Multi-criteria Scantling Optimisation of Cruise Ships

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ABSTRACT

A numerical tool for the optimisation of the scantlings of a ship is extended by considering production cost, weight and moment of inertia in the objective function. A multi-criteria optimisation of a passenger ship is conducted to illustrate the analysis process. Pareto frontiers are obtained and results are verified with Bureau Veritas rules.

Key words: optimisation, passenger ship, structure

1 Introduction

1.1 Outline

In the early stages of ship design, all technical and ecological requirements have to be considered in terms of their long-term impact on the entire ship life-cycle. However, life-cycle cost (LCC) optimisation is rarely applied in traditional ship design. Methods and tools are needed, which connect technical design parameters to life-cycle performance, allowing ship designers to quickly assess the impact of design options and parameters on the overall ship performance. Such an integrated view requires dedicated methods for the comparison of 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.

Interaction between design, life-cycle performance and production techniques have been highlighted in many papers as reviewed in *Borzecki et al.* (2003), *Bruce et al.* (2006) and *Caprace et al.* (2009). 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 suitable methods and allowed to consider many design alternatives, cost aspects, new fabrication technologies and materials. On the other hand, manufacturing quality, imperfections and accuracy have a significant impact on the structural performance, repair and maintenance and life cycle cost.

This paper deals with the development of scantling optimisation software integrating different life aspects of ships.

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1.2 Scantling optimisation

Ships and floating structures are complex structures, generally composed of strongly stiffened deck and bottom plates and sometimes intermediate decks, frames, bulkheads etc. The optimisation of such complex structures is the purpose of this paper. Scantling optimisation should be performed at the preliminary design stage, because it is the most relevant period to assess the construction cost, compare fabrication sequences and find the best frame and stiffener spacing and most suitable scantlings, minimising life-cycle cost. However at this stage of the project, few parameters are definitively fixed and standard finite element analysis (FEA) is often impossible, particularly for design offices and medium-sized shipyards.

An optimisation tool at this design stage can help significantly, *Rigo and Fleury* (2001). The purpose of the tool is the dimensioning and scantling optimisation of lock gates, ships and offshore structures. The goal is to create a multi-purpose optimisation model compatible with structural analysis modules based on codes and regulations. Such a model must contain various analysis methods for strength assessment that can be easily complemented by users. For example, the user should be able to modify constraints according to the structure type, the regulation code in force and design experience, which requires a user-oriented optimisation system in permanent evolution, i.e. evolving with the user and particular task requirements.

The structural analysis is performed for a model based on an extrusion of a ship cross section. Solution method is based on Fourier series expansions applied to the stiffened plate differential equations with, *Rigo* (2005).

In the scantling design of a ship, minimum production cost, minimum weight and maximum moment of inertia (stiffness) are conflicting objectives. The optimisation tool was extended in order to consider production cost, weight and moment of inertia in the objective function. Simultaneous optimisation of several sections of the ship is possible.

2 Overview of optimisation problem

2.1 Introduction

Ship design covers a complex non-linear space with multiple regions of local minima of LCC; some of these regions are blocked by constraints. Within a holistic ship design optimisation, multi-objective and multi-constrained optimisation problems should be solved. Basic elements of an optimisation problem are

- *Objective function* associated with an optimisation problem, which determines how efficient a solution is, e.g. the life-cycle cost of a ship.
- *Design variables* which may include main dimensions and hull form parameters, arrangement of spaces, structural elements and networking elements such as piping, electrical etc.
- *Design constraints* are limits resulting from regulations related to safety (stability requirements, yield stress of steel etc.), costs (e.g. steel, fuel, labour) etc.
- *Optimal solution* is a feasible solution that minimises the objective function. For multi-criteria optimisation problems, optimal design solutions are indicated by Pareto front and may be selected on the basis of trade-offs by the decision maker.

2.2 Optimisation of marine structure

Ship design has been based traditionally on a sequential and iterative approach. With the availability of non-linear optimisation tools, several researchers have attempted to solve the ship design problem using different optimisation techniques. Probably the first marine structure optimisation studies were made practically by hand in *Harlander* (1960). Afterwards, computer-assisted design and optimisation algorithms were developed, *Evans and Khoushy* (1963) and *Nowacki et al.* (1970). Important progress in ship structural optimisation was presented in *Hughes et al.* (1980) and

Hughes (1988). Forty years ago, optimisation tools focused on a single, limited aspect (shape, scantlings, propeller, ultimate strength etc.) and a single objective (e.g. weight, resistance or cavitation). Nowadays, optimisation tools tend to adopt a more generic approach and are more reliable. Design and optimisation techniques reported in *Cho et al.* (2006), *Seo et al.* (2003), *Rigo* (2005), *Khajehpour and Grierson* (2003), *Parsons and Scott* (2004), *Klanac and Kujala* (2004), *Zanic et al.* (2005) and *Xuebin* (2009) use integrated multi-criteria optimisation models including structural weight and production costs. They differ in design variables and constraints as well as in the analysis methods of the structural response, e.g. two- and three-dimensional FEA, analytical linear and non-linear etc. However, all authors agree that a single objective is not sufficient to model accurately the relevant aspects of marine structures.

Preliminary design is the most relevant and the least expensive period for the modification of design scantling and comparison of alternatives. The earlier information is available, the better decisions can be taken in the design process. It is however often too early for efficient use of many analysis methods mentioned. The methodology presented in this paper can be applied as soon as the first scantlings of the cross section of the structure are available, because it is based on the solution of the stiffened plate differential equations and not on traditional FEA techniques. The solution time is short; generally no more than one week of modelling and computing is required to find the Pareto front.

2.3 Single Criterion Problem

The single criterion optimisation problem is usually formulated as, *Parsons and Scott* (2004):

$$\min_{x} F(\vec{x}) = F_1(\vec{x}), \qquad \vec{x} = [x_1, x_2, ..., x_N]^T \tag{1}$$

subject to the equality and inequality constraints

$$\begin{aligned} h_i(\vec{x}) &= 0, \qquad i = 1, ..., I \\ g_i(\vec{x}) &\geq 0, \qquad j = 1, ..., J \end{aligned} \tag{2}$$

The single optimisation criterion or objective function $F_1(\vec{x})$ depends on N unknown independent design variables in the vector $\vec{x}$. The problem is subject to I equality constraints $h_i(\vec{x})$ and J inequality constraints $g_j(\vec{x})$.

2.4 Multi-criteria Optimisation

The multi-criteria optimisation problem involves $K > 1$ criteria and can be formulated as, *Parsons and Scott* (2004)

$$\min_{x} \vec{F}(\vec{x}) = [F_1(\vec{x}), F_2(\vec{x}), ..., F_K(\vec{x})] \quad \text{with } \vec{x} = [x_1, x_2, ..., x_N]^T \tag{3}$$

subject to equality and inequality constraints

$$\begin{aligned} h_i(\vec{x}) &= 0, \qquad i = 1, ..., I \\ g_i(\vec{x}) &\geq 0, \qquad j = 1, ..., J \end{aligned} \tag{4}$$

There are K multiple optimisation criteria $F_1(\vec{x})$ to $F_K(\vec{x})$ in the overall objective function $\vec{F}$, each depending on N unknown design variables in the vector $\vec{x}$. In general, this problem does not have a single solution due to conflicts among the criteria.

2.5 Pareto Optimum Front

If multiple criteria conflict, the most common definition of an optimum is the Pareto (or Edgeworth-Pareto) optimality: *A solution is Pareto optimal if it satisfies the constraints and is such that no criteria can be further improved without worsening at least one of the other criteria*. The Pareto optimality emphasises conflicting or competitive interaction amongst the criteria and typically results in a set of optimal solutions rather than in a single unique solution. However, a design team typically seeks a single result, which should be an effective compromise or trade-off amongst the conflicting criteria. This can often be reached by considering additional factors not included in the optimisation model, *Zanic and Frank* (2003), *Zanic et al.* (2005) and *Zanic et al.* (2006).

2.6 Global Optimum Criteria

Engineering design requires a specific result to be implemented, not a set of solutions such as provided by the Pareto optimal set. The most intuitive ways to achieve an effective compromise amongst competing criteria are the weighted sum, the min-max and the nearest to the utopian solutions. These solutions can be derived through the global criterion

$$P[F_k(\vec{x})] = \left\{ \sum_{k=1}^{K} \left[w_k \left| \frac{F_k(\vec{x}) - F_k^0}{F_k^0} \right| \right]^{\rho} \right\}^{1/\rho}, \qquad \sum_{k=1}^{K} w_k = 1 \tag{5}$$

F_k^0 is the value of the criterion F_k obtained when it is the single criterion used in the optimisation, i.e. the best value that can be achieved with that criterion considered alone. The scalar preference function $P[F_k(\vec{x})]$ replaces $F(\vec{x})$ in eq. (2) for the numerical solution.

The weighted-sum, the nearest to the utopian and the min-max solutions result from eq. (5) with $\rho = 1, 2$ and ∞, respectively. For example, for the min-max solution eq. (5) reduces to

$$P[F_k(\vec{x})] = \max_k \left[w_k \left| \frac{F_k(\vec{x}) - F_k^0}{F_k^0} \right| \right] \tag{6}$$

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

For the application case presented in this paper, eq. (5) can be adapted to two criteria in the objective function. This leads to eq. (7) where P is the objective function and F_1 and F_2 are the two criteria used, steel weight and production cost. F_1^0 and F_2^0 represent the optimum values of the criteria F_1 (steel weight) and F_2 (production cost), respectively obtained when the optimisation is performed only with one criterion as a single objective.

$$P = \left[\left(w_1 \left| \frac{F_1 - F_1^0}{F_1^0} \right| \right)^{\rho} + \left(w_2 \left| \frac{F_2 - F_2^0}{F_2^0} \right| \right)^{\rho} \right]^{1/\rho} \tag{7}$$

2.7 Mapping the Entire Pareto Front

When dealing with multi-criteria problems, it is recommended 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 be based on the criteria considered in the optimisation formulation as well as additional considerations not included in the model. This is feasible when there are two criteria but rapidly becomes impractical due to computational time and visualisation reasons when the number of criteria reaches three and more. In order to map the entire Pareto front, the following three 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 weighting factors.
- *Repeated weighted min-max solutions:* If the feasible object function space does not have a slope exceeding w_1/w_2, weighted min-max solutions can be obtained for systematically varied weighting factors.
- *Multi-criteria optimisation methods:* Multi-criteria implementations of Generic Algorithms (MOGA), Evolutionary Algorithms, Particle Swarm Optimisation etc. can produce the entire Pareto front in a single optimisation run.

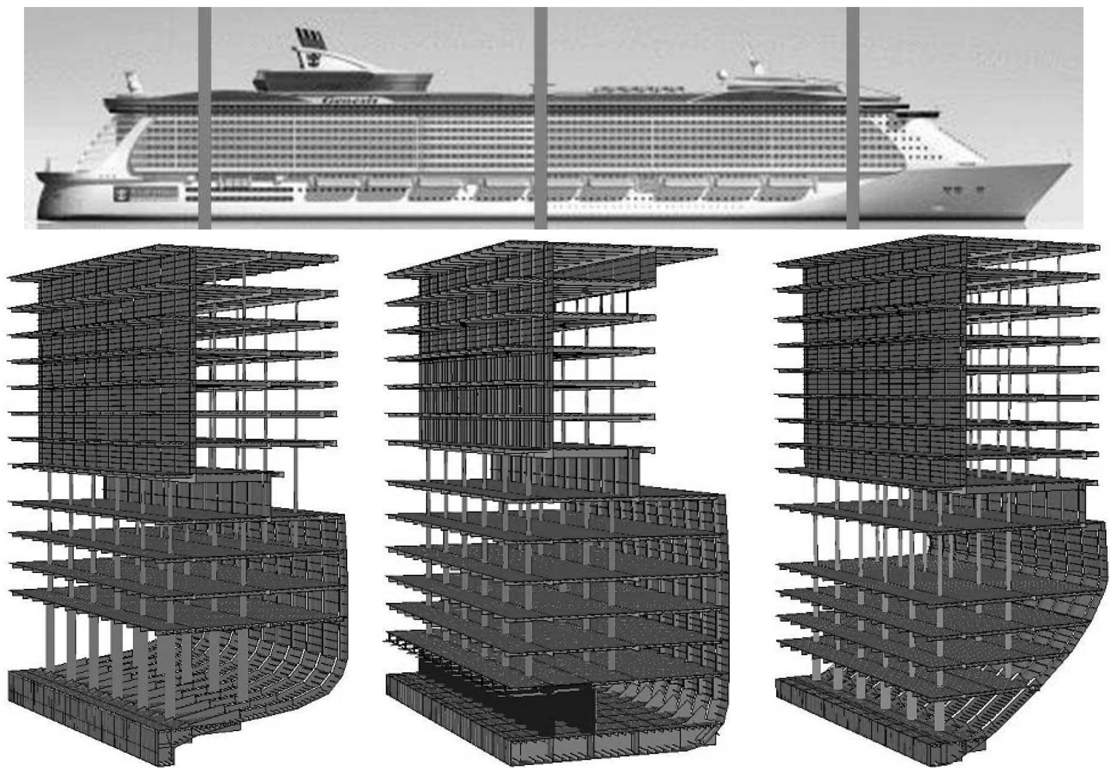
In this paper, the repeated weighted sum solution was used to map the entire Pareto front.

3 Applications

The approach is applied to the structural optimisation of a cruise ship with the length between perpendiculars *280* m and the overall length *315* m, Fig. 1.

3.1 Model

Three sections of the ship of the height *42* m and breadth *40* m, characterised by *14* decks, were simultaneously optimised, Fig. 1. Only half of the symmetrical structure was modelled.



aft section	midship section	fore section
81 panels	*78* panels	*93* panels
24 pillars	*25* pillars	*28* pillars

Fig. 1: Three sections of a cruise ship.

The structural analysis used here is applicable only to cylindrical structures, obtained from a 2D model extruded in the longitudinal direction. Fore and aft sections could not be analysed and optimised together with the midship section, but independent optimisation is possible. The main inconvenience of an independent optimisation is that several design variables (e.g. the stiffeners spacing) that should be the same for the considered parts, may have different values at the local optimum.

A multi-structures module was developed in order to optimise several structures simultaneously. The approach links design variables between these structures, e.g. the midship, fore and aft sections of a cruise ship. The multi-structures module optimises simultaneously the three sections and preserves compatible design variables. However, only some common design variables can be taken into account such as stiffener spacing or plate thickness. The link between the three sections is done by adding new equality constraints between variables. There is no link concerning strain or stress.

3.2 Load cases

The following load cases were considered for each section:

- sagging and hogging vertical bending moments with an exceedance probability of 10^{-8}, including still water pressures and static deck loads
- sagging and hogging vertical bending moments with an exceedance probability of 10^{-5}, including still water and wave pressures and static deck loads
- still water and wave pressures and static and inertial deck loads

Bending efficiency coefficients were considered in order to take into account the participation degree of each deck to the longitudinal bending. The hull girder shear force and bending moment depend on the distribution of gravity and buoyancy forces along the entire ship for a specific load case. If only a part of the ship is modelled, the shear force and moment in the studied section will not be the same as when the entire ship is considered. Therefore, the applied bending moment and the length of the model were artificially adjusted to obtain the adequate moment and shear force in the studied section for each of the five considered load cases at the fore and aft sections.

For the considered 2D model extruded in the third direction, hydrodynamic pressures and deadweight do not change along this direction. Applying bending moment M_1 to the extremities of the model, the equations for the bending moment M and shear force T become

$$M = M_1 + \frac{px^2}{2} - \frac{pxL}{2} \tag{8}$$

$$T = p\left(\frac{L}{2} - x\right) \tag{9}$$

x is the distance from the extremity and L the length of the model. For the whole ship the behaviour is more complex (pressure is not constant over the length) and must be studied to know the real distribution of the bending moment and the shear.

A position x should be selected where the structural constraints are applied: the equations above show that for each position x values of M and T differ. For the studied section, eq. (8) is solved to find bending moment M_1 that should be applied at the extremity and length L leading to the required M and T. Consequently the length of the model will be artificial and varying with load case.

4 Optimisation

4.1 Design variables

The three ship structures are modelled respectively with 81, 78 and 93 stiffened plate elements, Fig. 2. The structural response of the model is found by solving the non-linear differential equations of each stiffened plate element, *Rigo* (2001a) and *Rigo* (2001b). For each element, nine design variables are used:

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

1694 design variables were used for the whole ship model (*3* ship sections), which represents on the average of *6* to *7* design variables per stiffened panel. Only plate thicknesses and longitudinal members were optimised.

An optimisation algorithm which can solve non-linear constrained problems was used, based on a convex linearisation of the non-linear functions and a dual approach, *Fleury and Braibant* (1986). This algorithm is especially effective because only few (typically less than *10*) iterations are required.

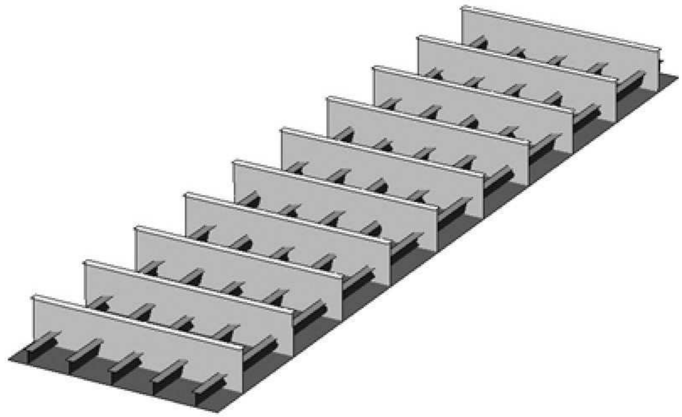


Fig. 2: Stiffened plate element.

4.2 Objective function

Production cost and minimum weight constitute the objectives considered. Production costs were subdivided into three categories, including material, labour and overhead costs, eq. (11).

The evaluation of *material costs* consists of quantifying volumes required for construction and obtaining prices from suppliers and subcontractors.

The best alternative to empirical formulations for *labour costs* is an analytic evaluation. It requires knowledge of the working time required for each standard labour task associated with a workstation as well as the distribution of the entire construction process to stations. The following equation

$$LC = QC \cdot UC \cdot KC \cdot AC \cdot WC \tag{10}$$

provides the Cost Evaluation Relationships (CERs) for the labour cost of a stiffened panel for a simple manufacturing activity (e.g. welding of two assemblies or the tacking of steel profiles). QC denotes quantity (welding length, number of brackets etc.), UC unitary cost (cost per unit), KC corrective coefficient used to calibrate the unitary cost, AC accessibility or complexity coefficient and WC workshop coefficient.

The relationships QC·UC are typically derived directly from the measurement of a single physical attribute such as dimensional data (plate thickness, profile length, profile scantling, welding length, welding throat etc.) or quantitative data (number of profiles, number of brackets, number of cut-outs, number of holes etc.) for QC and the unitary cost of carrying out the activity for UC, e.g. the labour for steel block assembly in hour/t or the labour for welding in a vertical position in hour/m. The unitary costs UC vary according to the type and the size of the structure, manufacturing technology, experience and facilities of the construction site, country etc. Usually, unitary costs are defined as a function of one or more design variables, e.g. plate thickness, welding throat, welding type (butt or fillet), welding position, bevels, profile scantling.

The catalogued cost scales (cost-per-unit) available do not always reflect accurately the expected costs. Therefore, these cost scales should be modified with an appropriate adjustment factor KC. This procedure has the double advantage of preserving the cost scales for control purposes and allowing the impact simulation of a facility or technology investment on the cost. An additional coefficient AC is introduced into the equation in order to adjust manufacturing cost assessment for increasing or decreasing relative accessibilities (complexities) of the ship or its sub-assemblies. The productivity changes from a workshop to another; the adjustment coefficient WC reflects gains or losses in productivity between workshops.

Production cost was calculated with an advanced cost module taking into account a detailed shipyard database. Around *60* fabrication operations are considered covering 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, *Toderan et al.* (2007).

Overhead cost includes any expenses that cannot be attributed to a specific work station of the construction process, but are linked to construction.

Combining these contributions, the production cost PC is

$$PC = MC + LC \cdot HC + OC \qquad (11)$$

MC is the material cost, LC labour content in man-hours, HC hourly cost and OC overhead cost.

In addition to the production cost, a maintenance and repair life cycle cost-earning model is currently studied. *Turan et al.* (2009) provided a theoretical and practical foundation but further research is required to develop maintenance and repair cost modelling systems.

4.3 Design constraints

Constraints are linear or non-linear functions of design variables, either explicit or implicit, expressing the limitations that the user wants to impose on the design variables. Different types of constraints were considered:

- *Technological* constraints due to manufacturing limitations
- *Geometrical* constraints guaranteeing a functional, feasible and reliable structure, based on expert knowledge about possible local strength failures (web or flange buckling, stiffener tripping etc.) or guaranteeing welding quality and easy access to the welds. For instance, welding of *30* mm with a *5* mm plate is not recommended.
- *Structural* constraints represent limitations in order to avoid yielding, buckling, cracks etc. and to limit deflections and stresses. These constraints are based on solid-mechanics phenomena and modelled with rational equations based on physics, solid mechanics, strength and stability analysis etc.
- *Global* constraints impose limitations on the centre of gravity (ship stability), fabrication cost or global bending strength (classification rules).
- *Equality* constraints are often added to avoid discontinuity of design variables. Panels of the same deck normally have the same thickness, stiffeners spacings are often homogeneous etc.

The problem is highly constrained and the adequacy of the used constraints can significantly influence the solution. In this case study, *3388* technological, *1696* geometrical, *16809* structural and *6* global constraints were used. All constraints were applied to a ship at the end of its service life, i.e. for the corroded structure after *30* year of life.

Tab. 1: Design constraints for *3* ship sections.

	Aft	Midship	Fore	Total
Number of strake elements	81	78	93	252
Design variables	550	460	684	1694
Technological constraints	1100	920	1368	3388
Geometrical constraints	558	446	692	1696
Structural constraints	5734	4035	7040	16809
Global constraints	2	2	2	6
Equality constraints	0	0	0	0
Total constraints	7394	5403	9792	21899
Equality constraints between sections				1173
Total				23762

5 Optimisation results

5.1 Pareto front

The Pareto front, Fig. 3, was mapped using the repeated weighted sum solutions. The process altered the weights in the weighted sum solution and solved the optimisation problem for each of the weights. *50* points were calculated. The Pareto front was generated over *28* hours with a Pentium Dual Core *2.52* GHz and *3* GB of RAM. The utopian point, the min-max solution and the initial solution are also shown. The min-max solution was obtained for a weighting factor 0.59 for the production cost and 0.41 for the weight. This analysis 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 taking into account factors and constraints that were not included in the optimisation problem.

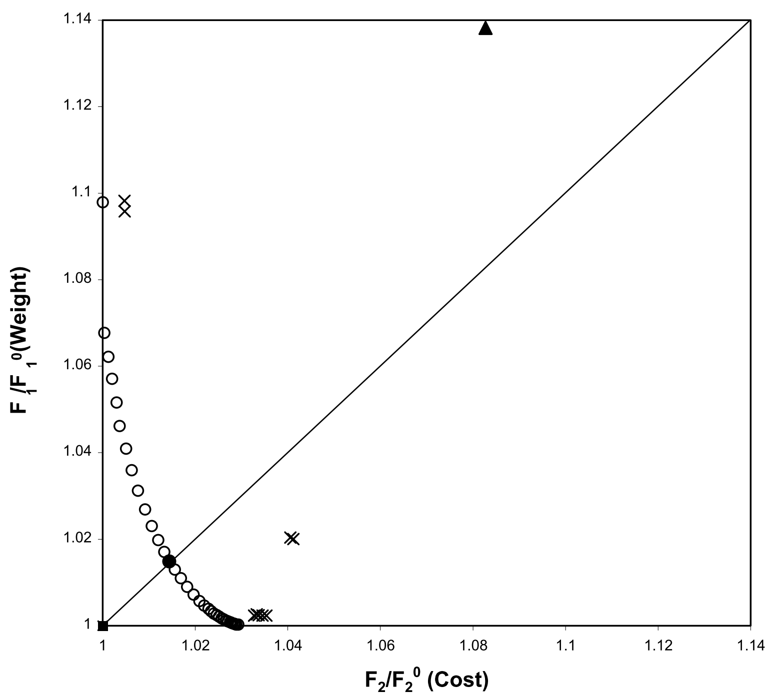


Fig. 3: Pareto front (○), initial design (▲), utopian point (■), not converged points (×) and the min-max solution (●).

5.2 Results

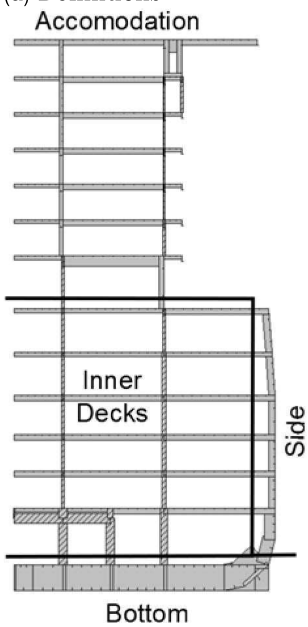
Table 2 provides the cost and steel weight savings between the initial and the minimum cost and minimum weight optimal designs, as well as min-max solution. Cost optimisation generates a significant increase of steel weight, thus the cost optimal solution is far from the optimum regarding weight. The min-max solution appears much more efficient for this ship than the other optimal solutions. This case study shows the advantage of considering multiple objectives.

Tab. 2: Savings in % of cost and steel weight.

	Weight optimisation	Cost optimisation	Min-max solution
Steel weight	-12.72	+5.1	-11.3
Production cost	-0.88	-4.52	-1.58
Material cost	-8.5	+0.89	-8.38
Labour cost	+4.22	-8.8	+2.96

Fig. 4 gives breakdowns of the gains for the main parts of the ship, i.e. bottom, side shells, inner decks and accommodations. Plate thickness was reduced everywhere. The highest gains in production cost and weight are obtained for the side shells.

(a) Definitions



(b) Breakdown table of savings in %

	Production cost	Steel weight
Bottom	-0.1	-7.71
Side	-18.42	-31.56
Inner decks	+4.33	-8.77
Accommodations	-1.92	-10.43

Fig. 4: Breakdown of improvements in min-max solution.

5.3 Validation of the results

The final scantlings of the min-max solution were verified with Bureau Veritas rules; all plates and stiffeners had thickness greater or equal to those required by the rules. Note that the optimisation did not take fatigue into account. Information of structural details required for reliable fatigue assessment is available only in the next design stages. This is a significant obstacle for an early design stage, because the decisions taken at this stage have a strong influence on the fatigue life of the hull girder. Structural modifications after the early design stage are expensive. In order to overcome this problem, a study is currently conducted to implement a rational model for fatigue assessment already in early design, *Remes et al.* (2009).

6 Conclusions

A structural multi-objective optimisation of a cruise ship has been undertaken. The developed method allows performing multi-criteria optimisation considering both production cost and weight in the objective functions. The entire Pareto front can be mapped using a process which alters the weights in the weighted sum solution and solves the optimisation problem for each of the resulting problems. Useful specific compromised solutions from the Pareto front, e.g. the nearest to the utopian and min-max solutions can be easily calculated.

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

These developments improve significantly the capability of the method to provide optimal scantling solution at the early stage of the design process. The method proposed here is suitable for basic design studies dealing with general multi-objective optimisation problems. However some additional developments such as early assessment of fatigue and a holistic life cycle cost module are still required.

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