Multicriterion Scantling Optimization of the Midship Section of a Passenger Vessel considering IACS Requirements

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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 optimization objective function. Moreover, IACS requirements regarding bending, shearing and buckling strength are currently available in LBR-5. Until now, only raw scantling optimizations were performed with LBR-5. Thanks to new developments using heuristics, it is now possible to realize discrete optimization so that a standardized and "ready to use" set of optimum scantlings can be obtained.

Keywords

Multicriterion optimization; scantling design; IACS requirements; passenger vessel; LBR-5 software.

Introduction

Scantling design involves multiple conflicting criteria, objectives or goals. It is, thus, a multicriterion optimization problem. The traditional approach to solve this type of problem is to use a weighted-sum of the multiple criteria as the optimization objective function. The conventional scalar numerical optimization methods can then be used to solve the problem. In this paper, the authors employed the LBR-5 software which uses the optimization algorithm CONLIN, based on convex linearization and a dual approach (Fleury, 1989; Rigo and Fleury, 2001). The most common definition of the multicriterion optimum is the Pareto front, which results in a set of solutions. In a design situation, one specific solution must be sought for implementation. Useful specific compromise solutions can then be defined, e.g. weighted sum, min-max and nearest to the utopian solutions.

The longitudinal scantlings of the midship section of a passenger ship were optimized with LBR-5. This section is characterized by 14 decks, a 40 m breadth and a 45 m height. IACS common structural requirements were imposed, while production cost and moment of inertia were both considered in the objective function. A maximum weight constraint was applied. The entire Pareto front was calculated, and the scantlings of the equal weights nearest to the utopian solution are shown in this paper.

Overview of Multicriterion Optimization

The following overview is adapted directly from Parsons and Scott (2004).

Single Criterion Problem

The single criterion optimization 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 optimization criterion or objective function $F_1(\mathbf{x})$ that depends on the N unknown design independent variables in the vector **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 **x**. The minimization form is general because a maximization problem can be solved by minimizing the negative or the inverse of the cost function.

Multicriterion Optimization

The multicriterion optimization 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 optimization criteria $F_1(\mathbf{x})$ through $F_K(\mathbf{x})$ and each depends on the N unknown design variables in the vector **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.

Pareto Optimum Front

When there are multiple conflicting criteria present, the most common definition of an optimum is Pareto optimality. This term was first articulated by the Italian-French economist V. Pareto in 1906. 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*. Note that 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 result can be reached by considering factors not able to be included in the optimization model.

Global Criterion Optima

As noted, 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:

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

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

where F_k^0 is the value of the criterion F_k obtained when that criterion is the single criterion used in the optimization - 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.

Mapping the Entire Pareto Front

In dealing with multicriterion problems, it is highly desirable to be able to study the entire Pareto front. This action 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 modeled in the optimization 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.
- *Multicriterion optimization methods*. Multicriterion implementations of Generic Algorithms (MOGA), Evolutionary Algorithms, Particle Swarm Optimization, etc. can obtain the entire Pareto front in one optimization run.

LBR-5 Software

The scantling design of ships is always defined during the earliest phases of the project. That is, the preliminary design stage or the first draft that corresponds in most cases to the offer. At this time, few parameters (dimensions) have been definitively fixed, and standard finite element modeling is often unusable, particularly for design offices and modest-sized shipyards. An optimization tool at this stage can, thus, provide precious help to designers. This is precisely the way the LBR-5 optimization software for stiffened structures was conceptualized (Rigo, 2001).

Scantling Design Variables

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

- Plate thickness.
- For longitudinal members (stiffeners, crossbars, longitudinals, 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).

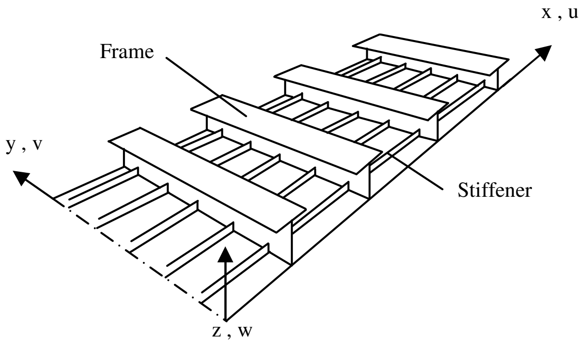

Fig. 1: LBR-5 Stiffened Plate Element

Rule-Based Structural Constraints

Structural constraints from IACS requirements and Bureau Veritas rules are now available in LBR-5. They are listed below:

- Hull girder strength (IACS requirements)
  - Bending/shear strength
    - $\sigma_a \leq 175/k$
    - $\tau_a \leq 110/k$

    with k = material factor

    σ_a = hull girder bending stress (N/mm²)

    τ_a = hull girder shear stress (N/mm²)
  - Buckling strength
    - Compressive buckling of plates
    - Shear buckling of plates
    - Compressive buckling of stiffeners
- Local strength (BV rules)
  - Stiffener bending strength

Multicriterion Optimization

Production cost, weight and moment of inertia can be used as objective function in LBR-5. They are considered simultaneously through Eq. 3 in a multicriterion problem. The Pareto Front can be mapped in LBR-5 by using the *Repeated weighted sum solutions* method described above.

Discrete Optimization

The scantling design variables are discrete by nature. The objective functions are nonlinear functions. As the objective and the constraints are nonlinear functions the scantling optimization of a ship belongs to the class of mixed-integer non linear problems (MINLP).

A heuristic is used to solve this problem (Bay et al., 2007). The method is a two-stage local search heuristic. At a strategic level, a *dive and fix* method controls the

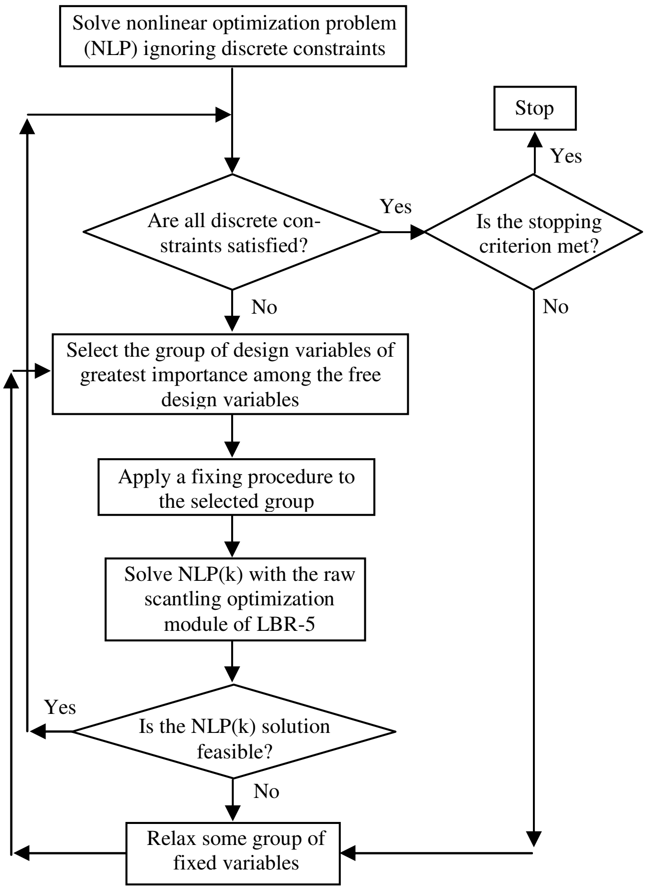

Fig. 2: Heuristic Flowchart

definition of nonlinear sub-problems. The generation of the explicit sub-problems and their optimization are performed at a tactical level by using the raw scantling optimization module of LBR-5 based on CONLIN algorithm (Fig. 2).

An initial scantling is given by the designer. This solution may be feasible or not, discrete or not. Given an initial scantling the heuristic starts computing an optimal solution of the NLP problem, i.e. the problem where all discretization constraints have been removed and all the variables are free (no variable has its value rounded and fixed).

At each iteration k, the heuristic starts with the solution of the previous iteration k-1. The group of design variables (for instance, plate thickness of all stiffened panel elements) of greatest importance among the free design variables is selected and the values are fixed according to a rounding procedure. This operation leads to a NLP(k) sub-problem which is solved with the raw scantling optimization module of LBR-5. If the NLP(k) problem appears to have no feasible solution, a relax procedure is applied to free the design variables that have been fixed at the previous iteration and the algorithm moves to the next iteration. If a feasible solution for NLP(k) is obtained, the algorithm moves to the next iteration (*diving*). This iterative scheme is repeated until all discretization constraints are satisfied.

The round and the relax procedures are the core of the *dive and fix* heuristic. They act jointly to define which regions of the solution space will be explored. They control the creation of the nonlinear sub-problems NLP(k) at each iteration by defining how the values for the design variables are rounded and fixed, taking into account the results of the previous iterations.

Application

Geometry and Load Cases

The midship section of a passenger vessel was imported into LBR-5 from Mars2000 (scantling verification software based on Bureau Veritas rules). Indeed LBR-5 allows the direct importation of Mars2000 geometry and loads. The Mars2000 model was initially prepared by Aker Yards, France. The section is characterized by 14 decks, a 40 m breadth and a 45 m height. Fig. 3 shows the imported midship section (transversal members and pillars were added manually). A total of 118 LBR-5 stiffened plate elements were used to define the model including 19 pillars. Based on structure symmetry, only the half structure was modelled.

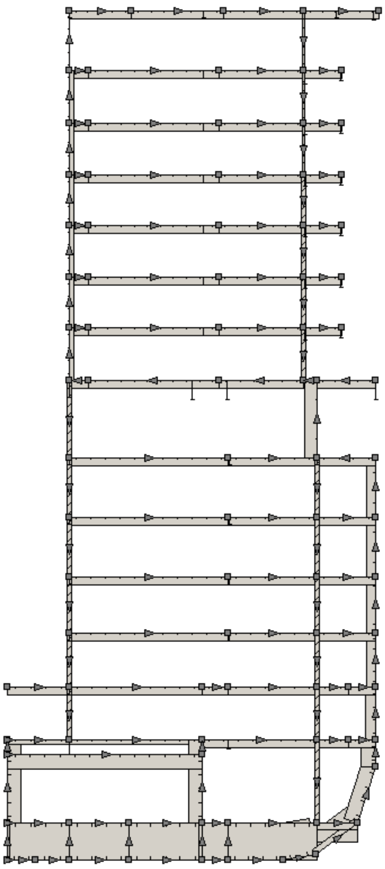

Fig. 3: LBR-5 Model of the Midship Section

Ten load cases were considered in the calculation:

- Two "IACS load cases" (hogging and sagging): still water bending plus wave bending with a probability of exceedance = 10^{-8}
- Eight "BV load cases" (hogging and sagging)
    - Load case "a": still water bending plus wave bending with a probability of exceedance = 10^{-5} plus sea pressure (scantling draft and ballast draft)
    - Load case "b": still water bending plus wave bending with a probability of exceedance = 10^{-5} plus sea pressure (scantling draft and ballast draft) plus inertial pressure

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.

Discrete Optimization

The solution space for the discrete design variables was defined with a step of 1 mm for the thicknesses and 10 mm for the web height and flange width. The spacing remains a continuous design variable.

Objective function

Production cost and moment of inertia (stiffness) were the two objectives considered in this application. The production cost was calculated with an advanced cost module that takes into account the detailed shipyard database of Aker Yards, France. 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).

Constraints

In each LBR-5 stiffened plate element, structural constraints were applied according to IACS requirements and BV rules (Table 1).

Table 1: Structural Constraints

	Load case		
	"IACS"	BV "a"	BV "b"
$\sigma_a \leq 175/k$	X		
$\tau_a \leq 110/k$	X		
Compressive buckling of plates	X		
Shear buckling of plates	X		
Compressive buckling of stiffeners	X		
Local stiffener bending strength		X	X

Equality constraints were also imposed between the longitudinal stiffener spacing of any two LBR-5 stiffened plate elements that are vertically aligned.

Global constraints regarding the hull girder minimum section modulus and moment of inertia were considered. These constraints were taken from IACS requirements. A maximum weight constraint was also applied. Moreover, the structural vertical center of gravity was not permitted to rise during the optimization process to avoid stability problems.

The problem can thus be summarized as follow:

- 118 LBR-5 stiffened plate elements,

- 10 load cases,
- 383 scantling design variables,
- 4 global constraints,
- 1418 structural constraints,
- 56 equality constraints.

Pareto Front

The entire Pareto front was obtained using a process that randomly altered the weights in the weighted sum solution and solved the optimization problem for each of these problems. The resulting convex Pareto front is shown in Fig. 4. More than 200 points were calculated. To avoid large computing time only raw scantling optimizations were performed. The Pareto front was generated in about 100 minutes with a Pentium 2.40 GHz and 512 Mo of RAM desktop. The equal weights min-max and nearest to the utopian solutions are also shown in Fig. 4.

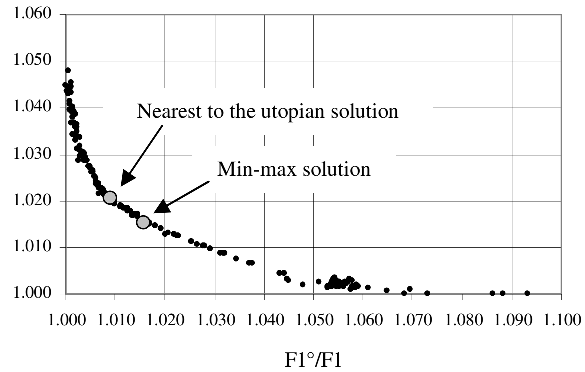

Fig. 4: Pareto Front
(F1 = Moment of Inertia and F2 = Production Cost)

Using Fig. 4, 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 optimization problem.

Equal Weights Nearest to the Utopian Solution

The equal weights nearest to the utopian solution was also calculated by performing a discrete optimization. The cost and stiffness savings, obtained by comparison with the initial scantling, are given in Table 2.

Table 2: Cost and Stiffness Savings

	Saving (%)
Production cost	1.758
Moment of inertia (stiffness)	14.992

Note that the initial scantlings did not satisfy some structural constraints, otherwise the cost savings would have been higher. Moreover, the associated weight to the cost objective could be increased to improve the cost saving, if desired.

The scantlings of the equal weights nearest to the utopian solution are shown in Figs. 5~6. For confidentiality reasons, the scantlings are expressed in percent of change from the initial design.

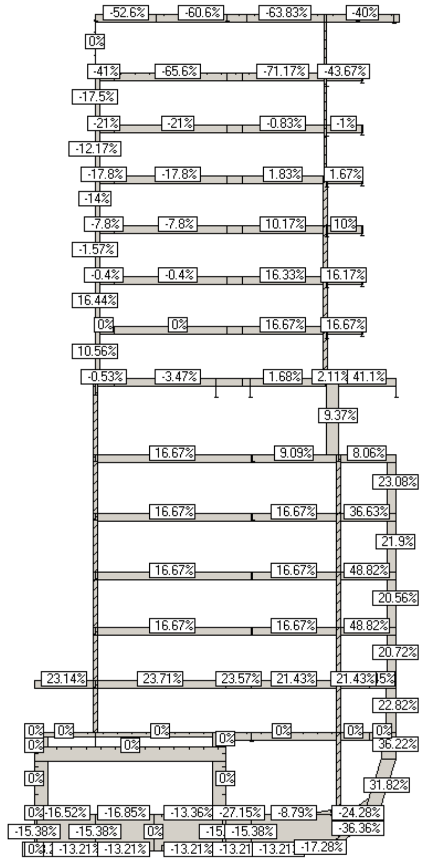

Fig. 5: Change in Plate Thickness (%)
(plus = decrease; minus = increase)

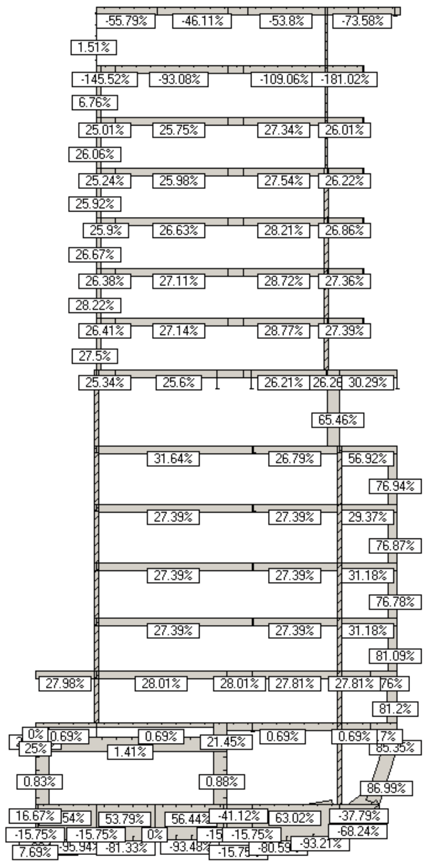

Fig. 6: Change in Stiffener Section Modulus (%)
(plus = decrease; minus = increase)

Conclusions

Thanks to the recent developments outlined here, the LBR-5 software allows performing multicriterion optimization by considering production cost, weight and moment of inertia in the optimization 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 optimization 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, it is now possible to perform discrete optimization with LBR-5 so that a standardized and "ready to use" set of optimum scantlings can be obtained.

Finally, IACS requirements, regarding bending, shearing and buckling strength are now available in LBR-5.

Acknowledgement

The present research was achieved with the funding and support of MARSTRUCT Network of Excellence (FP6 project funded by EU), IMPROVE (FP6 project funded by EU) and AKER YARDS SA, France.

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