IMPROVE - Design of Improved and Competitive Products using an Integrated Decision Support System for Ship Production and Operation

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Abstract

The paper gives an overview over the EC project IMPROVE. The project develops a 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 next-generation ship types (LNG, RoPax, chemical tanker).The system is expected to reduce life-cycle costs and improve ship performance.

1. Introduction

IMPROVE, http://www.improve-project.eu, is a three-year research project supported by the European Commission under the Growth Programme of the 6th Framework Programme. The project started in October 2006. The main goal of IMPROVE is to develop three innovative products:

1. LNG Carrier, Fig.1 - AKERYARDS has designed and built 17 LNG carriers (from 50 000 m^3, 75 000, 130 000 m^3 to latest 154 500 m^3). In the framework of IMPROVE, they are studying the design of a 220 000 m^3 unit.
2. Large RoPax ship, Fig.2 - ULJANIK Shipyard (Croatia) in the last 5 years has designed several car-carriers, ConRo and RoPax vessels. For a long period. ULJANIK has a strong cooperation with the GRIMALDI GROUP as respectable ship owner regarding market needs and trends.
3. Chemical tanker, Fig.3 - SZCZECIN shipyard (SSN, Poland) has recently built several chemical tankers (40000 DWT)

As the proposed methodology is based on multi-criteria structural optimization, the consortium contains not only designers, but also shipyards and ship-owners / operators (one per product). The research activity has been divided in three main phases:

1. Definition of stakeholders' requirements and specification of optimization targets and key performance indicators, Table I. In addition, project partners (particularly the shipyards) designed reference or prototype ships, one per each ship type, in a "first design loop".
2. All technical developments related to the selected structural optimization tool. Several modules such as fatigue assessment, vibration level investigation, ultimate strength, load assessment, production and maintenance cost, optimization robustness will be delivered and integrated into the existing tools (LBR5, OCTOPUS, and CONSTRUCT).
3. Application of the developed optimization platforms for the three target products.

This paper focuses on the first two phases, and gives details and some guidelines related to the selection of design criteria and to the development of different modules. The applications are described in detail for the LNG Carrier in *Toderan et al. (2008),* the RoPax ship in *Dundara et al. (2008),* and the chemical tanker in *Klanac et al. (2008b).*

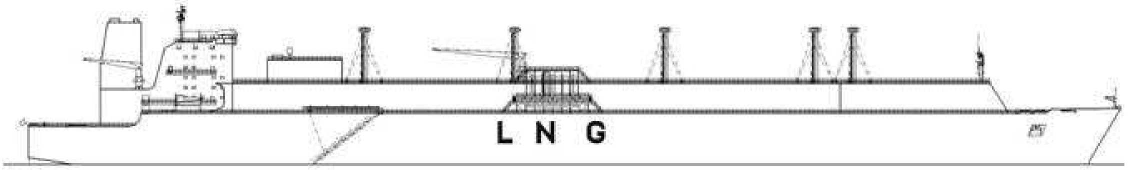


Fig.1: 220 000 m^3 LNG carrier studied by AKERYARDS (France)

Fig.2: RoPax vessel designed by ULJANIK Shipyard (Croatia)

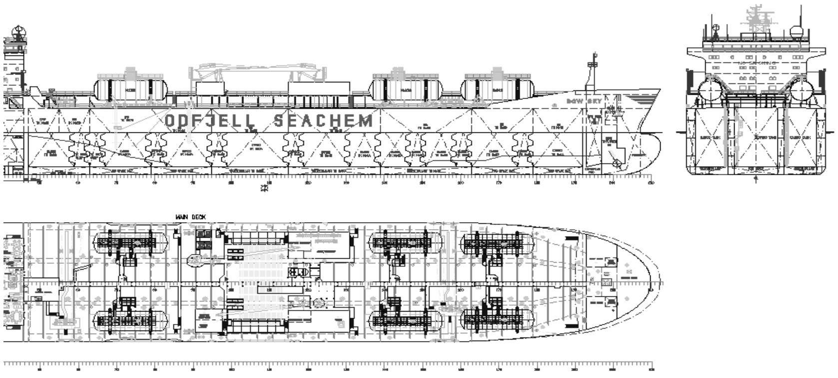


Fig.3: 40 000 DWT chemical tanker (SSN, Poland)

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. The objective is to increase shipyard competitiveness through improved product quality and performance based on cost effective and environmentally friendly production systems on a life-cycle basis. Target is to increase the shipyard competitiveness. 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 next 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, IMPROVE consortium identified next-generation prototypes of a large RoPax ship, a product/chemical carrier and an LNG carrier as the most suitable vessels to study (Annex 1).

The operators buying these ships generally operate them for the most of the ships' life, making maintenance characteristics of the design very important. Therefore, IMPROVE aims to design for lower operation costs. Designing ship structure in such a way as to reduce problems such as fatigue can help in this cause. Additionally, designing for minimal operational costs helps to increase structural reliability and reduction of failures thus increasing safety.

The full life-cycle design approach is the key issue in future design of ship structures. So IMPROVE initiators propose the coupling of existing decision-support problem (DSP) environments (multi-attribute and multi-stakeholder concurrent design problem) with life-cycle analysis, while deploying modern advanced assessment and design approaches. Ship-owners want to minimize short term investments but above all maximize their long term benefits. Currently however, design of ships considers the life-cycle costs with limitations, thus opening doors for significant improvements with respect to ship's economics and her competitiveness. Formal integration of the life-cycle cost in the design procedure and creating a long-term competitive ship could be used as a valid selling argument.

An integrated decision support system (DSS) for the design of ship structures can assist designer in challenging this task. This novel design approach considers the usual technical requirements, but also producibility, production cost, risk, performance, customer requirements, operation costs, environmental concerns, maintenance and the life-cycle issues. IMPROVE adopts and further develops this new design environment. The purpose is not to replace the designer but to provide experienced designers with better insight into the design problem using advanced techniques and tools, which give quantitative and qualitative assessment on how the current design satisfies all stakeholders and their goals and requirements.

The IMPROVE project focuses on the concept/preliminary design stage, since the main functionally and technologically driven parameters are defined in the concept design stage.

2.2. Scientific and technological objectives of the project

In order to improve or regain their competitiveness, the European shipbuilding industry and ship-owners/operators need development of next-generation of ships/vessels (products) for the most basic transport needs:

- multimodal transport of goods (advanced generic RoPax),
- transport of energents (gas, oil)/chemicals (advanced generic gas and chemical tankers).

This should be achieved through the application of:

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

and immediately used in the practice for ship design, production and operation.

The members of the IMPROVE have been surprised by the constant quest for revolutionary products, while the wisdom of quality product improvement based on the mature design procedures has not been properly harvested. For example, by using advanced optimization techniques, significant improvements in the design and production are feasible.

Such practical (non-academic, non-exotic) and profitable improvements require the synergetic cooperation of the basic stakeholders in the product design (i.e. designers, shipyards, ship-owners and ship-operators, Classification society, and research teams) to :

- improve design problem definition and solution,
- improve production streamlining (controlled from advanced design problem solution),
- improve operation/maintenance costs (controlled from advanced design problem solution),
- achieve competitive products.

Such improvements will be proved to the profession via three practical designs obtained by:

- Early definition of attributes and measures of design quality:
  - robustness, safety and comfort of product and its service,
  - operational/maintenance costs and energy consumption,
  - integration of advanced, low-mass material structures, e.g. steel sandwich structures, in the vessel design.

- Generation of sets of efficient competitive designs and displaying them 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), which are exemplary shown in Table 1. It is expected that the generated design alternatives 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 design obtained using classical methods,
  - <u>Decrease of steel cost</u> of at least 8% (and more for novel designs) compared to the design obtained using classical methods,
  - <u>Decrease of production cost</u> corresponding to standard production of more than 8-10% and even more for novel designs,
  - <u>Increase in safety measures</u> due to rational distribution of material and a priori avoidance of the design solutions prone to multimodal failure,
  - <u>Reduced fuel consumption,</u>
  - <u>Improved operational performance and efficiency</u>, including a benefit on maintenance costs for structure (painting, corrosion, plate/stiffener replacement induced by fatigue, etc.) and machinery.

2.3. Long-term goals

The long-term goal of the project is to improve design methodology by concentrating effort on advanced synthesis skills rather than improving multiple complex analyses. The structural design must integrate various technical and non-technical activities, namely structure, performance, operational aspects, production, and safety. Otherwise, it is highly possible to define a ship design which is difficult to produce, requires high amounts of material or labor, contains some design flaws, or may be not cost-effective in maintenance and operation. Additionally, ships should be robust, with high performance in cost and customer requirements criteria.

2.4. Methodology

IMPROVE uses existing design platforms and analytical tools, which allow partners to use simulation and visualization techniques to assess ship performance across its lifecycle. IMPROVE implements in these platforms an advanced decision support system (including optimization capabilities) 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) are used in IMPROVE:

The LBR5 software is an integrated package to perform cost, weight and inertia optimization of stiffened ship structures, *Rigo (2001, 2003), Rigo and Toderan (2003)*, allowing:

- a 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 an analysis of the structure based on the general solid-mechanics;
- an optimization of the scantlings (profile sizes, dimensions and spacing);
- a 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 the LBR5 models.

Only basic characteristics such as L, B, T, C_B, the global structure layout, and applied loads are the mandatory required data. It is not necessary to provide a feasible initial scantling. Typical CPU time is 1 hour using a standard desktop computer.

MAESTRO software combines rapid ship-oriented ship structural modelling, large scale global and fine mesh finite element analysis, structural failure evaluation, and structural optimization in an integrated yet modular software package. Basic function also include natural frequency analysis, both dry mode and wet mode. *MAESTRO*'s core capabilities 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 under an ease-of-use of a Windows-based graphical user interface for generating models and visualizing results.

Octopus is a concept design tool developed within MAESTRO environment, *Zanic et al. (2002, 2004).* Concept design methodology for monotonous, tapered thin-walled structures (wing/fuselage/ship) is including 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 design of large passenger ship 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 import of structural topology from NAPA Steel or the topology can be generated within CONSTRUCT.

CONSTRUCT applies the method of Coupled Beams, *Naar et al. (2005)*, to rapidly evaluate the structural response, fundamental failure criteria, Mantere (2007), i.e. yielding, buckling, tripping, etc. as suggested by *DNV (2005),* and omni-optimization procedure for generation of competitive design alternatives, *Klanac and Jelovica (2007b).* CONSTRUCT at the moment can apply two algorithms to solve the optimization problem: VOP, *Klanac and Jelovica (2007a,2008)*, and NSGA-II, *Deb et al.* (2002).

The philosophy behind CONSTRUCT is outmost flexibility. Therefore, it can concurrently tackle large number of criteria, either considering them as objectives or constraints, depending on the current user interests. Design variables are handled as discrete values based on the specified databases, e.g. table of bulb profiles, stock list of available plates, etc. Also, new computational modules can be easily included, e.g. to calculate crashworthiness of ships.

4. Contribution to enhancing the state-of-the-art in ship structure optimization

4.1. Enhancement of the rational ship structure synthesis methods and DSP approaches

IMPROVE shall not develop new mathematical optimization methods. IMPROVE focuses on the DSP based approach to the design of ship structures and not on search algorithms. IMPROVE aims for more efficient use of the available optimization packages and their integration in the design procedure. IMPROVE focuses on the methodology/procedure that a designer and shipyard should follow to improve efficiency in designing, scheduling and production of ships. IMPROVE introduces certain optimization techniques that can individually improve the overall design procedure. This methodology should be used to improve the link between design, scheduling and production, with close link to the global cost. We feel that it is only through such integration that specific optimization tools can be proposed to shipyards to improve their global competitiveness.

4.2. Enhancement of particular multidisciplinary links in the synthesis models

The proposed DSP-based approach has as objectives to enhance:

- 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” and therefore drive the design to a least-cost design (or a least weight if preferred)
- Link of “production” with “simulation” and therefore drive the design to a higher labor efficiency and a better use of man-power and production facilities

4.3. Enhancement of confidence in the state-of-art synthesis techniques via the development of three innovative ship products

Enhancement of present state-of-art products/procedures using new improved synthesis models includes:

- Demonstrate the feasibility on an increase of the shipyard competitiveness by introducing multi-disciplinary optimization tools
- Demonstrate acceleration of the design procedure
- Propose new alternatives to designs. Scantling, shape and topology optimizations can lead to new solutions that may or may not fit with standards and Class Rules. Such revised designs have to be considered by the designers as opportunities to “reconsider the problem, its standards and habitudes”, to think about the feasibility of alternative solutions, etc. At the end, the designer has still to decide, based on his experience, if there is a new way to explore (or not).
- Test newly developed design approach on three applications (RoPax, LNG carrier, chemical tanker) by associating a shipyard, a classification society, a ship owner and a university.
- IMPROVE focuses on the enhanced modeling of advanced structural problems in the early-design optimization tools (e.g. crashworthy hull structure, ultimate strength, fatigue limit state in structures).

5. Research works 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 Fig. 4.

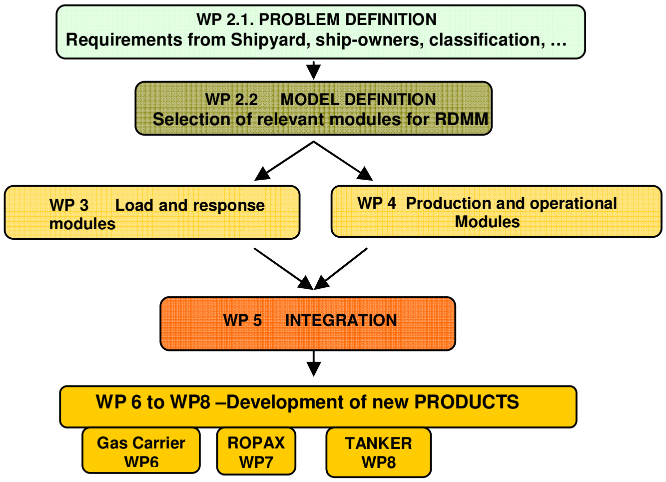


Fig. 4 : The IMPROVE flowchart

5.1 Problem & Model Definition (WP2)

In WP2, the consortium defines the structure of the integrated framework for design of ship structures to increase the functional performance and to improve manufacturing of those designs. The core of this work package is identification of rational decision making methods that would be assessed, evaluated and selected to be applicable for the use in the design of ship structures within shipyard environment.

Specific objectives of this work package are:

- Definition of the multi-stakeholder framework in design of ship structures,
- Definition of particular interests of stakeholder for the 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 design,
- Synthesis of needed actions into a framework.

One of the major results is given in Table I (part 1 to part 4). This table presents the extensive list of design objectives and design variables selected for the concerned ships. Quality measures, key performance indicators and potential selected tools are also listed. Some design objectives, such as comfort or seakeeping are not directly in line with the project (structure oriented) but have been listed to get a full picture of the shipyard and shipowner requirements.

5.2 Load & Response Modules (WP3)

In WP3 the load and response calculation modules are identified. They were selected to fit the design problems and design methods identified in WP2. Among the 11 load and response modules identified in WP3, there are:

- Response calculations for large complex structural models (LBR5, OCTOPUS/MAESTRO, CONSTRUCT),
- Very fast execution of numerous safety criteria checks, including ultimate strength, based on library of various modes of failure under combined loads.
- Accommodation for safety criteria defined in the deterministic and reliability formats.

– Module accommodation for calculation of structural redundancy, vibration and stress concentration for fatigue assessment.

5.3 Production & operational modules (WP4)

The overall objective of WP4 is to assess the life cycle impacts on the ship using various design alternatives (block splitting, scantling effects, etc.), applying simple and advanced existing tools, *Rigo (2001), Caprace et al. (2006)*. Existing generic toolkits were selected, tested and adjusted from the point of view of ship owners and shipyards. The WP tasks contain the following activities:

- Implementation of a production simulation to assess the impact of different design alternatives on the fabrication
- Implementation of a production cost assessment module to calculate of workforces needed for each sub assemblies used inside the production simulation
- Implementation of a operation and life-cycle cost estimator

All these tools are integrated into the global decision tool of IMPROVE, Fig.5.

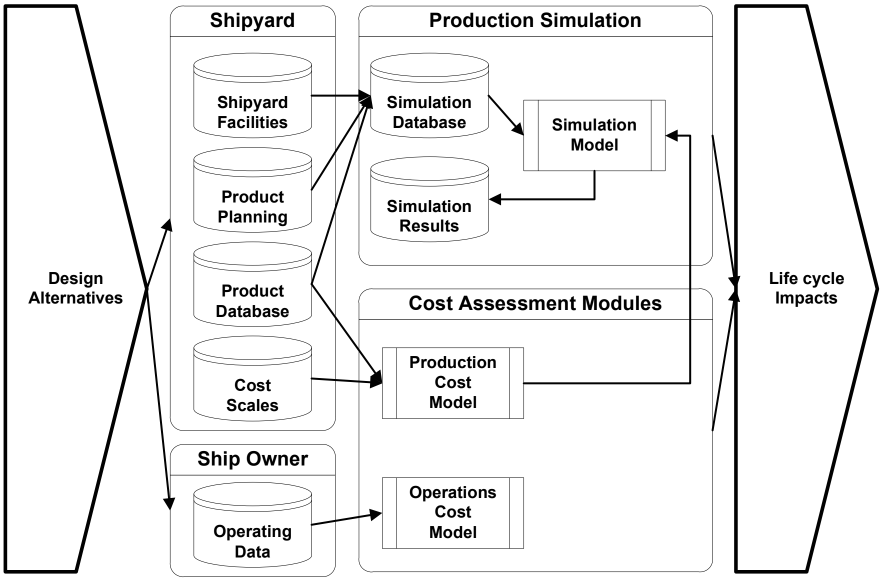


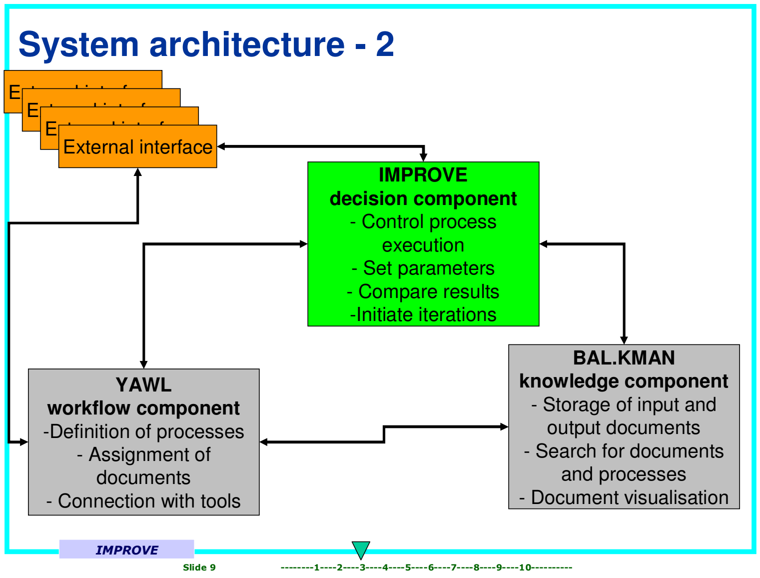
Fig.5: Software systems and interfaces used for production simulation

5.4 Modules Integration (WP5)

WP5 is the integration WP of the modules developed in previous WPs (WP2-WP4). Fig. 6 presents the Integration Platform that is currently considered. Main features are:

- A design desktop as central component and 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 organized based on workflow definition.

As MARS-BV is used by most of the partners, it is decided that MARS database will be the reference data concerning the geometry and loads. This means that all the modules (fatigue, vibration, cost, …) will consider the MARS data as basic data, Fig.7. Of course, additional specific data are required to make the link with the optimization tools (LBR5, CONSTRUCT, OCTOPUS). These additional data have to be specified by the tool owners in order to be considered in the integration of the platform.



System architecture - 2

External interface

IMPROVE
decision component
- Control process execution
- Set parameters
- Compare results
-Initiate iterations

YAWL
workflow component
-Definition of processes
- Assignment of documents
- Connection with tools

BAL.KMAN
knowledge component
- Storage of input and output documents
- Search for documents and processes
- Document visualisation

IMPROVE

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Fig. 6. : The IMPROVE Optimisation Platform

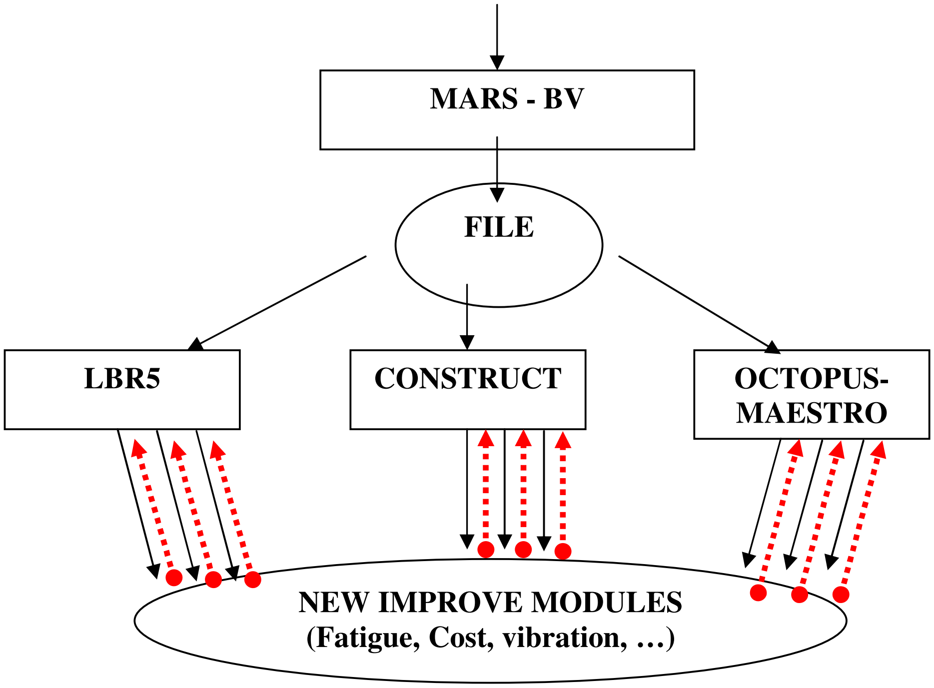

Fig. 7. : The IMPROVE optimization approach.

6. Conclusions

The IMPROVE project has reached its mid term. Major remaining work packages concern the integration of the various modules (WP5) and the multi-criteria optimization of the LNG carrier (WP6), the large RoPax (WP7) and the chemical tanker (WP8). These remaining tasks shall develop three new ship generations by applying the integrated IMPROVE decision support system (DSS). These activities are performed by a team of multidisciplinary partners (shipyard, operator/ship owner, designer and a university) having a large experience of multi-criteria based ship design and evaluation.

Acknowledgements

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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)
Aker Yards 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:
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Table I: List of Design objectives and List of Design Variables (part 1)

CT = Chemical Tanker

		DESIGN OBJECTIVES and Sub-Objectives	**QUALITY MEASURES including the KPIs KPI = Key Performance Indicator**	**DESIGN VARIABLES**	**TOOLS**
SHIP (NAVAL ARCHITECTURE) - (WP2)	**Max volume**	Increase carrying capacity (lane meters)	- additional trailer lane meters on tank top, - total lane meters, - decreased length of the engine room	General arrangement (GA), length of the engine room, hull form, required power output, type, size, number and configuration of main engines, boilers and other parts of machinery,	Concept design, tools for the design of machinery systems, reduction of power requirements (reduction of resistance and increase of efficiency of the systems),
		Increase carrying capacity by: → reducing the steel mass; → reducing the void spaces; → reducing the internal subdivisions; → maximizing cargo volume per dimensions	- steel mass, - volume of void spaces, - number and volume of ballast tanks, - cargo volume per ship dimensions	- GA, scantlings, - ratio of mild steel vs. high tensile steel or vs. DUPLEX steel (for CT), - stability requirements, loading conditions, lengths of fore, and aft peaks, bulkheads type and arrangement, volume of ballast tanks,	- Concept design tools, - Optimization tools (MAESTRO, OCTOPUS, Nastran LBR-5, Permas, modeFRONTIER), - machinery design tools
		Determine the optimum size for chemical tankers	- max utilization of cargo part volume - lightship weight (mass of steel, outfit) - possible future conversion allowance	cargo capacities, types of cargo, area of navigation,	- Concept design tools : - NAPA / NAPA STEEL - NAUTICUS / MARS - Economical analysis.
	Flex.	Achieve load carrying flexibility	Measure to be defined	RoPax: deck loading, tween deck clearances, number of cabins, no of aircraft seats, CT: number and position of cargo tanks	concept design,
	Hydrodynamics	Improve the seakeeping performance for the Mediterranean Sea	- speed loss in waves, - number of deck wetness, - number of propeller racings,	hull form, ship mass distribution,	seakeeping analysis software (FREDYN, SHIPMO),
		Improve the manoeuvrability of the ship	- turning ability index	hull form, main particulars, type and number of propulsors, bow thrusters and rudders,	manoeuvrability analysis software towing tank trials
		Reduce the hydrodynamic resistance	- power requirements, - trial speed	Hull form, main particulars,	- CFD analysis, towing tank trials, - Seakeeping concept design tool
		Maximize propulsion efficiency/Minimize the fuel consumption	FO consumption	hull form, propulsion system	Open water test, self propulsion tank tests,

Table I: List of Design objectives and List of Design Variables (part 2)

		DESIGN OBJECTIVES and Sub-Objectives	QUALITY MEASURES including the KPIs (Key Performance Indicators)	DESIGN VARIABLES	TOOLS
SHIP (NAVAL ARCHITECTURE) - (WP2)	**Economy**	Minimize the required freight rate	Required Freight Rate	economy parameters,	ANAST and CMT will provide tools
		Maximize the robustness of the required freight rate	SN ratio of RFR	economy parameters,	ANAST and CMT will provide tools
		Minimize the cost of the main engine and machinery	- main engine cost - machinery cost	required power output, type, size, number and configuration of main engines, boilers and other parts of machinery, efficiency of systems,	concept design, design of machinery systems, reduction of power (reduction of resistance and increase of efficiency of the systems),
	Safety	Maximize ship safety	- subdivision index, - redundancy index, - evacuation ability index - structural safety index (system and component - see STRUCTURE)	GA, scantlings, systems and equipment, freeboard height, number and positions of bulkheads, number of passengers, internal layout, number of independent propulsors, engines and engine rooms,	structural analysis (MAESTRO), evacuation ability simulations, Frontier - for damage stability calculations,
		Design for redundancy and simplicity of systems	- number of independent propulsors, - no. of engines and no. of engine rooms,	number of independent propulsors, engines, engine rooms, etc.,	
		Maximize reliability of the ship systems	measure to be defined	scantlings, detail design, GA, equipment,	structural analysis (MAESTRO) and fatigue assessment (), reliability analysis (CALREL),
	Specific	Maximize comfort → minimize vibrations → minimize noise levels	- vibration levels (displ., velocity, acceleration) - noise levels (dB) RO-PAX: - size of cabins/public spaces per pax, - No. of crew members per pax, - pax service facilities, - motion sickness incidences (MSI),	size of cabins and public spaces per passenger, number of crew members per passenger, passenger service facilities, vibration levels (GA, scantlings, shape of the stern part, vibration reduction devices), noise levels (insulation, materials, noise sources),	concept design, software for vibration analysis (Nastran, COSMOS,…), software for seakeeping analysis (FREDYN, SHIPMO),
		Achieve flexibility in regard to possible conversion due to new rules or comfort standards	measure to be defined	size of cabins and public spaces per passenger, number of crew members per passenger, passenger service facilities, seakeeping performance, vibration levels (GA, scantlings, shape of the stern part, vibration reduction devices), noise levels (insulation,)	concept design
		Reduce draft in ballast condition	measure to be defined	Size, number and type of propellers, manifold position,	concept design

Table I: List of Design objectives and List of Design Variables (part 3)

	DESIGN OBJECTIVES and Sub-Objectives	QUALITY MEASURES including the KPIs (KPI = Key Performance Indicator)	DESIGN VARIABLES	TOOLS
STRUCTURE - (WP3)	Minimize the steel mass (ALL SHIPS); Chemical Tanker(CT):minimize DUPLEX-steel mass; RoPax: minimize mass of freeboard deck ;	**- steel mass = additional deadweight**, - use of MS (% of total mass), - painted surface, - DUPLEX-steel mass (for CT), mass of freeboard deck (for RO-PAX), longitudinal spacing (for RO-PAX)	GA, scantlings, ratio of mild steel vs. high tensile steel vs. DUPLEX steel (for CT), bulkheads type (CT), direction and dimensions of bulkhead corrugations (CT), framing systems of decks and bulkheads, still water bending moment (CT)	concept design, optimization tools (MAESTRO, OCTOPUS, Nastran, LBR5, Permas, modeFRONTIER), still water bending moment distribution, analytical methods for structural analysis
	Maximize structural safety w.r.t. - extreme loads - fatigue life (constraint)	**Global deterministic safety measures:** - Max. Ul. Bend. Mom. in sagging ($M_{ult,sagg}$) - Max. Ul. Bend. Mom. in hogging ($M_{ult,hogg}$) - Max. racking moment for RO-PAX (M_{rack}) **Global reliability measures:** - System failure probability in long. strength - System failure probability in racking for RO-PAX	Scantlings, structural details, loads, GA, type of structural material, quality of fabrication and welding,	Accurate load estimation (especially of the wave loads with e.g. lifetime weighted sea method or CFD analysis), HYDROSTAR-BV Structural evaluation tools (MAESTRO, NASTRAN, DSA), fatigue analysis, reliability analysis (CALREL): - $M_{ult,sagg}$, $M_{ult,hogg}$ - modified Smith method, - M_{rack} - incremental FEM analysis, - $p_{f,\,US}^{syst}$ - β - unzipping, $p_{f,\,R}^{syst}$ - β - unzipping, - F.L. - Weibull, Joint Tanker Rules, -EVAL (Panel, Principal member) - $p_{f,\,fatigue}^{elem}$, p_f^{P}, $p_f^{F/G}$ - CALREL (SORM) - SN ratio - Fractional Factorial Experiments (FFE)
		Local deterministic measures: - Fatigue life of structural details (F.L. = No. of cycles to fracture) - Panel ultimate strength measure - Principal members ul. strength measure **Local probabilistic measures and robustness measures:** - Probability of fatigue failure of structural details - Probability of panel failure in regard to all relevant failure modes - Probability of frame/girder failure in regard to all relevant failure modes Panel and frame/girder robustness measure (SN ratio)		
	Minimize the height of deck transverses	Ship height, VCG	Loads, position and number of supporting members (pillars) ➔ effective spans of deck transverses, scantlings	Optimization tools (MAESTRO, OCTOPUS, LBR-5, Nastran, Permas, modeFRONTIER),

Table I: List of Design objectives and List of Design Variables (part 4)

	DESIGN OBJECTIVES and Sub-Objectives	**QUALITY MEASURES including the KPIs (Key Performance Indicators)**	**DESIGN VARIABLES**	**TOOLS**
PRODUCTION (WP4)	Minimize the production costs (compound objective)	**Production cost = material cost** [€] + **labor cost** [€] (steel production per unit of time (welding, bending, straightening,…) [t/h], compensated steel throughput per year [CGT/year], cost of steel work per mass [€/t], building blocks number [units], lead time/cost [TLH in hours or €] in dry dock (or slipway) and in all shops, key resource use [TS, in days] - time first part into resource until last part, degree of pre-fabrication = TLH / TS [%], usage of space per CGT [m²/CGT], degree of outsourcing - yard hours against subcontractor hours) + overhead costs [€]	Scantlings, complexity of parts, organization of the production process, materials, technologies needed, shops used, shipyard transportation equipment and available technical capabilities (like the capacity of panel line, sub-assembly and assembly shops, etc.), quality of fabrication in the steel mill, level of attention during the transportation and storage actions, number and size of curved parts	Production simulation tools, concept design, structural design tools,
	Minimize the additional construction cost due to a double-bottom height higher than 3 m	measure to be defined	Double-bottom height	
OPERATION, MAINTENANCE AND REPAIR (WP4)	Minimize the lifecycle cost of the ship (compound objective - selection from Pareto frontier)	**Lifecycle cost =** initial cost (**production cost +** other costs) + cost of operation (**preventive maintenance cost**, corrective maintenance cost **(repair cost),** fuel, crew and provisions, turnaround time in port and port charges, time out of service bond interest)		
	Minimize the maintenance costs	**- preventive maintenance costs** (including inspection costs), **- corrective maintenance costs (repair costs)**	Scantlings, quality of fabrication, design of systems and quality of components, availability of components for inspection,	
	Maximize the reliability of the ship's machinery	measure to be defined		
	Maximize the robustness of the propulsion system	measure to be defined		