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HOW TO MINIMISE PRODUCTION COSTS AT THE PRELIMINARY DESIGN STAGE

- Scantling Optimization -

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ABSTRACT

Guidelines and major configurations of a structural design are mainly defined during the earliest phases of a project. It is thus not difficult to understand why an optimisation tool for the preliminary design stage is attractive. It is during this stage that flexibility, modelling speed and easy-to use methods provide precious help to designers. At this stage, few parameters/dimensions have been fixed. This is the most relevant period to assess the construction cost, to compare fabrication sequences and to find the best design and most suitable scantlings to minimize the production costs. The LBR-5 package performs this task. Design variables are the dimensions of the longitudinal and transversal members, plate thickness and spacing between members. The software contains 3 modules. The "*Cost Module*" to assess the construction cost which is the objective function (least construction cost). The "*Constraint Module*" performs rational analyses of the considered structure, and the "*Opti Module*" contains the mathematical optimiser code. In this paper emphasis is on the construction cost assessment and on the optimisation of a medium capacity LNG ship designed by ALSTOM France (Chantiers de l'Atlantique).

1. INTRODUCTION

This paper presents an optimisation method of stiffened ship structures from which the LBR-5 software is issued. Its target is to ease and improve the preliminary design stage allowing least cost optimisation. The general structural layout is defined during the earliest phases of a project, i.e. the preliminary design stage that corresponds in most cases to the offer. It is thus not difficult to understand why an optimisation tool is attractive, especially one designed for use at the preliminary stage.

It is during the first stages of the project that flexibility, modelling speed and easy-to use methods provide precious help to designers. At this stage, few parameters/dimensions have been definitively fixed and a coarse modelling by standard finite elements is often unusable, particularly for design offices and small and medium-sized shipyards.

LBR5 is a rational optimisation design module that, in the preliminary stage, allows for:

- a 3D analysis of the general behaviour of the structure (usually one cargo hold);
- to explicitly take into account all the relevant limit states of the structure (service limit states and ultimate limit states) thanks to a rational analysis of the structure based on the general solid-mechanics theory;
- an optimisation of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;

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- an optimisation of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;

- to include the unitary construction costs and the production sequences in the optimisation process (through a production-oriented cost objective function).

Preliminary design is the most relevant and the least expensive time to modify design scantling and to compare different alternatives (sensitivity analyses). This paper explains how it is now possible to perform optimisation at the early design stage including a 3D numerical structural analysis. Extensive information on the proposed model is available in the literature [1-4].

2. LBR-5 AND ITS 3 BASIC MODULES

The optimisation problem can be summarized as follows:

X_i	$i = 1, N$	the N design variables,
$F(X_i)$		the cost objective function to minimize,
$Cj(X_i) \le CM_j$	$j = 1, M$	the M structural and geometrical constraints,
$X_{i\,min} \le X_i \le X_{i\,max}$		the upper and lower bounds of the X_i design variables, that is, technological limits (also called *side constraints*).

The structure is modelled with stiffened panels (plates and cylindrical shells). For each panel one can associate up to 9 design variables (X_i), that is:

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

LBR5 is built around three basic modules, respectively, *OPTI*, *CONSTRAINT* and *COST*.

The *OPTI module* contains the mathematical optimisation algorithm (CONLIN [2]) that allows solving non-linear constrained optimisation problems. It is especially effective because it only requires a reduced number of iterations. In general, less than 15 iterations, including a structure re-analysis, are necessary, even in the presence of several hundred-design variables (X_i). CONLIN is based on a convex linearisation of the non-linear functions (constraints and objective functions) and on a dual approach [5].

The *CONSTRAINT module* asks the user to select relevant constraints within constraint groups available in a database.

Constraints are linear or non-linear functions, either explicit or implicit in the design variables (X_i). One can distinguish:

- Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables.
- Geometrical constraints that impose relationships between design variables in order to guarantee a functional, feasible and reliable structure. They are generally based on “good practice” rules to

avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds.

- Structural constraints that represent limit states in order to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc. These constraints are based on direct analyses and are modelled with rational equations.

The *COST module:* In 2003, even for a first draft, a least weight optimisation process can no longer be justified and should be replaced by a least construction cost or, even better, by a minimum global cost (including operational costs). In the actual LBR5, the objective function (COST module) is the construction cost that includes, for instance, 65% of labour costs and 35% of material cost (almost proportional to the weight). In order to link the objective function (Euro) to the design variables (X_i), the unitary costs of raw materials (Euro/kg), the productivity rates for welding, cutting, assembling, etc. (man-hours/unit of work = m-h/unit) and labour costs (Euro/m-h) must be specified by the user.

These unit costs vary according to the type and the size of the structure, the manufacturing technology (manual welding, robots, etc.), the experience and facilities of the construction site, the country, etc. It is therefore obvious that the result of this optimisation process (scantling optimisation) will be valid only for the specified economic and production data. Sensitivity analyses of the economic data on the optimum scantling can also be performed, thus providing the manager with valuable information for improving the yard.

3. THE COST MODULE AND THE OBJECTIVE FUNCTION

Global construction costs can be subdivided into three categories: (a) cost of raw materials, (b) labour costs, and (c) overhead costs (Eq. 1).

$$\begin{array}{ccccccc} \text{Total Cost} & = & \text{Material costs} & + & \text{Labor Costs} & + & \text{Overhead Costs} \\ \mathbf{TC} & = & \mathbf{MatC} & + & \mathbf{LabC} & + & \mathbf{OvC} \end{array} \qquad (1)$$

The purpose of this analysis is essentially to allow a relative and objective comparison, on basis of cost, of the successive designs resulting from the optimisation process. So, the absolute cost is not needed and only the two first terms of Eq.1 are significant. The overhead cost (**OvC**), though far from negligible, can be ignored by the analytic cost model. This means that the considered cost in this analysis will be:

$$\begin{aligned} \mathbf{TC} &= \mathbf{MatC} + \mathbf{LabC} \\ &= \sum_{j=1}^{K} \underbrace{Qj}_{\text{Number of units}} \cdot \underbrace{Pj}_{\text{Euro/unit}} + \sum_{i=1}^{NT} \underbrace{Ti}_{\text{Man-hours per task}} \cdot \underbrace{Mi}_{\text{Task frequency}} \cdot \underbrace{Si}_{\text{Euro/m-h}} \end{aligned} \qquad (2)$$

where:

j = reference number of a given material, that is, 1 ton of steel plate, 1-m long of angle bar of 60x60x5, etc.
K = number of different materials, j=1,K,
Qj = expected quantity of the j material,
Pj = unit price of the *j material (Euro/unit),*
NT= number of different standard tasks,
i = reference number of a given task, i=1,NT,
Ti = required working load for the i standard task (man-hours),

Mi = number of times that the Ti task happens (frequency),
Si = hourly labour cost (Euro/man-hour) of a person doing the i standard task.

Even if Eq.2 accurately represents total construction costs, it does not show the diversity and the multitude of materials, and especially the multitude of elementary standard tasks included in the global construction process. Thus, the difficulty does not reside in equation calculation (Eq.2), but rather in the identification and subdivision of tasks into sub-tasks and, finally, into elementary standard tasks. An elementary standard task is defined as a task that cannot be subdivided further.

Thus, the global cost evaluation procedure requires:

- to divide the whole construction process in NT1 standard tasks of level 1, for example, dividing the whole structure into blocks. Several blocks can be identical (M_{i1} = 1,2,3...);
- to subdivide each of these NT1 standard tasks into NT2 sub-tasks;
- to repeat this process until reaching a group of elementary standard tasks (that cannot be subdivided further, or that one does not choose to divide further);
- to define the hourly unit cost (S_i) of each "i" elementary task, (i = 1 to NTn).

3.1 Modelling of the objective functions used by the LBR-5 model

Here is presented the cost objective function used by the LBR-5 model. A weight objective function can also be selected, which is in fact a simplified form of the cost objective function. This weight objective function is an explicit function of the design variables (plate thickness (δ), spacing (Δ_x, Δ_y) and dimensions of the longitudinal and frame cross sections (h,d,w,t). Thus, Fp, the weight objective function can be written for an orthotropic stiffened panel as:

$$Fp = \gamma . L . B . \left[\delta + \frac{(h.d + w.t)_X}{\Delta_X} + \frac{(h.d + w.t)_Y}{\Delta_Y} \right] \tag{3}$$

where L = length of the panel according to the X co-ordinate (m),
B = breadth of the panel according to the Y co-ordinate (m),
δ = plate thickness (m),
γ = specific weight (N/m^3),
$(h,d,w,t)_X$ = dimensions of web and flange of the longitudinals (stiffeners) fitted along X (m),
$(h,d,w,t)_Y$ = dimensions of web and flange of the transverse frames fitted along Y (m),
Δ_X = spacing between two longitudinals (stiffeners) fitted along X (m),,
Δ_Y = spacing between two transverse frames fitted along Y (m),,

Use of the weight objective function is particularly simple and easy because it requires no additional parameters, and is therefore particularly adapted to perform comparative and academic analyses. For industrial applications, it is, however, desirable to replace it by a cost objective function.

Theoretically, the cost model should be established in close relation to the specified production plan. Unfortunately, it doesn't seem possible to define a general model, valid in all situations. That is why a more global model was developed, not specific to a production plan, but that is able to accurately assess the relative cost and is sensitive to any changes in the scantling (design variables).

The cost module, currently used in the LBR-5 model, includes three components (Eq.4):

$$FC = F_{MAT} + F_{CONS} + F_{LAB} \quad \text{(in Euros)} \tag{4}$$

where

FC: global cost function (in Euros);
F_{MAT}: cost of basic materials (plates, bars, etc.);
F_{CONS}: cost of consumables necessary for the construction process (energy, welding materials, etc.);
F_{LAB}: cost of labour used for the building of the entire structure.

a) Cost of materials: F_{MAT}

The cost of materials (Eq. 5) is directly derived from the weight function (Eq.3). Each term of Eq.3 should be multiplied by the relevant C_i unitary material cost (plate, bulb profile, etc.). Thus, from Eq.3, one gets:

$$F_{MAT} = \gamma . L . B . \left[C_1 . \delta + C_2 . \frac{(h.d + w.t)_X}{\Delta_X} [1 + DW_2] + C_3 . \frac{(h.d + w.t)_Y}{\Delta_Y} [1 + DW_3] \right] \qquad (5)$$

where:

C_1 = cost per kg of a plate δ mm thick,
C_2 = cost per kg of the longitudinals/stiffeners,
C_3 = cost per kg of the transverse frames,
DW_2 = corrective factor (ratio of C_2) of the longitudinals/stiffeners for additional weight,
DW_3 = corrective factor (ratio of C_3) of the transverse frames for additional weight.

DW_2 and DW_3 are used to adjust the member weight, of respectively, the longitudinals and frames, to consider the extra weight induced by brackets (TAP), local stiffening as flat bars to stiffen high web-frames (see Figure 1).

In order to take into account a possible variation of the price per kg of the plates according to their thickness, the C_1, C_2 and C_3 parameters are defined as follows:

$$C_1 = C_1^o \left[1 + \Delta C_1 \left(\delta - E_0\right) 10^3\right] \quad \text{(Euro/kg)} \qquad (6a)$$

$$C_2 = C_2^o \left[1 + \Delta C_2 \left(dx - E_{0X}\right) 10^3\right] \quad \text{(Euro/kg)} \quad \text{for longitudinal members} \qquad (6b)$$

$$C_3 = C_3^o \left[1 + \Delta C_3 \left(dy - E_{0Y}\right) 10^3\right] \quad \text{(Euro/kg)} \quad \text{or frames and transverse members} \qquad (6c)$$

where:

C_1^o = Cost per kg of a plate with a thickness δ = Eo, (in m),
C_2^o = Cost per kg of longitudinal members having a web thickness = Eox,
C_3^o = Cost per kg of transverse members having a web thickness = Eoy,
Eo = Reference thickness for the plates (mean plate thickness), (in m),
Eox = Reference thickness for the longitudinal members (mean web thickness),
Eoy = Reference thickness for the transverse members (mean web thickness),
d_X,d_Y= Actual web thickness for stiffeners along X (long.) and frames along Y (transverse);
ΔC_1 = Change in % of C_1^0 (cost/kg) between plates of Eo and Eo +1 mm thick,
ΔC_2 = change in % of C_2^0 (cost/kg) of the longitudinals between web of Eox and Eox +1 mm thick,
ΔC_3 = change in % of C_3^0 (cost/kg) of the frames between web of Eoy and Eoy +1 mm thick,

b) Cost of Consumables: F_{CONS}

The welding cost per meter (energy, gas, electrodes, provision for the equipment depreciation, ...), excluding labour cost, is estimated using Eqs.7 and 8.

$$C_{8X} = C_{8X}^0 \; [1 + \Delta C_{8X} (d_X - E_{0X}) \, 10^3] \quad \text{for the longitudinals} \qquad (7a)$$

$$C_{8Y} = C_{8Y}^0 \; [1 + \Delta C_{8Y} (d_Y - E_{0Y}) \, 10^3] \quad \text{for the transverse members (frames)} \qquad (7b)$$

where:

C_8^0 = The "cost/m" of consumables to weld the web with its flange (2 welds),

ΔC_8 = Relative change (%) of C_8^0 between a (Eo) and a (Eo + 1 mm) plate thick, with E_O being E_{OX} or E_{OY}.

Then the consumable cost is:

$$F_{CONS} = L\,.\,B\,.\left(\left[\frac{2-\alpha_X}{\Delta_X}\right].\,C_{8X} + \left[\frac{2-\alpha_Y}{\Delta_Y}\right].\,C_{8Y}\right) \qquad \text{(Euro)} \tag{8}$$

where:

α_X, α_Y = 0, if the members are manufactured on the yard from standard plates. In this case, the welding costs to weld the flange and the web are added;

α_X, α_Y = 1, if the members are standard profiled members (IPE, HEA, HP bulb profile,…);

c) Labor Costs: F_{LAB}

$$F_{LAB} = \text{WLoad}\,.\,\text{Hourly Rate(Euro / m - h)} \tag{9}$$

where WLoad is the global working load (m-h) (Eq.10).

$$\text{WLoad} = L\,.\,B\,.\left[\begin{array}{l} \dfrac{1}{\Delta_X}.\,P_4 + \dfrac{1}{\Delta_Y}.\,P_5 \\ + \dfrac{1}{\Delta_X\,.\,\Delta_Y}\left(P_6 + \beta_X\,.\,\beta_Y\,.\,P_7\right) \\ + \dfrac{1}{\Delta_X}.\,P_{9X} + \dfrac{1}{\Delta_Y}.\,P_{9Y} \\ + P_{10} \end{array}\right] \tag{10}$$

where:

P_4 = working load to weld 1 meter of a longitudinal stiffener on the plating (side shell,...), (m-h/m)

P_5 = working load to weld 1 meter of a transversal stiffener on the plating (m-h/m)

P_6 = working load to prepare the intersection (slot) between a longitudinal and a transversal and to join these members (m-h/intersection).

P_7 = working load to fix bracket(s) at the intersection between a longitudinal and a transversal (m-h/intersection).

β_X,β_Y = ratio (in %) of the longitudinal stiffeners (β_X) and transverse stiffeners (β_Y) that requires brackets (e.g.: β_X = 0.33 means one bracketed longitudinal on 3 and β_Y = 1.0 a bracket on each frame);

P_{9X},P_{9Y}= working load to build 1 meter of stiffener/frame (assembling flange and web) from standard plates in the production plan (m-h/m). Additional work may be added (Figure 1)

P_{10} = working load to prepare 1 m^2 of plating (m-h/m^2). Generally this working load is linked to plate thickness and the ratio of the half-perimeter of the available plates (a.b) on its surface [(a+b)/(a.b)].

These working loads are defined as follows:

$$P_4 = P_4^o\left[1 + \left(d_X - E_{OX}\right).\,10^3\,.\,\Delta P_4\right] \tag{11a}$$

$$P_5 = P_5^o\left[1 + \left(d_Y - E_{OY}\right).\,10^3\,.\,\Delta P_5\right] \tag{11b}$$

$$P_{9X} = P_{9X}^o\left[1 + \left(d_X - E_{OX}\right).\,10^3\,.\,\Delta P_{9X}\right] \tag{11c}$$

$$P_{9Y} = P_{9Y}^o\left[1 + \left(d_Y - E_{OY}\right).\,10^3\,.\,\Delta P_{9Y}\right] \tag{11d}$$

where:

P_4^o, P_5^o ; P_{9X}^o, P_{9Y}^o = P_4, P_5, P_{9X}, P_{9Y} working loads (m-h/m) for the reference thickness, respectively E_{OX} for P_4

and P_{9X} and E_{OY} for P_5 and P_{9Y}.
ΔP_4, ΔP_5 ; ΔP_{9X}, ΔP_{9Y} = change (in %), by mm of dx (dy), of P_4^o, P_5^o and P_{9X}^o, P_{9Y}^o working loads.

$$P_{10} = P_{10}^{o}\left[1+(\delta - E_o).10^3 . \Delta P_{10}\right] \qquad (12)$$

where:
δ = plate thickness,
P_{10}^o = working load to prepare 1 m^2 of plating having the Eo reference thickness (m-h/m^2),
ΔP_{10} = change (in %), per mm of δ, of the P_{10}^o working load.

The aforementioned average values of P_4^o, P_5^o, P_6^o, P_7^o, P_9^o and P_{10}^o working loads are available in the literature [6]. Unfortunately nothing seems available in books and papers to determine the first derivative of these working loads according to plate thickness (ΔP_4, ΔP_5, ΔP_9 and ΔP_{10}). Hopefully with the ALSTOM's database, it was possible to quantify these parameters by calibrating the working loads with regards to weld sizes.

Additional works that can be considered:

- *D1: welding of the flat-bars (FB) on webs (for instance web-frames on double bottom),*
- *D2: Welding of the flat-bars (FB) with the longitudinals,*
- *D3: Brackets between the flat-bars (FB) and the longitudinals.*

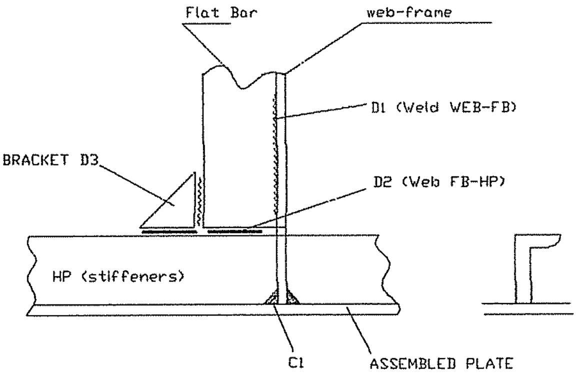

Figure 1: Works to consider in the web-frame construction (Unitary work load parameter P_{9Y})

4. LEAST COST OPTIMISATION OF A MEDIUM CAPACITY GAS CARRIER

This least cost optimisation example concerns the optimisation of a medium capacity gas carrier (LNG), designed by ALSTOM-Chantiers de l'Atlantique (France).

Due to the international competition between shipyards on such ships, a lot of valuable information will not be mentioned in the present paper. Nevertheless, the first author acknowledges ALSTOM for its courtesy for allowing use of the results of the optimisation process. In this paper, data are mainly presented in terms of ratios to avoid publishing sensitive confidential quantitative data.

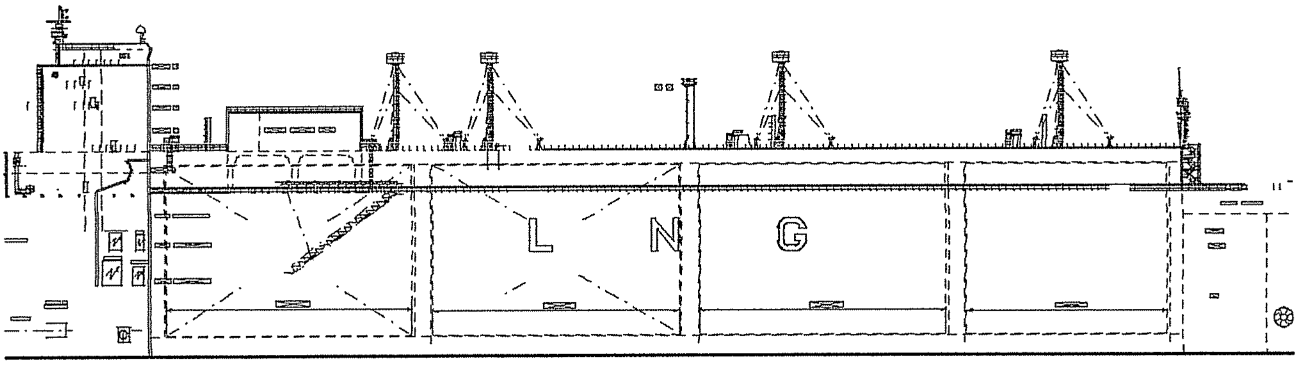

Figure 2: General view of a medium capacity gas carrier (ALSTOM, France)

The present optimisation concerns one of the four tanks (Figure 2). The goal is to define the optimum tank scantlings corresponding to the minimum construction cost. An additional aim is to assess feasible alternative designs (that is, improved general structural layouts).

To calibrate the current LBR5's cost module with the ALSTOM's unitary costs, the cost of a standard stiffened panel was assessed using the unitary production costs of ALSTOM. These unitary costs relate to:

- plate assembling and welding,
- longitudinal stiffener assembling and welding,
- transverse frame prefabrication,
- transverse frame assembling and welding (for different assembling sequences as the structure is mainly composed of double bottom, double deck and double side plates),
- slots, brackets, etc. (cutting, assembling and welding),
- ....

This assessment was used to define the LBR5 cost parameters: unitary prices of material (C1, ΔC1); unitary working loads for plate assembling (P10, ΔP10), frames and stiffeners (P4, P5, ΔP4, ΔP5, P9, ΔP9).

The ship is classified by Bureau Veritas and its MARS2000 software was used by ALSTOM to define the initial scantlings to be used by LBR5 (reference values). After optimisation, the new scantlings (optimum) are validated using MARS2000 to confirm the feasibility of the new layout and scantlings. This control fully confirms the LBR5 results and the possibility to save about 8 % of the tank's construction cost (cofferdam excluded).

Five loading cases were considered by LBR-5. They were obtained combining unitary load cases. The structural mesh model is shown on Figure 3. Based on structure symmetry, only half of the structure is modelled for structure optimisation with the LBR-5 model. The maximal sagging and hogging hull girder bending moments (still water level) were valued by ALSTOM through direct calculation (loading manual). The wave bending moments were obtained from classification rulebook.

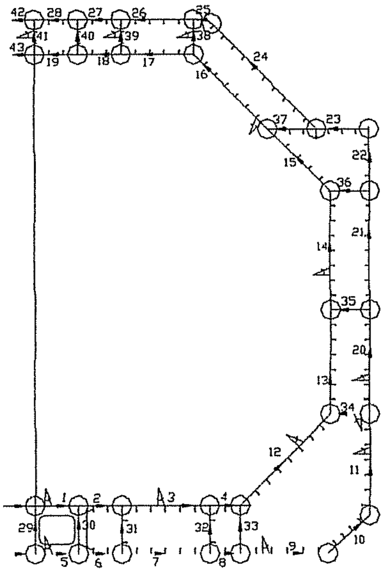

Figure 3: LBR5's Mesh Model of a Medium Capacity Gas Carrier

The mesh model of the medium capacity gas carrier (LNG) includes:

- 41 stiffened panels with 9 design variables each (some are not considered as variables);
- 4 additional panels to simulate the symmetry axis (boundary conditions);
- 278 design variables (on average 5 to 9 design variables per panel);
- 106 equality constraints between design variables are used, e.g., to impose uniform frame spacing for the deck, bottom and the side ballast tanks.

- 203 geometrical constraints (about 5 to 6 x 41 panels). For instance, longitudinal web heights are limited by such constraints to control the web slenderness.
- 1900 structural constraints (380 per load case):
  - σ_c frame (web/plate junction – web/flange junction and flange),
  - σ_c stiffener (web/plate – web/flange and flange) and σ_c plate, which verified that $\sigma_c \leq s_1.\sigma_o$ (with s_1 a partial safety factor and σ_o the yield stress);
  - local plate buckling: $\delta_{MIN} \leq \delta$ (with δ_{MIN} the minimum plate thickness to avoid buckling and yielding);
  - ultimate strength of stiffened panel: $\sigma / \sigma_{ULT} \leq s_2$ with s_2 a partial safety factor.

In addition side constraints are imposed on the design variables (XI_{MAX}, XI_{MIN}).

4.1 Minimizing the Construction Costs of the LNG Ship.

Tracks to reduce the construction cost of the medium capacity LNG ship are:

- To increase the web-frame spacing:
  $(N_w - 2)$ or $(N_w - 3)$ web-frames instead of N_w web-frames
- To increase the stiffener spacing (Δ_L):
  1.09 Δ_L , 1.15 Δ_L or 1.28 Δ_L instead of Δ_L

N_w and Δ_L refer to the initial design (before optimisation). N_w is the number of web-frames, Δ_W the frame spacing and Δ_L the average longitudinal stiffener spacing.

Aim of the LBR5 optimisation analysis is to provide a *least construction cost* and *feasible scantlings* of the 4 tanks. In principle, LBR5 directly provides the global optimum. In that case, it is not possible to assess the cost saving of each individual parameter like frame spacing, stiffener spacing, plate thickness, duct-keel layout, etc.

To assess these individual cost savings, the present optimisation was split in several sub-optimisations. So, starting from the Alstom's initial design, step by step, parameters are released and the layout modified (see Tables 1 and 2). Initially, the upper limit of each design variable is fixed at the Alstom's initial scantling value. Then, the upper limits of a group of design variables are released (typically starting with the frame spacing and stiffener spacing).

Main sub-optimisations are presented in Table 1. They are:

- Least cost optimisation (starting from the initial scantlings provided by ALSTOM, with fixed frame and stiffener spacings),
- Web-frame spacing (Δ_W) is released : $N_w \rightarrow (N_w - 2)$ frames,
- When feasible, the stiffener spacing is released: 1.15 Δ_L and 1.28 Δ_L instead of Δ_L,
- General structural layout is modified,
- Spacing of secondary frames is modified (typically 2 or 3 secondary frames between web-frames are considered, that is, respectively, $\Delta_C = \Delta_W/3$ and $\Delta_W/4$),

Table 2 assesses the cost saving associated with each sub-optimisation and with the global optimisation (cumulated cost saving). It shows clearly that the way to reduce construction cost of the concerned LNG ship is to increase the web-frame spacing (N_W-3) and to standardize the stiffener spacing at 1.15 Δ_L (in average). Such changes induce a cost saving of about 8.50% (material and labour costs).

Figures 4 compares the COST of the different configurations. Sub-optimisations and optimum solutions are marked.

Table 1: Steps of the Optimisation Process (with sub-optimisations)

	SEARCH FOR THE LEAST COST DESIGN (with continuous design variables)				STEPS OF THE OPTIMIZATION PROCESS
		SPACINGS			
	Optimum Type	Number of Web-frames	Secondary Frames (Δ_C)	Stiffeners (Δ_L)	N_W = Numer of Web-frames and Δ_W = Web-frame Spacing Δ_C = Secondary Web-frame Spacing (=Δ_W/4 or Δ_W/3)
1- ALSTOM	MARS BV	N_W	Δw/3	Δ_L (Alstom)	Initial "ALSTOM" layout used as reference point (before optimisation) With discrete design variables.
2- MET8 E00	Least Cost (*)	N_W	Δw/3	Δ_L (Alstom)	After optimisation of the ASTOM initial design with Δ_W, Δ_C and Δ_L unchanged. The design variables become continuous.
3- MET8 E90	Least Cost	N_W	Δw/3	1.15 Δ_L (*)	The stiffener spacings are released (1.15 the initial value)
4- MET8 B90	Least Cost	N_W -3 (*)	Δw/3	1.15 Δ_L (*)	The web-frame spacing is released (upper limit corresponds to 9 frames).
5- MET8 F90	Least Cost	NW -3	Δw/4 (*)	1.15 Δ_L (*)	As the web-frame spacing becomes larger, one additional secondary frame spacing is added (Δ_C = Δ_W/4 instead of Δ_W/3).
6- MET8 F	Least Cost	N_W -3	Δw/4	1.28 Δ_L (*)	The stiffener spacing's upper limit is increased to 1.25 the initial value

(*) Shows the modified parameter (or variable) between two successive steps

Table 2: Cost Saving at Each Step of the Optimisation Process

SEARCH FOR THE LEAST COST DESIGN (with continuous design variables)									
		SPACINGS			Duct keel bullhead. Plate Thickness	LEAST COST		WEIGHT	
CONFIGU-RATIONS	Optimum Type	Number of Web-frames	Second. Frame (Δ_C)	Stiffeners (Δ_L)		COST SAVING (%) (see 1)		(%)	
	Shown change(s) between 2 successive steps					Between 2 successive steps	Cumulated saving		
1- ALSTOM	MARS BV	N_W	Δw/3	Δ_L (Alstom)	100%	0.00%	0.00%	100% (ref)	Initial Design (used as reference)
2- MET8 E00	Least Cost	N_W	Δw/3	Δ_L (Alstom)	105%	-1.39%	-1.39%	98.34%	
3- MET8 E90	Least Cost	N_W	Δw/3	1.15 Δ_L	105%	-2.46%	-3.85%	101.61%	
4- MET8 B90	Least Cost	N_W -3	Δw/3	1.15 Δ_L	130%	-6.40%	-10.25%	104.73%	plate thickness too large
5- MET8 F90	Least Cost	NW -3	Δw/4	1.15 Δ_L	100%	1.67%	-8.58%	103.42%	OPTIMUM SOLUTION
6- MET8 F	Least Cost	N_W -3	Δw/4	1.28 Δ_L	100%	-0.53%	-9.11%	105.29%	(*) Poor efficiency
	(*) Stiffener spacing too large ==> cost savings of 0.5% but increased straightening work ==> not efficient !!								
(1 Variation induced by the changes occured between two configurations.									

The global optimum (MET8-F90) is characterised by an increase of the weight. To avoid this negative effect, ALSTOM proposed some layout improvement to keep the hull weight almost unchanged.

Based on the LBR5's proposals, ALSTOM modified their initial design and structure layout to define a revised solution that was used for the final design stage. Expected savings predicted by LBR-5 are confirmed through ALSTOM's additional workload assessment.

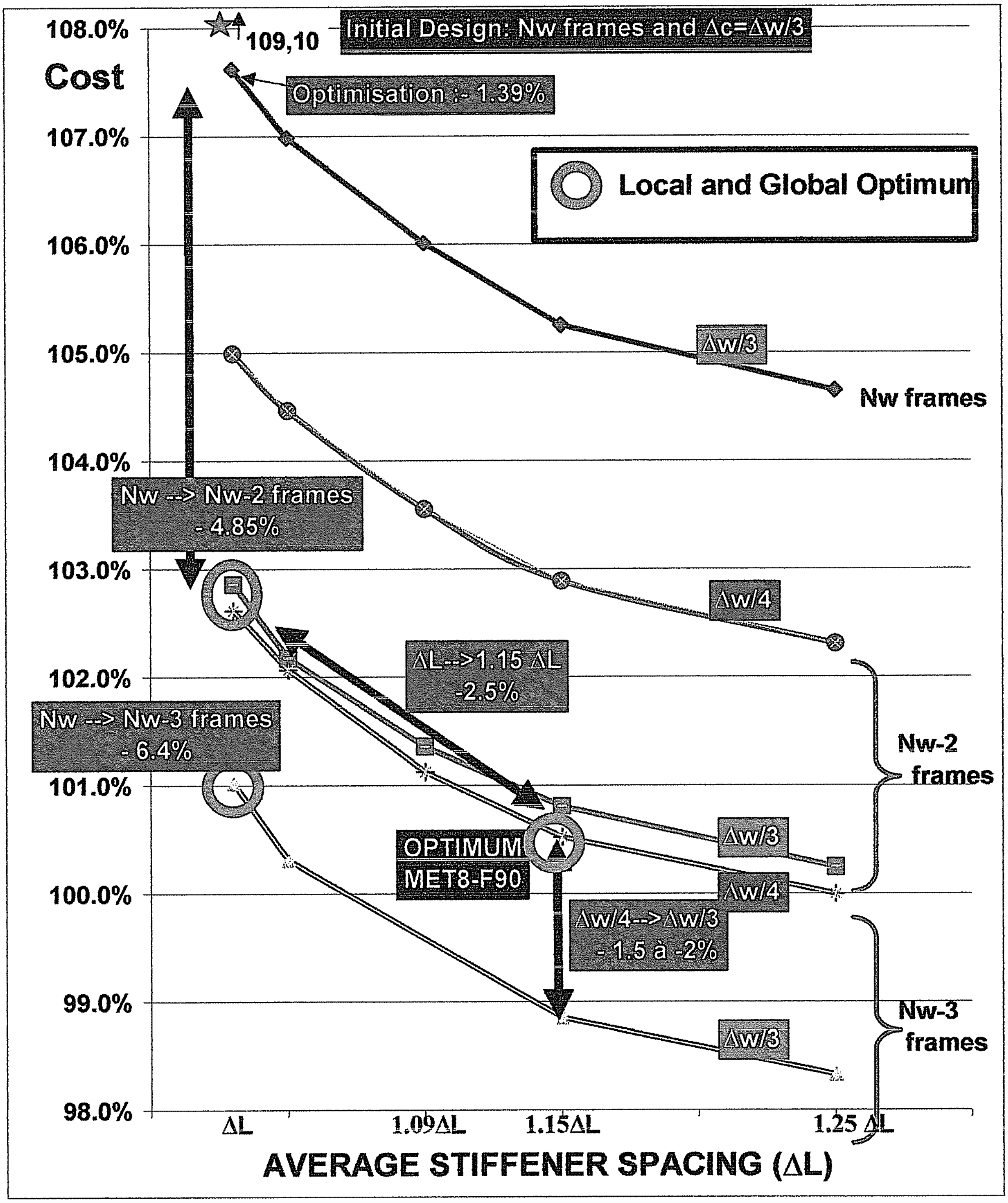

Figure 4: Sensitivity analysis of the stiffener spacing on the construction cost of a medium capacity LNG carrier (one hull tank)

5. CONCLUSIONS

LBR-5 is a structural optimisation tool for structures composed of stiffened plates and stiffened cylindrical shells. Design variables are plate thickness, longitudinal and transversal stiffener dimensions and their spacing. It is an integrated model to analyse and optimise ship structures at their earliest design stages: tendering and preliminary design.

Advantages and main characteristics are:

- Preliminary design oriented (easy and fast modelling, reduced amount of input data, etc.),
- Structure optimisation at initial design (initial feasible scantling is not required, etc.),
- Least construction cost and least weight (objective functions) based on a rational explicit formulations of the cost,
- Rational formulation of the constraints (technologic, geometric and structural constraints). They are not rule based. Ultimate strength of stiffened panels and ultimate bending moment are considered thought rational constraints,
- Efficient and reliable optimiser (only 10~15 iterations and 1 hour are necessary to get the optimum). Large structures can be studied (100 panels, 900 design variables and 5000 constraints to cover up to 10 loading cases).

Optimum analysis of a medium capacity LNG ship is presented as application of the LBR-5 least cost optimisation model. It confirms the feasibility to perform scantling optimisation of large structures using a minimum cost objective function at the preliminary design stage. For the original structural layout, LBR5's analysis has provided an effective cost saving of 8.5% for the hull tank construction.

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