation to the stakeholders for the final top-level selection;
- selection of preferred design alternatives by different stakeholders, exhibiting measurable and verifiable indicators defined as "Key Performance Indicators" (KPI).

At the start of the project, it was expected that the generated design alternatives will experience the following improvements:

- <u>Increase in carrying capacity</u> of at least 5% of the steel mass (about 15% may be expected for novel designs) compared to the design obtained by using classical methods,
- <u>Decrease in steel cost</u> of at least 8% (and more for novel designs) compared to the design obtained by using classical methods,
- <u>Decrease in production cost</u> of more than 8-10% and even more for novel designs compared to standard production,
- <u>Increase in safety measures</u> due to rational distribution of material and *a priori* avoidance of design solutions prone to multimodal failure,
- Reduced fuel consumption.
- <u>Improved operational performance and efficiency</u>, including savings in maintenance costs for the structure (painting, cor-

rosion, plate/stiffener replacement induced by fatigue, etc.) and machinery.

2.3 Long-term benefit of IMPROVE

The long-term goal of the project was to improve design methodology by devoting a great deal of effort to advanced synthesis skills rather than by improving multiple complex analyses. It was shown that the structural design must integrate various technical and non-technical activities, such as structure, performance, operational aspects, production, and safety. Otherwise, it is highly possible that the defined ship design would be difficult to produce, would require huge amounts of material or labor, would contain some design flaws, or may not be cost-effective in maintenance and operation.

2.4 IMPROVE methodology

IMPROVE was based on existing design platforms and analytical tools, which allowed partners to use simulation and visualization techniques in the assessment of ship performance during its life cycle. IMPROVE implemented an advanced decision support system (including optimization capabilities) in these platforms by coupling the decision-based design (multi-attribute and multi-stakeholder concurrent design problem) with the life-cycle analysis.

3 Fundamental design support systems in IMPROVE

The following three design support systems (DSS) were used in IMPROVE:

LBR5 software is an integrated package to perform cost, weight and inertia optimization of stiffened ship structures, see [6, 7, 8], which allows the following:

- 3D analyses of the general behavior of the structure (usually one cargo hold);
- inclusion of all the relevant limit states of the structure (service limit states and ultimate limit states) in the analysis of the structure based on the general solid-mechanics;
- optimization of the scantlings (profile sizes, dimensions and spacing);
- production cost assessment considering the unitary construction costs and the production sequences in the optimization process (through a production-oriented cost objective function);

LBR5 is linked with the MARS (*Bureau Veritas*) tool. MARS data (geometry and loads) can be automatically used to establish LBR5 models. Only basic characteristics such as L, B, T, C_B, the global structure layout, and applied loads are the required data. It is not necessary to provide feasible initial scantling. Typical CPU time is 1 hour if a standard desktop computer is used.

MAESTRO software, see [9], combines rapid ship-oriented ship structural modeling, large-scale global analysis and fine mesh finite element analysis, structural failure evaluation, and structural optimization in an integrated yet modular software package. The basic function also includes natural frequency analysis, both dry mode and wet mode. Core capabilities of *MAESTRO* represent a system for rationally based optimum design of large, complex thin-walled structures. In essence, *MAESTRO* is a synthesis of finite element analysis, failure or limit state analysis, and mathematical optimization, all of which is smoothly integrated by an easy-to-use Windows-based graphical user interface applied for generating models and visualizing results.

OCTOPUS is a concept design tool developed within the MAESTRO environment; see [10, 11, 12]. Concept design methodology for monotonous, tapered, thin-walled structures (wing/fuselage/ship) includes modules for: model generation; loads; primary (longitudinal) and secondary (transverse) strength calculations; structural feasibility (buckling/fatigue/ultimate strength criteria); design optimization modules based on ES/GA/FFE; graphics.

CONSTRUCT is a modular tool for structural assessment and optimization of ship structures in the early design stage of ships. It is primarily intended for the design of large passenger ships with multiple decks and large openings in the structure. It is also applicable for ships with simpler structural layouts as those tackled in IMPROVE. CONSTRUCT can generate a mathematical model of the ship automatically, either through the import of structural topology from NAPA Steel or the generation of topology within CONSTRUCT. CONSTRUCT applies the method of Coupled Beams, [13], to rapidly evaluate the structural response, fundamental failure criteria, e.g. yielding, buckling, tripping, etc., and also the omni-optimization procedure for the generation of competitive design alternatives, see [14]. At the moment, CONSTRUCT can apply VOP algorithms to solve the optimization problem, [15]. The philosophy behind CONSTRUCT is that of outmost flexibility. Therefore, it can concurrently tackle a large number of criteria, either considering them as objectives or constraints, depending on the current user interests.

4 Contribution to the state of the art in ship structure optimization

4.1 Improvement of the rational ship structure synthesis methods and DSP approaches

IMPROVE developed new mathematical optimization methods. IMPROVE focused on the DSS based approach to the design of ship structures and not on search algorithms. IMPROVE aimed at using the available optimization packages more efficiently and at integrating them in the design procedure. IMPROVE focused on the methodology/procedure that a designer and a shipyard should follow to improve efficiency in the design, scheduling and production of ships. This methodology was used to foster the link between design, scheduling and production, with a close link to the global cost. IMPROVE confirmed that it is only through such integration that specific optimization tools can be proposed to shipyards to improve their global competitiveness.

4.2 Development of particular multidisciplinary links in the synthesis models

The IMPROVE DSS-based approach improved the following:

- Link of "design" with "maintenance and operational requirements" which may differ from the shipyard interest
- Link of "design procedure" with "production" through an iterative optimization procedure
- Link of "design procedure" with "cost assessment" which drives the design to a least-cost design (or a least weight if preferred)

- Link of “production” with “simulation” which drives the design to a higher labor efficiency and a better use of manpower and production facilities

4.3 Enhancement of confidence in the structural DSS approaches through the development of three innovative ship products

IMPROVE made a step forward in the current design procedure by introducing new improved synthesis models. The project also:
- Demonstrated the feasibility of an increase in the shipyard competitiveness by introducing multi-disciplinary optimization tools,
- Demonstrated the acceleration of the design procedure by using a design integrated tool,
- Proposed new alternatives to designs that may or may not fit the existing standards and Class Rules. Such revised designs have to be considered by the designers as opportunities to reconsider the standard design solutions and to think about the feasibility of alternative solutions, etc.
- Validated the newly developed design approach tested on real applications (RoPax, LNG, chemical tanker) by associating a shipyard, a class society, a shipowner and a university.
- Enhanced modeling of advanced structural problems in the early-design optimization tools (e.g. crashworthy hull structure, ultimate strength, vibration, fatigue, sloshing load, etc.).

5 Research performed within IMPROVE

IMPROVE includes 7 inter-dependent work packages (WP2-WP8). The schematic representation of these WPs with the exchanges of information/data is shown in Figure 4.

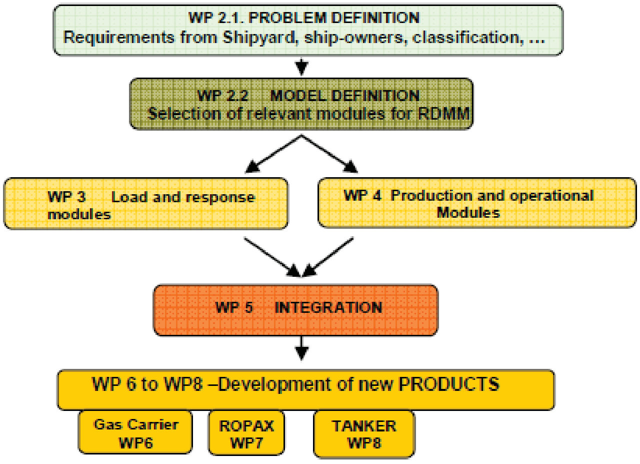


Figure 4 **The IMPROVE flowchart**
Slika 4 **Dijagram toka projekta IMPROVE**

5.1 Problem & model definition (WP2)

In WP2, the consortium defined the structure of the integrated framework for the design of ship structures to increase the functional performance and to improve the development of those designs. The aim of this WP was to identify rational decision-making method for the use in the design of ship structures within the shipyard environment. Specific objectives of this work package were:
- Definition of the multi-stakeholder framework in the design of ship structures.
- Definition of particular interests of stakeholders for specific application cases.
- Definition of design criteria (objectives and attributes), variables and constraints.
- Identification and selection of methods to solve the structural, production and operational issues affecting the design.
- Synthesis of required actions in a framework.

One of significant and valuable results of IMPROVE is the extensive list of design objectives and design variables selected for the concerned ships (which was published by the ISSC international scientific association, see [16]). Quality measures, key performance indicators and potential selected tools were also listed.

5.2 Load & response modules (WP3)

In WP3, the load and response calculation modules were identified. These modules were selected and upgraded to fit the design problems and design methods identified in WP2. Response and load modules extended and developed in WP3 are:
- Module for response calculations for large complex structural models, including models for equivalent modeling of corrugated bulkheads, cofferdams and double bottom.
- Module for vibration calculation in the early design stage (local and global natural frequency).
- Module for the calculation of hull girder ultimate strength (extended Smith method, CB method).
- Module for fatigue calculation in the early design stage.
- Module to assess design loads (hydrodynamic loads, sloshing) and accidental loads (crashworthiness).

5.3 Production & operational modules (WP4)

A new module for tankers was developed to assess the life cycle impacts, applying simple and advanced existing tools, see [17]. The WP tasks contained the following activities:
- Implementation of an operation and life-cycle cost estimator for tanker vessels;
- Implementation of a production simulation to assess the impact of different design alternatives on fabrication,
- Implementation of a production cost assessment module to calculate workforce needed for each sub assembly used in the production simulation.
- Development of robustness module to assess robustness of structural solution related to various fabrication and operational aspects.

5.4 Integration of modules (WP5)

In the framework of IMPROVE all modules and tools developed through WP3 and WP4 were integrated into global decision tools through the developed IMPROVE integration platform. Main features of the IMPROVE Integration Platform are:
- A design desktop as a central component and a control centre;

- All calculations can be initiated and their results can be stored project-wise;
- Iterations and comparisons will be supported;
- Applications and file exchange are organized based on the workflow definition.

As opposed to many other projects, IMPROVE was not primarily aimed at setting up a generic integration platform. Instead, a pragmatic approach to let the tools used in different work packages communicate with each other easily was the goal of the integration work package. By specifying an IMPROVE database and a set of interfaces to the components involved, a powerful environment was developed. It covers all aspects of integration as described by the requirements of the IMPROVE partners, see Figure 5.

6 LNG Carrier - "An innovative concept for a large liquefied natural gas carrier" (WP6)

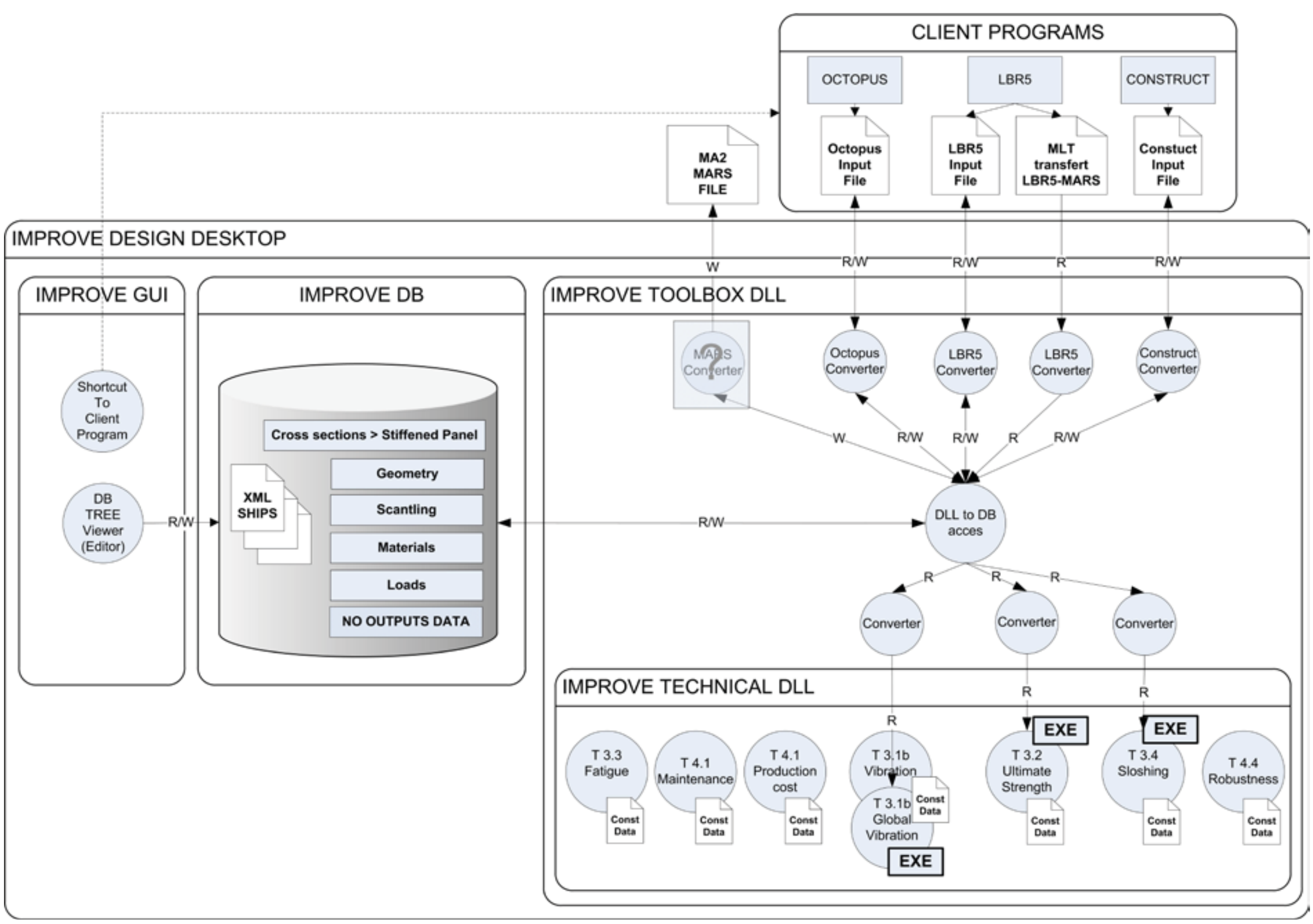
A new forward-looking design for a 220 000 m^3 capacity liquefied natural gas carrier (see Figure 6) emerged as part of the project, following a study by *STX France S.A.* Over recent years, the Saint-Nazaire shipyard (formerly *Chantiers de l'Atlantique*), currently *STX France S.A.*, has designed and built several LNG carriers for different shipowners, implementing innovative ideas such as the first diesel-electric dual-fuel LNG carrier. Continuing a long tradition of innovation, the French shipyard proposes once more a new design concept for liquefied natural gas carriers. The designers of the *STX France* shipyard propose a solution to reduce the need for ballasting in order to prevent biological invasions of marine organisms transported in ballast water and sediment transfer. Moreover, energy, and consequently money, will be saved by decreasing the huge amounts of sea water transported, almost unnecessarily.

As part of the IMPROVE project, *STX France* was meticulous about addressing a host of vessel attributes that add up to a state-of-the-art ship design for LNG transportation. These attributes include ensuring the large cargo carrying capacity within minimum dimensions, the observance of best practice in shipbuilding, high levels of safety, economic feasibility, low maintenance cost, high screw comfort, and security in terms of environmental protection.

The standard LNGC features, such as a complete double-hull, worldwide trade, speed of 19.5 knots or the accommodation quarters in the aft part, are maintained. The ship will also feature five membrane cargo tanks, with suitable cofferdams.

The innovative part is a change in the hull shape in combination with an adapted type of propulsion unit. The solution is

Figure 5 **The IMPROVE integration platform**
Slika 5 **Integracijska platforma projekta IMPROVE**



based on a V-shape hull and a pod-type propulsion technology to eliminate the need for ballast water in good seaway conditions. The special hull form allows a sufficient draft in most loading conditions with a reduced volume of ballast water.

A diesel-electric power station is proposed, using four-stroke, dual-fuel (running on boil-off gas or marine diesel oil) engines at 514 rev/min. At the start of the project, the concept was based on the dual fuel engines supplied by Wärtsilä, but when the study began, other dual fuel main engines options surfaced from *MAN Diesel*.

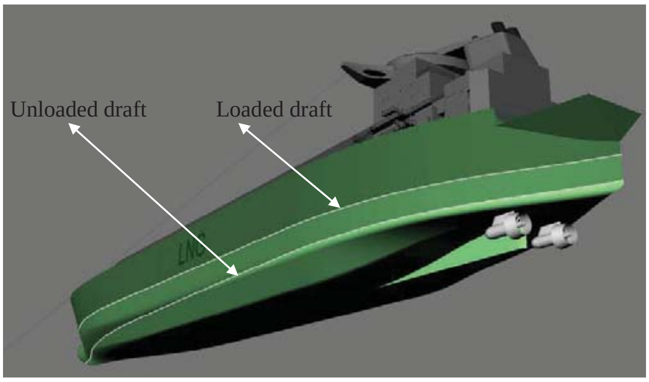


Figure 6 **New concept of a 'two-draft' ship, using minimal or no ballast in the unloaded condition**
Slika 6 **Novi koncept broda 's dva gaza' koji u stanju bez tereta plovi s minimalnim ili bez balasta**

6.1 Ballast difference

A conventional design for such a LNGC size requires more than 65 000 tons of ballast water. There are sea water ballast tanks (SWBTs) arranged in the double-hull tanks, forward and aft. In the STX design, in the unloaded condition, the ship will be able to sail with a minimum volume of sea water or even without it. The use of these SWBTs is in a strong contrast with the ballast tanks onboard of a conventional LNG carrier, where the vessel is either full of LNG with empty SWBTs ("loaded") or empty of LNG with full SWBTs ("unloaded").

With the new concept, the SWBTs will only be used for two particular situations:

- Situation 1: during the loading/unloading operations of LNG, to reach a draft for the vessel to be within the range of loading arms.
- Situation 2: if the vessel meets bad weather conditions during a voyage and the master wishes to achieve a safer sailing condition from his point of view.

In either of these particular situations, the ship will not have to renew or clean the sea water within the SWBTs when the ship is sailing. This can be envisaged as:

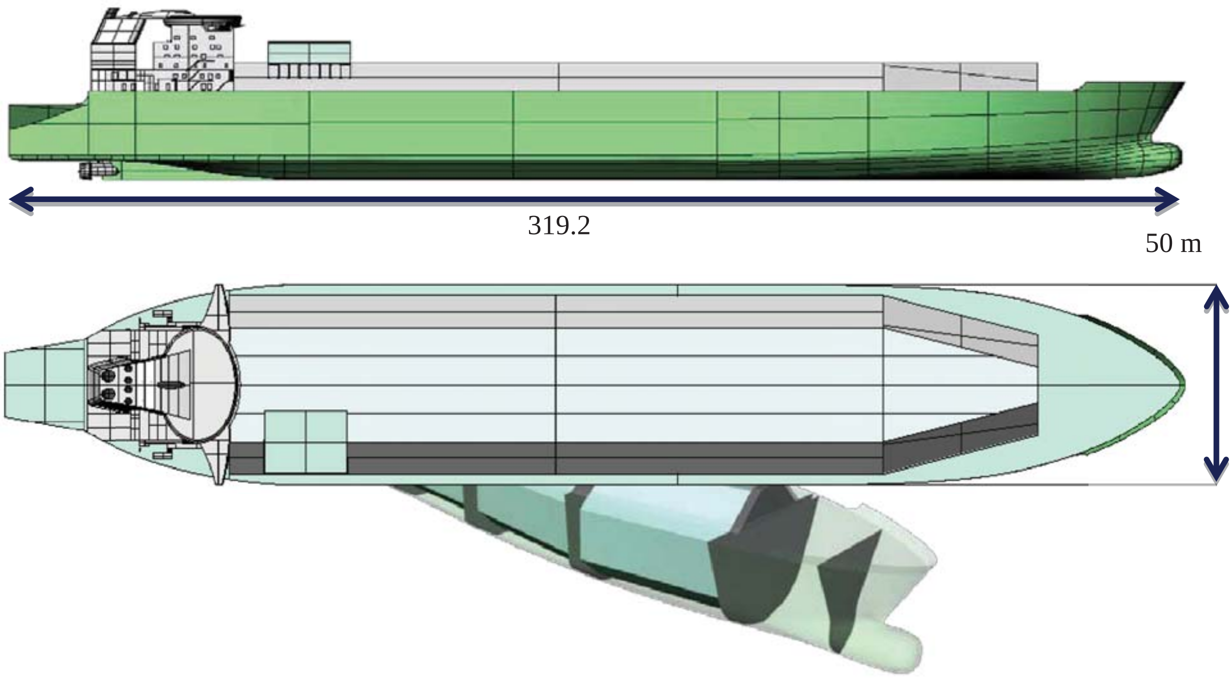
- Situation 1: used sea water is discharged before departure or in a zone close to the terminal at the beginning of sailing.
- Situation 2: the sea water used to reach a safer situation is considered as clean.

Thus, the International Maritime Organization (IMO) recommendation to treat the ballast water is either fulfilled or not needed.

6.2 Cargo containment

The proposed containment system is of the membrane type, with five (5) tanks based on Gas Transport and Technigaz (GTT) technology, see Figure 7. Sloshing problems will be avoided by following the GTT and classification society requirements. The

Figure 7 **The LNG with five cargo tanks, offering a capacity of 220 000 m^3**
Slika 7 **LNG brod s pet tankova, kapacitetom od 220 000 m^3**



insulation of the cargo tanks was designed to give a natural boil-off-rate (BOR) of about 0.135 % (per day) of the loaded cargo volume. Other containment solutions with independent tanks, such as Aluminum Double Barrier Tank (ADBT), are possible and adaptable to the ship design with further studies.

The hull form is designed with more than 80 % of developable surfaces, which minimizes the cost of production of the hull.

For a conventional LNGC, the exploitation conditions are 50 % of the time in the loaded condition and 50 % of the time in the unloaded condition. For the *STX France* design, the partition of the exploitation conditions are the same but, within the unloaded condition, 80% of the time only a minimum volume of sea water is required, or even no sea water, and the remaining 20% of the time in considered with full SWBT. In such conditions, around 8.6 tons of LNG used as fuel can be saved per day. This is equivalent to a 9 % saving when compared to a diesel electric dual fuel LNG carrier with about the same size and conventional features.

STX France is currently designing other LNGC sizes, such as a “medmax” LNGC, using the same principle.

6.3 Structural optimization (least weight, least cost)

In the framework of IMPROVE the scantling of the cargo tanks was optimized (including frame and stiffener spacing), considering sloshing assessment performed by BV.

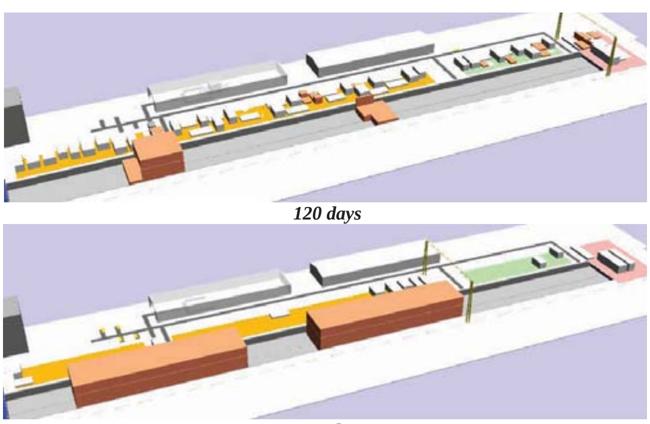
The least weight optimization (objective function being the minimization of the weight) reveals a potentials gain of the order of 15 % (including the cofferdams). Concerning the production cost (least cost optimization) the gain is around 5%.

6.4 Production simulation

Simulation of the assembling in the St Nazaire dry dock was performed to validate the scheduling. Figure 8 shows the status after 120 days and 420 days.

A significant reduction in lead time and cost can be expected after the scantling optimization of amidships section in the early design stage of the project. A gain of 3% for the budget, 29% for the lead time, 7% for labor cost has been highlighted here while the results show a reduction in the labor cost of 3.06%. More can be saved after the improvement in the organization by using a new block splitting strategy or by optimizing the surface allocation. A new block splitting using blocks with higher dimensions can generate some additional gains, especially for the lead time. These gains would be much bigger when outfitting is considered.

Figure 8 **Simulation model at different processing stages**
Slika 8 **Simulacijski model u različitim proizvodnim fazama**



6.5 Conclusions on the LNG ship

The analysis confirmed that performing a least-cost structural optimization with the above modules results in a multi-objective optimization, as the production cost and the weight are merged in the objective function. Based on these optimization tools, the design of a highly innovative LNG carrier was performed, making significant gains as compared to conventional LNG carrier designs. The process involved sloshing, crashworthiness fatigue and stress analyses. Within this framework one could conclude that tools and methods developed within the IMPROVE project as well as the IMPROVE LNG carrier design have great potential for stimulating European shipbuilding industry.

7 Large Ro-Pax ship (WP7)

An innovative Ro-Pax ship with capacity for 3000 lane meters of freight and 300 cars, together with 1600 passengers was designed (see Figure 2). The design was based on a successful existing design of a STANDARD SHIP used as a prototype. Then a NEW SHIP was designed during the first period of the project. This design was improved in terms of main particulars, general arrangement, hydrodynamic and propulsion performance. Then the IMPROVE SHIP was designed based on the NEW SHIP design, using multi-criteria structural optimization which includes production and maintenance models [18].

7.1 General ship design

The leading partner for the design of the IMPROVE Ro-Pax vessel is a highly experienced car-carrier, Con-Ro and Ro-Pax shipbuilding yard. Extensive multi-objective structural optimization of a Ro-Pax structure using OCTOPUS/MAESTRO software was performed, resulting in the development of a ship design with minimum initial cost, minimum weight, and high level of safety, while also satisfying structural constraints such as yielding, buckling, displacements, and ultimate strength of hull girder and ship panels. Meanwhile, large operational savings were achieved due to the adoption of a novel propulsion concept. A more detailed description of different propulsion variants with the evaluation of results is given in [18]. The main dimension criteria required a ship with a maximum length of slipway of 230 m, and a maximum breadth given as 30.40 m. These criteria were satisfied. In response to the feedback from owners, the new vessel was developed for Mediterranean Sea operations. The vessel was designed for load carrying flexibility and improved operational performance and efficiency as compared to the existing (STANDARD) ships, see [18]. The design also achieved: redundancy and simplicity of systems; improved maneuverability; optimized sea-keeping performance; maximized comfort and minimized vibrations, see [22]. Following the ship-owners’ feedback, the vessel was designed with an 8% increase in carrying capacity (lane meters) on the tank top by decreasing the length of the engine room. This involved the development of a new stern design. Within set requirements, the design considered large variations in seasonal trade (summer: 3000 passengers; winter: 100 passengers).

A mono-hull was selected that features a superstructure that may be constructed using steel or composites, but not aluminum.

Ultimate vessel dimensions were optimized to improve hydrodynamic performance, while a slow-speed main engine was selected to reduce maintenance costs and fuel consumption.

Other challenges which were successfully met were:

- Improvement in design using existing and improved tools for early design stage.
- Rule calculation and simplified CAD modeling leading to simplified FEM and LBR5 modeling.
- Accurate calculation of building tolerances and deformation constraints at the early design stage.
- Superstructure deck effectiveness in the longitudinal strength.
- No pillars in the cargo space area.
- Web frame spacing and longitudinal spacing optimization.
- Minimum weight of freeboard deck transverses.
- Minimum height of deck No.3 and deck No.4 transverses
- Minimum height of deck transverses.

Furthermore, the design was optimized in terms of life-cycle maintenance costs over a 25 year period. The design also takes into account the probability of a potential conversion after 10 years due to new rules or comfort standards (thus, the current ship design is flexible enough for easy conversion). Cargo handling is of the traditional type with a stern door and internal ramps. In terms of sea-keeping performance improvement, no fin stabilizers were fitted; instead, internal active tanks were used in this design. The design offers an estimated 10% reduction in production costs, a 12% reduction in fuel oil consumption and a 10% reduction in the expected maintenance costs. The production process was simplified via standardization, increase in subassembly activities and reduction in hull erection time on berth from 18 to 9 weeks (plus three weeks for completion). Production costs are further reduced by decreasing the number of erection blocks from 330 to 130 blocks, with all parts painted prior to the erection.

Regarding the general ship design, the following design characteristics are included:

- Selection of low resistance hull form for reduced fuel consumption, Figure 9.
- Smaller propulsion engine for the same speed.
- Design of hull form to reduce the length of engine room (increased length of cargo space).

The length of engine room was reduced (increased length of cargo space). Small Main propulsion engine was chosen which allowed a smaller engine room, i.e. more cargo space available. A comfort-friendly hull form and general arrangement were designed.

In terms of the propulsion system, two propulsion system options were the most suitable [18]:

Option 1:

- A slow speed main engine directly coupled to a fix pitch propeller.
- An active rudder/azipod with propulsion bulb to increase the main propeller efficiency.

Option 2:

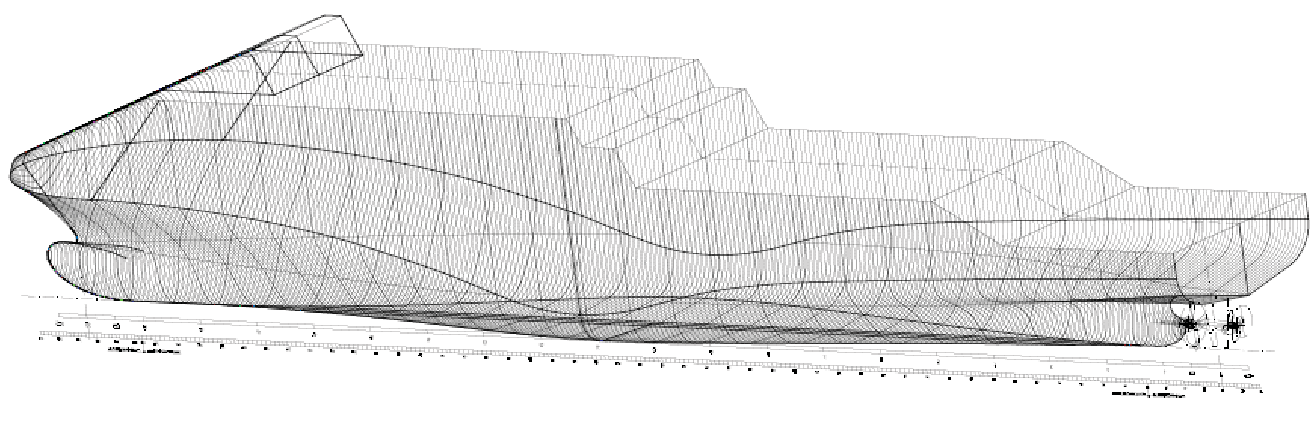
- Two medium speed main engines coupled via a gearbox to a CP-propeller.
- Two retractable side thrusters.

The aim was to minimize the need for running electrically-driven thrusters in seagoing condition, i.e. to use them only during maneuvering in harbor to eliminate the need for tugs. The owners' basic requirement was that the ship must never stop. The owners preferred the configuration with two main engines coupled via a gearbox to one CP-propeller (Option 2). This arrangement gives the ability to operate vessel with one main engine running and to carry out maintenance on the other main engine. Maneuvering analysis of the IMPROVE Ro-Pax vessel was also carried out, see [22]. Empirical methods were used to estimate the missing data required for the analysis. The aim of this study was to evaluate the maneuvering characteristics of the vessel. Simulations were carried out for the loading condition 4 defined in the Trim and Stability booklet. The types of simulated maneuvers were based on the guidelines provided in IMO Resolution MSC.137(76) Vessel; these included the following two critical maneuvers: 1) Turning circle and 2) Zig-zag test. The IMPROVE Ro-Pax vessel, under the designed layout/sizing of the steering system, was able to meet IMO requirements with very good margins.

7.2 Ship structural design and interaction with the general ship design

For the IMPROVE SHIP design, extensive structural analyses (global and detailed FE analyses) were performed to evaluate structural feasibility and to eliminate hot spots and stress concentration problems. A detailed description of novel structural

Figure 9 **Body Lines of the New Ro-Pax Ship**
Slika 9 **Linije novog (IMPROVE) Ro-Pax broda**



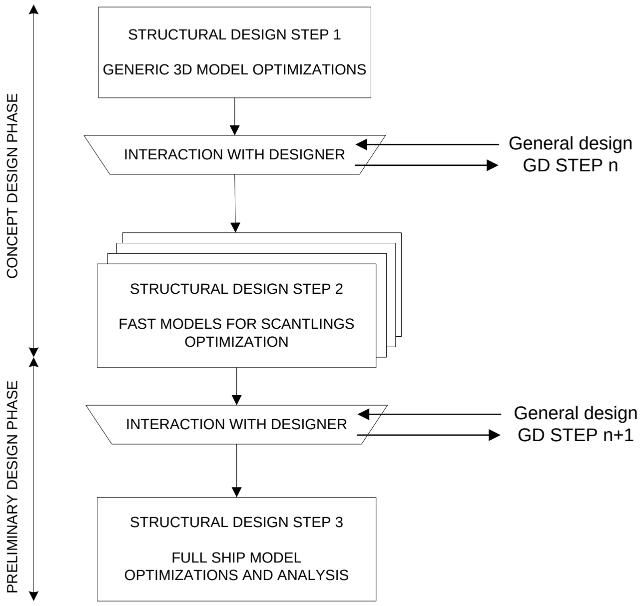


Figure 10 **Overall design procedures**
Slika 10 **Projektni postupak**

design methodology and the achieved results are given in [19]. The arrangement of cargo space without pillars required sophisticated structural solutions. Reducing the height of deck structure was a very demanding task. However, it was beneficial as the final design offers:

- Lower VCG (better stability).
- Reduced light ship weight (increased deadweight).
- Lower gross tonnage.

Advanced synthesis and analysis techniques, built in OCTOPUS/MAESTRO software, were used at the earliest stage of the design process with respect to structure, production, operational performance, and safety criteria. The challenge is to efficiently generate optimal design solutions for concept and preliminary design stages, using such demanding models.

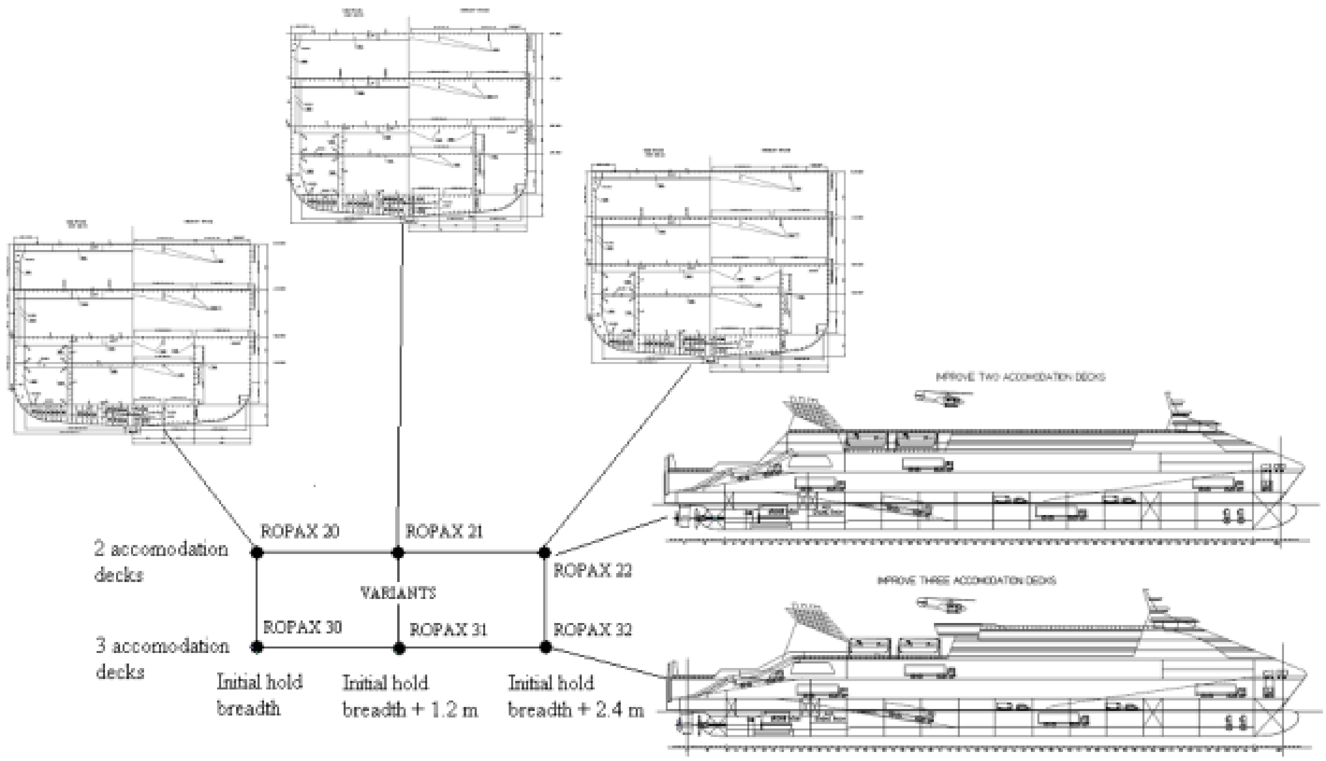
The methodology combines three design steps for rapid and rational concept exploration, see Figure 10. A more elaborated description is given in [19]. The general design process (GD STEP n), with its goals and constraints interacts with the structural subsystem decision making (SD STEPS 1-3).

A brief summary of the design procedure is given in the sequel.

Design step 1: Analysis of the generic tapered 3D FEM ship models based on gross-elements/surrogates, see [20], according to class Rules, should be performed. Optimization of different design concepts for given objectives (cost, weight, VCG, safety, etc.), with respect to the topological, geometrical and scantling variables, enables their fair comparison. In the context of general design, the designer's selection should be performed using the global design quality measures on the grid of optimized variants.

Design step 2: Control structures (bays) of different ship segments were modeled, using the computationally very fast 2.5D

Figure 11 **Ro-Pax ship - different structural arrangements**
Slika 11 **Različite topološke varijante Ro-Pax broda**



FEM models, see [21], in the generation of design alternatives on the Pareto frontier. In Ro-Pax case, they were further validated using the *IMPROVE* developed adequacy and quality measures (fatigue, robustness, LCC and production cost).

Design step 3: The full ship 3D FEM coarse mesh model was developed to validate and synthesize optimal design variants using safety, weight, cost, fatigue and vibration criteria. Direct wave load calculations were performed and applied for the generation of design loads.

Six different structural arrangements, i.e. accommodations with two or three tiers and three different midship sections with respect to longitudinal bulkhead positions, were analyzed as a multi-objective design problem, see Figure 11.

Structural optimization of different design concepts for given objectives (cost, mass, VCG, safety, etc.), with respect to the topological, geometrical and scantling variables, enables their fair comparison. In parallel with the structural part, *ULJANIK* performed general naval architecture calculations (probabilistic damage stability, power, resistance, cargo capacity, etc.) for each of three midship section variants. Also, probabilistic damage stability calculations were performed for each variant to achieve the minimal depth of freeboard deck (height of Deck 3) which satisfies damage stability criteria, see [18] and [19].

For preliminary design, the FEM macro-element model was further extended with the aft and fore structure, see Figure 12, and the final optimization was performed for three selected modules between Fr. 72 and Fr. 200.

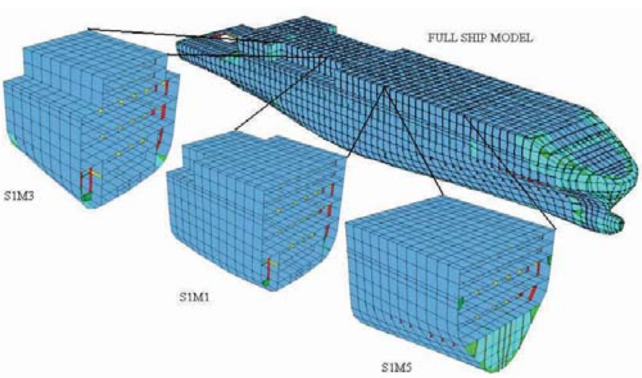


Figure 12 **Selected ship zones for structural optimization in the preliminary design stage**
Slika 12 **Zone broda uključene u strukturnu optimizaciju u preliminarnoj fazi projektiranja**

The application of the developed design procedure resulted in the optimal structural design of Ro-Pax with two superstructure decks, optimal parking area on lower decks, VCG position, etc., combined with the minimization of the ship lightweight and related savings in fuel and other operating costs. Overall savings, from a prototype to the proposed (standardized) design are significant: 18% in weight, 19% in cost and 4475 mm in ship height. This proves that the cascade of optimization steps in the novel design procedure produced very satisfactory results. Because of this, the required propulsion power and fuel oil consumption were further decreased by 5 % (19 560 kW instead of 20 500 kW). A gain of 5% in trailer lanes (cargo capacity) on the tank top was achieved by investigating different positions of the longitudinal ballast tank bulkhead and by minimizing the ballast volume at the same time, see [18] and [19].

7.3 Conclusions on the Ro-Pax ship

Challenging goals for the Ro-Pax application case, as defined at the beginning of the IMPROVE project, were fully achieved during this project. The shipowner's profit was significantly increased due to a reduction in fuel consumption (better propulsion and ship hull form, reduced weight, etc.), and an increase in payload (increased parking area). It is also very important to acknowledge that the reduction in fuel consumption significantly reduced CO_2 emissions, thus increasing the environmental friendliness and also ensuring that legal requirements related to the pollution can be satisfied more easily in the future. One of the major driving forces of these achievements is a novel design methodology that has closely joined two collaborating design systems (general ship design and structural design) as well as basic stakeholders (Owner, Yard, Designers, Regulatory institutions) through the formulation of Decision Support Problem for rational decision making. The developed methodology gives EU yards and owners a possibility to select competitive design solutions by following the basic IMPROVE paradigm: a better ship for the yard production and a more profitable ship for the owner regarding maintenance and operational aspects within life-cycle costs.

8 Chemical tanker (WP8)

The third product developed under the IMPROVE project is a chemical tanker suitable for carrying chemical cargoes of lMO type I/II/III, petroleum products, vegetable, animal and fish oils, and molasses. A new generation design of a 40 000 DWT chemical tanker (Figures 13 and 14) resulted from the IMPROVE project. Advanced synthesis and analysis techniques at the earliest stage of the design process were used, concurrently considering the structure, production, operational performance, and safety criteria.

The design procedure was carried out in three stages:

1. The first stage was attributed to the identification of stakeholders' requirements and the definition of key performance indicators. The project partners (particularly the shipyards) designed reference or prototype ships. As part of this stage, it was realized that operators require ships with the longest possible lifetime and that this can be achieved by improving the quality and performance. The main design objectives were a reduction in manufacturing costs and production lead-time as well as a reduction in structural maintenance costs for shipowners. Several calculations were performed to test existing tools and identify potential gains at the conceptual stage of design.
2. The second stage was concerned with the development of new modules to be integrated in the optimization tools in order to satisfy the requirements defined in the first stage. All technical developments were based on selected structural optimization tools. Several modules, such as fatigue assessment, ultimate strength, load assessment, and production and maintenance cost reduction, were generated and integrated into existing tools, e.g. LBR5, OCTOPUS, CONSTRUCT, etc.
3. The final stage was the application of the new optimization tools for the final chemical carrier design. In brief, IMPROVE

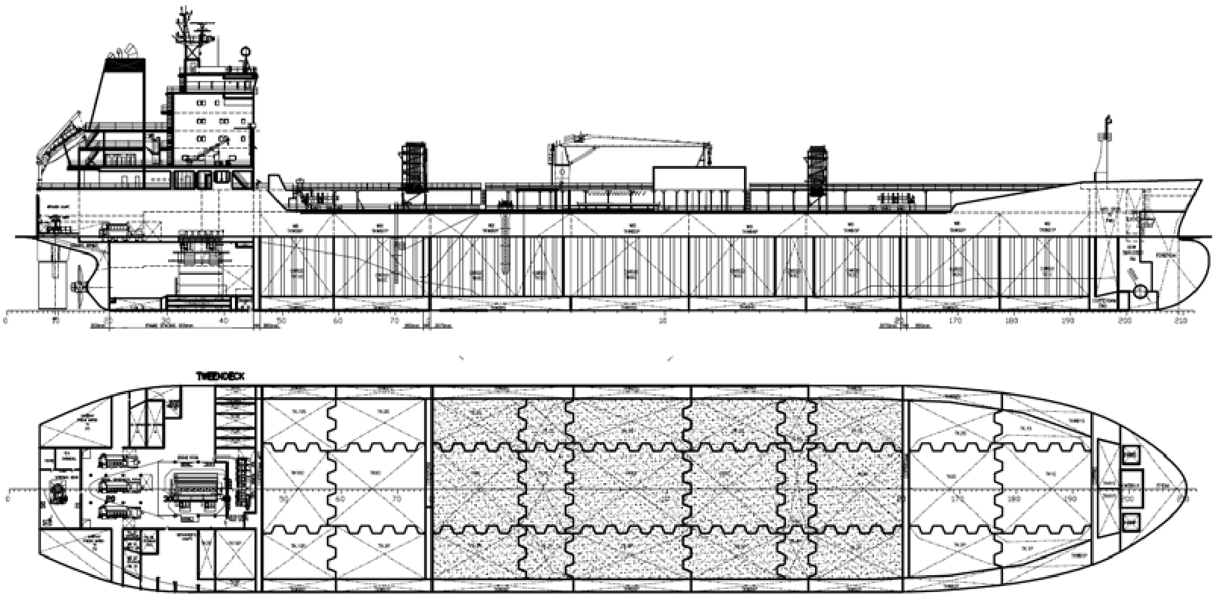


Figure 13 **A 40 000 DWT chemical tanker designed by *SSN***
Slika 13 **40 000 DWT tanker za kemikalije - projekt *SSN***

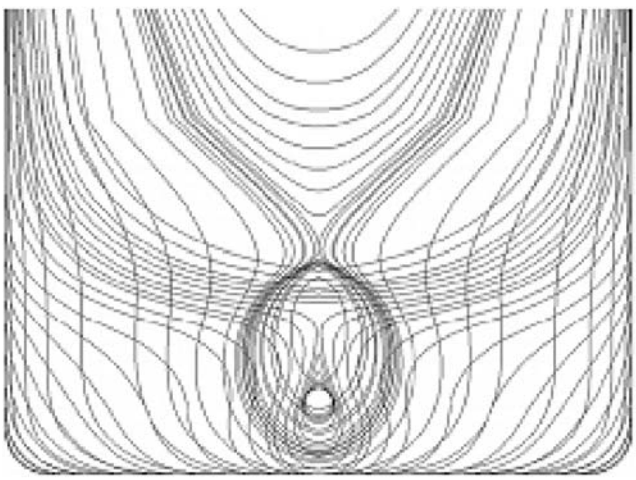


Figure 14 **Body plan of the chemical tanker**
Slika 14 **Nacrt rebara tankera za kemikalije**

delivered an integrated decision support system for a methodological assessment of ship designs. This system provided a rational basis for making decisions regarding the design, production and operation of a highly innovative chemical carrier. This support system can be used to make careful decisions that can contribute to reducing the life-cycle costs and improving the performance of a ship. Based on this system, all the aspects related to the general arrangement, propulsion, hull shape and dimensioning of the structure were investigated.

The relation between structural variables and relevant cost/earning elements was explored in detail. The developed model is restricted to the relevant life-cycle cost and earning elements, namely production costs, periodic maintenance costs, fuel oil costs, operational earnings and dismantling earnings. The maintenance/repair data were collected from three ship operators and were used for the purposes of a regression analysis. The design is based on a multi-objective optimization of the structure using the guided search versus the conventional concurrent optimization. The results of the adopted approach were compared with the conventional concurrent optimization of all objectives utilizing the NSGA-II genetic algorithm. The results showed that the guided search brings benefits particularly with respect to structural weight, which is normally a very challenging parameter to optimize successfully.

The IMPROVE partner shipyard based the design on a reference design, the B588-III chemical carrier, aiming mainly at achieving lower building costs. The following alternatives to the reference design were considered:

<u>Alternative 1</u>

- Main dimensions as in the B588-III original design.
- Wing cargo tanks made of mild steel instead of Duplex steel.
- Reduced number of centre cargo tanks from eighteen to twelve.
- Reduction in service speed to 15.0 kn.
- A shaft generator is not included.

<u>Alternative 2</u>

- Reduction in cargo tanks capacity to about 45 000 m^3.
- Removal of cofferdam bulkheads and replacing them by vertically corrugated bulkheads.
- Reduction in the depth of the vessel to 15.0 m.
- Use of Duplex steel for centre tanks only.
- Removal of six deck tanks.
- Reduction of service speed to 15.0 kn.
- A shaft generator is not included.

<u>Alternative 3</u>

- Same as Alternative 2 except for the arrangement of Duplex tanks which are arranged in the middle part of the vessel / wing and centre tanks.

The calculation of building costs done based on 2007 market data showed that the most effective cost reduction was achieved by adopting Alternative 3. Thus, the partners decided to develop that design and optimize it by using IMPROVE tools. The propulsion system consists of a low speed, two-stroke diesel ME (type 6S50 - ME -B9) which directly drives a FP propeller at a service speed of 15.0 knots.

The sea-keeping analyses, based on the chosen design, indicated that in general, the vessel is expected to exhibit good sea-keeping characteristics since most of the worst response modal periods are either far from the dominant wave periods or wave headings may be adjusted to avoid severe responses. Analyses also showed that the IMPROVE chemical tanker satisfies the stability requirements of applicable rules and regulations.

According to the preliminary opinions/requirements of the shipyards and shipowners, the cost, weight and fatigue life were included as objectives into structural optimization. The knowledge of the relationship between these different objectives was required to obtain a reliable techno-economic evaluation of tanker structures, see Figure 15.

A thorough fatigue analysis was implemented. The hull optimization resulted in a significant production cost reduction. Life-cycle costs were also assessed. The CONSTRUCT optimization results indicate that the relation between the fatigue life and cost are almost linear. For a design alternative with a 30 year fatigue life, the ultimate strength is also clearly increased compared to the minimum weight design, but the cost and weight are also increased in this case, from 10% to 15%.

For the optimization of cargo tank arrangement, an important target was to reduce the quantity of duplex steel to minimize cost. For the final design, the total optimum number of duplex stainless steel tanks is eighteen, having different capacities. Duplex stainless steel cargo tanks are separated from the mild steel cargo tanks by cofferdams. Moreover, longitudinal bulkheads are vertically corrugated and transverse bulkheads may be vertically or horizontally corrugated. Interfaces between the longitudinal vertically corrugated bulkheads and the transverse horizontally corrugated bulkheads were subjected to FEM analyses. Calculations of the capacity of cargo tanks and the arrangement for three different specific gravities of acid, i.e. 1.50, 1.65, and 1.85 t/m^3, were performed.

To validate the obtained Pareto optimum result, a detailed finite element analysis is carried out. The finite element model includes the tanker structure with a length of 73.4 m. The structure is loaded with external water pressure, cargo pressure and boundary moments. In total, six loading cases are analyzed. Also, accelerations are included where necessary by including them into gravity constants and calculating the equivalent pressure based on gravity. The model with the loading set up is shown in Figure 16.

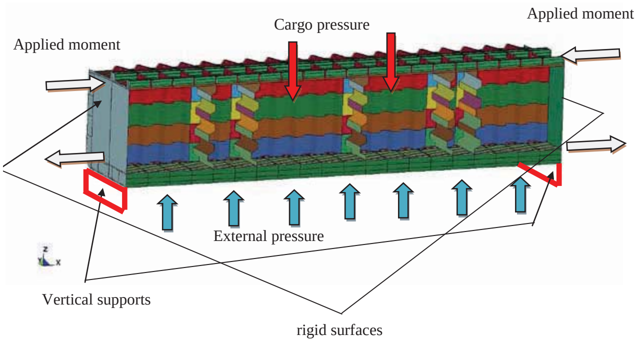


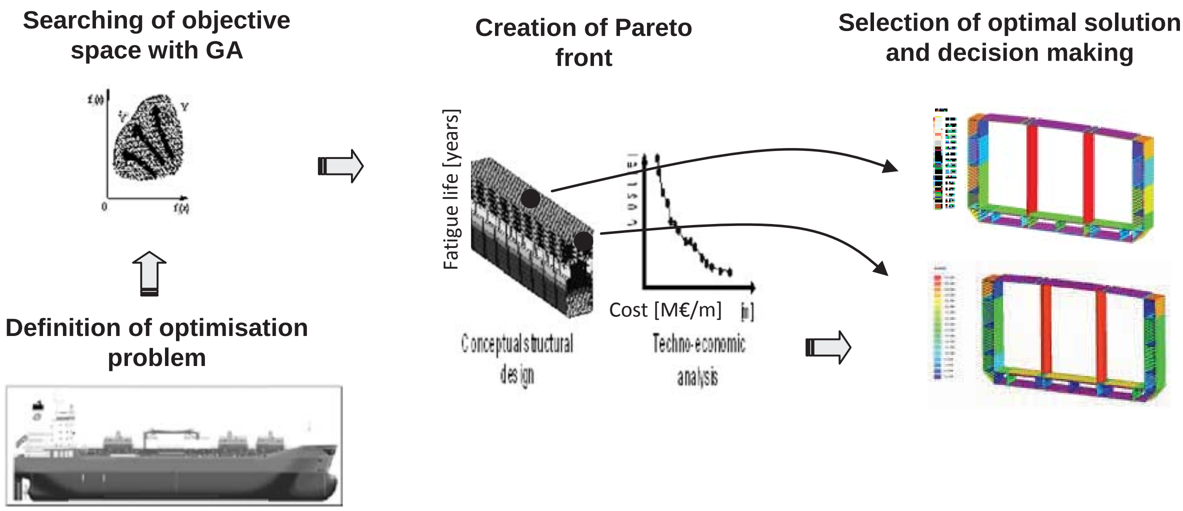
Figure 16 **A 3D FE model of the chemical tanker**
Slika 16 **3D MKE model tankera za kemikalije**

8.1 Conclusions on the chemical tanker

As a result of the structural optimization and decision making process, the following can be concluded:

- If fatigue improvement is not important, then the light weight design is good, as expected.
- If fatigue is to be improved, and the owner is willing to pay 100k€ or 1M€ per year of increase, then a design alternative was found, with improvements of 6.7 years in fatigue life. Higher investments would prove to be too high for the owner.
- In both cases, when there is a desire to increase the fatigue life, it seems that the quality of the engineered design alternatives is not as good as with the present design, meaning that

Figure 15 **Techno-economic evaluation of tanker structure using optimization and decision making**
Slika 15 **Tehničko-ekonomska evaluacija strukture tankera koristeći optimizaciju i tehnike odlučivanja**



the stakeholders may have considerable reservations about accepting the proposed solution.

9 Conclusions

The paper describes a new concept of integrated decision support system for a methodological assessment of ship design. To show its applicability to the real examples, three innovative ship designs were developed by multidisciplinary teams of researchers (shipyard, shipowner, designer, classification society, and university, see Annex) and the main outcomes were given. The presented research was carried out within the EU FP6 project IMPROVE. The main outcomes, on the product level, are:

- The design by *STX France* of a new concept of LNG carriers with reduced ballast, that provides a significant benefit for the shipowners. In addition, a weight saving of 10-15% was identified and a reduction in production cost of 5% was also reached.
- The design by *ULJANIK Shipyard* of an improved Ro-Pax, with a large reduction in fuel consumption (12%) due to a new Ro-Pax propulsion concept. The structural optimization also showed a significant reduction in weight (18%) for the improved safety with regards to the BV classification society requirements.
- The design by *SSN* of a new general arrangement of a chemical tanker, including reduced weight of duplex steel, intensive use of corrugated bulkheads and the improved safety with regards to the classification society requirements.

The final goal is to increase EU shipyard competitiveness through the improved product quality and performance based on cost-effective and environmentally friendly production systems on a life-cycle basis, using the presented concept of design development.

More detailed information (with a detailed conclusion and a quantitative assessment of the benefits) was presented at the final IMPROVE workshop, see [22].

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Annex 1

IMPROVE

DESIGN OF IMPROVED AND COMPETITIVE PRODUCTS USING AN INTEGRATED DECISION SUPPORT SYSTEM FOR SHIP PRODUCTION AND OPERATION

The IMPROVE project proposes to deliver an integrated decision support system for a methodological assessment of ship designs to provide a rational basis for making decisions pertaining to the design, production and operation of three new ship generations. Such support can be used to make more informed decisions, which in turn will contribute to reducing the life-cycle costs and improving the performance of those ship generations.

IMPROVE Project

IMPROVE is a three-year research project which started on the 1st October 2006. The project is supported by the European Commission under the Growth Programme of the 6th Framework Programme.

Contract No. FP6 - 031382.

Project Partners:

ANAST, University of Liege	Belgium (project coordinator)
STX-France shipyard	France
Uljanik shipyard	Croatia
Szczecin New Shipyard	Poland
Grimaldi	Italy
Exmar	Belgium
Tankerska Plovidba Zadar	Croatia
Bureau Veritas	France
Design Naval & Transport	Belgium
Ship Design Group	Romania
MEC	Estonia
Helsinki University of Technology	Finland
University of Zagreb	Croatia
NAME, Universities of Glasgow & Strathclyde	United Kingdom
Centre of Maritime Technologies	Germany
BALance Technology Consulting GmbH	Germany
WEGEMT	United Kingdom

Further Information

More information about the IMPROVE project can be found at the project website

http://www.improve-project.eu/ or http://www.anast-eu.ulg.ac.be/

Alternatively you can contact the project co-ordinator:

Prof. Philippe Rigo
at ph.rigo@ulg.ac.be (+32-4-366 9366), ANAST, University of Liege, Belgium

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KRALJEVICA SHIPYARD

SHIPBUILDING SINCE 1729

The **KRALJEVICA** Shipyard, shipbuilding and shiprepairing company, is the oldest shipyard on the eastern coast of the Adriatic Sea.
The continuity of shipbuilding in **KRALJEVICA** has been lasting uninterrupted since 1729, when the Shipyard has been established by the Austrian Emperor Karl VI.

The **KRALJEVICA** Shipyard ranks, in view of its capacities, among medium-sized shipyards (500 employees, area of 110,000 m^2).

The **KRALJEVICA** Shipyard's activities are divided in three main groups: newbuildings (asphalt tankers, multipurpose vessels, container vessels, dry cargo vessels, paper carriers, RO-RO vessels, car ferries, offshore supply vessels, tugs, yachts, fishing vessels, small aluminum crafts, etc.), navy vessels (patrol vessels, corvettes, coast guard vessels, etc.), shiprepairing/retrofitting (merchant and navy vessels).

As from the end of Second World War, the Shipyard built more than 180 vessels of which 80 navy vessels and more than 100 merchant vessels on two open slipways of up to 10,000 tdw (125 x 21 m) and one sheltered slipway in hall (for vessels up to 60 x 11 m).

Shiprepairing and marine service-conversions for vessels up to 25,000 tdw in two floating docks of 450 tons and 6,500 tons lifting capacity (for vessels of maximum 155 x 21 m), and on shiprepairing quay of 575 meters in length.

The Shipyard have awarded for his quality two prestigious prizes:

- in Year 1989 for RO-RO/Container/paper carrier of 3,400 tdw
  as one of **the Most Outstanding Ship of the Year**
  (by US magazine "Maritime Reporter & Engineering News")
- in Year 2005 for Asphalt carrier of 9,200 tdw
  as one of **the Significant Ship of the Year**
  (by UK magazine "The Naval Architect")

BRODOGRADILIŠTE SHIPYARD KRALJEVICA 1729

KRALJEVICA Shipyard
Obala Kralja Tomislava 8, P.O.Box 35,
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+385 21 / 883 201 (Sales Department)
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e-mail: sales@brodotrogir.hr

SHIPREPAIR DIVISION
Put brodograditelja 16
21220 TROGIR - CROATIA
Phone: +385 21 / 883 303
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