Integration of a Bottom-Up Production Cost Model in LBR-5 Optimization Tool

Catalin Toderan, University of Liege, Liège/Belgium, Catalin.Toderan@ulg.ac.be
Eugen Pircalabu, University of Liege, Liège/Belgium, Eugen.Pircalabu@ulg.ac.be
Jean-David Caprace, University of Liege, Liège/Belgium, jd.caprace@ulg.ac.be
Philippe Rigo, University of Liege, Liège/Belgium, ph.rigo@ulg.ac.be

Abstract

The LBR-5 software allows the optimization of ship structures following different objectives as the highest inertia, least weight and/or least cost. The interest of European shipyards to optimize the ship structure is basically related to the production cost and mainly to the labor cost. In order to increase the quality of cost estimation, a bottom-up module has been developed by University of Liege in partnership with AKERYARDS France. This module has been validated on different types of ships (LNG, Cruise Vessels, Fast Ferry) and integrated in the LBR-5 optimization process. The bottom-up cost module has two important goals. The first one is to estimate accurately the labor cost of a given ship structure taking into account the production breakdown, the block splitting sequence and all the individual operations required by the fabrication process. The second one is to compute properly the sensitivities of the design objective (construction cost) related to the design variables (scantlings). The paper also presents the results of a validation test on a large passenger vessel. The effect of the bottom-up cost module on the optimal scantling and on the cost gain is highlighted through a comparison with the results obtained using a basic cost module.

1 Introduction

LBR5 is a structural optimization tool that, in the early design stage of the project, allows:

- a 3D structural analysis of a portion of the structure (usually located in the mid-ship region, where the global bending moment is maximal);
- a scantling optimization of the structural elements (plate thickness, size and spacing of the longitudinal and transversal members), based on different objective functions as highest inertia, least weight and/or least cost.

The cost-based optimization can be performed using one of the two available cost modules:

- The basic cost module (BCM) is based on a simplified assessment of labor and material costs. To calibrate the module, the cost of a standard LBR-5 stiffened panel, Fig.1, is assessed using the unitary production costs of the shipyard.
- The advanced cost module (ACM) is a more complex cost assessment tool that takes into account detailed shipyard database. About 60 different fabrication operations are considered, covering the different construction stages.

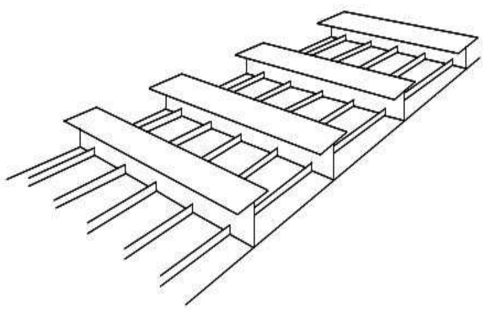

Fig. 1: Standard LBR-5 stiffened panel

2 Description of the Basic Cost Module of Lbr-5 (Bcm)

The basic cost module of LBR5 is able to compute the material cost (as a function of weight) and the labor cost using a simplified methodology. In order to link the objective function to the design variables, the unitary costs of raw materials, the productivity rates for welding, cutting, assembling must be specified by the user.

These unitary 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 optimization process (scantling optimization) 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.

Global construction costs can be classified into three distinctive categories: cost of raw materials, labor costs and overhead costs (Eq. 1).

$$TC = MatC + LabC + OvC \tag{1}$$

The overhead cost is not function of the design variables, so it can be ignored by the analytical cost model. Therefore, the considered cost will be:

$$TC = MatC + LabC \tag{2}$$

The material cost and the labor cost are expressed in Equations 3 and 4:

$$MatC = \sum_{j=1}^{k} Q_j \times P_j \tag{3}$$

$$LabC = \sum_{i=1}^{NT} T_i \times M_i \times S_i \tag{4}$$

where:

- j = reference number of a given material; k = number of materials;
- Q_j = expected quantity of the j material;
- P_j = unit price of the j material (Euro / unit); i = reference number of a given task; NT number of tasks;
- T_i = required working load for the standard i task (man-hours);
- M_i = number of repetitions for the T_i task;
- S_i = labor cost (Euro / man-hour).

Detailed information about the basic cost module (BCM) is given in *Rigo (2001, 2003).*

3 Development of the advanced bottom-up cost module (ACM)

The cost assessment performed with the basic cost module (BCM) for large complex ship structures presents rather important differences with respect to the shipyard predictions. A number of significant parameters related to production costs (as preparing, transport, workshop type, …) cannot be taken into consideration. More than that, the cost related to structural details (as collar plates, flat stiffeners on the web, …) is not considered by BCM. In some cases, the construction of structural details requires an important labor load and its cost could be related to the basics scantlings variables (spacing, thicknesses). ANAST carried out since 2002 a research with the partnership of AKERYARDS France for the development of a cost module that will better fulfill the shipyard's needs.

The new advanced cost module (ACM) complies with a number of issues that were incompatible with the BCM:

- the specificity of each LBR-5 panel is considered according to the real structure (horizontal - vertical, straight – formed etc.), for a distinctive use of the shipyard's unitary costs;
- better implementation of the unitary cost variations with the thickness of the structural members, which is not always linear;
- considering the extra costs related to the stiffening of important web height members (ex: flat bar stiffening of the web-frames);
- considering that several workshops are involved in the construction, with different production costs;
- introduction of an exhaustive representation of the fabrication operations in relation with the selected design variables.

The integration of ACM in LBR-5 tool is based of the flow-chart presented in Fig.2.

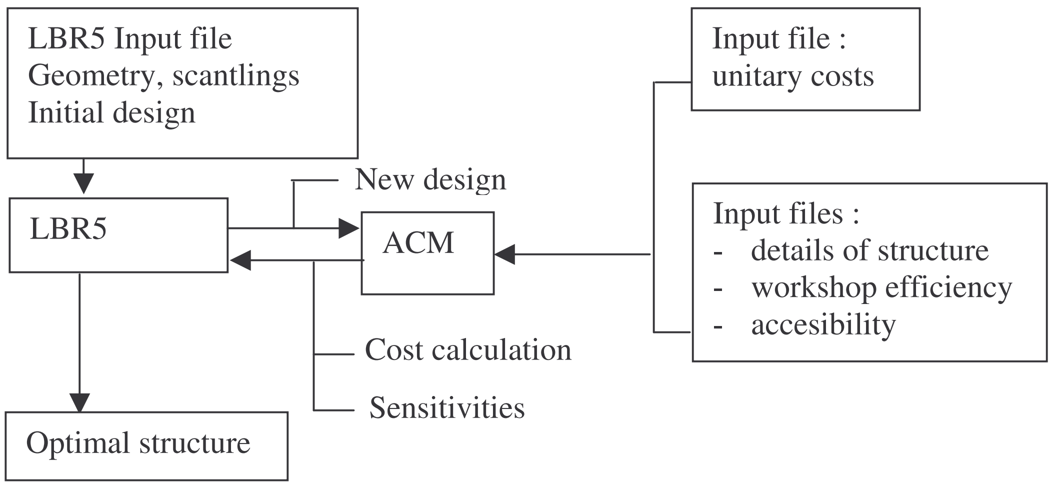

Fig.2: Integration of ACM in LBR-5

The ACM module includes about 60 basic production operations selected prior to the development following their level of labor cost. The following construction stages are covered by this selection :

- fabrication of pieces : stiffeners, individual plates, collar plates, flat-bars, …
- pre-pre fabrication : fabrication of web-frames (including cutting and stiffening), girders and longitudinal bulkheads
- panel line : fabrication of plate panels
- pre-assembling of plate panels and frames, girders, bulkheads
- building of blocks from different assembly
- assembling of blocks.

The cost for each operation is calculated with a general analytical expression (Eq. 5).

$$CO_{ik} = Q_{ik} \times CU_{ik} \times K_{ik} \times CA_{ik} \times CAT_{ik} \qquad (5)$$

where:

i	= LBR-5 panel index;
k	= operation index;
CO_{ik}	= cost for operation k on panel i;
Q_{ik}	= operation related quantity (welding length, number of brackets etc.);
CU_{ik}	= operation related unitary cost;

K_{ik} = corrective coefficient used to calibrate the operation related quantity with respect with model particularities;
CA_{ik} = accessibility coefficient for the operation k on panel i ;
CAT_{ik} = workshop coefficient for the operation k on panel i.

The total structure cost will be the sum of all CO_{ik} (Eq. 6):

$$CT = \sum_{i} \sum_{k} CO_{ik} \tag{6}$$

When the BCM is used, the cost function is continuous and its sensitivities could be calculated analytically. This advantage is lost if the cost function is evaluated by the ACM. Basically, the ACM sensitivities can be written with the Equation 7 for each LBR5 panel, each design variable and each operation.

$$\delta_{ijk} = (T_1 \times CU_{ik} + T_2 \times Q_{ik}) \times K_{ik} \times CA_{ik} \times CAT_{ik} \tag{7}$$

where: T_1 = sensitivity of the quantity by each design variable X_j (Eq. 8), which is calculated analytically; T_2 = sensitivity of the unitary cost by each design variable X_j (Eq. 9), which is usually a discrete function (Fig. 3) and its calculation requires a numerical procedure.

$$T_1 = \frac{\partial Q_{ik}}{\partial X_j} \tag{8}$$

$$T_2 = \frac{\partial CU_{ik}}{\partial X_j} \tag{9}$$

A number of tests were performed on simplified structures - double hull panel, Fig.4, and on real hull structures in order to validate the ACM in terms of design variables sensitivities and total costs.

The cost sensitivity related to some design variables on the selected double hull panel was analysed. Figure 5 shows for instance the total cost variation as a function of the strake 1 thickness. As it can be noticed, the ACM calculation gives a clearly improved slope with respect to the direct calculated cost, compared to the BCM result. The average uncertainty related to the ACM, taking as reference the direct calculation is about 4%.

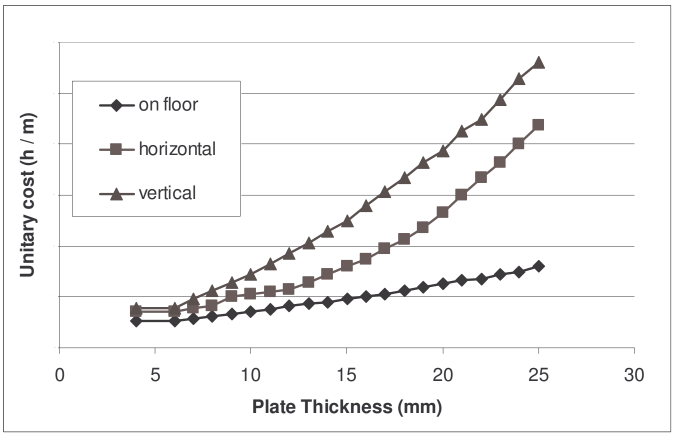

Fig.3: Unitary cost variation for different welding positions

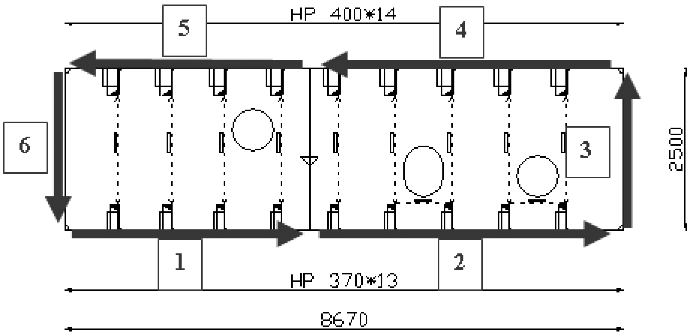

Fig.4: Double hull panel

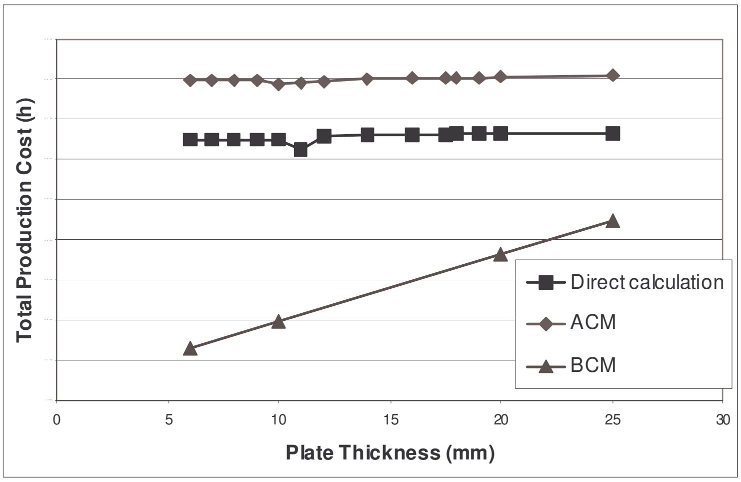

Fig.5: Total production time versus plate thickness

Straightening costs can be taken into account with both the BCM and the ACM. The welding of structural elements involves local heating of the steel. This phenomenon causes deformations which have to be reduced to obtain an acceptable surface flatness. The straightening is the process that consists in removing/reducing these distortions in order to improve the structure flatness for esthetical and service reasons. The straightening process involves non negligible labor cost; it is thus required to estimate the straightening impact on the production workload to improve the research of an optimal solution. The cost assessment of the plate straightening is done by using a general formula linking the straightening cost to the scantlings and to other section characteristics, *Caprace et al.(2007*). This formula was obtained trough a data mining method, using statistical data on straightening costs for a number of 12 ships built by AKERYARDS France. Fig.6 illustrates the variation of the straightening costs (in hours/m^2), for different regions of the ship, as function of the weight of the defined lots.

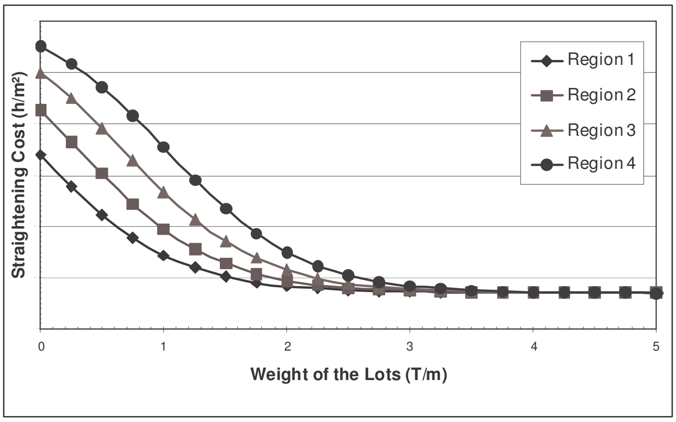

Fig. 6: Straightening costs for different regions of the ship

4 Validation test for the advanced cost module (ACM)

4.1 Structural model

The LBR-5 model of the ship's mid-section was imported from an existing Mars2000 (scantling verification software based on Bureau Veritas Rules) model prepared by AKERYARDS France. LBR-5 disposes of an automatic data transfer module allowing the use of Mars2000 geometry and loads, *Richir et al. (2007)*. Fig.7 shows an imported mid-ship section (transversal members and pillars were added manually). A number of 98 LBR-5 panels were used to define the model (77 stiffened plates and 21 pillars).

Based on structure symmetry, only half of the structure was modelled. Five load cases were considered for the calculation:

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

Bending efficiency coefficients were considered in order to take into account the participation degree of each deck to the longitudinal bending. These coefficients are directly imported from the Mars2000 model.

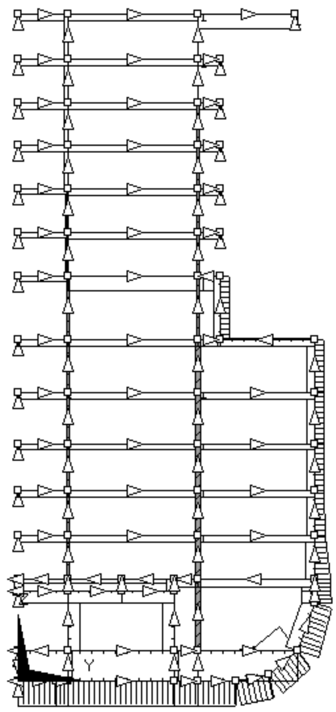

Fig.7: LBR-5 model of the ship mid-section

4.2 Optimization model

The design variables used in the optimization are (for each LBR-5 stiffened panel):

- plate thickness;
- web height (longitudinal and transversal members);
- web thickness (longitudinal and transversal members);
- flange width (longitudinal and transversal members);
- spacing (longitudinal and transversal members).

Technological constraints were assigned to the design variables to define the search space of the optimization problem. These constraints are formulated on basis of technological limitations, like minimum plate thickness considering corrosion, or maximum size or thickness of plates and members with respect to welding process.

The structural constraints imposed throughout the model to satisfy the limit states are related to:

- plate buckling based on *Hughes (1988)* formulations;
- ultimate strength of stiffened panels
- yielding in plates and longitudinal stiffeners;
- yielding in transversal members at web-plate and web-flange junctions.

The structural constraints are imposed for each load case, and when needed, at more than one point of each LBR-5 panel.

A number of equality constraints between design variables belonging to different panels were also imposed to reach a rational and exploitable solution. Transversal member spacing is considered equal all over the section. Plate thickness and transversal member web thickness are supposed to be constant on each deck. A global constraint relative to the gravity center vertical position was imposed to limit its variation between fixed lower and upper limits.

The size of the optimization problem is illustrated in Table I.

Table I: Size of the optimization problem

Type of constraints	Number of constraints
Technological	627
Structural	4109
Geometrical	622
Equality	137
Global	1

4.3 Optimization results

Due to the international competition between shipyards, a lot of valuable information will not be mentioned in the present paper. Nevertheless, the authors acknowledge AKERYARDS France for its courtesy for allowing use of their results. In this paper, data are mainly presented in terms of ratios to avoid publishing sensitive confidential quantitative data. The structural optimization was performed with both the BCM and the ACM and a comparative analysis has been carried out on the optimal configurations. These configurations (scantlings) are "feasible" solutions, which mean that all the constraints imposed to optimization are satisfied. The convergence of the cost objective function required only five iterations for both cost modules. The results revealed differences between cost assessments of the two modules, but also in terms of cost savings. This was expectable as the sensitivities of the design variables are less realistic with the BCM, compared to direct cost calculation. Figs.8 and 9 show respectively the BCM and the ACM gains in terms of production costs, considering as reference the initial design cost assessments.

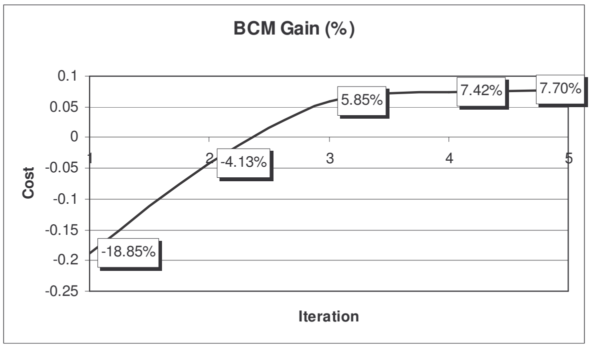

Fig.8: Gain obtained with the BCM

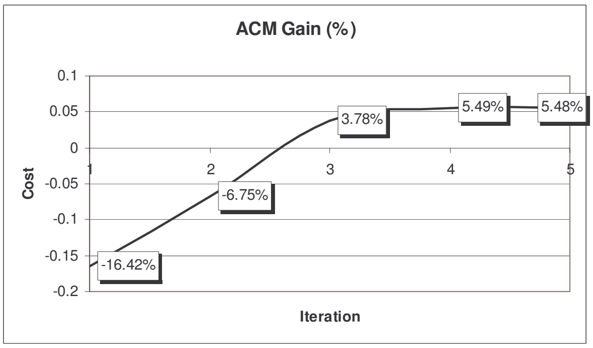

Fig.9: Gain obtained with the ACM

The initial cost assessment shows a difference of 20.4% between the BCM and the ACM calculations. The optimal solutions present a 7.7% gain for the BCM and a 5.5% gain for the ACM, meaning a 2.2% difference in gain. This gap is given by the different cost assessments on one hand and the different sensitivities on the other. A way to evaluate the effect of sensitivities alone is to assess the costs of BCM based optimal scantlings using the ACM approach and then compare it with the ACM optimal solution. This calculation showed a gap of 0.93%. In other words, almost half of the 2.2% difference between gains obtained with the BCM and the ACM is due to the optimization process.

The general tendency for the ACM based optimization was to increase the plate thickness by ~80% on the upper decks and ~31% on the double-bottom. The longitudinal members section modulus also increased up to ~286% on the upper deck and ~260% on the double bottom, while it was reduced with ~32% in the neutral axis region. The plate and longitudinal members general increase is fully compensated by a reduction of the number of stiffeners (~27% for the transversals members respectively 20 to 38% for the longitudinal members), as well as a reduction by ~20% of the transversal member section.

The same trend was observed with the BCM based optimization, the main differences in terms of scantlings are found for the plate thickness and stiffener scantlings. The plate thickness was increased with ~100% on the upper decks and ~30% on the double bottom. The section modulus for the longitudinal stiffeners increased with ~183% on the upper deck and ~262% on the double bottom; in the neutral axis region a 32% reduction is noted. The spacing of the transversal members is the same for both methods, as it reaches each time the maximum limits of the technological constraints. Table II resumes the differences between the two calculations in terms of final scantlings.

Table II: Scantlings comparison

Structural item	Ship region	BCM	ACM
Plate thickness	Upper deck	-100%	-80%
	Double bottom	-30%	-31%
Stiffener modulus	Upper deck	-183%	-286%
	Double bottom	-262%	-260%
	Neutral axis	+32%	+32%
Stiffener spacing	Upper deck	+38%	+38%
	Lower decks	+20%	+20%
	Double bottom	-34%	-34%
Transverse spacing	Overall	+20%	+20%

5 Conclusions

The ACM is a new feature of the LBR5 software. It was developed for and with the support of AK-ERYARDS France, but can be used for other shipyards as well, if exhaustive specific information about unitary costs and technologies of production is available.

This paper presents an example of scantling optimization performed with the LBR-5 software. The goal was to minimize the production costs for a large passenger vessel using the two available cost assessment tools. Plate straightening was taken into account with both the BCM and the ACM.

A comparison was made between solutions found with the two cost modules. The cost assessment made with the advanced cost model (ACM) based optimization was found to be about 20% less optimistic than the simplified BCM approach. The ACM optimization found a 5.5% gain compared to the initial cost assessment, while the BCM found a 7.7% gain. The difference between these two ratios is the result of a more realistic cost assessment and calculation of sensitivities for the ACM.

Nevertheless, the general optimization trend is similar with the two approaches, as plate thickness and longitudinal stiffeners section modulus grow, while the number of longitudinal and transversal members decreases.

Acknowledgments

The authors thank University of Liege, AKERYARD FRANCE (Saint-Nazaire) for their collaboration within R&D1-15 research project (2002-2007), BUREAU VERITAS (Paris), the MARSTRUCT - Network of Excellence on Marine Structures (www.mar.ist.utl.pt/marstruct/) and the STREP IMPROVE Project (031382- FP6 2005 Transport-4).

References

CAPRACE, J.D. ; BAIR, F. ; LOSSEAU, N. ; RIGO, P. (2007), *A data mining analysis applied to a straightening process database,* COMPIT'07, Cortona, pp.186-196

HUGHES, O.F. (1988), *Ship Structural Design: A Rationally-Based, Computer-Aided Optimization Approach*, Edited by the SNAME, New Jersey, 566p.

RICHIR, T.; LOSSEAU, N.; PIRCALABU, E.; TODERAN, C.; RIGO, P. (2007), *Least cost optimization of a large passengers vessel*, MARSTRUCT 2007, Glasgow

RIGO, P. (2001), *A module-oriented tool for optimum design of stiffened structures*, Marine Structures 14/6, pp.611-629

RIGO, P. (2003), *An integrated software for scantling optimization and least production cost*, Ship Technology Research 50, pp.126-141

RIGO, P. (2005), *Differential equations of stiffened panels of ship structures and Fourier series expansions*, Ship Technology Research 52, pp.82-100