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An Integrated Software for Scantling Optimization and Least Production Cost[1]

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1 Introduction

The general structural layout is usually defined during the preliminary design. An optimization tool at this stage featuring flexibility, modeling speed and user-friendliness may provide precious help to designers. At this stage, few parameters/dimensions have been fixed and standard finite element modeling is often unusable, particularly for design offices and small and medium-sized shipyards.

The LBR5 software is an integrated package to perform cost and weight optimization of stiffened ship structures, *Rigo (1992,2001a,b,2003), Rigo and Fleury (2001), Karr et al. (2002)*, allowing:

- a 3D analysis of the general behavior of the structure (usually one cargo hold);
- to include all the relevant limit states of the structure (service limit states and ultimate limit states) in an analysis of the structure based on the general solid-mechanics;
- an optimization of the scantlings (profile sizes, dimensions and spacing);
- to include the unit construction costs and the production sequences in the optimization process (through a production-oriented cost objective function).

Only basic characteristics such as L, B, T, C_B, the global structure layout, and applied loads are the required data. It is not necessary to provide a feasible initial scantling. Typical CPU time is 1 hour using a Pentium III desktop computer.

Methods similar to LBR-5 are proposed by *Hughes (1980,1988,1992)* with Maestro, *Rahman (1992,1995), Sen (1989)*, and many others. Compared to Maestro, LBR-5 is more preliminary design oriented. The structure modeling is so simple and fast, but not simplified, that optimized scantling can be obtain within a couple of hours (maximum one day for complex structures if starting from scratch). LBR-5 does not have the capability of a finite element analysis and is restricted to prismatic structures and linear 3D analysis. But, on the other hand, LBR-5 uses explicit exact first-order sensitivities (derivatives of the constraint and objective functions by the hundreds of design variables). Heavy and time consuming numerical procedures are not required. Sensitivities are directly available as the method is based on an analytic solution of the differential equations of cylindrical stiffened plates using Fourier series expansions. So, sensitivity formulations are known analytically. In addition LBR-5 does not need to use the concept of local and global design variables used by Hughes, Rahman, and Sen. Due to the efficient CONLIN mathematical optimization algorithm (convex linearization and dual approach), optimization of the full structure can be performed with hundreds of design variables and constraints using less than 10$\sim$15 global structure re-analysis (iterations).

2 State of the art

The first ship structure optimization studies were made practically by hand, *Harlander 1960)*. Then, with computer assistance, researchers tried to develop design and optimization algorithms. Optimization first appears in the works of *Evans (1963), Mandel and Leopold (1966), Moe and Lund (1968), Nowacki et al. (1970)*. The work of Moe and Nowacki long served as a reference for naval structure optimization, *Winkle and Baird (1986)*. An important step for naval structure optimization

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appeared with Hughes' work, *Hughes (1980,1988,1992)* and *Mistree et al. (1992)*. The evolution of design techniques and optimization are reported by ISSC (Int. Ship Structural Congress: 1988 to 2000). Major references on optimization include *Vanderplaats (1984), Save et al. (1985, 1990), Wisniewski et al. (1990)*; Examples of ship structure optimization include *Lyons (1982), Hung (1987), Jang and Na (1991), Kriezis (1991), Krol (1991), Park et al. (1991), Rahman and Caldwell (1992,1995), Hatzidakis and Bernitsas (1994), Nobukawa et al. (1995), Na et al. (1994), Karr et al. (2002)*.

Most of the scientific literature deals with optimization mathematical tools and analysis methods for limit states assessment (strength, deflection, etc.). Few accessible articles concern the choice of the objective function, and more precisely a construction cost objective function, although most studies show the necessity of establishing objective criteria integrating production costs and to compile a meaningful database of unitary construction costs, *Southern (1980), Kuo et al. (1984), Winkle and Baird (1986), Bunch (1989, 1995), Hills and Buxton (1989), Blomquist (1995), Hengst et al. (1996), Kumakura et al. (1997), Keane and Fireman (1993), Ennis et al. (1998), Schneekluth and Bertram (1998), Rigo (2001b), WEGEMT (2002)*.

The term "ship structural optimization" is interpreted differently by different people. For ship-owners, to optimize the structure of a new ship means determining the main ship dimensions in order to attain the highest profitability rate, *Mandel and Leopold (1966), Buxton (1976), Sen (1978)*. For the designer, "structural optimization" simultaneously concerns both the hull forms and the structural components (scantling), *Keane et al. (1991)*. For the structural engineer, "structural optimization" essentially consists in defining optimum scantling of the decks and the bottom and side shells. In this analysis, "structural optimization" essentially consists of defining optimum scantling of the decks and the bottom and side shells (including the framing). In this ship-sizing optimization, the general dimensions and the hull forms are considered as fixed. Only the frame and stiffener spacing are use as topological design variables.

Concerning ship-sizing optimization, the general dimensions and the hull forms (shapes) are considered as fixed and it should be noted that since 1980 the FEM has become a standard to evaluate constraints on stress, displacement and ultimate strength at each iteration, *Hughes (1980,1988), Zanic et al. (2000)*. With FEM, structure analysis of a large structure is quite demanding and thus represents the major portion of computing time. Thus two options have appeared: either to develop more effective mathematical algorithms in order to reduce the number of FEM re-analyses, *Fleury (1993)*, or to divide the optimization problem of the structure into two levels, *Hughes (1980), Sen et al. (1989a,b), Krol (1991), Rahman et al. (1992,1995)*. The first alternative is used in this study.

The University of Newcastle-Upon-Time is a well known for its research center on multi-objective optimization (Multi-Object Decision Model and Multi Criteria Decision-Making), *Sen (1998)*. The use of genetic algorithms for large size multi-criteria optimization has recently become popular, *Goldberg (1989), Okada et al. (1992)*. Multi-criteria optimization have been applied to ship structures by *Parsons and Singer (2000), Singer and Parsons (2003), Shi (1992), Trincas et al. (1994), Kim and Han (1994), Ray and Sha (1994)*.

For more than 15 years, shape optimization has witnessed the most important progress in the domain of structure optimization, *Beckers (1991)*. Thus, it is now possible to automatically search for optimal hull forms. Fluid-structure interaction is a difficult matter that, within the framework of a shape optimization procedure, makes the problem quite complex, thus explaining the few industrial applications.

Thanks to the continuous development of computer capabilities, topological optimization is a research field that, in the last few years, has enabled us to discern various industrial applications. Topological optimization is a dream that is slowly becoming a reality, but the applications are so far rather "academic", *Bensoe and Kikuchi (1988), Duysinx (1996), Buannic and Besnard (2002)*.

3 LBR5 and its 3 basic modules

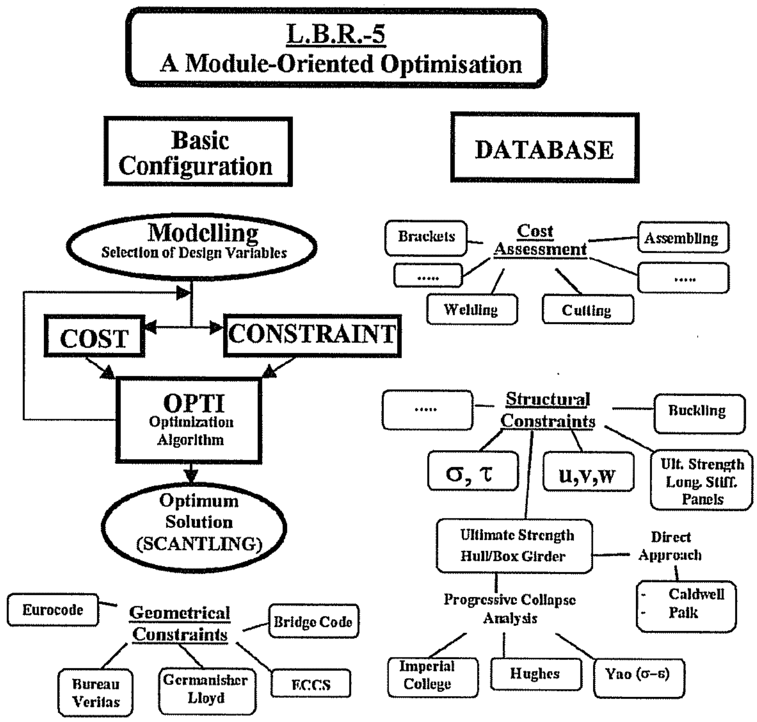

Fig.1: Basic configuration of the LBR5 model and basic modules

The optimization problem can be summarized as follows:

X_i	$i = 1, N$	the N design variables,
$F(X_i)$		the cost objective function to minimize,
$C_j(X_i) \leq CM_j$	$j = 1, M$	the M structural and geometrical constraints,
$X_{i,\min} \leq X_i \leq X_{i,\max}$		the upper and lower bounds of the X_i design variables (side constraints)

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

- 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:

1. The OPTI module contains the mathematical optimization algorithm (CONLIN, *Rigo and Fleury (2001)*) that allows solving non-linear constrained optimization 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. CONLIN is based on a convex linearization of the non-linear functions (constraints and objective functions) and on a dual approach, Fleury (1989). This module uses as inputs the results of the two other basic modules, i.e. CONSTRAINT for the $C(X_i)$ constraints and COST for the $F(X_i)$ objective function. First derivative of these functions are also required $(\partial C/\partial X_i, \partial F/\partial X_i)$.

2. The CONSTRAINT module asks the user to select relevant constraints within constraint groups available in a database. Several coherent constraint sets are proposed to facilitate this selection. These sets are based on national and international rules (Eurocodes, European Convention for Constructional Steel Work Recommendations as *ECCS 60 (1990)*, classification societies, etc.).

   Constraints are linear or non-linear functions, either explicit or implicit in the design variables:

   - Technological constraints (side constraints) provide the upper and lower bounds of the design variables.
   - Geometrical constraints impose relations between design variables 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 represent limit states to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc. These constraints are based on direct analyses and are modeled with equations. The model's behavior are often so complex that it is not possible to explicitly express the relation between the parameters (stress, displacement,...) and the design variables. This happens when one uses mathematical models like finite element modeling (FEM). In this case, one generally uses a numeric process that consists in replacing the implicit function by an explicit "approximated function" adjusted in the vicinity of the initial values of the design variables (e.g. using Taylor series expansions). In this way, the optimization process becomes an iterative analysis based on a succession of local approximations of the model's behavior, *Fleury (1989), Rigo and Fleury (2001)*.

3. The COST module: a least weight objective can no longer be justified and should be replaced by least construction cost (if not least global cost including operational costs). Here the objective function (COST module) is the construction cost that includes e.g. 65% of labor costs and 35% of material cost (almost proportional to the weight). In order to link the objective function [Euro] to the design variables, the unit costs of raw materials [Euro/kg], the productivity rates for welding, cutting, assembling, etc. [man-hours/unit of work = m-h/unit] and labor 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. Obviously, the result of this optimization process (scantling optimization) will be valid only for the specified economic and production data. They cannot be extrapolated to other production units without performing a new analysis. Sensitivity analyses of the economic data on the optimum scantling can be performed, providing valuable information for improving a shipyard.

The example presented here is only valid for the concerned shipyard and considered ship type. Results cannot be extrapolated to other production units without performing a new analysis. Nevertheless, the example is valuable to validate the methodology, i.e. to reduce the production costs through a structure optimization performed at the early design stage.

4 The cost module and the objective function

Global construction costs can be subdivided into three categories:

1. Cost of raw materials
   The evaluation of material costs consists in quantifying volumes required for construction and obtaining prices from suppliers and subcontractors. This task is a priori simple, but contains numerous uncertainties as the quantity assessment (number of parts) that is improved with the project progress. Scrap parts constitute also an important unknown, especially at the beginning of a project. A classic evaluation is 5-10%, but the percentage can be higher, depending on the zone studied (aft and fore, machinery area) and the selected design details (bracket shape, slot type, etc.).

2. Instead of using empirical formulations, the best alternative to evaluate labor costs is an analytic assessment. Such an approach requires knowing the work time required for each standard labor task associated with a workstation as well as the subdivision by stations of the entire construction process. All operations should be included. The keys to a reliable evaluation of labor costs are as follows:

   - Split the entire construction into the different construction tasks and quantify the work to be performed for each task. E.g.: cutting lengths should be classified according to plate thickness, welding length according to welding systems: manual, semiautomatic, automatic,....
   - Obtain a reliable and realistic productivity evaluation (in man-hours) for each workstation. Unfortunately, our experience shows that uncertainties are the highest in this regard.

3. Overhead Costs
   Overhead includes expenses that cannot be attributed to work stations of the construction process, but that are, however, linked to construction. It is necessary to distinguish between variable costs and fixed costs. Variable costs include expenses that vary with production labor such as fringe benefits, workman's insurance, product insurance, water, electricity, gas, heating, etc. The fixed costs are loads incumbent to the yard, but that are independent of production level.

4.1 Analytic evaluation of the construction costs

The purpose of this analysis is to allow a relative and objective comparison, on basis of cost, of the successive designs resulting from the optimization process. So, the absolute cost is not needed. The overhead cost, though far from negligible, can be ignored in our analytic cost model. We then consider material cost C_{mat} and labor cost C_{lab} for the "total" cost:

$$C_T = C_{mat} + C_{lab} = \sum_{j=1}^{K} Q_j \cdot P_j + \sum_{i=1}^{N_T} T_i \cdot M_i \cdot S_i \tag{1}$$

j is the reference number of a given material, K the number of different materials, Q_j the expected quantity of the j material, P_j the unit price of the j material [Euro/unit], N_T number of different standard tasks, i the reference number of a given task, T_i the required work load for the i standard task [man-hours], M_i number of times that the T_i task happens, S_i the hourly labor cost [Euro/man-hour] of a person doing the i standard task.

Eq.(1) 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 resides in the identification and subdivision of tasks into sub-tasks and, finally, into elementary standard tasks. Eq.(1) is therefore a condensed version of a more general equation in which the hierarchy of tasks, explicitly appears:

$$C_{lab} = \sum_{i1=1}^{N_{T1}} M_{i1} \left[\sum_{i2=1}^{N_{T2}} M_{i2} \left[... \left[\sum_{ik=1}^{N_{Tk}} M_{ik} \left[... \left[... \sum_{in=1}^{N_{Tn}} M_{in} \cdot T_{in} \cdot S_{in} \right] \right] \right] \right] \right] \tag{2}$$

k is the hierarchical level of the task: $k = 1$ superior level (block), $k = 2, 3, ...$ intermediate levels (panels,...), $k = n$ elementary level. Thus, the global cost evaluation procedure requires successive hierarchical subdivision of tasks and defining unit costs for elementary tasks.

4.2 Normalized cost

In *Moe and Lund's (1968)* 'Equivalent Weight Concept', the total cost C_T [Euro] is written as:

$$\begin{aligned} C_T &= \text{[Unit Mat. Cost]} \cdot \text{[Weight]} + \text{[Unit Lab. Cost]} \cdot \text{[Work load]} && (3)\\ &= \text{[Unit Mat. Cost]} \cdot E_{QP} && (4) \end{aligned}$$

E_{QP} =Mat. Weight+$\eta \cdot k \cdot W_{Load}$ [t] is an equivalence weight factor.

$$k = \frac{S}{Q} = \frac{\text{Unit Lab. Cost [Euro/m-h]}}{\text{Unit Mat. Cost [Euro/t]}} \left[\frac{\text{t}}{\text{m-h}}\right] \tag{5}$$

η is an efficiency parameter to characterize the production yard, W_{Load} the global work load [man-hours].

The equivalent weight k allows easy evaluation of the total cost for a series of material unit prices Q and labor S, thus permitting a comparison between countries where the k coefficient varies. For Western countries, k varies from 0.03 to 0.10 t/man-hour. The k coefficient is linked only to the living cost.

4.3 Modeling of the objective functions used by the LBR5 model

Cost is the objective function in the LBR5 model. Weight can also be selected as a simplified form of the cost objective function. The weight objective function F_w is written for an orthotropic stiffened panel as:

$$F_w = \gamma \cdot L \cdot B \cdot \left[\delta + \frac{(h \cdot d + w \cdot t)_x}{\Delta x} + \frac{(h \cdot d + w \cdot t)_y}{\Delta y}\right] \tag{6}$$

L [m] is the length of the panel in x, B [m] its breadth in y, δ [m] the plate thickness, γ [N/m^3] the specific weight, $(h, d, w, t)_x$ the dimensions of web and flange of the longitudinals (stiffeners) fitted along x, $(h, d, w, t)_y$ along y, Δx the spacing between two longitudinals (stiffeners), and Δy the spacing between two transverse frames. 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, one should use a cost objective function.

Theoretically, the cost model should be established in close relation to the specified production plan. Unfortunately, it does not seem possible to define a general model, valid in all situations. Therefore 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 model used here includes three components:

$$F_C = F_{MAT} + F_{CONS} + F_{LAB} \tag{7}$$

F_C is the global cost function [Euro]; F_{MAT} cost of basic materials (plates, bars, etc.); F_{CONS} cost of consumables necessary for the construction process (energy, welding materials, etc.); and F_{LAB} cost of labor used for the building of the entire structure.

a) Cost of materials: F_{MAT}

The cost of materials is directly derived from the weight function. Each term of Eq.(6) should be multiplied by the relevant C_i unit material cost (plate, bulb profile, etc.):

$$F_{MAT} = \gamma \cdot L \cdot B \cdot \left[C_1 \cdot \delta + C_2 \cdot \frac{(h \cdot d + w \cdot t)_x}{\Delta x}[1 + DW_2] + C_3 \cdot \frac{(h \cdot d + w \cdot t)_y}{\Delta x}[1 + DW_3]\right] \tag{8}$$

C_1 is the cost per kg of a plate δ mm thick, C_2 the cost per kg of the longitudinals/stiffeners, C_3 the cost per kg of the transverse frames, DW_2 the corrective factor (ratio of C_2) of the longitudinals/stiffeners for additional weight, and DW_3 the 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, Fig.2. The C_1, C_2, and C_3 parameters [Euro/kg] are defined to take into account a possible variation of the price per kg of the plates according to their thickness:

$$\begin{aligned} C_1 &= C_1^0[1 + \Delta C_1(\delta - E_0) \cdot 10^3] \\ C_2 &= C_2^0[1 + \Delta C_2(d_x - E_{0x}) \cdot 10^3] \text{ for longitudinal members} \\ C_3 &= C_3^0[1 + \Delta C_3(d_y - E_{0y}) \cdot 10^3] \text{ for frames and transverse members} \end{aligned} \tag{9}$$

C_1^0 is the cost per kg of a plate with a thickness $\delta = E_0$ [m], C_2^0 the cost per kg of longitudinal members having a web thickness $= E_{0x}$, C_3^0 the cost per kg of transverse members having a web thickness $= E_{0y}$. E_0 is the reference thickness for the plates (mean plate thickness) [m], E_{0x} the reference thickness for the longitudinal members (mean web thickness), E_{0y} the reference thickness for the transverse members (mean web thickness), d_x, d_y the actual web thickness for stiffeners along x (long.) and frames along y (transverse); ΔC_1 the change in % of C_1^0 (cost/kg) between plates of E_0 and E_0 + 1mm thick, ΔC_2 the change in % of C_2^0 (cost/kg) of the longitudinals between web of E_{0x} and E_{0x} + 1mm thick, and ΔC_3 the change in % of C_3^0 (cost/kg) of the frames between web of E_{0y} and E_{0y} + 1mm thick.

$C_1^0 = 0.55$ Euro/kg for mild steel (AE 235) and 0.61 Euro/kg for HTS (AE355).
$\Delta C_1 = -0.006$ (this means 0.6% per mm); ΔC_2 and ΔC_3 are usually similar.

In order to evaluate C_2^0 and C_3^0, note that:
$C_2^0 = 0.9\ C_1^0$ in Belgium (this means 10% less than standard plate),
$C_2^0 = 1.25\ C_1^0$ in Bangladesh (this means 25% more than standard plate),
$C_3^0 = 0.9\ C_1^0$: In Belgium (this means 10% less than standard plate),
$C_3^0 = 1.4\ C_1^0$: In Bangladesh (this means 40% more than standard plate),
Bulb profile (C_2^0 and $C_3^0 = 1.2\ C_1^0$) are about 20% more expensive than standard plate (C_1^0).

b) Cost of Consumables: F_{CONS}

The welding cost per meter (energy, gas, electrodes, provision for the equipment depreciation, ...), excluding labor cost, is estimated:

$$C_{8x} = C_{8x}^0[1 + \Delta C_{8x}(d_x - E_{0x}] \cdot 10^3] \quad \text{for the longitudinals} \tag{10}$$

$$C_{8y} = C_{8y}^0[1 + \Delta C_{8y}(d_y - E_{0y}] \cdot 10^3] \quad \text{for the transverse members (frames)} \tag{11}$$

C_8^0 is the 'cost/m' of consumables to weld the web with its flange (2 welds), ΔC_8 the relative change [%] of C_8^0 increasing the plate thickness from E_0 to (E_0 + 1mm, with E_0 being E_{0x} or E_{0y}. Then the consumable cost [Euro] is:

$$F_{CONS} = L \cdot B \cdot \left(\frac{2 - \alpha_x}{\Delta x} \cdot C_{8x} + \frac{2 - \alpha_y}{\Delta y} \cdot C_{8y}\right) \tag{12}$$

α_x, $\alpha_y = 0$ 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, $\alpha_y = 1$ if the members are standard profiled members.

C_8^0 and ΔC_8 are defined using experience. In our approach we used to data from E.S.A.B. S.A. (for semiautomatic welding and manual welding) and the shipyard database.

$$
\begin{aligned}
C_8^0 &= 0.90 \text{ Euro/m with } E_0 = 10\text{mm (Semi automatic welding, in 1998)}\\
&= 1.00 \text{ Euro/m with } E_0 = 10\text{mm (Manual welding)}\\
&= 0.25 \text{ Euro/m with } E_0 = 5\text{mm (Semi automatic welding)}\\
&= 0.30 \text{ Euro/m with } E_0 = 5 \text{ mm (Manual welding)}\\
\Delta C_8 &= \text{Relative change of } C_8^0 \text{ (Euro/m) between a } (E_0) \text{ and a } (E_0{+}1 \text{ mm) plate thick.}\\
&= 0.24 \text{ (24\%) between 8 and 20 mm: } E_0 = 10\text{mm, Manual welding (1998)}\\
&= 0.30 \text{ (30\%) between 8 and 20 mm: } E_0 = 10\text{mm, Semi automatic welding (1998)}\\
&= 0.22 \text{ (22\%) between 3 and 7 mm: } E_0 = 5\text{mm, Manual welding (1998)}\\
&= 0.17 \text{ (17\%) between 3 and 7 mm: } E_0 = 5\text{mm, Semi automatic welding (1998)}
\end{aligned}
$$

c) Labor Cost: F_{LAB}

With an efficiency parameter ($0 < \eta \leq 1$) for the considered production plan, we have:

$$F_{LAB} = \eta \cdot k \cdot C_1^0 \cdot W_{Load} \tag{13}$$

$$W_{Load} = L\dot{B} \cdot \left[\frac{P_4}{\Delta x} + \frac{P_5}{\Delta y} + \frac{P_6 + \beta_x \cdot \beta_y \cdot P_7}{\Delta x \cdot \Delta y} + \frac{P_{9x}}{\Delta x} + \frac{P_{9y}}{\Delta y} + P_{10}\right] \tag{14}$$

P_4 [m-h/m], is the work load to weld 1 m of a longitudinal stiffener on the plating (side shell,...), P_5 [m-h/m] the work load to weld 1 meter of a transversal stiffener on the plating, P_6 [m-h/intersection] the work load to prepare the intersection (slot) between a longitudinal and a transversal and to join these members, P_7 [m-h/intersection] the work load to fix bracket(s) at the intersection between a longitudinal and a transversal, β_x, β_y the ratio [%] of the longitudinal stiffeners and transverse stiffeners that requires brackets (e.g.: $\beta_x = 0.33$ means one bracketed longitudinal on 3 and $\beta_y = 1$ a bracket on each frame), P_{9x}, P_{9y} [m-h/m] the work load to build 1 m of stiffener/frame (assembling flange and web) from standard plates in the production plan. Additional work may be added, Fig.2, P_{10} [m-h/m2] the work load to prepare 1 m^2 of plating. Generally this work load is linked to plate thickness and the ratio of the half-perimeter of the available plates $(a \cdot b)$ on its surface $[(a+b)/(a \cdot b)]$.

These work loads are defined as follows:

$$
\begin{aligned}
P_4 &= P_4^0[1 + (d_x - E_{0x}) \cdot 10^3 \cdot \Delta P_4]\\
P_5 &= P_5^0[1 + (d_y - E_{0y}) \cdot 10^3 \cdot \Delta P_5]\\
P_{9x} &= P_0^{9x}[1 + (d_x - E_{0x}) \cdot 10^3 \cdot \Delta P_{9x}]\\
P_{9y} &= P_0^{9y}[1 + (d_y - E_{0y}) \cdot 10^3 \cdot \Delta P_{9y}]
\end{aligned} \tag{15}
$$

P_4^0, P_5^0 ; P_{9x}^0, P_{9y}^0 [m-h/m] are the work loads 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} are the changes [%], per mm of dx (dy), of P_4^0, P_5^0, and P_{9x}^0, P_{9y}^0 work loads.

$$P_{10} = P_{10}^0[1 + (\delta - E_0) \cdot 10^3 \cdot \Delta P_{10}] \tag{16}$$

P_{10}^0 [m-h/m^2] is the work load to prepare 1 m^2 of plating having the E_0 reference thickness, ΔP_{10} the change [%], per mm of δ of the P_{10}^0 work load.

Average values of P_4^0, P_5^0, P_6, P_7, P_9^0, and P_{10}^0 work loads may be obtained from *Winkle and Baird (1986)*.

First derivative of these work loads according to plate thickness ΔP_4, ΔP_5, ΔP_9, and ΔP_{10}) based on our experience (or shipyard experience) are on average:

- P_4^0, P_5^0, P_{9x}^0, $P_{9y}^0 = 0.6$ to 1.2 m-h/m (without additional work). Additional work like bracket, local stiffening associated with these numbers may be considered through the P_9 parameters considering an additional average working load per meter of member: P_{9x}^0 for long members and P_{9y}^0 for transverse members. For web frame of double bottom, additional work (P_{9y}^0) can reach 2.0 m-h/m.

- ΔP_4, ΔP_5, ΔP_{9x}, and $\Delta P_{9y} = 0.1$ (10%)
- $P_6 = 0.2$ to 0.6 m-h/intersection; and $P_7 = 0.3$ to 1.2 m-h/intersection.
- $P_{10}^0 = 0.3$ to 1.5 (m-h/m^2) without straightening.
- $\Delta P_{10} = 0.07$ (7%)

In our application, we used the shipyard's database to quantify these parameters calibrating the work loads with regards to weld sizes.

Additional work that can be considered:
- D_1: welding of the flat-bars (FB) on webs (for instance web frames on double bottom),
- D_2: Welding of the flat-bars (FB) with the longitudinals,
- D_3: Brackets between the flat-bars (FB) and the longitudinals.

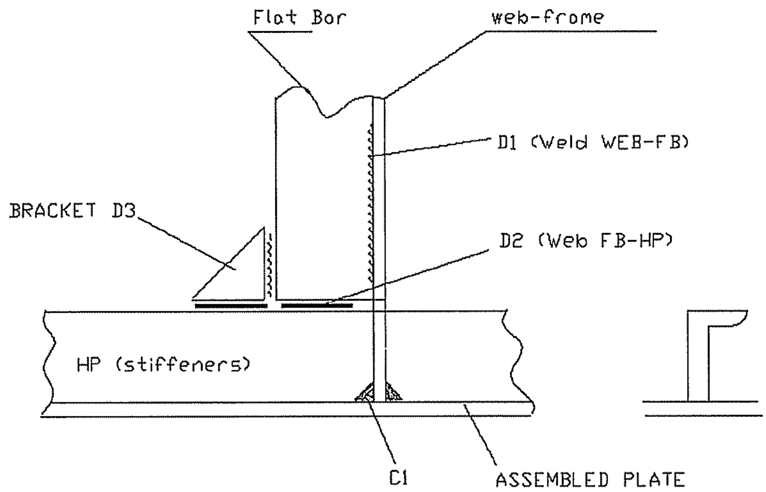

Fig.2: Work to consider in the web frame construction (Unit work load parameter P_{9y})

5 Least cost optimization of a medium capacity gas carrier

This least cost optimization example concerns the optimization of a medium capacity gas carrier (LNG), designed by ALSTOM-Chantiers de l'Atlantique (France), *Rigo and Toderan (2003)*. The present optimization shall determine the optimum scantlings associated with the minimum construction cost for one of its four tanks. An additional aim is to assess feasible alternative designs. Data are presented in non-dimensional form to avoid publishing sensitive shipyard's confidential data.

We calibrated our cost module with the shipyard's unit costs for a standard stiffened panel. Unit costs related 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 unit prices of material (C_1, ΔC_1); unit work loads for plate assembling (P_{10}, ΔP_{10}), frames and stiffeners (P_4, P_5, ΔP_4, ΔP_5, P_9, ΔP_9).

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

Five load cases were considered by LBR5:

1. Maximum lateral pressure defined by MARS (BV) for all the load cases defined by the classification,
2. The rule load case corresponding to the maximum transverse bending of the double bottom (empty tank, maximum draft)
3. The rule load case corresponding to the maximum transverse bending of the side tank (full tank, minimum draft),
4. The rule load case corresponding to the maximum hull girder hogging bending moment,
5. The rule load case corresponding to the maximum hull girder sagging bending moment.

The load cases were obtained combining unit load cases following BV rules. Using structure and load symmetry, only half of the structure was modeled, Fig.3. The maximal sagging and hogging hull girder bending moments (still water level) were evaluated by the shipyard through direct calculation (loading manual). The wave bending moments were obtained from the classification rules.

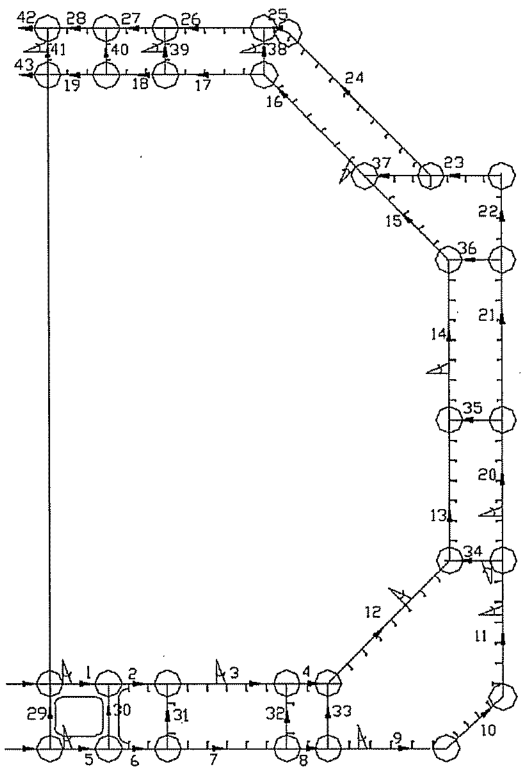

Fig.3 LBR5's mesh model of medium-capacity gas carrier

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 per panel). E.g., 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 $\sigma_c \leq s_1 \cdot \sigma_0$ (with s_1 a partial safety factor and σ_0 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.

Constraints are imposed on the design variables, e.g.:

	δ	$\leq$ 25 mm
2.00 m $\leq$	Δ_{Frames}	$\leq$ 4.00 m
0.50 m $\leq$	$\Delta_{\text{Stiffeners}}$	$\leq$ 1.00 m
0.10 m $\leq$	$h_{\text{web stiffeners}}$	$\leq$ 0.50 m
8.0 mm $\leq$	web frames thickness	$\leq$ 25.0 mm

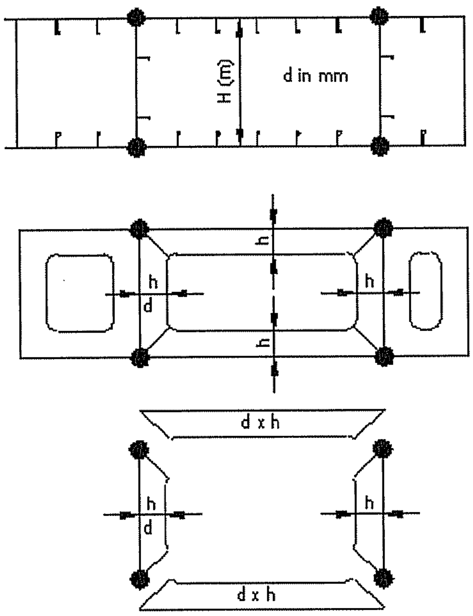

Fig.4: LBR5's principle to model a double sided stiffened tank
Top: Actual tanks composed of stiffened panels sharing a transverse web frame (h, d),
Center: Approximated modeling in LBR5
Bottom: Tank modeled with 4 stiffened panels having independent frames (h, d).

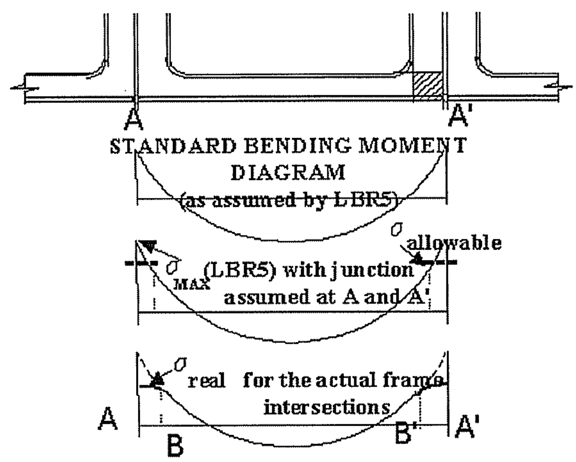

Fig.5 : LBR5's stress distribution at the junction between framed panels

Fig.4 points out a major difficulty to use LBR5 for double hull ships. Being a principle of the method, *Rigo (1992)*, each web frame is attached to a unique panel and cannot be shared by all the constitutive panels of a double bottom, Fig.4. Thanks to the shipyard support, a new methodology is under development to face this problem.

Fig.5 explains another LBR5 assumption, namely that the junction between frames coincides with the panel's node (A or A') and not to B (or B'). This means that the stresses are overestimated near the frame's junction. Two approaches may be used to solve this problem:
(a) to consider in the constraints the stress at point B (B') instead of A (A'),
(b) to consider points A and A' but to increase the allowable stress by a ratio (σ_A/σ_B) or $(\sigma_{A'}/\sigma_{B'})$.

5.1 Minimizing the construction costs

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

- To increase the web frame spacing, decreasing the number of web frames N_w:
  - $(N_w - 2)$ web frames instead of N_w web frames $\rightarrow$ Cost saving: 4.85 %
  - $(N_w - 3)$ web frames instead of N_w web frames $\rightarrow$ Cost saving: 6.40 %

- To increase the average longitudinal stiffener spacing Δ_L:
  - 1.09 Δ_L instead of Δ_L $\rightarrow$ Cost saving: 1.61 %
  - 1.15 Δ_L instead of Δ_L $\rightarrow$ Cost saving: 2.40 %
  - 1.28 Δ_L instead of Δ_L $\rightarrow$ Cost saving: 2.97 %

  Straightening cost are not considered.

N_w and Δ_L refer to the initial design (before optimization).

5.2 Steps of the LBR5 optimization process

In principle, LBR5 directly provides the global optimum and it is not possible to assess the cost saving induced by each change on the frame spacing, stiffener spacing, plate thickness, duct-keel layout, etc.

To assess the cost savings of these individual parameters the present optimization was split in several sub-optimizations. So, starting from the shipyard's initial design, step by step, parameters are released and the layout modified, Tables I and II. Initially, the upper limit of each design variable is fixed at the shipyard'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-optimizations are:

- Least cost optimization (starting from the initial scantlings, with fixed frame and stiffener spacing),

- Web frame spacing Δw is released: $N_w \rightarrow (N_w - 2)$ frames,

- When feasible, the stiffener spacing Δ_L 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: secondary web spacing $\Delta_C = \Delta_W/3$ or $\Delta_W/4$).

Table I assesses the cost saving associated with each sub-optimization and with the global optimization (cumulated cost saving). Clearly the way to reduce construction cost of the concerned LNG ship is to increase the web frame spacing $(N_w - 3)$ and to increase the (average) stiffener spacing to 1.15 Δ_L. Such changes induce a cost saving of about 8.5% (material and labor costs). The global cost optimum (MET8-F90) increases the weight by 3.4%. To avoid this, the shipyard proposed some layout alternatives keeping the hull weight almost unchanged, (MET8C-78 and MET12). MET-12 is characterized by $N_w - 2$ web frames (instead of N_w). Cost savings still reach 6.9% with, in addition, a small weight reduction (99.7% of the initial weight).

Table I: Cost saving at each step of the optimization process (without and with weight constraint)

Search for the least cost design (with continuous design variables)								
	Spacings			Duct keel	Least Cost		Weight	
Configu-rations	No. of web frames	Second. frame ΔC	Stiff-eners ΔL	bulkh. plate thickn.	Cost Saving] [%]		[%]	
	Changes between 2 successive steps				betw. 2 succ. st.	Cumul. saving		
1-Alstom	N_w	$\Delta w/3$	ΔL	100%	0.0%	0.0%	100.0%	Initial design
2-MET8 E00	N_w	$\Delta w/3$	ΔL	105%	-1.4%	-1.4%	98.3%	
3-MET8 E90	N_w	$\Delta w/3$	1.15 ΔL	105%	-2.5%	-3.9%	101.6%	
4-MET8 B90	N_w-3	$\Delta w/3$	1.15 ΔL	130%	-6.4%	-10.3%	104.7%	duct keel plate too thick
5-MET8 F90	N_w-3	$\Delta w/4$	1.15 ΔL	100%	1.7%	-8.6%	103.4%	opt. solution
6-MET8 F	N_w-3	$\Delta w/4$	1.28 ΔL	100%	-0.5%	-9.1%	105.3%	inefficient*)
3'-MET8 C-78	N_w-2	$\Delta w/3$	ΔL	122%	-4.9%	-6.2%	100.2%	duct keel plate too thick
4'-MET12*)	N_w-2	$\Delta w/3$**)	ΔL	88%	-0.7%	-6.9%	99.7%	opt. solution (discr. var.)
5'-MET12.b*)	N_w-2	$\Delta w/3$**)	ΔL	88%	0.5%	-6.5%	100.9%	opt. solution (cont. var.)

*) Stiffener spacing too large; thus cost savings of 0.5% in assembling, but increased straightening work afterwards.
**) Layout modified

6 Conclusions

The optimization tool LBR5 allows to study large structures (100 panels, 900 design variables and 5000 constraints to cover up to 10 loading cases). Limitations and shortcomings are:

- Only prismatic structures can be considered (e.g. ship hold, box girder, etc.)
- Loads must be given. They are usually rule based, static or quasi-static (no direct analysis).

The industry application to a medium capacity LNG ship confirms the feasibility of the approach. In the case presented, the optimization provided an effective cost saving of 8.5% (7% when a weight constraint is also considered) for the hull tank construction.

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