Scantling Multi-objective Optimisation of a LNG Carrier

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Abstract

Numerous real-world problems related to ship design can be solved by various alternatives. However, the scantling design has conflicting objectives such as minimum production cost, minimum weight and maximum moment of inertia (stiffness). Therefore a multi purpose solution had to be settled in order to meet all these requirements at once. Ship design is a complex endeavour requiring successful coordination of many different disciplines, both technical and non-technical. Basic design is the least defined stage of the ship design process and seeks to define the optimal amidships section structure. For that purpose, recent improvements have been made to a numerical tool in order to optimise the scantling of ship sections by considering production cost, weight and moment of inertia in the optimisation objective function. A multi-criteria optimisation of a LNG carrier is conducted in this paper to illustrate the analysis process. Pareto frontiers are obtained and results have been validated by the Bureau Veritas rules. The methodology presented in this paper has demonstrated its effectiveness in optimising scantling of ships at a very early design stage thanks to a management of critical problems usually studied at a later stage of the design.

Keywords: Scantling optimisation, Multi-criteria optimisation, Multi-objective optimisation, LNG carriers, Shipbuilding, Production cost, Basic design, Amidships section

1. Introduction

1.1. Outline

. Sustainability of technologies has been the main concern of many recent international debates, seminars and forums. Designing for sustainability requires a consideration of social, economical and environmental factors throughout the product life. The Life Cycle Performance (LCP) as a measure of sustainability and competitivity 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 of a ship, all technical and ecological requirements have to be considered in terms of their long-term impacts on the entire ship life cycle. An engineering designer should not only transform a need into a description of a product but should also ensure the design compatibility with related physical and functional requirements. Therefore it should take into account various measurable factors of the product life such as its performance, effectiveness, producibility, reliability, maintainability, supportability, quality, recyclability, and cost.

. Life cycle optimisation in a sense of selecting the right design options on a given 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. It also requires tools for life cycle optimisation in the different design and production phases of a ship.

. The closest inter-dependencies between design, life cycle performance and fabrication techniques have been highlighted in a lot of papers [1, 2, 3]. These interactions are bidirectional:

- Construction cost and manufacturing conditions are to a large extent defined in early design phases.

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It is therefore important that the designer is provided with clear methods and also allowed to consider many design alternatives, cost aspects and new fabrication technologies and materials in his work.

- Manufacturing quality, imperfections and accuracy have a significant impact on the structural performance, repair and maintenance and life cycle cost.

. Though a holistic approach of the ship design problem appears theoretically well established, researchers and engineers still have 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, and to be performed by properly trained naval architects. This paper deals with the development of scantling optimisation software integrating different life aspects of ships.

1.2. The scantling optimisation

. The determination of the scantlings of marine structures always brings up numerous problems to designers. Ships and floating structures are indeed complex structures, generally composed of strongly stiffened plates, deck plates, bottom plates, and sometimes intermediate decks, frames, bulkheads, etc. The optimisation of these complex structures is the purpose of this paper.

. 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, [4].

. LBR-5 is the French acronym of "Stiffened Panels Software" version 5.0. The purpose of the tool is the sizing/scantling optimization of hydraulic (lock gates), ship and offshore structures. The development of the LBR-5 module is included in the development of a module-oriented optimization approach, [5]. The goal is to create a multi-purpose optimization model, opened to users and compatible with other structure analysis modules based on codes and specific regulations. Such a model must contain various analysis methods for strength assessment that can easily be enriched and complemented by users. The user must be able to modify constraints and add complementary limitations according to the structure type (hydraulic, ship and offshore structures, etc.), the code or the regulation in force and to his experience and ability in design analysis. The objective is to create a user-oriented optimization technique in permanent evolution, i.e., that evolves with the user and his individual needs.

. 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, [6].

. In the scantling design of a ship, minimum production cost, minimum weight and maximum moment of inertia (stiffness) are conflicting objectives. For that purpose, recent improvements have been made to the LBR-5 software in order to optimise 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 subsections of the ship simultaneously (not only the amidships section). A multi-criteria optimisation of a LNG carrier is conducted in this paper to illustrate the analysis process. Pareto frontiers are obtained and results have been validated by the Bureau Veritas rules. The methodology presented in this paper has demonstrated its effectiveness in optimising scantling of ships at a very early design stage thanks to management of critical problems usually studied at a later stage of the design.

2. Overview of optimisation problem

2.1. Introduction

. 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 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 follows:

- **Design variables** This refers to a list of variables characterizing the design being optimised. For ship design, variables include ships main dimensions (unless specified by the ship owners requirements) and may be extended to include a ships 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 efficient 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 requirements, yield stress of steel, etc.) and may be extended to the cost of materials (for ships: steel, fuel and/or labour cost).
- **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 indicated by Pareto front and may be selected on the basis of trade-offs by the decision maker.

2.2. *Optimisation of marine structures*

. 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 [7]. Then, with computer assistance, researchers tried to develop design and optimisation algorithms. Optimisation first appears in the works of [8] and [9]. Few years later, an important step for optimisation of marine structures has been done by Hughes [10, 11].

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

. The evolution of design and optimisation techniques are well reported by [12] table 2 p.539. [13, 14, 15, 16, 17, 18, 19] are all integrated multi-criteria optimisation model that incorporate structural weights and/or production costs. The differences appears for design variables and constraints (yielding, buckling, deflection, weight, cost, fatigue, etc.) as well as for the analysis of the 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 least expensive period to modify design scantling and to compare different alternatives. The earlier information is known, the better the decisions are taken in the design process. Unfortunately, it is often too early for efficient use of many method mentioned before. The methodology presented in this paper can be applied very quickly as soon as the first scantling of the cross section of the structure is available because it is based on the solving of the stiffened plate differential equations and not on traditional FEM techniques. Moreover, in this case, the modelling time is reduced to the minimum; generally no more than one week of modelling/computing is required to find the Pareto front.

. This paper explains how it is now possible to perform a multi criteria optimization of a LNG carrier at the early design stage, including a 3D numerical structural analysis and a quasi-static sloshing pressure applied in the inner hull structure.

2.3. *Multi-criteria optimisation*

. The following overview is adapted directly from [16]. The multi-criteria optimisation problem involves $K > 1$ criteria and can be formulated by the equation 1 and 2, where there are now K multiple optimisation criteria $F_1(x)$ through $F_K(x)$ and each depends on the N unknown design variables in the vector x. This equation is subject to I equality constraints and J inequality constraints $h_i(x)$ and $g_j(x)$, respectively, that also depend on the design variables in the vector x defined in equation 3 and 4. The overall objective function F is a vector in comparison with a single criteria optimisation. In general, this problem does not have any single solution due to conflicts amongst the K criteria.

$$\min_x F(x) = [F_1(x), F_2(x), ..., F_K(x)] \quad (1)$$

$$x = [x_1, x_2, ..., x_N]^T \quad (2)$$

$$h_i(x) = 0, i = 1, ..., I \quad (3)$$

$$g_j(x) \geq 0, j = 1, ..., J \quad (4)$$

2.4. Pareto optimum front

. In case of a multiple criteria conflict, the most common definition of an optimum is the Pareto optimality. This has first been exposed 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 criteria can be further improved without worsening at least one of the other criteria*. Note that this emphasizes the conflicting or competitive interaction amongst 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 amongst the conflicting criteria. This can often be reached by considering factors than cannot be included in the optimisation model.

2.5. Global criterion optima

. As noted before, engineering design requires a specific result to be implemented, not a set of solutions as provided by the Pareto optimal set. The most intuitive ways to achieve an effective compromise amongst competing criterion are, amongst others, the weighted sum, the min-max and the nearest to the utopian solutions. These solutions can be obtained through the global objective function presented in equations 5 and 6.

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

$$\sum_{k=1}^{K} w_k = 1 \quad (6)$$

. 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 weighted sum solution results from equation 5 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 equation 5 with $\rho = \infty$ and is defined in equation 7.

$$P\left[F_k(x)\right] = \max_k\left[w_k\left|\frac{\left(F_k(x) - F_k^0\right)}{F_k^0}\right|\right] \quad (7)$$

. Moreover, a solution could be obtained for various 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, equation 5 can be adapted to two criteria in the objective function. This lead to the equation 8 where P is the objective function and F_1, F_2 are the both criteria analysed in this paper i.e. respectively the steel weight and the production cost. Furthermore, F_1^0 represents the value of the criterion F_1 (i.e. steel weight) obtained when the optimisation is performed only with this criterion in the objective function (single objective) while F_2^0 represents the value of the criterion F_2 (i.e. production cost) obtained when the optimisation is performed with only this criterion in the objective function (single objective).

$$P = \left[\left[w_1\left|\frac{F_1 - F_1^0}{F_1^0}\right|\right]^{\rho} + \left[w_2\left|\frac{F_2 - F_2^0}{F_2^0}\right|\right]^{\rho}\right]^{1/\rho} \quad (8)$$

2.6. Mapping the entire Pareto front

. When dealing with multi-criteria problems, it is highly 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 then be based on the considerations modelled in the optimisation formulation as well as on the multiple additional considerations, factors, and constraints not included in the model. This is feasible when there are two criteria but rapidly becomes impractical due to computational time and visualization reasons when the number of criteria reaches three and up.

. In order to map the entire Pareto front, the following three methods can be used, [16]:

- 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 $w1/w2$, 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 leads to the entire Pareto front in one single optimisation run.

. In the present paper, the repeated weighted sum solution method has been used to map the entire Pareto front.

3. Case study

3.1. Introduction

. This paper relates to the structural optimisation of a new *free ballast* generation design of a 220 000 m^3 capacity Liquefied Natural Gas (LNG) carrier [20]. The length between perpendiculars is about 303 m, the overall length about 319 m and the ship contains 5 tanks where 4 are prismatic. Fig. 1(a) shows the outline of the ship.

. This new solution is based on reduced ballast tank (or even without ballast tank), modified hull form (V-Shape hull with reduced C_b), INOVELIS Pod technology (smaller diameter of propellers in nozzle) and simplified hull form (80% of the surface is developable).

In comparison to the midship section of an equivalent typical LNG carrier, the neutral axis is higher and, therefore, critical stress at the top is lower. This implies a lower cross-section area that contributes to decrease the mass of steel structure.

In spite of a slightly lower propeller efficiency of the proposed design in comparison to a conventional LNG carrier with the same main dimensions, LNG savings (consumed by engines) reach between 0.56% and 10%, corresponding to 0.53 and 9.5 tons of gas per day. Furthermore, the quantity of ballast water transported is reduced by more than 80% in the most pessimistic hypothesis.

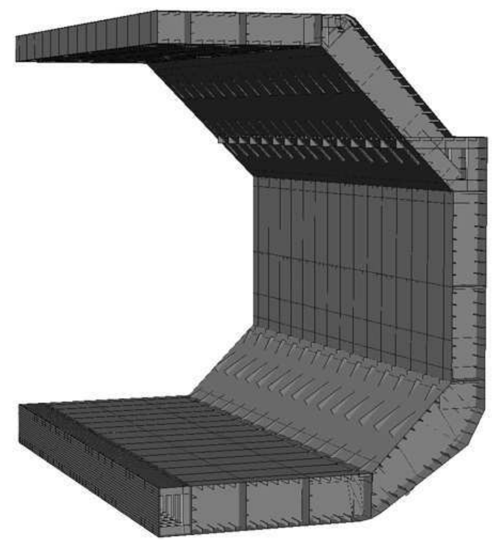
. The advantages of this new design are the lower fuel consumption, the lower production cost and the beneficial impact on the environment (no invasive marine species are transported). The risks are the slamming of the aft part and the strength fatigue in the side bilges.

. This new concept of LNG carrier has been studied within the IMPROVE European project in partnership with STX Europe.

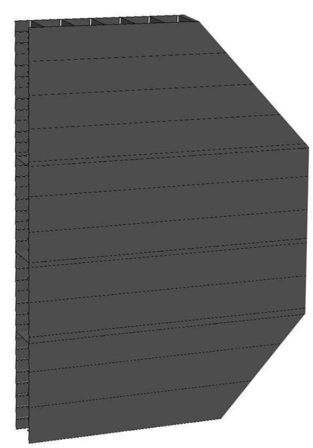
3.2. Model

. The amidships section of the LNG carrier and a bulkhead have been simultaneously implemented in the LBR-5 software. These two sections have been imported from Mars2000 software (scantling verification software based on Bureau Veritas rules). The section is characterized by double hull skin, 50 meters breadth, 36 meters height and 40.5 meters length. Fig. 1(b) shows the amidships section model and Fig. 1(c) shows the cofferdam. Based on structural symmetry, only half of the structure has been modelled.

(a) LNG outlines



(b) LNG amidships section



(c) LNG cofferdam

Figure 1: LNG amidships section and outlines

. The structural module of LBR-5 only allows 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 bulkhead section of a ship could not be analysed and optimised together with the amidships section, but this optimisation is however possible independently. The main inconvenience of an independent optimisation is that several design variables (for example the stiffeners spacing) that should be the same for the considered structures, may have different values at the local optimum.

. A multi-structures module has been recently implemented in order to optimise several structures simultaneously. The original feature of this module is to link design variables between these structures, for example the amidships section with bulkhead section of a LNG carrier (see Fig. 2). The multi-structures module optimises simultaneous both sections in order to obtain compatible design variables. However only several common design variables can be taken into account such as stiffener spacing or plate thickness. The link between both sections is done through design variables: new equality constraints are added between variables. There is no link about the strain or stress.

. In practice, both sections are optimised independently but some design variables are linked together in order to find a realistic and global optimum solution.

3.3. Load cases

3.3.1. Sea state and cargo pressures

. The Bureau Veritas load cases have been considered during this analysis. The innovative free ballast design has been developed in order to navigate 90% of its life without any ballast. However, depending on the sea condition, the ballast can be used during 10% of the ship life. Out of seven load cases considered, five are load cases "without ballast" and two "with ballast".

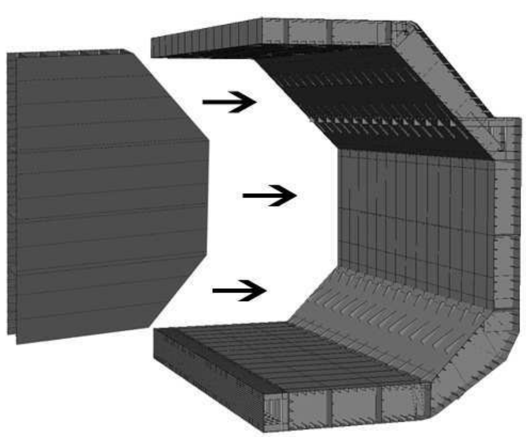


Figure 2: Linked design variables between the two models

Tab. 1 shows the different load cases considered in this study.

ID	BV	Draught *m*	Condition	Sag/Hog	Bending moment *kNm*
1	A2	14.1	Full loading	Sagging	9 198 820
2	B2	14.1	Full loading	Sagging	9 198 820
3	D	14.1	Full loading	Sagging	5 899 634
4	A1	9.525	Ballast loading	Hogging	9 318 206
5	C	9.525	Ballast loading	Hogging	6 403 800
6	A1	5.03	Unloaded	Hogging	9 342 081
7	C	5.03	Unloaded	Hogging	6 420 629

Table 1: Load cases

3.3.2. Sloshing

. Sloshing phenomenon represents one of the major considerations in the design of vessels carrying liquid cargo, and in particular for vessels operating LNG. Sloshing may be defined as a violent behaviour of the liquid contents in tanks that are subjected to the external forced motions.

. A sloshing module has been recently integrated in the LBR-5 software. This new module provides quasi-static pressures to be applied on the inner hull structure supporting the membrane cargo containment system at preliminary design stage. These quasi-static sloshing pressures have been obtained through numerical CFD calculations carried out by Bureau Veritas and cross-checked with different sloshing model tests campaigns carried out by Bureau Veritas in cooperation with Ecole Centrale de Nantes and GTT, [21, 22]. Standing and braking waves at high fillings and progressive waves at low fillings have been considered (Fig. 3).

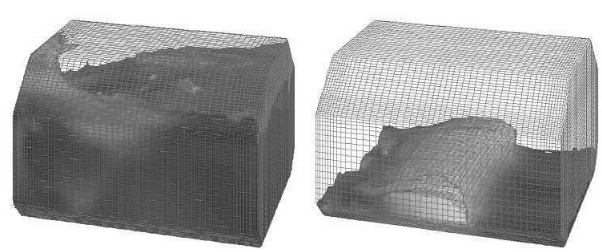


Figure 3: Standing & braking waves at high fillings (left), progressive wave at low fillings (right)

. The sloshing module is based on 2 main steps:

- Firstly, the hydrodynamic analysis allowing to calculate the motion of the LNG, once the environmental data is given. The purpose of hydrodynamic analysis is to evaluate the range of wave first order motions in order to determine sloshing excitation for either numerical or small-scale model tank. After having obtained the transfer functions, the motions in irregular waves of a given wave energy spectrum are obtained by performing spectral calculations. The results include significant magnitude and average period of the motions. In this case the environmental data for sloshing analysis refers to North Atlantic trade route with 40-years return period wave height envelope.

- Secondly, the sloshing analysis itself which consists in both experiments and numerical calculations using Computational Fluid Dynamics (CFD). The experiments consist in moving a small scale model tank (scale 1/70) with water at ambient conditions, in order to measure pressures at various locations for a given case (filling ratio, heading, ship speed, wave period). Sloshing small-scale model tests provide identification and confirmation of the most critical cases. Because impact pressures depend on many parameters (such as density ratio, hydro-elasticity, cryogenic environment with free surface condition at boiling point of gas, etc.) which are difficult to reproduce at model scale, sloshing model tests are used in a comparative manner. Afterwards, numerical sloshing simulations provide an overall evaluation of fluid kinematics and an independent verification of sloshing effects on cargo tank walls, and overall evaluation of representative design loads on ship inner-hull structure.

. The module has provided quasi-static pressures to be applied on the inner hull structure for the following 4 LNG tank capacity ranges: $< 125\,000m^3$, $125\,000 - 140\,000m^3$, $140\,000 - 155\,000m^3$ and $155\,000 - 180\,000m^3$. However some restrictions have been provided for any capacity larger than $155\,000m^3$.

3.4. Optimisation

3.4.1. Design variables

. The ship structure is modelled with 67 stiffened plate elements (Fig. 4). The structural response of the model is solved thanks to the resolution of the non-linear differential equations of each stiffened plate element [23]. For each element, there are nine available design variables:

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

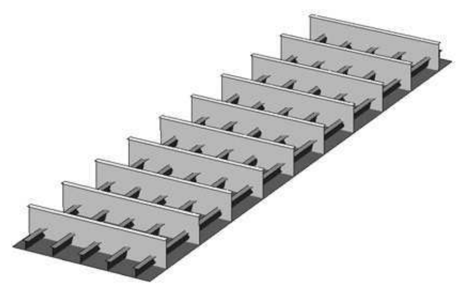


Figure 4: LBR-5 stiffened plate element

. In this case study, a total of 381 design variables were activated for the whole ship model which represents an average of 5-6 design variables per stiffened panel.

. In order to deal with this huge number of design variables, an optimisation algorithm which can solve non-linear constrained problems has been used. It is based on both a convex linearisation of the non-linear functions and a dual approach [24]. It is especially effective because only few iterations are required; typically less than 15.

3.4.2. Objective function

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

. Production costs (PC) has been subdivided into three categories according to equation 9:

- the cost of raw materials (MC) – The evaluation of material costs consists in quantifying volumes required for construction and obtaining prices from suppliers and subcontractors.

- the labour costs (LC) – The best alternative to using empirical formulations to evaluate labour costs is an analytic evaluation. Such an approach requires a knowledge of the working time required for each standard labour task associated with a workstation as well as the subdivision by stations of the entire construction process. Equation 10 provides the Cost Evaluation Relationships (CERs) of the labour cost of a stiffened panel for a simple manufacturing activity e.g. the welding of two assemblies, the tacking of steel profiles, etc. The production cost has been calculated with an advanced cost module taking into account a detailed shipyard database. Around 60 fabrication operations are considered, covering the different construction stages, such as girders and web-frames prefabrication, plate panels assembling, blocks preassembling and assembling, as well as 30 types of welding and their unitary costs, [25].

- the overhead costs (OC) – Overhead includes any expense that cannot be attributed to a specific work station of the construction process, but that is, however, linked to construction.

$$PC = MC + LC \times HC + OC \tag{9}$$

where
PC Production cost (€),
MC Material cost (€),
LC Labour cost (man-hours),
HC Hourly cost (€/hour),
OC Overhead costs (€).

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

where
LC Labour cost (man-hours),
QC Quantity (welding length, number of brackets, etc.),
UC Unitary costs (cost-per-unit),
KC Corrective coefficient used to calibrate the unitary costs,
AC Accessibility/Complexity coefficient,
WC Workshop coefficient.

. The CER (see equation 10) provides the basic means to assess the cost. This relationship ($QC \times UC$) is typically developed 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 cutouts, number of holes, etc.) for a given shipbuilding activity (QC), and the unitary cost of carrying out the activity (UC), e.g. the labour for steel block assembly at n man-hours/tonne or the labour for welding in a vertical position at n hours/meter.

. The unitary costs (UC) vary according to the type and the size of the structure, the manufacturing technology (manual welding, robotic welding, etc.), the experience and facilities of the construction site, the country, etc. Usually, unitary costs are defined as a function of one or more design variables like plate thickness, welding throat, welding type (butt or fillet), welding position, bevels, profile scantling, etc.

. The catalogued cost scales (cost-per-unit) available do not always reflect accurately the expected costs for the cost assessment. Therefore, these cost scales can be modified thanks to 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 to the equation to adjust manufacturing cost assessments in case of increase or a decrease in the relative accessibilities/complexities of the ship or its sub-assemblies (ship, blocks, panels, etc.). The more dense, difficult to reach and complex the structure is, the more the manufacturing cost will increase.

. The productivity changes from a workshop to another. Usually shipyards wish to consider this type of change in their costs assessments. For that purpose we use another adjustment coefficient (WC) reflecting certain gains or losses in productivity within specified shipyard activities, such as in which workshop the product is assembled.

. Beside the production cost, a maintenance/repair oriented life cycle cost/earning model is currently being studied in order to improve the cost objective function. [26] provided good theoretical and practical foundation but further research and development are still required to develop a more mature maintenance/repair cost modelling systems.

3.4.3. Design constraints

. Constraints are linear or non-linear functions, either explicit or implicit of the design variables. These constraints are analytical expression of the limitations that the user wants to impose by themselves on the design variables or parameters such as displacement, stress, ultimate strength, etc.

. Different types of constraints have 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 being 5 *mm* thick is not recommended.
- *Structural constraints* represent limit states in order to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc. 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 treatises, etc. and that differ 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 center 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. Panels of a same deck normally have the same thickness, stiffeners spacing's are often homogeneous, etc.

. The problem is highly constrained and the adequacy of these constraints can greatly influence the solution provided. In this specific case study, 762 technological constraints, 236 geometrical constraints, 2458 structural constraints, 2 global constraints and 209 equality constraints have been used.

3.5. Pareto front and results

3.5.1. Pareto front

. The Pareto front has been mapped by using the repeated weighted sum solutions method described in section 2.6 using a process that altered the weights in the weighted sum solution and solved the optimisation for each of them. The resulting convex Pareto front is shown in Fig. 5. Fifty points were calculated. The Pareto front was generated over around 8 hours with a laptop Pentium Dual Core 2.52 GHz and 3 Go of RAM. Thanks to the optimization algorithm features, all scantlings presented in Fig. 5 are feasible solutions, which means that all of the constraints imposed to optimisation are being satisfied.

. The utopian point, the min-max solution ($\rho = \infty$), and the initial solution are also shown in Fig. 5. Min-Max solution has been obtained for a weighting factor equal to 0.47 for the production cost and 0.53 for the weight. This analysis has highlighted that the initial design is relatively far from the Pareto front.

. Using Fig. 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.

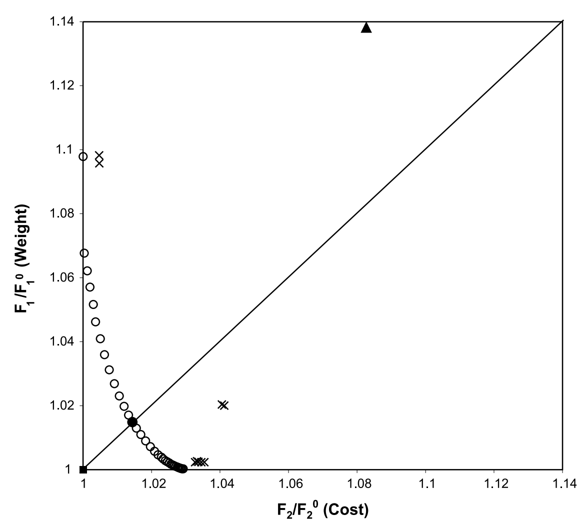


Figure 5: Pareto front (▲ Initial design – ■ Utopian point – ○ Pareto front – × Not converged points – • Min-Max Solution)

3.5.2. Results

. In this paper, data 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. Tab. 2 provides the cost and steel weight savings between the initial design and the production cost optimisation solution, between initial design and a weight optimisation solution, and finally between the initial design and the min-max solution. A production cost breakdown of the initial design is also presented in Fig. 6.

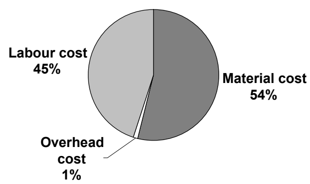


Figure 6: Cost breakdown for the initial design

	Cost Opt. Continuous Saving (%)	*Weight Opt. Continuous* Saving (%)	*Min-Max Solution Continuous* Saving (%)	*Min-Max Solution Discrete* Saving (%)
Steel weight	**-9.85%**	**-18.43%**	**-15.24%**	**-13.11%**
Production cost	**-6.18%**	**+12.45%**	**-3.34%**	**-2.89%**
Material cost	-10.57%	-18.04%	-15.52%	-13.08%
Labour cost	-0.92%	+48.55%	+11.06%	+12.21%
Overhead cost	-5.18%	+38.10%	+7.48%	+8.33%

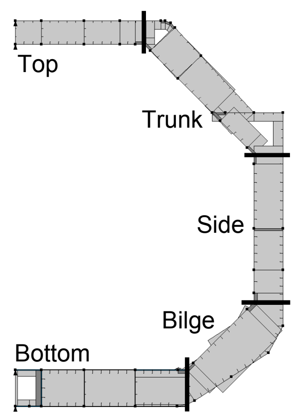
Table 2: Cost and steel weight savings

. Results show that a weight optimisation generates an important increase of production cost. Thus the weight optimal solution is far from the optimum in term of production cost. The study has shown as well that, for a weight gain between 10% and 15%, the cost is only reduced by 3%, when for a weight gain between 15% to 18% (the maximum value), the production cost is increase by 12%. Consequently for this ship the Min-Max solution is probably much more efficient than a weight optimisation (i.e. production cost gain of 3% and weight gain of 12%). This case study clearly shows the advantage of a multi-objective optimisation in comparison with a single one.

. The scantling variables are discrete by nature while we are using a continuous optimization algorithm, i.e. the final thickness's might be 14.33 mm. A discrete optimization algorithm is currently under development [27], but until today the computation time could not yet be reduced adequately. However in this present paper, the final min-max solution has been standardised manually after the optimization results, i.e. the continuous design variables has been replaced by discrete design variables for instance a plate thickness of 14.33 mm has been replaced by 14 mm. Tab. 2 also gives the the cost and steel weight savings between the initial design and the min-max solution with discrete design variables.

. After this standardisation the author has highlighted a reduction of the weight of 2.13% and a reduction of the production cost of 0.45%.

. The breakdown of the gain for each main part of the ship, i.e. the bottom, the bilge, the side shells, the trunk and the tank top, is presented on Fig. 7. The results shows that plate thickness has been reduced everywhere except for the top tank. The highest reduction in terms of production cost and steel weight applies to the bilge part of the ship.



(a) Labels

	Production Cost Saving (%)	Steel Weight Saving (%)
Bottom	+2.1%	-11.6%
Bilge	-24.2%	-38.5%
Side	-11.6%	-25.0%
Trunk	-7.8%	-11.4%
Top	+19.3%	+10.5%

(b) Breakdown table

Figure 7: Gain breakdown of the discrete min-max solution

3.5.3. *Validation of the results*

. The final discrete scantling of the min-max solution has been validated in the MARS2000 Bureau Veritas (BV) software. All plates and stiffeners scantlings were validated by the BV Rules except for three plates from the inner part of the side shell and the bilge. However, the discrepancy between the thickness required by the BV and the thickness given after the optimisation is only 0.5 mm.

. Despite these satisfactory results, the author would like to remind that the optimisation results do not consider the fatigue phenomenon. Indeed, information of structural details which includes the requirements for reliable fatigue assessment is only available in the next design stages. This is a significant obstacle to an early design stage because the decisions taken at this stage strongly influences the fatigue life of the hull girder. Moreover, any structural modification done after the early design stage is usually restricted and expensive for production. In order to overcome this problem, a study is currently being in order to implement a rational model assessing fatigue at the early design stage, [28].

4. Conclusions

4.1. Conclusion

. A structural multi-objective optimisation of a LNG carrier has been proposed in the present analysis. Thanks to the recent developments outlined here, the LBR-5 software allows performing multi-criteria optimisation by considering both production cost and weight in the optimisation objective functions.

. The entire Pareto front can be mapped by using a process altering the weighting factors in the weighted sum solution and solves the optimisation problem. Useful specific compromised 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 ensuring the compatibility of the design variables between the different sections (i.e. amidships section and bulkheads).

. These new developments improve significantly the capacity of the software to provide optimal scantling solution at the early stage of the design process. It is obvious from this investigation that the method proposed here is suitable for basic design study of ships and suits with dealing with general multi-objective optimisation problems. However some additional developments such as an early assessment of the fatigue and a holistic life cycle cost module (not only production) are still required to improve the final optimum solution.

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