Multi-criterion Scantling Optimisation of Passenger Ships

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Abstract

In the scantling design of a passenger ship, minimum production cost, minimum weight and maximum moment of inertia (stiffness) are conflicting objectives. For that purpose, recent improvements were made to the LBR-5 software (French acronym of "Stiffened Panels Software", version 5.0) to optimize the scantling of ship sections by considering production cost, weight and moment of inertia in the optimisation objective function. A real multi-criterion optimisation of a passenger ship is presented in this paper. Results highlight that LBR-5 is competitive software to optimise scantling of ships at very early design stage with management of critical problems studied normally at a later step of the design.

1. Introduction

1.1 Outline

Sustainability of technologies has been the central focus of many international debates, seminars and forums. Designing for sustainability requires the consideration of social, economical and environmental factors throughout the product life. The Life Cycle Performance (LCP) as a measure of sustainability and competitiveness covers a number of key aspects, such as Life Cycle Cost (LCC), environmental friendliness, end-of-life impacts or safety.

In the early stages of design and development all technical and ecological requirements have to be considered in terms of their long-term impacts on the entire ship life cycle. An engineering design should not only transform a need into a description of a product but should ensure the design compatibility with related physical and functional requirements. Therefore it should take into account the life of the product as measured by its performance, effectiveness, producibility, reliability, maintainability, supportability, quality, recyclability, and cost.

Life cycle optimisation – in a sense selecting the right design options on ship and system levels – is poorly applied. Methods and tools are needed, which connect technical design parameters to life cycle performance, allowing technical experts to quickly assess the impact of design options and parameters on the overall ship performance. An integrated view requires dedicated methods to compare production and operational costs, safety and environmental aspects as well as tools for life cycle optimisation in the different design and production phases of a ship. The closer inter-dependencies between design, life cycle performance and fabrication techniques have been highlighted in a lot of papers *Borzecki et al. (2003), Bruce et al. (2006), Caprace et al. (2009)*. These interactions are bidirectional:

- Construction cost and manufacturing conditions are to a large extent defined in early design phases. It is therefore important that the designer is provided with methods and tools which enable him to sufficiently consider design alternatives, cost aspects, new fabrication technologies and materials in his work.
- Manufacturing quality, imperfections and accuracy have a significant impact on structural performance, repair and maintenance and life cycle cost.

Nowadays, market drivers induce permanent innovation through better designs and more efficient fabrication techniques. Fuel costs force better hydrodynamics efficiency, harbour environmental concerns force lower slow-speed propeller wash, navigational constraints force better manoeuvring and control systems, steel cost force better optimisation of the hull structures, etc.

Though a holistic approach to the ship design problem appears theoretically well established, it remains for the researchers and engineers to develop and implement a long list of applications, addressing the complex problem of ship design for life-cycle. This is a long term task of decades, requiring profound skills and understanding of the physics, technology and design of ships, a clear domain of properly trained naval architects. This paper deals with the development of scantling optimisation software (LBR-5) integrating different life aspects of ships.

1.2 The scantling optimisation

To be attractive for shipyards, scantling optimisation has to be performed at the preliminary design stage. It is indeed the most relevant period to assess the construction cost, to compare fabrication sequences and, to find the best frame/stiffener spacing's and most suitable scantlings to minimize the life cycle cost of ships.

In the scantling design of a passenger ship, minimum production cost, minimum weight and maximum moment of inertia (stiffness) are conflicting objectives. For that purpose, recent improvements were made to the LBR-5 software (French acronym of “Stiffened Panels Software”, version 5.0) to optimize the scantling of ship sections by considering production cost, weight and moment of inertia in the optimisation objective function.

A new module has been recently integrated to improve the quality of the optimised scantling solution. This module allows the optimisation of several sub-sections of the ship simultaneously (not only the amidships section).

A real multi-criterion optimisation of a passenger ship is presented in this paper. Results highlight that LBR-5 is competitive software to optimise scantling of ships at very early design stage with management of critical problems studied normally at a later step of the design.

2 Overview of optimisation problem

2.1 Introduction

What is the primary objective of a shipyard? As every business school in the world has taught us, the primary goal is to maximize free cash flow to investors. The free cash flow is primarily driven by profit, so that the first objective of the shipyard becomes to increase profit by reducing the production cost. Many people may argue that safety, ship performance, and delivery should be the shipyard’s main goals. No doubt these are important goals. However, these are simply important requirements that must be met. Minimising life cycle cost should be the goal. The ship design is a complex multidimensional space. Safety, quality, environmental, productibility, and other product attributes are constraints that must be met to some target level in order for the ship to be viable in the market.

Because the ship design is a non-linear complex space, there are multiple regions of localized minimum for LCC. Some of these targets are blocked by the constraints. Within a holistic ship design optimisation we need to mathematically understand exhaustive multi-objective and multi-constrained optimisation procedures. Optimisation problems and their basic elements may be defined as the following:

- **Design variables** – This refers to a list of parameters characterizing the design being optimized; for ship design this includes ship’s main dimensions, unless specified by the ship owner’s requirements and may be extended to include a ship’s hull form, arrangement of spaces, structural elements and networking elements (piping, electrical, etc), depending on the availability of the input data.
- **Design objective function** – A function associated with an optimisation problem which determines how good a solution is, for instance, the total Life Cycle Cost of a ship.

- **Design constraints** – This mainly refers to a list of limits mathematically defined in order to keep a feasible solution at the end of the optimisation process. Basically these limits result from regulatory frameworks related to safety (stability limit, yield stress of steel, etc.) and may be expanded by the cost of materials (for ships: cost of steel, fuel, labour) and other case specific constraints.
- **Optimal solution** – A feasible solution that minimizes (or maximizes, if that is the goal) the objective function is called an optimal solution. For multi-criteria optimisation problems, optimal design solutions are called Pareto front and may be selected on the basis of trade-offs by the decision maker.

2.2 Single Criterion Problem

The following overview is adapted directly from *Parsons and Scott (2004).* The single criterion optimisation problem is usually formulated as

$$\min_x F(\mathbf{x}) = F_1(\mathbf{x}), \qquad \mathbf{x} = [x_1, x_2, \ldots, x_N]^T$$

subject to the equality and inequality constraints

$$h_i(\mathbf{x}) = 0,\ i = 1, \ldots, I$$
$$g_j(\mathbf{x}) \geq 0,\ j = 1, \ldots, J \qquad (1)$$

where there is a single optimisation criterion or objective function $F_1(\mathbf{x})$ that depends on the N unknown design independent variables in the vector $\mathbf{x}$. For a practical engineering solution, the problem is usually subject to I equality constraints and J inequality constraints $h_i(\mathbf{x})$ and $g_j(\mathbf{x})$, respectively, that also depend on the design variables in the vector $\mathbf{x}$. The minimization form is general because a maximization problem can be solved by minimizing the negative or the inverse of the cost function.

2.3 Multi-criterion Optimisation

The multi-criterion optimisation problem involves K > 1 criteria and can be formulated as

$$\min_x F(\mathbf{x}) = [F_1(\mathbf{x}), F_2(\mathbf{x}), \ldots, F_K(\mathbf{x})],$$

$$\mathbf{x} = [x_1, x_2, \ldots, x_N]^T$$

subject to equality and inequality constraints

$$h_i(\mathbf{x}) = 0,\ i = 1, \ldots, I$$
$$g_j(\mathbf{x}) \geq 0,\ j = 1, \ldots, J \qquad (2)$$

where there are now K multiple optimisation criteria $F_1(\mathbf{x})$ through $F_K(\mathbf{x})$ and each depends on the N unknown design variables in the vector $\mathbf{x}$. The overall objective function F is now a vector. In general, this problem has no single solution due to conflicts that exist among the K criteria.

2.4 Pareto Optimum Front

When conflicting multiple criteria are present, the most common definition of an optimum is Pareto optimality. This was first articulated by the Italian-French economist V. Pareto in 1906. This is also referred to today as Edgeworth-Pareto optimality: A solution is Pareto optimal if it satisfies the constraints and is such that no criterion can be further improved without causing at least one of the other criteria to decline. This emphasizes the conflicting or competitive interaction among the criteria. These definitions typically result in a set of optimal solutions rather than a single unique solution. A design team, of course, typically seeks a single result that can be implemented in the design. This result should be an effective compromise or trade-off among the conflicting criteria. Often this can be reached by considering factors not able to be included in the optimisation model.

2.5 Global Criterion Optima

Engineering design requires a specific result for implementation, not a set of solutions as provided by the Pareto optimal set. The more intuitive ways to achieve an effective compromise among competing criteria are, among others, the weighted sum, the min-max and the nearest to the utopian solutions. These solutions can be found through the global criteria:

$$P[F_k(\mathbf{x})] = \left\{ \sum_{k=1}^{K} \left[w_k \left| \left(F_k(\mathbf{x}) - F_k^0 \right) / F_k^0 \right| \right]^{\rho} \right\}^{1/\rho} ,$$

$$\sum_{k=1}^{K} w_k = 1 \qquad (3)$$

F_k^0 is the value of the criterion F_k obtained when that criterion is the single criterion used in the optimisation - the best that can be achieved with that criterion considered alone. The scalar preference function $P[F_k(\mathbf{x})]$ replaces $F(\mathbf{x})$ in Eq. 1 for numerical solution.

The weighted sum solution results from Eq. 3 when $\rho = 1$, whereas the nearest to the utopian solution results when $\rho = 2$ and the min-max solution when $\rho = \infty$. The numerical implementation for the min-max solution uses the equivalent of Eq. 3 with $\rho = \infty$,

$$P[F_k(\mathbf{x})] = \max_k \left[w_k \left| \left(F_k(\mathbf{x}) - F_k^0 \right) / F_k^0 \right| \right] \qquad (4)$$

Moreover, a solution could be obtained for a number of values of ρ and then the design team could decide which solution best represents the design intent.

2.6 Mapping the Entire Pareto Front

In dealing with multi-criterion problems, it is highly desirable to be able to study the entire Pareto front. This allows the design team to consider all options that meet the Pareto optimality definition. The final design decision can then be based on the considerations modelled in the optimisation formulation as well as the many additional considerations, factors, and constraints that are not included in the model. This is practical when there are two criteria, but rapidly becomes impractical, for computational time and visualization reasons when the number of criteria increases beyond two.

To map the entire Pareto front, the three following methods can be used:

- *Repeated weighted sum solutions*. If the feasible object function space is convex, weighted sum solutions can be obtained for systematically varied weights.
- *Repeated weighted min-max solutions*. If the feasible object function space does not have a slope that exceeds w_1/w_2, weighted min-max solutions can be obtained for systematically varied weights.
- *Multi-criterion optimisation methods*. Multi-criterion implementations of Generic Algorithms (MOGA), Evolutionary Algorithms, Particle Swarm Optimisation, etc. can obtain the entire Pareto front in one optimisation run.

3 LBR-5 software

This paper is related to the development of the optimisation software LBR-5. This tool allows the optimisation of ship structures following different objectives such as the highest inertia, least weight and/or least cost. The scantling design of ships is always defined during the earliest phases of the project. At this time, few parameters (dimensions) have been definitively fixed, and standard FEM is often unusable, particularly for design offices and modest-sized shipyards. An optimisation tool at this stage can, thus, provide precious help to designers. This is precisely the way the LBR5 optimisation software was conceptualized, *Rigo (2001)*.

No initial preliminary sizing is required so that the engineer can directly start with an automatic research of the optimal design. It is not necessary that the initial scantlings correspond to an admissible solution although the convergence will be facilitated if the initial scantling is not too far from the feasible domain.

The main features of the software are:

- The scantling optimisation of hydraulic and naval stiffened structures
- The 3D analysis of the mechanical behaviour of the structure
- The use of all the relevant limit states of the structure (service limit states and ultimate limit states)

3.1 Scantling Design Variables

In LBR-5, a structure is modelled with stiffened plate elements, Fig. 1. For each element, nine design variables are available:

- Plate thickness.
- For longitudinal members (stiffeners, crossbars, girders, etc.),
    - web height and thickness,
    - flange width,
    - spacing between two longitudinal members.
- For transverse members (frames, transverse stiffeners, etc.),
    - web height and thickness,
    - flange width,
    - spacing between two transverse members (frames).

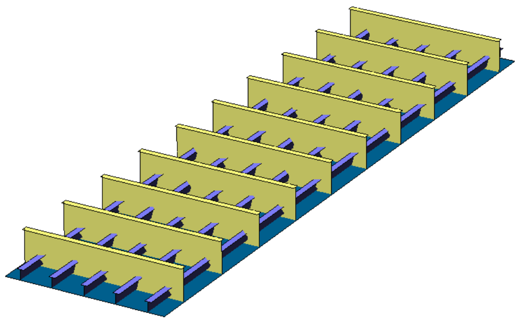


Fig. 1 : LBR-5 Stiffened Plate Element

3.2 The new multi-structures module

The structural module of LBR5 allows only the analysis of 2.5 D structures, obtained from the definition of a 2D model and extruded through the longitudinal direction. It is obvious that a fore and aft sections of a ship could not be analyzed and optimized together with the amidships section, but this optimisation is possible independently. The main inconvenient of an independent optimisation is that several design variables (for example the stiffeners spacing or the plate thickness of decks) that should be the same for the considered structures, may have different values at the local optimum. The multi-structures module allows to LBR-5 to optimize several structures simultaneously. The main interest is to link design variable between these structures, for example the amidships section with fore and aft section of a passenger ship. The multi-structures module optimizes simultaneous the three sections in order to obtain compatible design variables, but only several common design variables can be taken into account. The link between the various sections is done only by design variables: new equality constraints are added between variables. There is no link about the strain or stress. In practice, the three sections are optimized independently but some design variables are linked together in order to find a realistic solution.

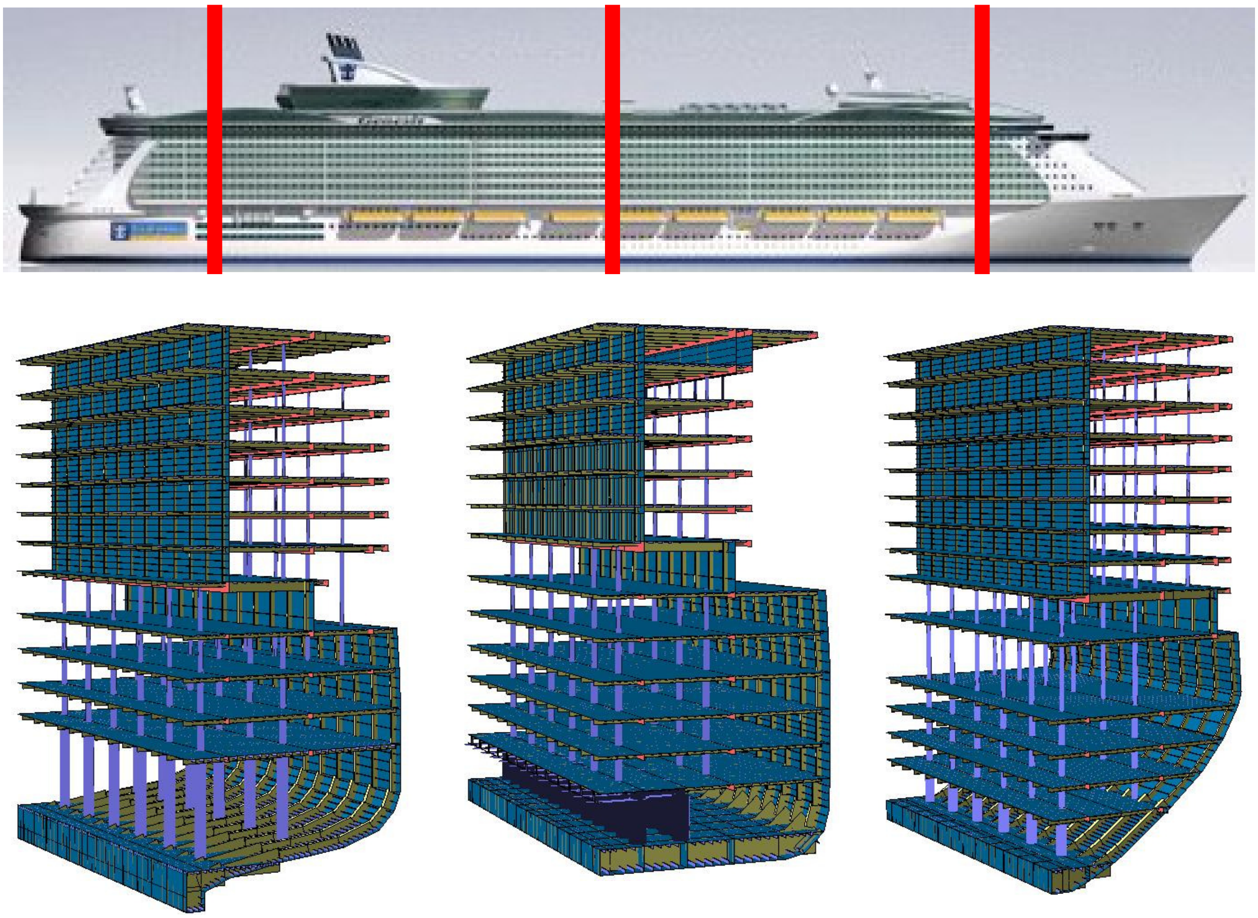
3.3 Multi-criterion Optimisation

Production cost, weight and moment of inertia can be used as objective function in LBR-5. They are considered simultaneously through Eq. 4 in a multi-criterion problem. The Pareto Front can be mapped in LBR-5 by using the repeated weighted sum solutions method described above.

4 Applications

4.1 Geometry and load cases

Three amidships sections of a passenger ship has been simultaneously implemented inside LBR-5. The central one has been imported from Mars2000 (scantling verification software based on Bureau Veritas rules). The sections are characterized by 14 decks, 40 m breadth and 42 m height. Fig. 2 shows the three considered sections. Based on structure symmetry, only the half structure was modelled.



81 panels	*78 panels*	*93 panels*
24 pillars	*25 pillars*	*28 pillars*
Aft ship section [A]	***Amidships section [M]***	***Fore ship section [F]***

Fig. 2 : Three amidships section of a cruise ship

For each section five load cases were considered in the calculation. Loads are: hydrodynamic pressures, deck loads, deadweight and bending moment. Difficulty of the modelling is to get adequate moment and shear forces in the aft and the fore ship section. Indeed shear force is a resultant force coming from the general behaviour of the ship. It is influenced by its length, weight and water pressures. If we model only a part of the ship, we do not have the same behaviour: the shear force and moment in the studied section are not the same as in reality. To solve the problem we have artificially modified the bending moment applied and the length of our model to get the adequate couple moment/shear force in the studied section.

4.2 Design Variables

Five scantling design variables were activated in each LBR-5 stiffened plate element:

- Plate thickness
- For longitudinal stiffeners,
    - web height and thickness,
    - flange width,
    - spacing between two longitudinal stiffeners.

4.3 Objective function

Production cost and least weight were the two objectives considered in this application. The production cost was calculated with an advanced cost module that takes into account a detailed shipyard database. About 60 different fabrication operations are considered, covering the different construction stages, such as girders and web-frames prefabrication, plate panels assembling, blocks pre-assembling and assembling, as well as 30 types of welding and their unitary costs, *Richir et al. (2007)*.

4.4 Constraints

The problem is strongly constrained and the adequacy of these constraints can influence greatly the solution found. Constraints used in the model can be divided into three categories: geometrical constraints, structural constraints and global constraints. Firstly geometrical constraints are used on each panel to ensure feasibility of the solution from a technical point of view. Thicknesses of the plates and of the stiffeners cannot be too different for welding reasons. Ratio between flange and web of stiffeners should also respect certain rules, etc. Secondly we need to impose structural constraints. These constraints are the most important to ensure the integrity of the ships over ages. Classical Von Mises stresses constraints are used, but also some more sophisticated as buckling and yielding constraints – of plates and stiffeners. Deflections are also important and limitations are imposed on each beam. Finally, we have also imposed a limitation to the variation of the gravity centre to avoid stability problem.

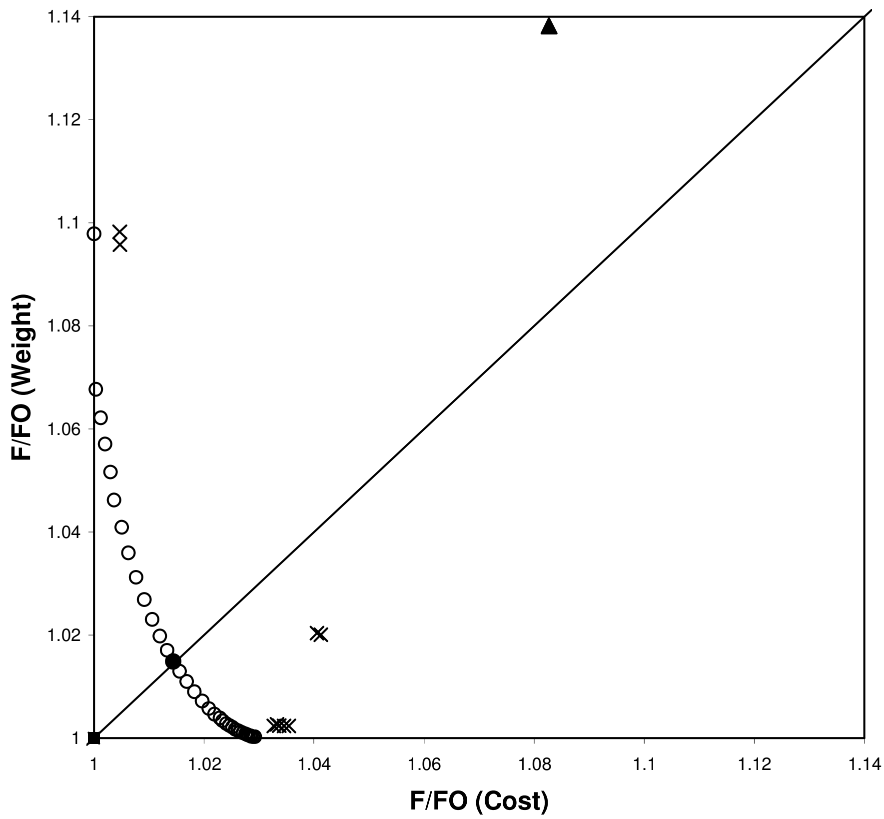
To facilitate the production equality restrictions are often added to avoid discontinuity of design variables. Panels of a same deck have normally the same thickness, stiffeners spacing's are often homogeneous, etc. Here we did not apply any equality restrictions to let a total freedom to the design engineer.

5 Results and Pareto front

The entire Pareto front was obtained using a process that altered the weights in the weighted sum solution and solved the optimisation problem for each of these problems. The resulting convex Pareto front is shown in Fig. 3. 50 points were calculated. The Pareto front was generated in about 28 hours with a laptop Pentium Dual Core 2.52 GHz and 3 Go of RAM.

The utopian point, the min-max solution ($\rho=\infty$), and the initial solution are also shown in Fig. 3. Min-

Max solution has been obtained for a weighting factor equal to 0.59 for the production cost and 0.41 for the weight. This analysis has highlighted that the initial design is relatively far from the Pareto front. Using Fig. 3, the design team is now able to choose a compromise solution from the Pareto front, by considering additional factors and constraints that are not included in the optimisation problem.



▲ Initial design ■ Utopian point ○ Pareto front

× Not converged points • Min-Max Solution (ρ=∞)

Fig. 3 : Pareto front

Table I gives the cost and steel weight savings between the min-max solution and the initial design. Note that the initial scantlings did not satisfy all structural constraints.

Table I: Cost and Steel Weight Savings

	Cost Optimisation	***Weight Optimisation]***	***Min-Max Solution***
	Saving (%)	Saving (%)	Saving (%)
Production cost	7.6%	4.4%	6.2%
Steel weight	3%	12.1%	6.4%

6 Conclusions

Thanks to the recent developments outlined here, the LBR-5 software allows performing multi-criterion optimisation by considering production cost and weight in the optimisation objective functions. The entire Pareto front can be mapped by using a process that randomly alters the weights in the weighted sum solution and solves the optimisation problem for each of these problems. Useful specific compromise solutions from the Pareto front, e.g. the nearest to the utopian and min-max solutions, can be easily calculated.

Moreover, with the new multi-structures module, it is now possible to simultaneously optimise different sections of a ship guarantying the compatibility of the design variables between the different sections.

These new developments improve significantly the capacity of the software to provide optimal scantling solution at the early stage of the design process.

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