EARLY STRUCTURAL ASSESSMENT AND OPTIMISATION OF PASSENGER SHIPS

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SUMMARY

A multi-criteria optimisation of a passenger ship is conducted in this paper. Minimum production cost and minimum steel weight are the both objective studied. Moreover the study answers to the following question: "From when will the higher costs of high tensile steel should be offset by a gain of steel weight?". For a passenger ship, a significant reduction of the steel weight, for a controlled raise of the gravity centre, should lead either to a reduction of fuel consumption either to an additional deck, which for a ship owner means a faster return on investment. Pareto frontiers are obtained and results are validated by classification rules.

1. INTRODUCTION

Preliminary design refines the major ship characteristics affecting cost and performance in order to offer detailed specifications, delivery date, price, etc. to the ship owner. Certain controlling factors, such as length, breadth, horsepower, payload or deadweight would not be expected to change significantly in this phase. It is in preliminary design, however, that basic decisions are made, such as structural components, scantlings and the principal structural materials such as use of high tensile steel, ordinary steel or combination of these. It is therefore the most relevant period to assess the steel weight and production cost, to compare fabrication sequences and to find the optimal frame/stiffener spacings and the most suitable scantling to increase the ship life cycle performance.

2. LOCAL OR GLOBAL OPTIMISATION?

Nowadays we can state that performing concurrent design tasks is the current practice, at least for the large design groups and shipyards. But, can we say the same concerning the optimisation tasks? Is it possible to perform concurrently optimisation tasks?

Here after, we try to answer at this question and to identify the place and the challenge of the "ship structure optimisation" in the global context, which is the "ship optimisation".

The ship design optimisation is a kind of natural tasks that the naval architect tries to perform during the various loops of the design spiral. The "Spiral" is definitively an optimisation process. Each loop can be considered as an iteration of the optimisation process. But when specialists are called, as it is usually the case at each step of the design (see spiral, Figure 1), the concerned optimisations become definitively local optimisations.

By local optimisation we understand an optimisation that tackles a single specific issue (hydrodynamics, propulsion, structure, safety, etc.), the others being frozen. For instance, is it popular to consider the hull form and the General Arrangement (GA) as fixed, when we optimize the ship structure (scantling) to reduce the weight and/or the production cost.

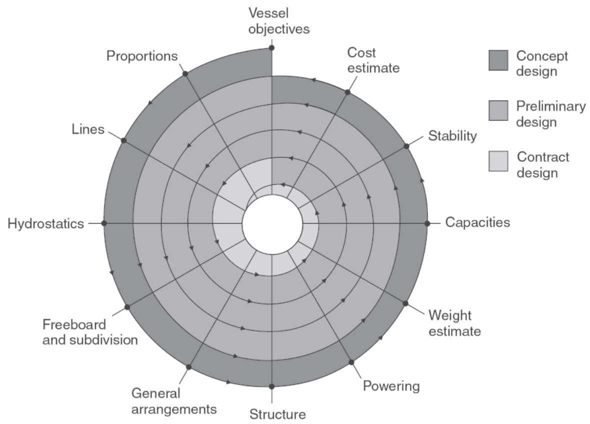


Figure1: Typical Design Spiral as presented in various teach book [1]

Similarly, in CFD optimisation analyses we consider often the structure (weight, cost, gravity centre) as fixed. Alternatively, rules of thumb or statistical curves (weight = Fct (Δ, L, B, T, Cb, etc.)) are used to adjust the weight according to the hull form. There are also the ship production teams, which try to optimize workflow and workload to reduce delivery time. They are working in the field of *Design for Production* and the target is to optimize the ship focusing on the production keeping fixed the other parameters (hull form, scantling, block splitting, etc.), [2].

It is clear and obvious that it is not suitable neither efficient to perform sequential local optimisation. But nowadays, it is still the current industrial practice to reach an improved design. For sure, engineers know that they do not reach the global optimum but they are confident to be in the right direction.

Local optimisation is an industrial practice starting 20-25 years ago when advanced dedicated numerical tools were available. These tools were specialized in one design tasks, as modifying the hull form to increase speed, reduce fuel consummation or improve seakeeping, improving ship structures to reduce weight or production cost, or modifying GA for better safety (fire escape) and increasing the number of cabins, etc.

Mathematicians have demonstrated that performing sequential local optimisation may not drive to the global optimum. So the solution is definitively to move to a global optimisation. That means an optimisation in which the technical interacting tasks are considered simultaneously.

Here above, we have explained that for designing a ship it is nowadays possible to tackle all the technical tasks altogether. Therefore, the current solution is a series of concurrent design tasks.

On the other hand, for the optimisation it is clear that it is nowadays impossible to perform a global optimisation (all in one) – at least not with the current technologies available in the ship and marine industry. So the solution is to perform a series of local optimisation. This is the current practice. There are indeed on the market efficient and reliable tools that perform hull form optimisation, scantling optimisation, GA optimisation, etc.

Therefore the challenge for tomorrow is to move to a concurrent optimisation. That means that several tools will run simultaneously, using the same data and the same initial design (geometry, loads, etc.). There are currently some tentative to initiate such procedure (such as VRSHIPS, VIRTUE (CFD) and IMPROVE (Structure) EU projects). All of them are facing similar problems:

- Difficulty to share similar data. Standard formats are required and must be accepted by the different developers, which are in fact often competitors. Currently, keeping a different format is a way to avoid competitors and repulse new developers with alternative modules (which can be more effective than own module).
- Difficulty to move from CAD data to CFD, from CAD to structural models (FEM) and above all, from CFD to structural models, and vice versa.
- Level of accuracy of the CAD data is rather different then the expected level required for structure analysis. Some data may be missing. But, more often, too much CAD data are available to easily and automatically produce a coarse mesh for FEA. In this case, how to automatically generate a simplified model from a detailed CAD model, and later, when the optimisation is achieved, how to update a detailed CAD model with data (usually geometry) coming from a coarse mesh? The key issue is to avoid re-meshing and manual data-transfer, or even worse, retyping the data.
- Most of the tools are in fact “black boxes” for the other developers. Therefore data exchange is rather slow and cumbersome.

In conclusion, a promising direction of research is the development of a concurrent optimisation platform, which could be the intermediate step between a series of sequential local optimisations and a full global optimisation which remains a rather long term goal.

3. SHIP STRUCTURE OPTIMISATION

3.1 STATE OF THE ART

Ship design traditionally has been based on a sequential and iterative approach. With the availability of non-linear optimisation tools, many researchers have attempted to solve the ship design problem using different optimisation techniques. This allows the development of competitive new designs while considering various interactions within the system in a shorter time span.

The first marine structure optimisation studies were made practically by hand by [3]. Then, with computer assistance, researchers tried to develop design and optimisation algorithms. Optimisation appears in the works of [4] and [5]. Few years later, an important step for optimisation of marine structures has been done by [6, 7]

Forty years ago, standard optimisation tools focused on a single and limited aspect (e.g. shape, scantling, propeller, ultimate strength, etc.) and a single objective was targeted (weight, resistance, cavitations, etc.). Nowadays, optimisation tools tend to adopt a more generic approach coupled with the fact that they have also become much more reliable.

The evolutions of design and optimisation techniques are well reported by [8, 9, 10, 11, 12, 13, 14, 15] have all integrated multi-criteria optimisation model that incorporate structural weights and/or production costs. The differences concern the selected design variables and the constraints (yielding, buckling, deflection, weight, cost, fatigue, etc.) as well as the analysis used to assess structural response (2D FEM, 3D FEM, analytical linear, analytical non-linear, etc.). However all authors unanimous agree that one single objective is not sufficient to model accurately the various aspects of the marine structures.

Preliminary design is the most relevant and the most effective period to modify design scantling and to compare different alternatives. The earlier information is known, the better decisions are taken in the design process. Unfortunately, it is often too early for efficient use of many methods mentioned before.

3.2 DEFINITION

Before to go ahead, it is necessary to clarify the meaning of *ship structure optimisation*. Indeed the meaning may defer according to the person. Naval architects may understand general arrangement of the ship, location of the watertight bulkheads and decks, etc. The engineers of the structural units will probably think about scantling, types of framing (longitudinal, transverse or mixed), types of stiffeners (bulb profile, T bars, L shape, etc.), frames and stiffeners spacing's but will consider the structural GA as fixed.

Both of them are right. The difference comes from the fact that the two problems also solved one after the other by different persons, even if their problems interact. A possible way to avoid such misunderstanding is to rank structural optimisation tasks and methods in relation with the design level(s) at which they are performed keeping in mind that a structural optimisation task always refers to a specific design stage.

3.3 OPTIMISATION AND DESIGN STAGES

We usually identify 3 key steps in the design process, which are focusing on different levels (parts) of the ship structure and therefore have different optimisation needs (or focuses):

- The conceptual design stage
- The basic design stage
- The detailed design stage

3.4 THE CONCEPTUAL DESIGN STAGE

The conceptual design stage is characterized by:

- Few data are available.
- Performed within few weeks (i.e. 3 weeks).
- It is done by the naval architect team, which often does not rely so much on advanced numerical tools (such as optimisation tools).
- Focus is on the hull form, GA, propulsion and client requirements. Structure concerns are limited to weight and gravity centre.
- Even if a significant benefit in production (design for production) can be obtained at this level it is usually not a concern of the naval architects. They mainly focus on propulsion efficiency and global weight (assuming the weight is a relevant measure of the cost – which completely wrong if we think in term of production cost).
- A first CAD model of the hull form is available as stability is assessed.

3.5 THE BASIC DESIGN STAGE

The basic design stage is characterized by:

- Performed at the tender stage and finished with the contract (if any).
- Performed within few months (i.e. 2-3 months).
- Data are available but a lot are still missing.
- First structural calculations rely on classification tools such as the MARS2000 software of Bureau Veritas.
- It is the time to build a first 3D structural analysis (coarse mesh model, if a FEA is achieved, which is not always the case for small and medium ships).
- Potential cost savings are huge but a lot of uncertainties remain (due to concurrent engineering all the data are not available such as hydrodynamics loads like sloshing, slamming, etc.)
- Fatigue, vibration, noise are not considered in deep, even if they are key issues for the life cycle cost (particularly fatigue).
- It is the last chance to optimize the structure considering the production aspects (Design for Production)

3.6 THE DETAILED DESIGN STAGE

The detailed design stage is characterized by:

- Start when the contract is signed.
- Performed within several months (i.e. 5-10 months) and requires a large staff.
- Data are usually available.
- This stage is in fact not focusing on design but much more on validation based on quantitative assessments (stress, deflection, fatigue, bucking, vibration, noise, etc.) using advanced calculation tools that are available.
- Problems identified at this stage (such as fatigue or vibration) will be solved, but usually at high costs (adding new elements as brackets, delay in production, late change in elements which are already under production, etc.).
- Time is lacking as there is a strong constraint on the delivery date. The production of some elements may be started before the completion of all the detailed analysis (that explains the cost of future changes).
- Detailed analyses are time consuming and require significant experienced staff.
- It is definitively too late to optimize!

Based on this design procedure and design stages, what are the challenges to optimize ship structures?

- Need specific tools for conceptual and basic design stages. Indeed the early design stages are the only opportunities to select (by optimisation) an effective scantling considering the production requirements (simplicity, accessibility, least production cost, etc.). Later will be too late.
- Need tools that can be used at the conceptual design stage and later at the basic design stage without re-meshing or re-modelling. It could be the same tool that can handle more advanced data and have a wider scope (not only hull girder bending but also local structural constraints and production constraints). Or it can be different tools but avoiding re-meshing and re-modelling.

- Need a tool (or IT platform) that can be used with the limited data available at the first design stages to develop coarse mesh models dedicated to optimisation. Later, at the detailed design stage, these models must be able to be re-used (to save time and avoid re-meshing)
- Need fast and reliable modelling tools with interface with standard commercial CAD tools which are used by the naval architects and the classification societies.
- Need to target multi stakeholders (shipyard, ship-owner, classification society, IMO, etc.) and therefore multi objective optimisation.

4 A SHIP STRUCTURAL OPTIMISATION TOOL

As many optimisation tools, to optimize the structures of a ship we need objectives functions (criteria), design variables and constraints. We also need an optimisation algorithm (mathematical approaches as simplex, steepest descent, SQP or heuristic and genetic approaches).

4.1 OBJECTIVE FUNCTIONS

Objective functions depend on design variables in an explicit or implicit way, and may be assessed using numerical or mathematical expression. Typical objective functions are weight, production cost, life cycle cost, safety index, etc.

4.2 DESIGN VARIABLES

The design variables refer to a list of variables characterizing the design being optimised. The design variables can be the main dimensions of the structure (or part of it) but also local parameters such as the web thickness of the stiffeners of a given deck. Design variables can be the types of material or grade, the types of stiffeners (bulb, T, L), the overall section of a deck, etc. That explains we can have structural optimisation problems with few design variables (10-50) when only few main dimensions or parameters are selected, but also optimisation problems with few hundreds (100-1000) design variables (typically when the dimensions of each element are considered as independent design variables).

The selection of the design variables depends of the target of the optimisation and the design stage. In the next parts of this paper, design variables will typically be the scantling of the stiffened panels that compose the ship structures. A ship is usually composed of stiffened panels (sub-elements of the decks, bottoms, side shells, bulkheads, etc.). The design variables relate to the scantling of these stiffened panels. The panel scantling varies from panel to panel even if standardization is usually achieved for obvious production considerations. By panel scantling we understand the plate thickness, the frame spacing, the stiffener spacing and the dimensions of these frames and stiffeners (for instance HP200 or FB100x10).

4.3 DESIGN CONSTRAINTS

The design constraints mainly refer to a list of limits mathematically defined in order to keep a feasible solution at the end of the optimisation process. Selection and modelling of the constraints are in fact the most difficult part of the optimisation process. To get a reliable industrial solution, all the constraints involved in the structural design must be considered. Different types of constraints can be considered:

- *Technological constraints* (or side constraints) that provide the upper and lower bounds of the design variables.
- *Geometrical constraints* impose relationships between design variables in order to guarantee a functional, feasible and reliable structure. These are generally based on expert knowledge to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds. For instance, welding a plate of 30 mm thickness with another one of 5 mm thick is not recommended.
- *Structural constraints* are selected to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc (for the different limit states). These constraints are based on solid-mechanics phenomena and modelled with rational equations. By rational equations, we mean a coherent and homogeneous group of analysis methods based on physics, solid mechanics, strength and stability laws, etc. and that differs from empirical and parametric formulations. Thus these structural constraints may limit the deflection level of the structure, the stress in an element and the safety level related to buckling, ultimate resistance and tripping.
- *Global constraints* impose limitations for centre of gravity to ensure ship stability, fabrication cost to ensure producibility or flexional inertia to ensure the respect of the classification rules.
- *Equality constraints* are often added to avoid discontinuity of design variables and promote standardization. Panels of a same deck normally have the same thickness, stiffeners spacing’s are often homogeneous, etc.

Constraints find usually their origin from classification societies (rule based design) or from direct calculation (rational analysis, FEA, etc.), but also from the yard’s best practice and yard’s standards.

One of the main difficulties encountered when operating the optimisation methods are to correctly define the problem to be solved. This generally must be extracted from the whole design set of constraints, and put in a very formal way, which is not a straightforward operation, and actually not a natural way of thinking for a designer. In practice, this often leads to bad formulated problems and to a trial and error process to define things correctly.

Note that the difference between an objective function and a constraint is rather limited. Cost, weight, stress, gravity centre can be consider as a criteria that we want to minimize (maximize) or as a constraint (for which an upper or lower bound is fixed). So it is convenient when the user can select a criterion as a constraint or as an objective function. The relationship between the function and the design variables does not change.

4.4 OPTIMISATION ALGORITHMS

There are basically two main types of optimisation algorithms: the mathematical approaches (deterministic) and the heuristic and genetic approaches.

The purely deterministic approaches: starting from an initial design (feasible or not), the deal is to identify the best direction of propagation. Such methods are the simplex, the steepest descent, BFGS, SQP, Dual approach, etc. The authors experience and best practice concerns the convex linearization and dual approach (CONLIN software, [16]). Even with hundreds of design variables and thousands of constraints, the convergence in the feasible domain is guarantied and the optimum is reached within 10 iterations (this means 10 reanalyzed of the real problems).

The heuristic and genetic approaches are based on an "intelligent scanning" of all the feasible design space. These methods guaranty to find the global optimum (if enough runs are performed) and are not influenced by the initial design. They are very efficient and effective methods if the computation time for each reanalysis is short as few thousands of runs are often required.

It is not the relevant place to discuss here which approach is the best. In fact, there is no best method. The selection of a suitable method is highly problem dependant. In the framework of ship structure optimisation few relevant advantages and shortcomings can be highlighted.

The deterministic approaches: these methods consist in minimizing a given objective function by searching in the design space with help of deterministic algorithms. They are prone to converge to a local optimum, and they require expensive effort to assess the first derivative of the constraints. There are methods which do not require the first derivative but in that case much more iterations are usually required. It is a common practice to say that, at least, one iteration is needed per design variable if a linear approach is selected. Hopefully less iterations are required if the first (and sometimes the second) derivatives are used (Newton, BFGS, SQP, etc.). For instance, only few iterations can be required for a structure optimisation with hundreds of design variables and thousands of constraints.

- The solution depends of the initial design as it is a convergence process.
- They are suitable to solve problems with continuous design variables. The discrete design variables induced some difficulties.
- They cannot be used with noisy or non-derivable functions, as good quality gradients are requested.
- They need a completely clean and reliable estimate of the functions and their derivatives, and are not robust with respect to any failure in this area.
- They usually have a quick convergence (5 to 10 iterations), which counteracts the time-consuming gradients calculation.

The heuristic/stochastic approaches - This other type of algorithms consists in introducing a random strategy in the search for an optimum, which lets one expect to reach an absolute optimum after a sufficient number of trials.

- They are rather easy to implement, even if they require calibration to speed up the convergence for the specific problems.
- They are rather generic and the same algorithm can be used in many fields. That explains why they are now so popular.
- They are very efficient if the number of solutions is limited (that means a reduced number of design variables).
- Independent of an initial design.
- Prone to find the global optimum.
- Effective for multi objective optimisation to define the Pareto front.
- Much more efficient with discrete design variables than with continuous design variables.
- They are very robust with respect to inaccuracy of failures in the analyses.

This "random" but oriented search can be based on several types of algorithms:

- the simulated annealing methods which take roots in thermodynamics and uses the analogy with energy minimisation of physical systems ruled by the Boltzmann law. In this case, there is always a probability of a temporary increase of energy, during the cooling process, this probability decreasing together with the temperature.
- the genetic algorithm methods which take roots in the concept of natural selection (evolution theory). They are based on the simulation of the evolution of a population on which different kinds of operations are applied (combination,

mutation, etc.) and sub-mitted to a selection at each generation.

- the particle swarm methods [17]

5 THE FUTURE CHALLENGE OF THE PASSENGER SHIP STRUCTURE OPTIMISATION

Currently, as for the design, the most challenging issues concerning ship structural optimisation are the integration of fatigue as constraint and the implementation of direct calculations of the loads.

5.1 FATIGUE ANALYSIS

To be cost effective optimisation of scantling has to be performed at the basic design stage but the fine and very fine mesh models to assess fatigue are only available at detailed design stage. So, the challenge to implement fatigue in the ship structure optimisation is to develop fast and simplified fatigue assessment module to be embedded in the optimisation loop. Module requirements are to be fast and accurate. In optimisation the most important is to identify the direction of optimisation. The quality of the trend is more important than the quantitative quality of the values themselves. The importance is to identify the best alternative(s). At the end, a final assessment is performed in the detailed design stage, but it is essential to have a fatigue module at the basic design stage to compare different alternatives and provide the best directions of the optimisation.

5.2 DIRECT CALCULATION OF LOADS

Static loads and wave bending moments are quite well defined by classification societies. Still water bending moments are now easily assessed at the conceptual stage by the naval architects. But the hydrodynamic loads (sloshing, slamming, torsion moment, etc.), especially for innovative ships as trimaran, fast ferry or cruise ships which are strongly governing the ship scantlings, need advanced direct calculations that are usually not performed before the detailed design stage. So, as for the fatigue, the challenge to implement direct load assessment modules in the ship structure optimisation is the development of fast and simplified load assessment modules to be embedded in the optimisation loop.

6 LBR5 - A LEAST COST STRUCTURAL OPTIMISATION METHOD

To be attractive to 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 ships life cycle cost. However at this stage of the project, few parameters (dimensions) have been definitively fixed and standard FEM is often unusable, particularly to design offices and modest-sized shipyards. Therefore, an optimisation tool at this design stage can provide precious help. This is precisely the purpose of the LBR-5 optimisation software, [18, 19, 20].

LBR-5 is the French acronym of "Stiffened Panels Software" version 5.0. The purpose of the tool is the sizing/scantling optimisation of ship and offshore structures.

The structural analysis is performed on a model based on an extrusion of the cross section of the structure (2D+) solving the stiffened plate differential equations with Fourier series expansions, [20].

The whole model is made up of 3 basic modules (objective function, optimisation algorithm and constraints), which forms the framework of the tool.

Figure 2 shows the basic configuration of the LBR-5 software with the 3 fundamental modules (objective function, optimisation algorithm and constraints).

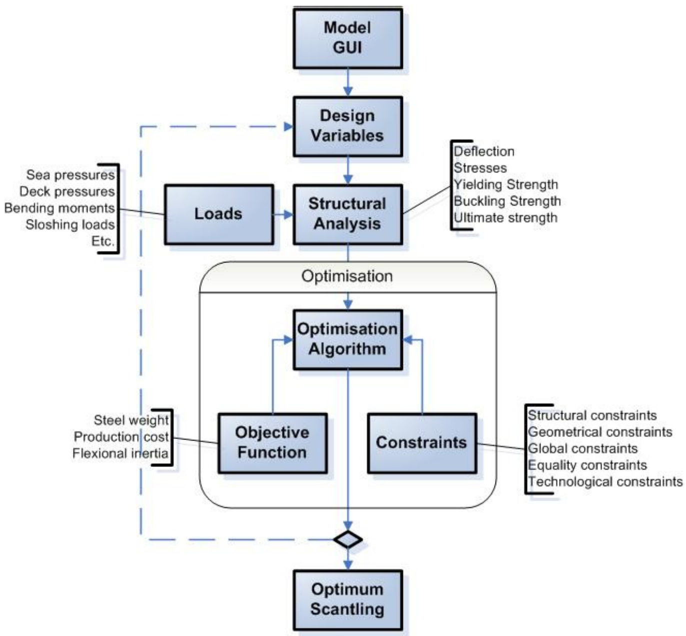


Figure 2 : Flow chart of the LBR5 optimisation software

6 APPLICATIONS TO OPTIMISATION OF CRUISE VESSELS

6.1 INTRODUCTION

This section relates to the structural optimisation of a cruise ship. The length between perpendiculars is about 280m and the overall length is about 315m.

6.2 MODEL

The amidships section of the ship has been implemented in LBR-5. The section is characterized by 14 decks, 40 m breadth and 42 m height. Based on structure symmetry, only the half structure is modelled. Figure 3 shows the considered section.

The structural module of LBR-5 allows the analysis of 2.5 D structures, obtained from the definition of a 2D model and extruded through the longitudinal direction.

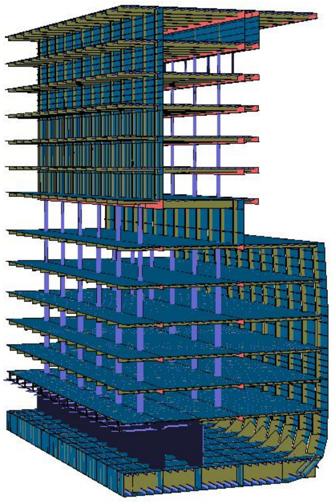


Figure 3: Amidships section of a passenger vessel (78 panels, 25 pillars)

6.3 LOAS CASES

The following load cases were considered:

- sagging and hogging wave vertical bending moments with a probability of 10-8; still water pressures; static deck loads;
- sagging and hogging wave vertical bending moments with a probability of 10-5; still water and wave pressures; static deck loads;
- no hull bending moment but maximum still water and wave pressures; static and inertial deck loads.

Deck bending efficiency coefficients were considered in order to take into account the participation degree of each deck to the longitudinal bending.

6.4 OPTIMISATION - DESIGN VARIABLES

The ship structure is modelled with 78 stiffened plate elements (Figure 3). The structural response of the model is solved with the resolution of the non-linear differential equations of each stiffened plate element, [18]. For each element, nine design variables are available:

- Plate thickness.
- For longitudinal members (stiffeners, cross-bars, 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).

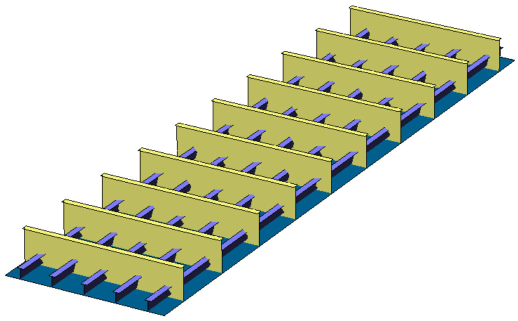


Figure 4: LBR-5 Stiffened Plate Element

In this case study 460 design variables were activated. Only plate thicknesses and longitudinal members have been optimised. To deal with this huge number of design variables the LBR-5 optimisation algorithm which can solve non-linear constrained problems has been used. It is based on both a convex linearization of the non-linear functions and a dual approach, [16]. It is especially effective because only few iterations are required; typically less than 10.

6.5 OPTIMISATION - OBJECTIVE FUNCTION

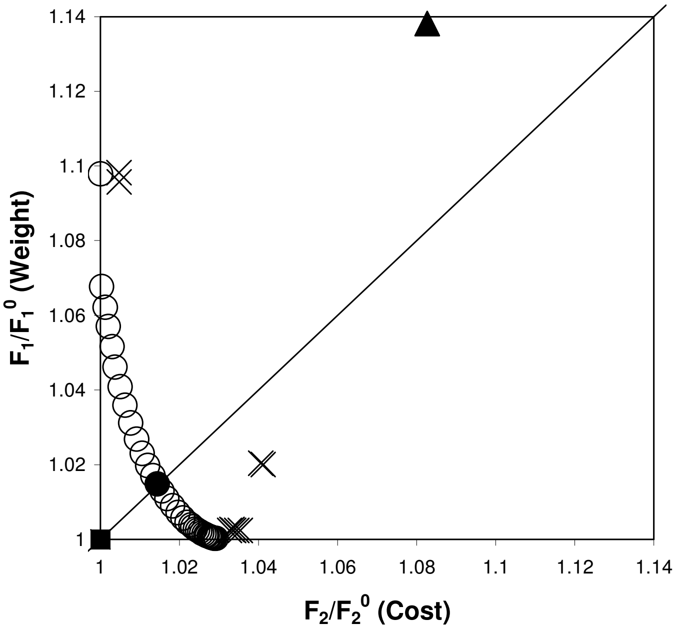
Production cost and minimum weight constitute the double objective considered in this application.

6.6 OPTIMISATION - DESIGN CONSTRAINTS

Constraints are linear or non-linear functions, either explicit or implicit of the design variables. These constraints are analytical relationships of the limitations that the user wants to impose on the design variables or parameters such as displacement, stress, ultimate strength, etc.
The problem is highly constrained and the adequacy of these constraints can greatly influence the solution provided. In this specific case study, 920 technological constraints, 446 geometrical constraints, 4035 structural constraints and 2 global constraints have been used. All the previous constraints have been applied to a ship at the end of his service life, i.e. for the corroded structure after 30 years of life.

6.7 OPTIMISATION - PARETO FRONT

The Pareto front has been mapped by using the repeated weighted sum solutions method using a process that altered the weighting factors in the weighted sum solution and solved the optimisation for each of them. The resulting convex Pareto front is shown in Figure 5 (50 points were calculated). The Pareto front required 28 hours with a laptop Pentium Dual Core 2.52 GHz and 3 Go of RAM. Thanks to the optimisation algorithm features, all scantlings presented in Fig. 9 are feasible solutions, which mean that all of the constraints imposed to optimisation are being satisfied.



▲ Initial design ■ Utopian point ○ Pareto front
× Not converged points • Min-Max Solution (ρ=∞)
Figure 5: Pareto front of the cruise ship optimisation

Table 1: Cost and Steel Weight Savings

	Weight Optimisation	***Cost Optimisation***	***Min-Max Solution***
	Saving (%)	Saving (%)	Saving (%)
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%

The utopian point, the min-max solution (ρ=∞), and the initial solution are also shown in Figure 5. 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 Figure 5, the design team is now able to choose a compromise solution from the Pareto front, by considering additional factors and constraints that could not be included in the optimisation problem.

6.8 RESULTS

In this application, results are mainly presented in terms of ratios to avoid publishing sensitive confidential quantitative data. A comparative analysis has been carried out on the several optimal configurations. Table 1 provides the cost and steel weight savings respectively between the initial design and a cost optimisation, between initial design and weight optimisation and finally between initial design and the min-max solution.

Results show that a cost optimisation generates an important increase of steel weight. Thus the cost optimal solution is far from the optimum in term of steel weight. Consequently for this ship the Min-Max solution is probably much more efficient than a weight optimisation (i.e. production cost gain of 1.58% and weight gain of 11.3%). This case study clearly shows the advantage of a multi-objective optimisation in comparison with a single one.

During this study we have also tried to answer to the following question: "From when will the higher costs of high tensile steel should be offset by a gain of steel weight?".

The objective was to optimize the central part using the same design variables and constraints but different steels (235 MPa, 355 MPa, 460 MPa and 500 MPa) to see how the weight and the cost of the structure are influenced by using high tensile steel instead of normal steel. For each type of steel and combination of them were made two optimisations: one for cost and one for weight. For each optimisation the material cost was changed in conformity with type of steel used. Different combinations and different values for labour cost coefficients, material cost, limits for stiffeners spacing and plate thickness were used in this purpose.

From all the cases studied best solution found is for steel with 355 MPa in the upper deck and 235 MPa in the other areas.

The lower limit for the plate thickness is reached by the panels which form the latest decks of the structure. Although the yielding limit for the high tensile steel is better, the plate thickness, the elements dimensions and the space can't reach a lower dimension or thickness because of some constraints. This is due to the fact that an active structural constraint is the plate buckling which is not directly dependent of the yielding characteristics of the steel. Using high tensile steel in these areas is therefore not really interesting.

In this work we had done sensitive analyses by changing the material ratio cost/labour cost and also by changing the difference of price between each material. In all this cases the conclusions are the same; it seems that there is no real interest to use high tensile material (at least not higher than 355 MPa).

6.9 VALIDATION OF THE RESULTS

The final scantlings of the min-max solution were verified with Bureau Veritas rules (Mars2000); 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 stage. 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 has been conducted to implement a rational model for fatigue assessment at the early design, [21].

7 CONCLUSIONS

The future challenge in the field of cruise ship structure optimisation does not concern the optimisation algorithm itself but the development of some specific modules and mainly their integration.

The identified challenges and needs are the following:

- Development of fast and reliable modules to assess structural constraints such as fatigue and loads, at the early design stage (conceptual design stage but more probably at the basic design stage).
- Develop interfaces and/or open platforms for an easy plug and play (integration) of external modules. Initiative started by the IMPROVE user group must be encouraged and development of open platforms as ModeFrontier or BOSS-Quattro is encouraged.
- Integrate the optimisation tools in design chains, with direct links to the major CAD/CAM tools and FE software to avoid data retyping and time consuming re-meshing.
- Implement multi stakeholders and multi objectives approaches to better converge towards reliable industrial solutions, which are always a fact of comprise between objectives of the different stakeholders.
- Integrate life cycle cost, and particularly the maintenance and operation costs within the global cost assessment for the entire life of the ship. In that case, optimisation will be a supportive design tool toward the “Design for Maintenance” and “Design for operation”.

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