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A Framework for Simulation-Based Design of Ship Structures

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Designing mechanical systems involves achieving simultaneous, though sometimes competing, objectives. The systems must perform their function while conforming to structural, economic and production constraints. The present design framework consists of establishing the structural system and composite subsystems, which optimally satisfy the topology, shape, loading and performance constraints while simultaneously considering the manufacturing or fabrication processes in a cost-effective manner. In this paper a generic design methodology is described. The performance of the system, the manufacturing process of the system and the associated life-cycle costs are considered in an integrated fashion. The proposed framework uses a computerized virtual environment in which CAD product models, physics-based models, production process models and cost models are used simultaneously by a designer or a design team. Three separate ship design environments are used to illustrate components of the design framework. The first is the ISSMID-T, an integrated process/product model for midship section and cargo hold design for tankers. The second is the LBR-5 computer package that performs optimum midship scantlings (plating, longitudinal members and frames) at preliminary design. The third is a computer-based design environment in which immersive virtual reality is used to assess the design and production of portions of a cargo vessel.

Introduction

SHIP DESIGN methodology is a very broad subject, and it is not the purpose here to review the varied aspects of ship design. Comprehensive lists can be found in the Committee IV ISSC reports (Catley et al 1997, Pradillon et al 2000). Rather, this paper describes an attempt to establish a framework or model which accommodates simultaneously several specific aspects of the design. Attention is focused on encompassing environmental, product, process, and cost models in what we call a generic framework for simulation-based design of ship structures.

The newly developed generic framework is in close relation with discipline integration in advanced design trends and the so-called "concurrent engineering" approaches (Bennett & Lamb 1996, Elvekrok 1997, Keane & Tibbits 1996, Parsons et al 1999). Compared to the traditional design procedure, concurrent design methodology allows further reduction of the "global time" (i.e., design time and construction time). Traditional methodologies do not usually integrate at the earliest product design phase the production (process model) and the costs as design constraints in a formal manner. The lack of such data often induces higher production costs and, all too often, production delays as the designs may have poor compatibility with actual production characteristics (standardization, experience, worker skills, available facilities and manpower, etc.).

The present methodology seeks to integrate in the structural design process *all* of the dominant production and operational parameters. These parameters can be defined as model parameters or as design variables (dynamic variables) in order to optimize the product model (ship parts) and/or the process model (production parameters). Product and process models can be optimized separately or within the same loop. All these alternatives are shown to fit within the present framework, starting from the most traditional structural analysis approach, for example, assuming the hull girder

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behaves like a beam model, to the most advanced simulation models including 3-D nonlinear structural analysis, fluid-structure interaction, CFD analysis (ship stability, seakeeping, etc.), topological and shape optimization, and advanced limit states (fracture mechanics, ultimate strength, etc.) of reliability-based design.

General framework

In this generic design methodology or framework, the performance of the system, the manufacturing process of the system and the associated life-cycle costs are considered in an integrated fashion. The framework is referred to as global, in the sense that one establishes the design objectives and variables in a complete and comprehensive fashion. The framework is also scalable; the method remains self-similar whether used by a manufacturer whose global consideration is the production and sale of a component or a ship designer whose global consideration is vessel of specified cargo, tonnage, and speed.

The framework is used within a computerized virtual environment in which CAD product models, physics-based models, production process models and cost models are used simultaneously by a designer or design team. The performance of the product or process is in general judged by some time independent parameter, which is referred to as a response metric (R). Specifications for the system must be established in terms of these Response Metrics. The formulation of the design problem is thus the same whether the product or process systems (or both) are considered. Three existing computer applications are used to illustrate components of the generic design framework. They are:

1. The "LBR-5" optimization module for stiffened structures which is preliminary design oriented (Rigo 2001).
2. The "ISSMID-T" integrated process/product model for the design of midship hull of tankers (Na et al 1994).
3. The use of virtual reality simulations to study the motion of a high-speed containership and to assess the design and production of a cargo vessel's double bottom section (Beier 2000).

The general framework as shown in Fig. 1 consists of a system definition module, a simulation module and a design module.

The system definition module [Y(U,V,W)] is used to build an environmental model [U], a product model [V] and a process model [W]. The system definition module receives operational requirements [Z] such as owner's requirements. These operational parameters are presumed fixed throughout the design. They, of course, can eventually be changed if no acceptable design is es-

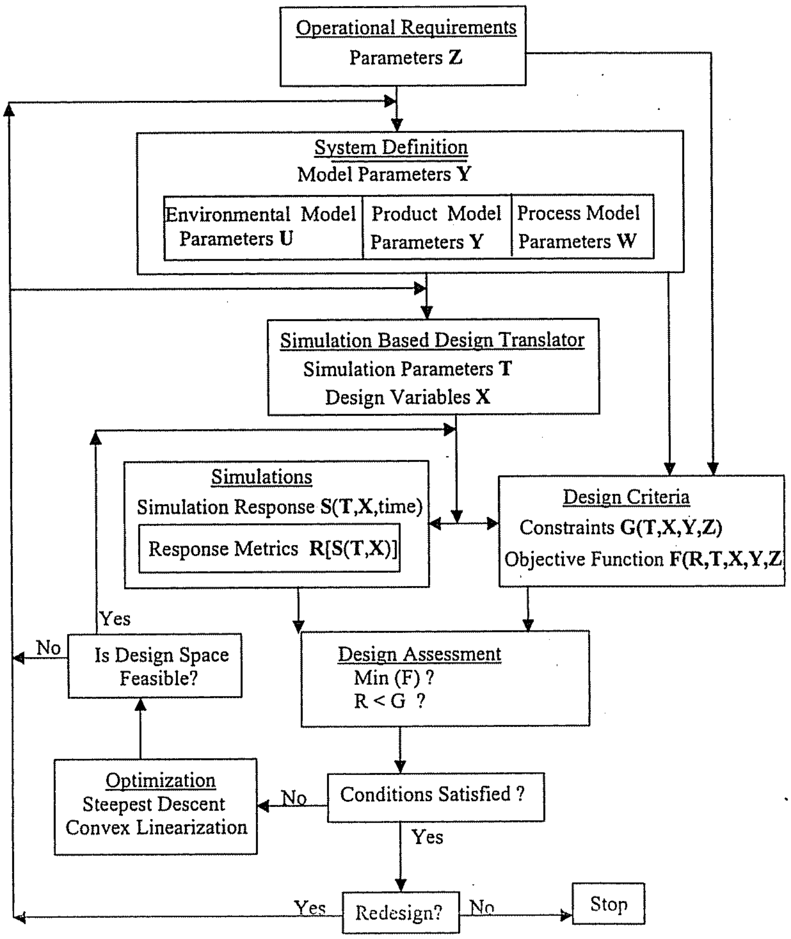


Fig. 1 General framework

tablished, but presumably any design would have operational parameters which would not be sacrificed.

The environmental model [U] includes the still water and wave loading conditions and the product model [V] contains the production information, for example. The process model [W] is built to consider or define the fabrication sequence.

A translator (simulation-based design translator) assigns some [Y] model parameters to the simulation parameters [T] and design variables [X]. These parameters are selected based on the available simulation tools [S] that require specific data ([T],[X] and time).

The simulation module [S(T,X,time)] is used to produce simulation responses such as "Response Metrics" [R[S(T,X)]]. The time is needed to consider the dynamic effects and actual dynamic load conditions [U].

The optimum design module includes the Design Criteria, the Design Assessment and the Optimization components. The design criteria provide constraints [G(T,X,Y,Z)] and objective functions [F(R,T,X,Y,Z)]. These are used to assess the design through the Design Assessment component of the module (for example, $R < G$). The constraints are obtained by considering not only the simulation parameters [T] and the design variables [X] but also the operational requirements [Z] and the system definition parameter [Y]. Also, the objective function is calculated using the response metrics [R], the operational requirements [Z], the system definition parameter [Y], as well as the design variables [X] and simulation parameters [T].

Based on the results of the Design Assessment (F and $R < G$) several strategies for the design procedure (iterations) can be followed.

(a) If the object function does not reach its minimum value or the response metrics do not satisfy the constraints, an optimization algorithm (steepest descent, dual approach and convex linearization, evolutionary strategies, etc.) is adopted to find a new set of design variables.

- If the optimizer fails to find an improved solution (unfeasible design space), it is required to change the simulation parameter values [T] and/or design variables selection [X] or even to modify the Model Parameters [Y].
- Otherwise, the design space is feasible, and a change of design variable values [X] is performed based on the optimizer solution (in other words, a new iteration).

(b) If the object function reaches its minimum value and the response metrics satisfy the constraints, two alternatives are examined:

- change the operational requirements parameters [Z] to compare with other alternative designs, or
- end the design procedure.

Integration of existing design tools

This section explains how the three design environments fit with the new generic framework.

ISSMID-T model

ISSMID-T is an interactive structural design system for the optimum design of the midship part of double-hull oil tankers. ISSMID-T consists of a system definition module [Y], a simulation module [S] and an optimization module [O]. The operational requirements [Z] such as deadweight, ship speed and classification are entered into the system definition module, along with initial design data such as principal particulars and general arrangement. The system is depicted schematically in Fig. 2. Note that the methodology is of the form depicted in the general framework of Fig. 1.

The system definition module [Y] is built by making an environment model [U], a product model [V] and a process model [W]. The environment model [U] determines the loading conditions and the maximum wave and still water bending moments from classification rules such as DNV and Lloyds. The product model [V] is made by determining the number of panels, longitudinals and web frames, the dimensions of panels, longitudinals and web frames, longitudinal type and material properties. The process model [W] is made by determining the number of blocks, fabrication sequence, welding method and block length.

The simulation module [S] is built by making a structural analysis model, a fabrication model, a weight estimation model and a cost estimation model. Parameters [T] and design variables [X] are chosen from the environment, product and process model. The parameters of the product model [T_{pd}] are the number of panels, material properties, classification, longitudinal type and dimensions of flanges. The parameters of the process model [T_{pc}] are erection block length, number of blocks, welding method, welding pose, fabrication stage, and assembly order. The design variables [X] are the thickness and height of each panel, longitudinal spaces and web frame space. The scantlings of longitudinal members are determined by applying classification rules such as DNV, Lloyds and ABS. The scantlings of transverse and transverse bulkhead members are determined by the generalized slope deflection method, which considers axial deformation from the existing slope deflection method (Na et al 1994).

The optimization module [O] is built by calculating constraints [G], object functions [F] and penalty functions [P]. The constraints [G] are rule requirements for the longitudinal members and allowable stresses for the transverse and transverse bulkhead members.

The object functions are structural weight (F_1) and fabrication cost (F_2). The structural weight (F_1) is obtained by summation of the cargo hold, fore and after body weights. The cargo hold weight is obtained by summation of the weight of the longitudinal, transverse and transverse bulkhead members. The fore and after body weights are obtained by the estimation formula. The fabrication cost (F_2) is obtained by estimating a relative structural fabrication cost (Winkle & Baird 1986, Bong 1990) using "Standard Fabrication Man-Hour Tables." The relative fabrication cost is obtained by multiplying this man-hour by the unit labor cost. To estimate the relative fabrication cost considering fabrication sequence, ship structures are divided into several blocks, and each block is divided into several pre-erection blocks, assemblies, medium-assemblies, components and fabrications.

The penalty functions (P_1, P_2) are produced when the design variables violate the constraints.

The evolutionary strategies (ES) method is adopted as a multi-objective function method (Shin 2000). The optimization algorithm is as follows:

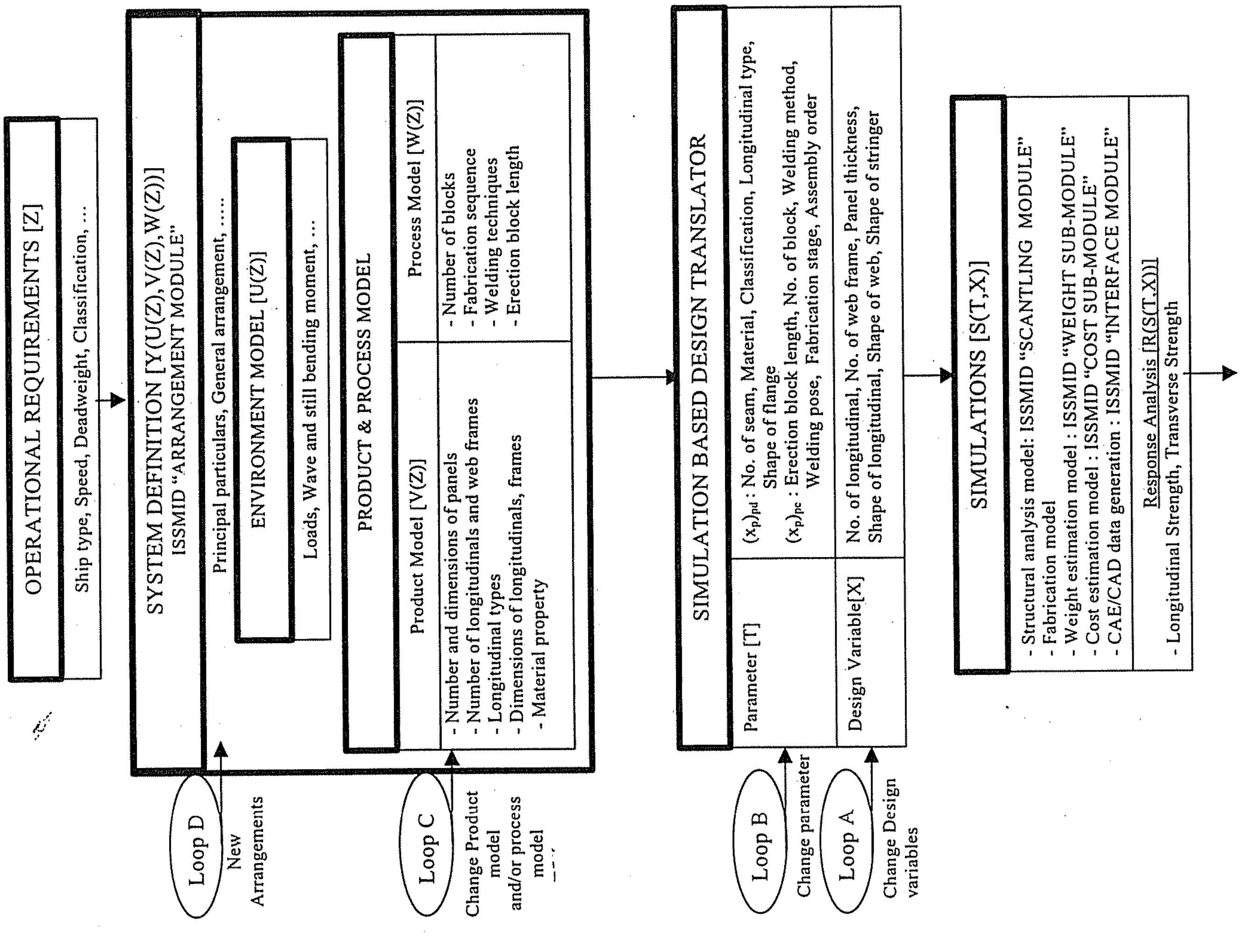


Fig. 2(a) ISSMID-T framework (Part 1)

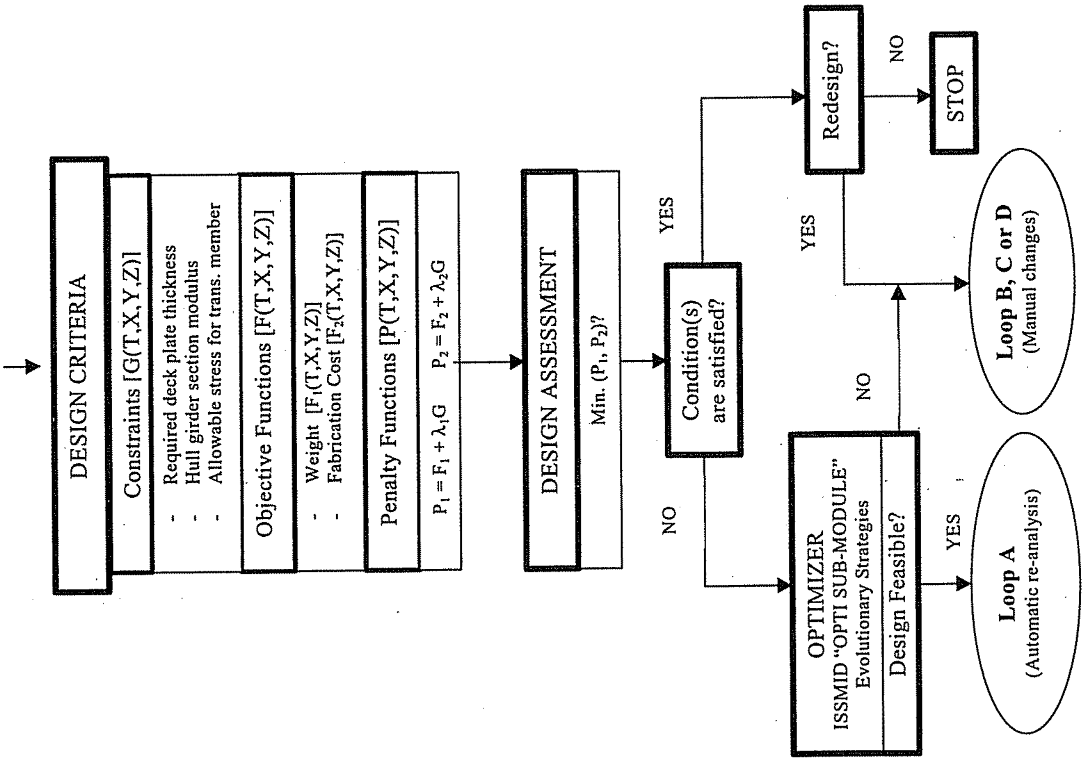


Fig. 2(b) ISSMID-T framework (Part 2)

Table 1 Standard fabrication man-hour table (butt welding)

Unit: m-h/m

Welding Technique			Stage	Pose	Jointing	Welding						
				Plate thickness (mm)		12	14	16	18	20	22	24
BUTT	Manual		Assembly	F	0.30	2.87	3.58	4.38	5.26	6.23	7.29	8.44
				V	0.66	3.56	4.43	5.39	6.45	7.61	8.87	10.23
				H	0.72	3.38	4.19	5.11	6.11	7.21	8.41	9.71
				O	0.75	3.82	4.70	5.69	6.78	7.96	9.24	10.62
			Erection	F	1.57	3.61	4.51	5.51	6.62	7.83	9.14	10.55
				V	2.27	4.48	5.56	6.77	8.11	9.56	11.12	12.79
				H	2.21	4.24	5.27	6.42	7.68	9.06	10.56	12.18
				O	2.72	4.80	5.91	7.16	8.52	10.0	11.60	13.32
	CO2		Assembly	F	0.30	1.85	2.11	2.39	2.70	3.04	3.41	3.81
				V	0.66	2.91	3.37	3.88	4.42	5.02	5.68	6.40
				H	0.72	2.83	3.27	3.76	4.29	4.87	5.50	6.18
			Erection	F	0.83	2.33	2.65	3.01	3.40	3.82	4.27	4.75
				V	1.05	3.66	4.24	4.87	5.56	6.31	7.12	7.99
				H	1.15	3.56	4.12	4.73	5.40	6.12	6.89	7.71
	AUTOMATIC	FAB	Assembly	F	0.30	1.00	1.10	1.19	1.30	1.43	1.58	1.75
			Erection	F	0.83	1.25	1.37	1.50	1.64	1.79	1.95	2.12
		FCB	Assembly	F	0.30	0.85	0.91	0.98	1.05	1.13	1.21	1.29
		SAW I	Assembly	F	0.30	0.21	-	-	-	-	-	-
		SAW Y	Assembly	F	0.30	0.22	0.27	0.33	0.41	0.50	0.60	0.71
		SAW X	Assembly	F	0.30	-	-	-	0.33	0.40	0.48	0.57
		SG2	Plate Thickness (mm)			12	14	16	18	20	22	24
			P.E.	V	0.66	1.63	1.84	2.07	2.09	2.31	2.55	2.81
			Erection	V	1.05	2.28	2.57	2.89	2.92	3.23	3.56	3.92
		SES	Plate Thickness (mm)			22	24	26	28	30	32	34
			P.E.	V	0.66	6.02	6.24	6.45	6.67	6.88	7.39	7.62
			Erection	V	1.05	10.82	11.20	11.59	11.97	12.35	13.27	13.69

Table 2 Standard fabrication man-hour table (fillet welding)

Unit: m-h/m

Welding Technique		Stage	Pose	Jointing	Welding					
			Throat Thickness (mm)		3.5	4.0	4.5	5.0	5.5	6.0
FILLET	CO2	Assembly	Flat (F)	0.24	0.12	0.15	0.19	0.23	0.27	0.33
			Vertical (V)	0.27	0.25	0.31	0.38	0.46	0.54	0.62
		Erection	F	0.51	0.15	0.19	0.24	0.29	0.34	0.41
			V	0.62	0.31	0.39	0.48	0.57	0.67	0.78
	Manual	Assembly	F	0.24	0.40	0.51	0.63	0.71	0.76	0.82
			V (Up)	0.27	0.74	0.92	1.13	1.19	1.35	1.38
			V (Down)	0.27	0.25	0.31	0.38	0.50	0.59	0.69
			Overhead (O)	0.57	0.68	0.80	0.86	0.96	1.14	1.33
		Erection	F	0.51	0.51	0.64	0.79	0.89	0.95	1.03
			V (Up)	0.62	0.93	1.16	1.42	1.49	1.70	1.74
			V (Down)	0.62	0.32	0.39	0.48	0.63	0.74	0.87
			Overhead (O)	0.95	0.86	1.00	1.08	1.21	1.43	1.67

(1) Generate parent points and standard deviations (σ) randomly throughout the design space, and make discrete design variables.

(2) Calculate the object functions, constraints and penalty functions, and select the best points that satisfy the constraints.

(3) From these best points, generate a new set of points according to selected standard deviations using a Gaussian random number generator, and make discrete design variables.

(4) Calculate contraints, objective and penalty functions, and choose the points that are in the Pareto optimal set. This set contains the points for which it is impossible to decrease the value of a certain objective function without increasing that of other objective functions. These points become the best points for next generation.

(5) Check convergence conditions. The convergence conditions are that the number of points within the Pareto optimal set be greater than the maximum Pareto number, or the number of generation be greater than the maximum generation number.

(6) Repeat 3–5 until these points satisfy the convergence conditions. If the convergence conditions are not satisfied and the design space is feasible, change the design variables according to the algorithm. If the convergence conditions are not satisfied and the design space is not feasible or if a redesign is needed, the parameters, product model and/or the process model are manually changed. If the convergence conditions are satisfied and a redesign is not needed, the program is stopped.

LBR-5 model

LBR-5 is optimization software to facilitate the preliminary design of stiffened marine and naval structures (Rigo 1992,2001). LBR-5 is the French acronym for *Logiciel des Bordages Raidis*

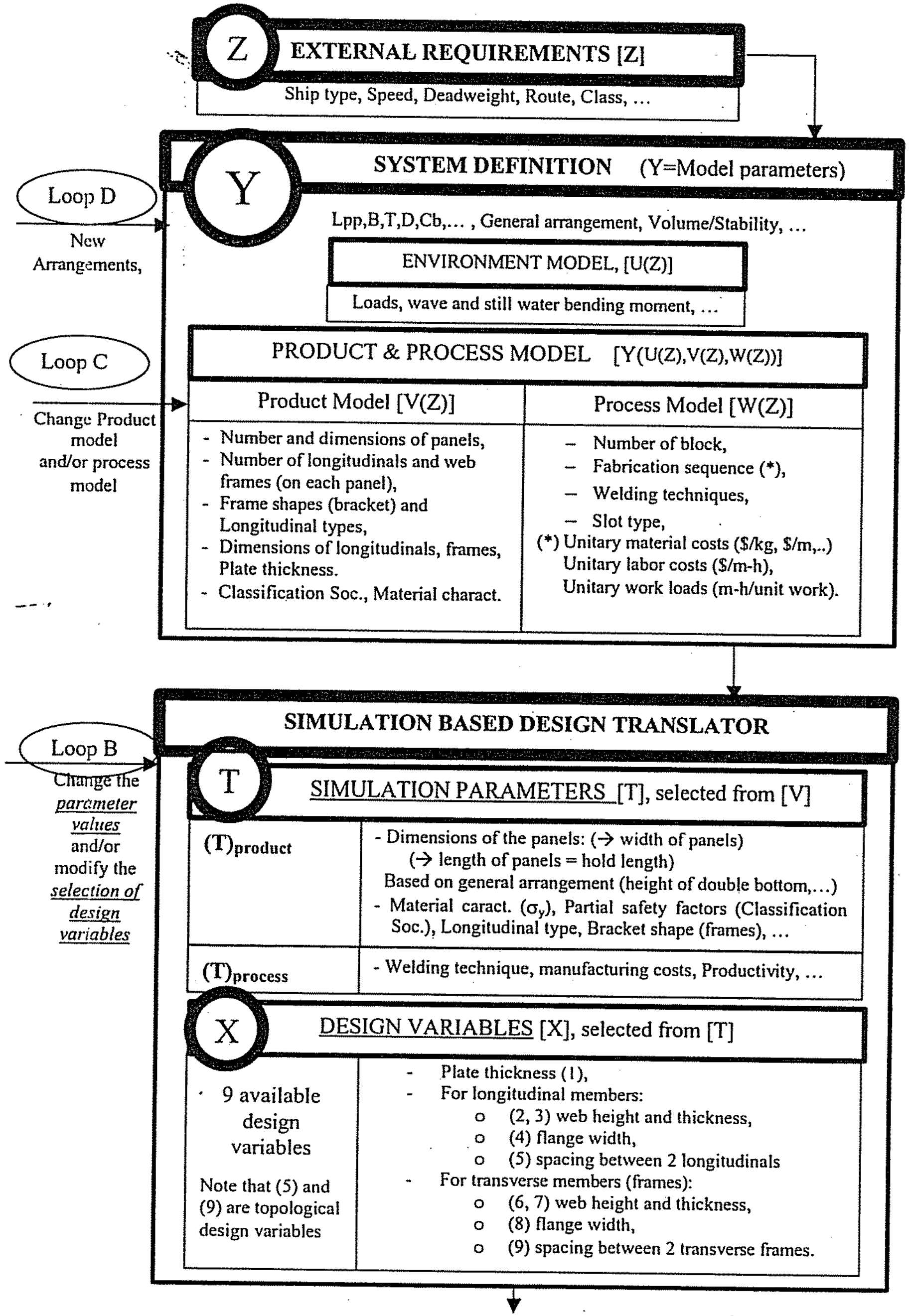


Fig. 3(a) LBR-5 framework (Part 1)

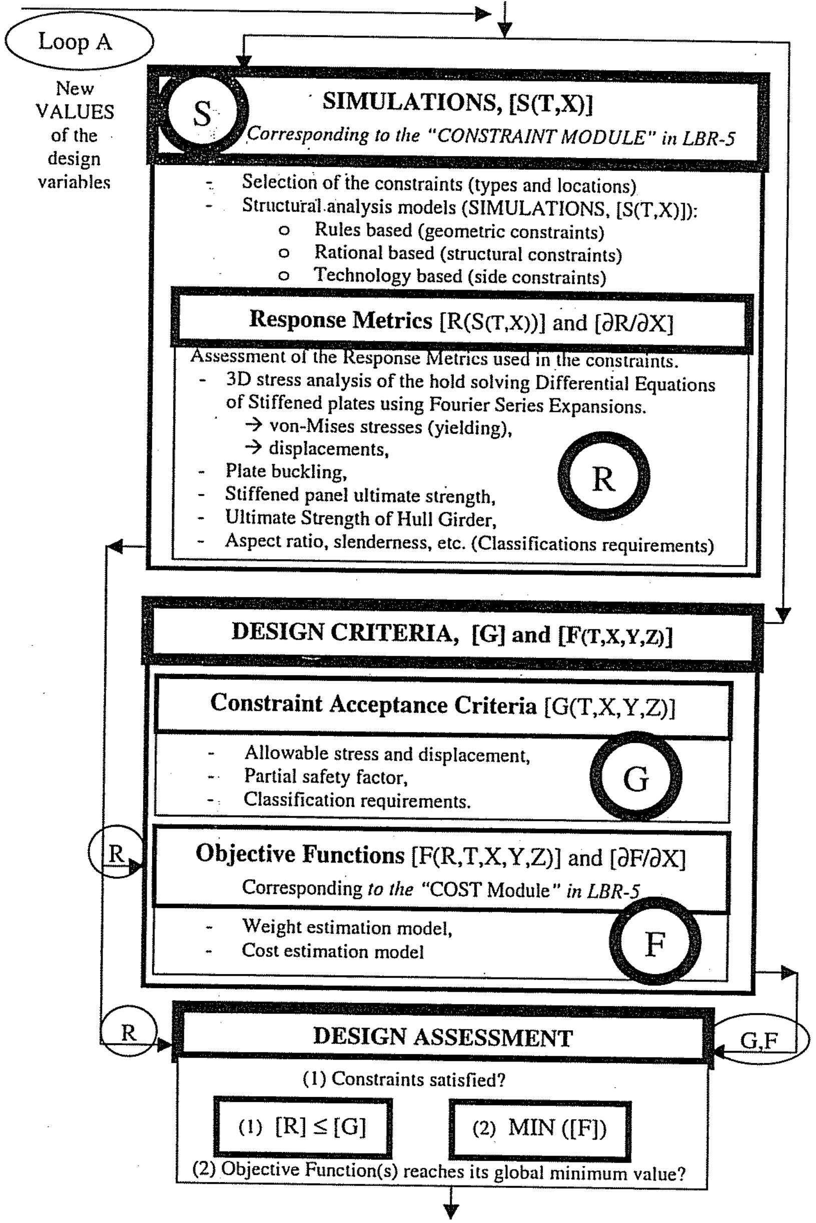


Fig. 3(b) LBR-5 framework (Part 2)

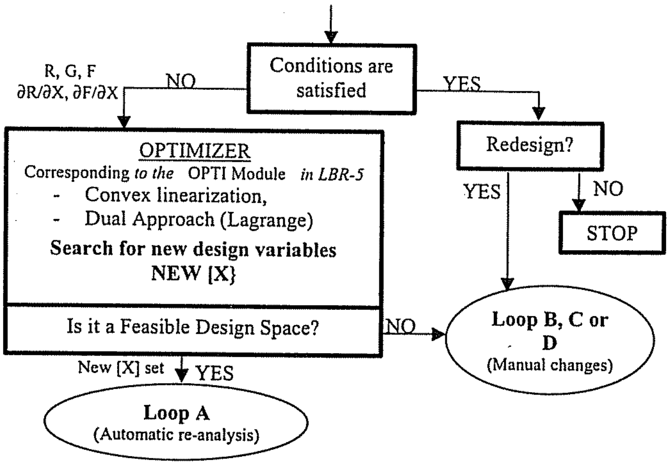


Fig. 3(c) LBR-5 framework (Part 3)

(Stiffened Panels Software), version 5.0. It provides the optimum scantling of the midship section including plates, longitudinal members and transverse frames. Least building cost and/or least weight can be performed.

A detailed presentation of LBR-5 is available in a companion paper (Rigo 2001). Here, the LBR-5's presentation is revised to fit with the new framework and its terminology (Figs. 3*a–c*). Later in this paper the automatic design procedure of a midship VLLC is presented as an example (Figs. 14, 15, and 16).

LBR-5 contains three major modules: *CONSTRAINT, COST* and *OPTI* (Fig. 4). Usually, the considered structure is a cargo hold (between two transverse bulkheads). The dimensions of this hold, its general arrangement ([Z] external requirements) and the loads ([Y(U)] environmental data) have to be provided. Then, the structure is modeled ([Y]) using stiffened panels (Figs. 5 and 6). The modeling is based on the general arrangement ([Z]) and the global geometric dimensions associated to this arrangement (Product variables [V]). The number of panels (N) is independent of the frame spacing (Δy) and of the stiffener spacing (Δx) of each panel. N, Δx and Δy are product variables [V] but also simulation parameters [T]. The number of frames and stiffeners can be optimized without changing the product model [Y]. The only limitation is that, for a given panel, all the frames are identical (as well as for the longitudinal stiffeners).

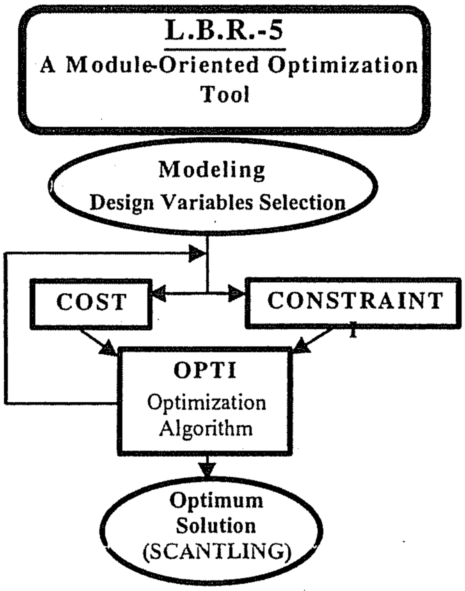


Fig. 4 LBR-5 optimization model

For each panel (Fig. 5) the user can select up to nine design variables ([X] = design variables selected within the simulation parameters [T(V)]). For LBR-5, these nine design variables [X(T,Y(V))] are respectively:

(1) Plate thickness,
(2–3) Longitudinal web height and thickness,
(4) Longitudinal flange width,
(5) Spacing between two longitudinal members,
(6–7) Transverse web height and thickness,
(8) Transverse flange width,
(9) Spacing between two transverse members (frames).

The dimensions of a panel (product model variables [V] and simulation parameter [T]) are not considered as design variables for the optimization with LBR-5. Nevertheless, at a later stage (Loop B), the user can, based on his experience and the previous analysis, modify these dimensions in order to change, for instance, the global arrangement or the double bottom height. For example, Loop B for a revised optimization using the same [Y] model or Loop C and Loop D for a higher level revised optimization using new product and process models [V, W → Y].

The *CONSTRAINT* module is used to define the relevant constraints ([R(S(T,X,Y(V,U),Z))]. Maximum and minimum values [G] of these constraints are based on design rules and codes such as Eurocodes, Classification Societies, etc.

Constraints ([R] ≤ [G]) are linear or nonlinear functions, either explicit or implicit of the design variables (X) and product model [Y]. These constraints are the analytical "translations" of the limitations that the user wants to impose on the design variables themselves or to any [R] *Response Metrics* such as, displacements, stresses, ultimate strength, etc. We can differentiate:

—*Technological constraints (or side constraints)* that provide the upper and lower bounds of the design variables.

—*Geometrical constraints* impose relationships between design variables in order to guarantee a functional, feasible and reliable structure. They are generally rules based.

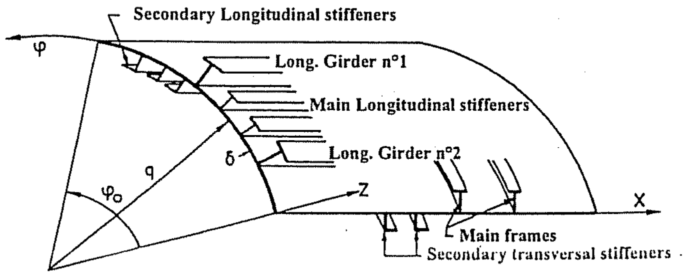


Fig. 5 A stiffened panel (basic product element) of an LBR-5 mesh model (including longitudinal and transversal members)

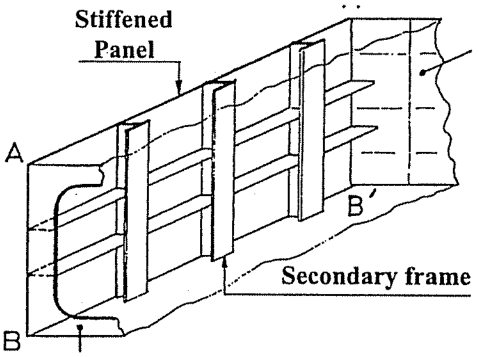


Fig. 6 A stiffened plate with frames and longitudinals (between two bulkheads)

—*Structural constraints* represent limit states in order to avoid yielding, buckling, fatigue, etc., and to limit deflection, stress, etc. These constraints are based on solid-mechanics phenomena and modeled with rational equations.

For each constraint, a *simulation model* [S(T,X,Y,Z)] is used. For instance, the stress level and the displacements are assessed through an analytical resolution of the governing differential equations of stiffened plates using Fourier series expansions. The first derivatives of constraints and objective function are also provided [∂R/∂X(i), ∂F/∂X(i)].

The *COST* module: LBR-5 can perform optimization for minimum construction cost or minimum weight. In order to link the cost objective function [F($) = F(R,T,X,Y,Z)] to the design variables [X], the unit costs of raw materials ($/kg), the productivity rates for welding, cutting, assembling, . . . (man-hours/unit of work = m-h/unit) and the labor costs ($/m-h) must be specified by the user. These data are process model variables [W].

The *OPTI* module (Fig. 7) contains the mathematical optimization algorithm to solve nonlinear constrained optimization problems. It is based on a convex linearization of the nonlinear functions (constraints [R ≤ G] and objective functions [F]) and on a dual approach (Lagrangian multiplicators). This module uses as inputs the results/outputs of the two other basic simulation modules, i.e., to get the constraints ([R(S)] ≤ [G]) and *COST* for the F([X]) objective function.

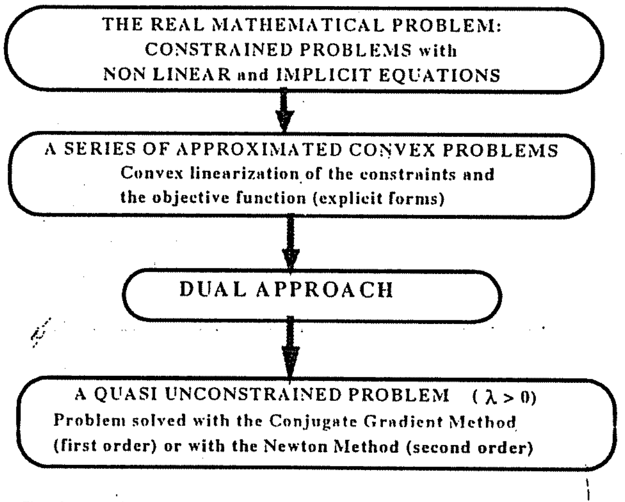


Fig. 7 An optimization module using convex linearization and dual method

Then the global problems solved by LBR-5 can be summarized as follows:

$X_i = i = 1,N$, the N design variables [X]
$F(X_i) = [F]$ objective function
$R_j(X_i) = j = 1,M$, M structural and geometrical constraints
$X_{i\ min} \le X_i \le X_{i\ max}$ = technological upper and lower bounds of [X] design variables

Virtual reality simulations

Within the generic framework (Fig. 1), the simulation module [S] can include a variety of simulation tools. These tools involve either automatic algorithms that produce simulation responses [R] or interactive analysis systems that involve humans in the evaluation process. Often, a combination of both is used.

A virtual reality model is an interactive model to be evaluated by humans. It consists of three-dimensional geometry derived from the product model [V] and it may include functionality and behavior based on the environmental model [U] and the process model [W]. Often, the functionality of a virtual reality model is driven by physics-based simulation algorithms as, for example, a ship motion simulation program.

Immersive virtual reality deploys viewing technologies like head-mounted displays or CAVE systems that present the virtual model in full scale and in stereo. The user can walk around or fly through the virtual product model, which is often referred to as a virtual prototype. Response metrics R that relate to human factors (visibility, accessibility, reachability, operability, etc.) can be best evaluated in immersive virtual reality. Figure 8 illustrates the inspection of a double-bottom design using a CAVE system.

Not all virtual simulations require expensive immersive technologies. Once the virtual model has been created, it can also be viewed in a nonimmersive way, for example, on a computer's monitor. Of increasing interest is the international standard VRML (Virtual Reality Modeling Language) that allows for the distribution of virtual simulations over the Internet and for viewing of these models using standard Web browsers.

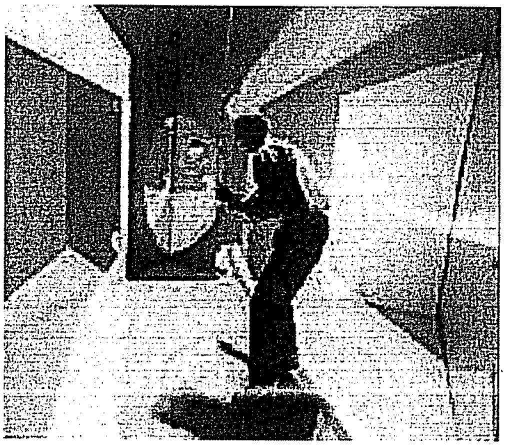
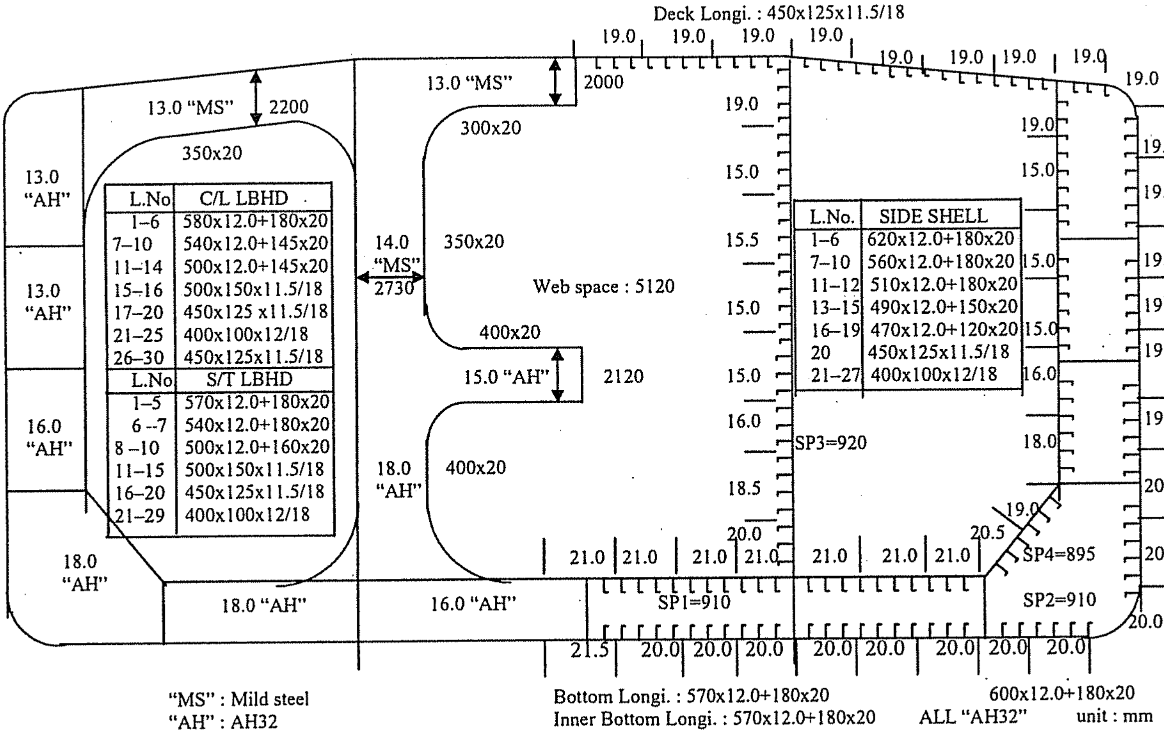


Fig. 8 Full-scale representation of a double-bottom model in a virtual reality CAVE system



L.No	C/L LBHD
1–6	580x12.0+180x20
7–10	540x12.0+145x20
11–14	500x12.0+145x20
15–16	500x150x11.5/18
17–20	450x125 x11.5/18
21–25	400x100x12/18
26–30	450x125x11.5/18

L.No	S/T LBHD
1–5	570x12.0+180x20
6 –7	540x12.0+180x20
8 –10	500x12.0+160x20
11–15	500x150x11.5/18
16–20	450x125x11.5/18
21–29	400x100x12/18

L.No.	SIDE SHELL
1–6	620x12.0+180x20
7–10	560x12.0+180x20
11–12	510x12.0+180x20
13–15	490x12.0+150x20
16–19	470x12.0+120x20
20	450x125x11.5/18
21–27	400x100x12/18

Fig. 9 Existing VLCC ship design

The response metrics R derived from a virtual reality simulation can include a variety of parameters that may affect constraints G and object function F. Examples are geometric inconsistencies (like gaps or overlaps) that become clearly visible in a virtual model, accessibility of spaces for welding or maintenance operations, collisions during assembly sequences, and others.

Creating a virtual reality simulation is part of the simulation based design translator in Fig. 1. Quite often, this can be an automatic process that translates CAD representations from the product model V into a VRML or related format. Functionality is often added in a similar way or requires the combination of components using existing authoring tools.

Applications

This section presents specific applications for each of the three design environments. For the ISSMID-T model and the LBR-5 model, illustrative examples for a double-hull tanker are presented. The similarities and differences of the two environments are described in terms of the generic framework. In the future we plan to further our comparison by performing an optimized structural design of the vessel using both systems with the same design constraints. Here we restrict our attention to the formulation of the design problem for each system. Our third specific example is virtual reality environment developed for a double-hull cargo vessel.

Design of a 300 000 DWT VLCC—General data

Figure 9 shows the existing ship (300 000 DWT double-hull VLCC) designed to DNV classification, and Fig. 10 shows general arrangement of the ship. Figure 11 shows the six loading conditions required by DNV classification. The maximum total bending moments of sagging and hogging conditions are 1.688×10^6 ton-m and 1.694×10^6 ton-m, respectively.

ISSMID-T Model

Design variables (X)—The 31 design variables are: deck plate thickness (X1), longitudinal spaces (X2–X5) and web frame space (X6), the height and thickness of each web (X7–X19), the height and thickness of each stringer (X20–X31).

Constraints (G)—The 48 constraint requirements are: minimum deck plate thickness (G1), minimum hull section modulus at bottom and deck (G2, G3), allowable bending, shear and equivalent stresses of each web (G4—G30), allowable bending, shear and equivalent stresses of each stringer (G31—G48).

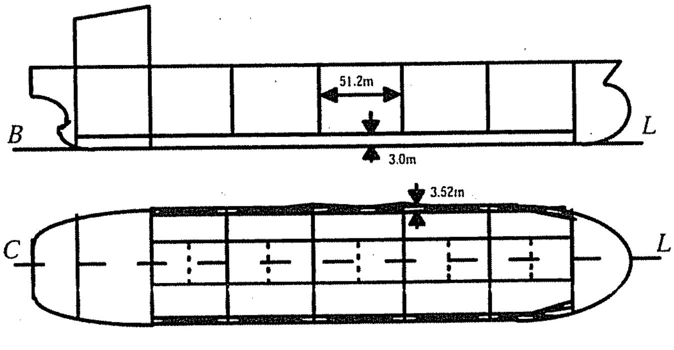


Fig. 10 General arrangement (L = 320 m, B = 58 m, D = 31 m, T = 22 m, and C_b = 0.83

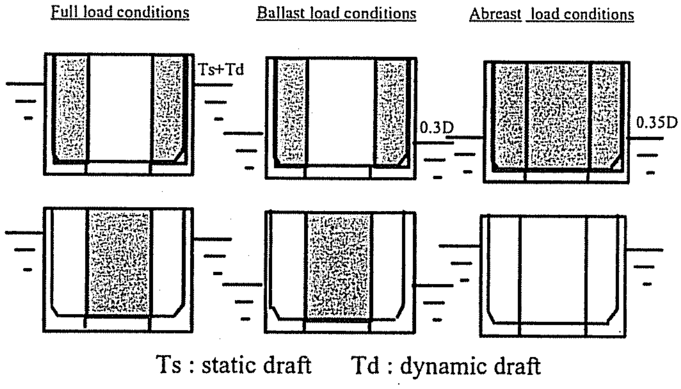


Fig. 11 Loading conditions

Objective functions (F_1,F_2)—Two objective functions are considered, hull weight and cost. For hull weight objective function, $(F_1) = W_L + W_T + W_B + W_F + W_A$, where:

$W_L = (W_l + L_h) \times \{0.4 + 0.6(3 + C_B)/4\}$
$W_T = (W_{tc} \times N_{tc} + W_{tw} \times N_{tw}) \times \{0.4 + 0.6(3 + C_B)/4\}$
$W_B = W_b \times N_b$
$W_F = 160 \times (L_f \times B \times D \times C_B/1000)^{0.728}$
$W_A = 530 \times (L_a \times B \times D \times C_B/1000)^{0.469}$
W_L = weight of longitudinal members
W_T = weight of transverse members
W_B = weight of transverse bulkhead members
W_F, W_A = weight of forebody and afterbody
W_l = longitudinal weight per unit length
L_h = cargo hold length (=256 m)
W_{tc}, W_{tw} = weight of web in cargo and wing tanks
N_{tc}, N_{tw} = number of web in cargo and wing tanks
W_b = weight of a transverse bulkhead
N_b = number of transverse bulkheads

Structural cost (F_2) = Material cost + Labor cost
(1) Material cost: = structural weight × unit material cost.
(2) Labor cost: (Tables 1 and 2) = jointing and welding m-h) × unit labor cost.
—jointing M-H = joint length × unit joint m-h
—welding M-H = weld length × unit weld m-h
Penalty functions (P_1, P_2)

$$P_1 = F_1 + \lambda_1\Sigma G, \quad P_2 = F_2 + \lambda_2\Sigma G$$

where λ_1, λ_2 = Lagrange multiplier.

Design example (block length is 25.6 m)—Figure 12(a) shows the ship structures of one block length, which is divided into several erection blocks. Figure 12(b) shows the center block, which is divided into pre-erection blocks. Then, the double-bottom pre-erection block is divided into several assemblies, mid-assemblies, components and fabrications. The fabrication cost is obtained by multiplying jointing and welding man-hour by unit labor cost (= \$15/m-h) and the number of blocks (=10) in the cargo holds.

As shown in Fig. 13, the Pareto optimal set is obtained by considering the longitudinal, transverse and transverse bulkhead members simultaneously for total cargo holds. The weight shows the hull weight of total ship length, and the cost shows the fabrication cost of total cargo holds. Designers can choose a better design from the obtained Pareto optimal set according to current yard facilities and environment.

LBR-5 model

Application of the LBR-5 design environment for the same VLCC vessel is formulated as follows.

The *Z requirements* are defined in the general arrangement (Fig. 10). The Y model parameters of the structure (System Definition) are the following (see U, V and W parameters).

The *U environment* model is fully defined by the loading cases of Fig. 11.

The *W Process* model includes:

- Block length = 51.2 m,
- Unitary material and fabrication costs (Rigo 2001).

In the present example the global building cost is evaluated using the following costs and productivity factors:

- Reference plate thickness = 20 mm,
- k = Unitary Labor Cost (\$/m-h)/Mat. Cost (\$/t) = 0.08 (in U.S.) or 0.03 (in Korea)
- Unitary prices of steel: C1 = 0.50 \$/kg,
- Unitary price of welding (materials only): C8 = 2.00 \$/m,
- Unitary working load (labor):
  —Plate assembling: P10 = 0.25 m-h/m^2,
  —Welding stiffeners on the panel: P4 = 0.5 m-h/m,
  —Welding frames on the panel: P5 = 1.5 m-h/m,
  —Built the members: P9 = 1.5 m-h/m (if built on site), otherwise P9 = 0.0 m-h/m,
  —Slot for stiffener: P = 0.6 m-h/piece,
  —Bracket or web stiffener: P7 = 0.6 m-h/piece.

These values are only given as examples. They vary from shipyard to shipyard and from country to country. The process model will therefore influence the optimum scantling.

The *V* Product model—

- The mesh model (Fig. 14) of the tanker hold includes 47 stiffened panels (Fig. 6) and nine design variables each. These values are only given as examples. There are also additional panels to model the symmetry axis (or boundary conditions) and to simulate the double-bottom and the double-side hull (not visible in the Fig. 14).

The *X* Design variables—

- NT = 423 design variables (9 × 47 panels);
- NE = 70 to 250 equality constraints between design variables. This number changes according to the level of standardization. For instance, uniform deck plating requires five equality constraints and identical stiffeners in the double bottom needs 44 equality constraints.
- NI = 173 to 353 independent design variables (NI = NT − NE).

The *R* Response Metrics—

- 2015 structural constraints (403 × 5 load cases; 8–11 constraints per panel).
- Two constraints on the hull ultimate bending moment.

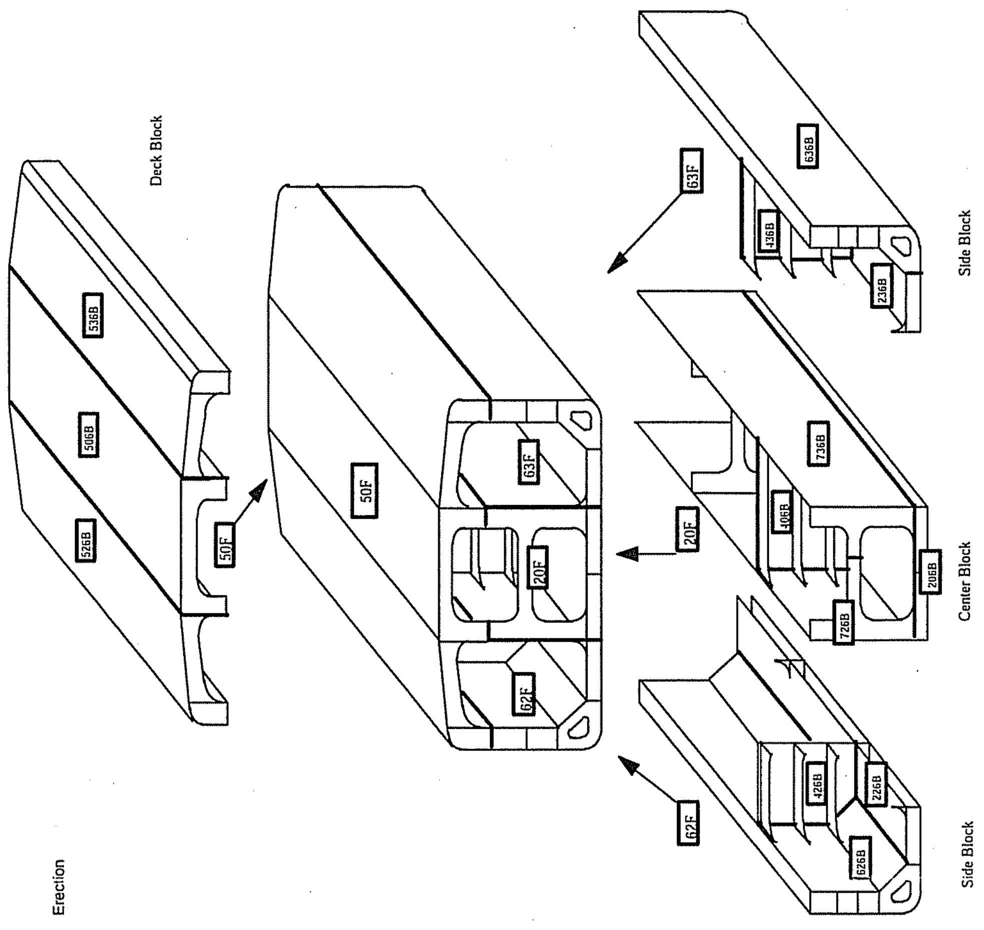


Fig. 12(a) Fabrication sequence diagram (Part 1)

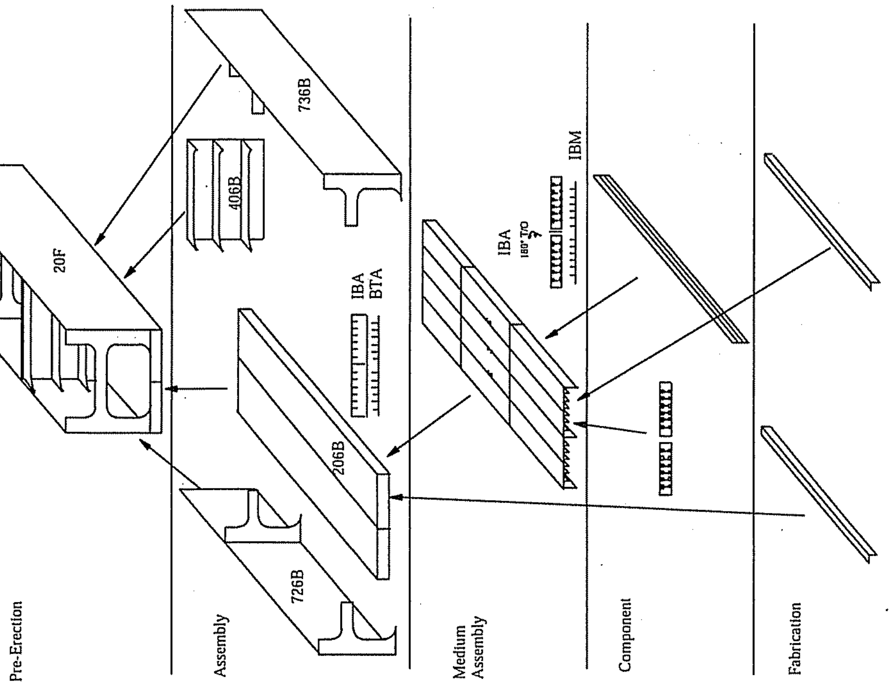


Fig. 12(b) Fabrication sequence diagram (Part 2)

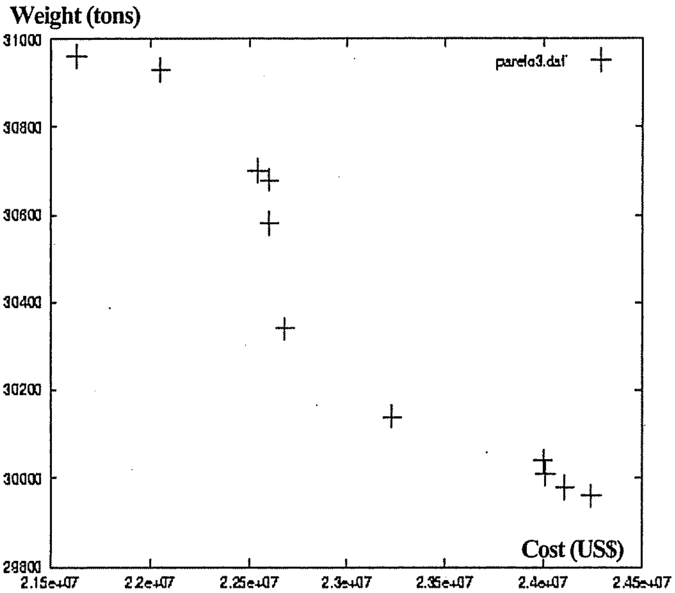


Fig. 13 Pareto optimal set—optimum weight versus optimum cost

- One constraint on the vertical position of the gravity center.
- 198 geometrical constraints (7 × 47 panels).

Structural constraints mainly concern:

- plate yielding (von Mises) and plate buckling,
- stiffener yielding (web and flange),
- frame yielding (web and flange),
- stiffener ultimate strength.

Geometrical constraints deal with:

- slenderness of the web stiffeners,
- ratio between web height and flange width (for stiffener only),
- ratio between plate and web thicknesses (for stiffeners and frames),
- ratio between flange and web thicknesses (for stiffeners and frames).

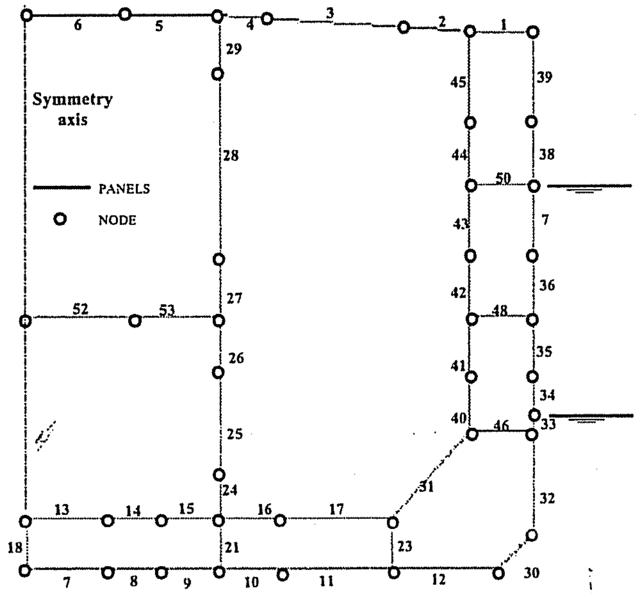


Fig. 14 LBR-5 product mesh model

The *S* Simulations Model—

The *R* structural constraint's response metrics are obtained using different *S* simulation models:

- The differential equations of stiffened panels (von Karman plate theory) to assess displacements and stresses (against yielding) (Rigo 1992).
- Parametric models for biaxial plate buckling (Hughes 1988) and ultimate strength model (Paik & Mansour 1995, Paik et al 1996).
- The geometrical constraints are provided by simple formulation (rules based).

The *G* constraint acceptance criteria—

- Against yielding the criteria is $\sigma_{(\text{von Mises})} < 1.0$ Yield Stress (σ_y)
- For plate buckling: $\sigma_{(\text{effective})} < 1.0\ \sigma_{(\text{buckling})}$
- For stiffened panel (axially compressed): $\sigma_{(\text{effective})} < 0.8\ \sigma_{(\text{ultimate strength})}$
- For ultimate bending moment of hull girder (in sagging and hogging): $M_{(\text{required by Class. Soc.})} < 0.8\ M_{(\text{Ultimate Bending Moment})}$
- Maximum position of the gravity center is fixed with regards to the stability. For tanker this constraint is not relevant but would be for other ship types.

The *F* objective functions—

- Using the unitary material and fabrication costs (see above in the process model) the construction cost is assessed using a simulation model (Rigo 2001).

Typical LBR-5's output is the optimum scantling given in table format (not shown here) and a review of the constraint intensity such as displacements (Fig. 15) and stresses (Fig. 16).

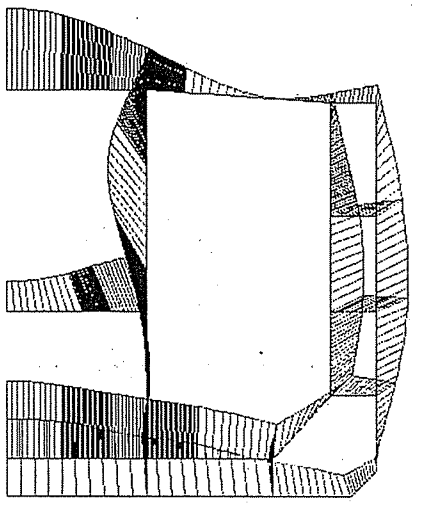


Fig. 15 Transversal displacement (δ) at mid-span of a block: $\delta_{max} = 30$ mm; 2-D analysis using a refined mesh model (load case 1)

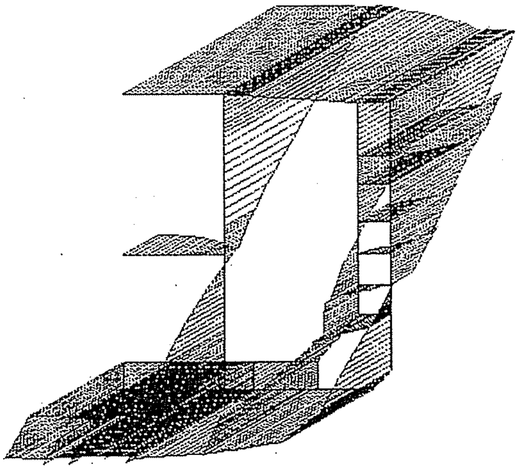


Fig. 16 Longitudinal stress: $\sigma(x) = 210$ N/mm^2, 3-D analysis (sagging + load case 2)

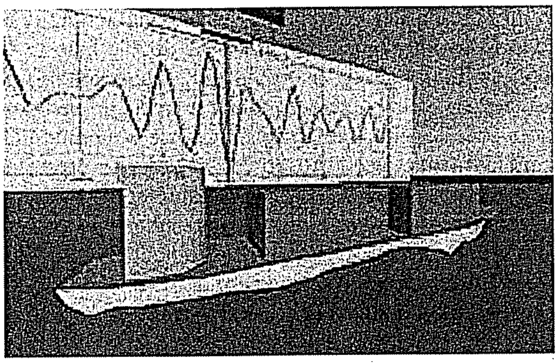


Fig. 17 VRML animation of ship motion simulation

Virtual reality simulations

Ship motion simulation—In this application, the motion of a high-speed containership traveling in head seas was pre-calculated by a linear analysis algorithm. The results were then used to animate a VRML model consisting of three object groups: Animated wave surface, moving ship hull with superstructure, and bending moment indicator displayed as a background graph (Fig. 17). As the vessel travels through the waves (with animated pitch), a moving red line on the background graph indicates the current bending moment. Interactive time controls for forward, rewind, and freeze allow studying any situation of interest in detail.

Analysis of a Double-Bottom Design—Derived from a CAD representation of a double-bottom section, this virtual prototype (Fig. 18) was analyzed in immersive and nonimmersive virtual reality. A walk through the model revealed several design errors typically found in initial CAD models created at an early design stage. Often, these errors are quite embarrassing and, if not found,

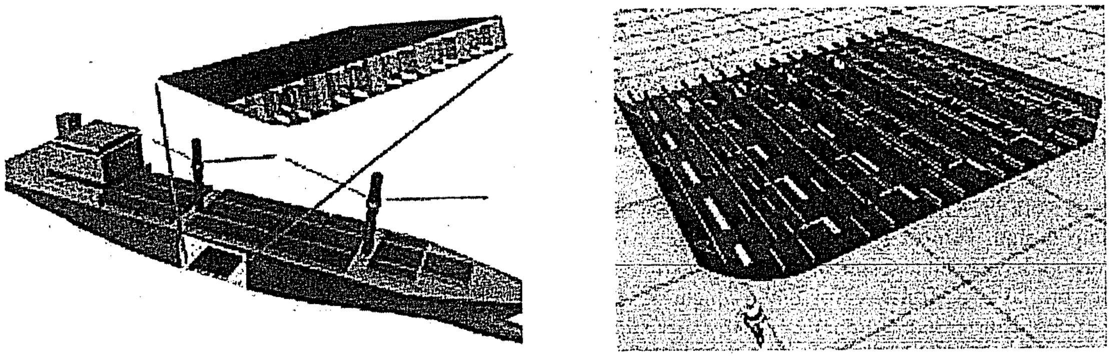


Fig. 18 Location of double-bottom section (*left*) and interior structure with top plate removed (*right*)

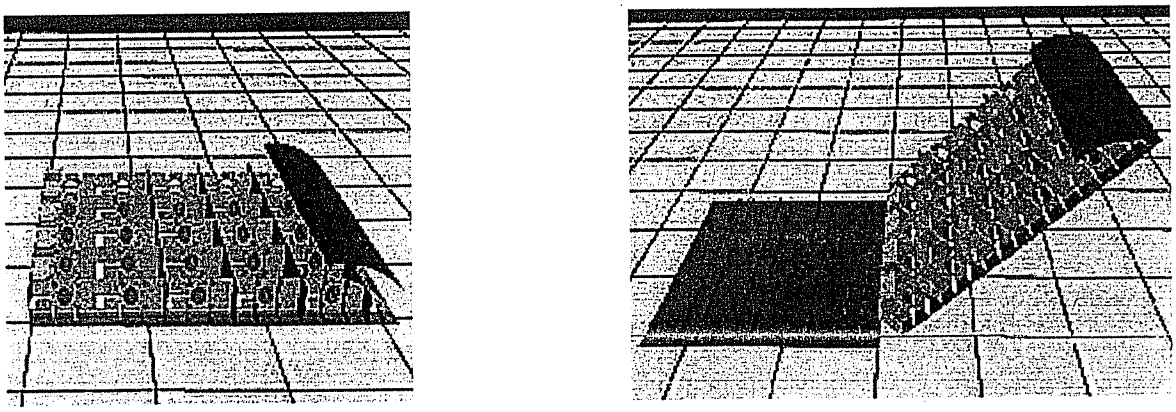


Fig. 19 Stages of animated assembly sequence

can result in costly time delays during the manufacturing process. In this case, several compartments of the double-bottom section are not accessible at all and it would not be possible to weld the section together. Simply adding more manholes proved not to be a solution since longitudinal stiffeners on the bounding plates of these compartments needed to be cut in order to create access. These stiffeners contribute to the structural integrity of the section and, therefore, cannot be removed. As a result of the analysis, the entire design needed to be changed.

A proposed assembly sequence for the same double-bottom model, as provided by a shipyard, was implemented as a VRML animation (Fig. 19). This simulation illustrates this process clearly for the manufacturing department, but also allows for the study of clearances, possible collisions during this process, required welding operations at various stages, necessary crane operations, and other production aspects.

Conclusions

Designing mechanical systems involves achieving simultaneous, though sometimes competing, objectives. The systems must perform their function while conforming to constraints and boundary conditions. Acceptable performance is usually measured in terms of static and dynamic response levels such as displacements, stress levels, and vibration amplitudes. The design process consists of establishing the structural system and composite subsystems, which optimally satisfy the topology, shape, loading and performance constraints while simultaneously considering the manufacturing or fabrication processes in a cost effective manner. It is definitively clear that use of the present generic framework is not limited to the three presented applications. Of course, the framework fits with these three packages but it has been thought to be broad enough to include most of the advanced design procedures (Birmingham et al 1997, Ennis et al 1998, Hills & Buxton 1989, Pugh 1996).

The new framework presents a generic methodology for simulation-based ship design. Two existing models dedicated to preliminary ship design have been assessed as being compatible with this new framework, as is a virtual reality environment in which the assembly process is assessed. Comparison with other simulation tools is welcome to improve the framework and to further establish its versatility.

Valuable use of this generic framework could be found in professional and educational environments (Pugh 1996). It could even form the basis for ship design improvement based on production and design integration, advanced research in a shipyard's planning, and progress in ship optimization tools. It is hoped that designers and shipyards alike find this new design scheme useful and an influence on the design approach, particularly in integrating simulation tools within their design and optimization procedures.

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