L3c DESIGN PROBLEM DECOMPOSITION

CONTENTS

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1. DESIGN PROBLEM FORMULATION

New generation of structural optimization techniques.

It implies:

❑ **Multilevel decomposition** for larger problems

- global problem (level 1) - ship cross-section,
- local subproblems (level 2) - structural subsystems,
- coordination implies modifying:
  a) the constraint set (restriction on minmax bounds),
  b) objective functions (penalty for divergence from global optimum).

- **Multiple Criteria Decision Making** (MCDM)

  a) MODM approach is used for global problem

  b) MADM used for local problems (increased computer speed → generation of large number of designs)

- **Second generation of approximation techniques**

  a) usage of intermediate variables (substructure areas)

  b) approximations for global stress constraints

  c) metamodeling of criteria functions or entire subspaces (e.g. X^N) for fast behavior prediction

2. Global problem rationale-MODM

- **Basic**

a) large-scale structural problems → small contribution of each failure function to failure envelope → linearization → feasible designs envelope is piecewise linear hyper-surface.

b) structural weight/cost are monotonous w.r.t. scantlings → optimal designs lie on that surface → usage of the most simple and efficient LP methods (e.g. ABS SHIPOPT → MAESTRO → OCTOPUS).

3. Local subproblem rationale-MADM

- **Basic**

(a) increased speed of workstations → complex optimisation problem can be replaced by multiple evaluation process

(b) usage of random search methods

(simplest, most robust nongradient techniques):

- search from a population of points,
- robust to local minima.

(c) sufficient density of non-dominated points gives a **design mapping** as 'discrete' inversion of the **evaluation mapping** →optimization oriented MODM replaced with selection oriented MADM

(d) process is non-dominance driven, sequential and adaptive

(e) problems of discrete variables and multiply connected domain, prohibiting application of MODM methods, become irrelevant

(g) profile type identifiers can be easily used as design variables instead of profile scantlings

(h) Alghoritm phases :

(1) generation, evaluation and filtering of nondominated designs in affine space,

(2) selection procedure in metric space.

❑ Local MADM strategies

(S1) Monte Carlo sampling in **X** to get n non-dominated designs in t trials to start S2-S3.

(S2) Sequential adaptive random generation of ND designs:

(a) designs surviving feasibility are tested for dominance

(b) ND used as centers of subspaces for “chain” generation of non-dominated hypersurface

(S3) Fractional Factorial Designs (FFD) application:

(a) in higher cycles of adaptive generation in subspaces

(b) OA (L9, L27) - 3 levels; up to 13 design variables

4. Modeling of envelope of local failure surfaces

- **Basic**

  Function $\hat{g}(\mathbf{p}^i)$ = minimal normalised safety factor over all safety criteria, all loadcases, Obtained from nondominated designs : min. weight-max. safety

  → $\hat{g}(\mathbf{p}^i)$ is carrying all the knowledge obtained on the local (substructure i) level

  Feasible nondominated designs satisfy $\hat{g}(\mathbf{p}) \geq 0$ → **Contour** $g(\mathbf{p}^i)=0$ is used in global optimization as minimal substructure area constraint.

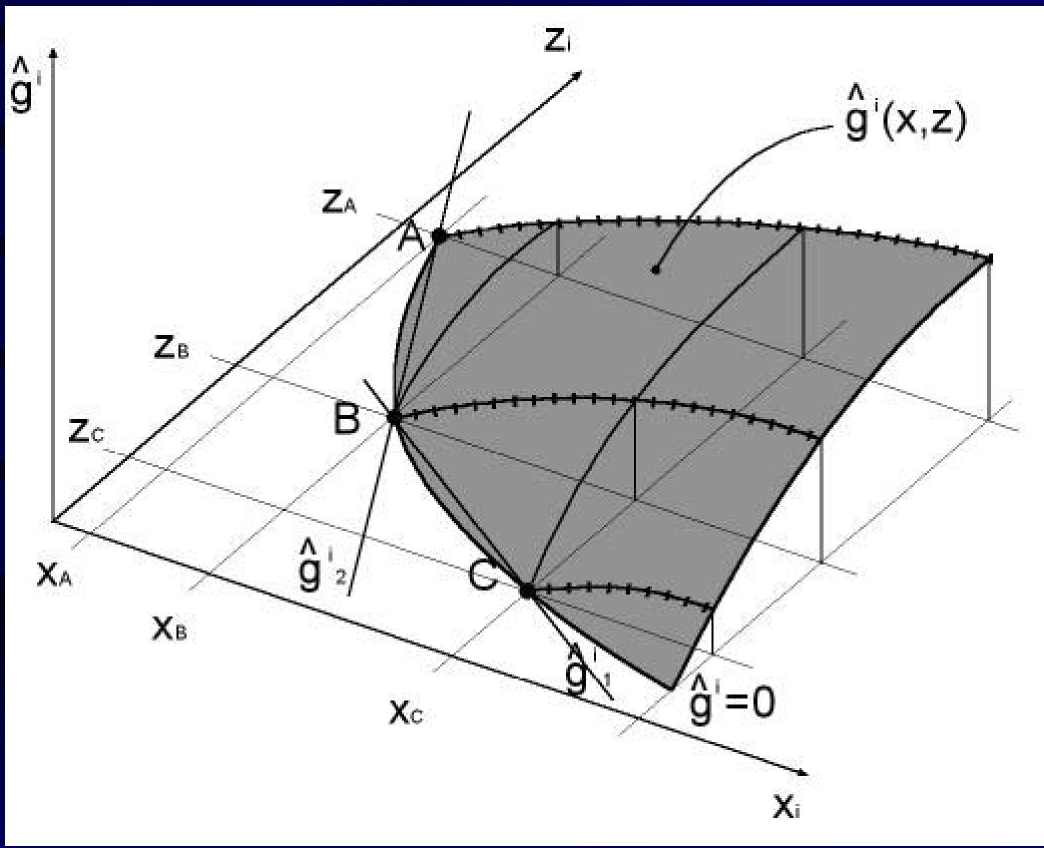
- **Procedure**

(1) Design vector $\mathbf{p}^i=\{x, z\}^i=\{$sec. area of substr. i, sec. modulus of ship C.S. for substr. i$\}$.

Taylor series expansion of $\hat{g}^i(.)$ uses nine (3x3) characteristic nondominated designs generated in cycles k=1-3 of preliminary exploration in attribute space) :

$[\mathbf{p}^{k1}=\{x, z\}^{k1}$= minimum weight designs,
$\mathbf{p}^{k2}$=compromise designs, $\mathbf{p}^{k3}$=maximal safety designs$]^i$

Nondominated designs (min x, max $\hat{g}_{min}$) for substructure i



Surface of nondominated designs then reads:

$$\hat{g}(\mathbf{p}) = \hat{g}(\mathbf{p}^0) + (\mathbf{p}-\mathbf{p}^0)^T\ \mathbf{G}^1 + \tfrac{1}{2}\ (\mathbf{p}-\mathbf{p}^0)^T\ \mathbf{G}^2\ (\mathbf{p}-\mathbf{p}^0) + \varepsilon\ ;$$

e.g. $\mathbf{p}^0 \equiv \mathbf{p}^{k2}$; $\mathbf{p} \equiv \mathbf{p}^i$

where $\mathbf{G}^1 = \begin{Bmatrix} \hat{g}^t_{,x} \\ \hat{g}_{,z} \end{Bmatrix}$; $\mathbf{G}^2 = \begin{bmatrix} \hat{g}_{,xx} & \hat{g}_{,xz} \\ \hat{g}_{,xz} & \hat{g}_{,zz} \end{bmatrix}$.

Contour of minimal substructure area for minimal acceptable feasibility $\hat{g}(\mathbf{p}) = 0$ reads:

$$\hat{g}(\mathbf{p}) = C_0 + \mathbf{p}^T\ \mathbf{C}^1 + \tfrac{1}{2}\ \mathbf{p}^T\mathbf{G}^2\ \mathbf{p}\ = 0\ ;$$

where $C_0 = \hat{g}(\mathbf{p}^0) - \mathbf{p}^{0T}\ \mathbf{G}^1 + \tfrac{1}{2}\ \mathbf{p}^{0T}\ \mathbf{G}^2\ \mathbf{p}^0$;

$\mathbf{C}^1 = \mathbf{G}^1 - \mathbf{G}^2\ \mathbf{p}^0$.

(2) **Derivatives** needed in $\mathbf{G}^1$ and $\mathbf{G}^2$ are calculated using modified procedure for curvilinear finite differences.

(3) **Special procedures** for boundary curve $\hat{g}(\mathbf{p}) = 0$.

(a) for given z^k = const. the values $x_{1,2}$ are the solution of the quadratic equation :

$$\hat{g}(x,) = C_0 + \mathbf{p}^T \mathbf{C}^1 + \tfrac{1}{2}\, \mathbf{p}^T \mathbf{G}^2\, \mathbf{p} = a + b\,x + c\,x^2 = 0$$

(b) simplified procedure: the coefficients a, b and c are obtained from three designs $\mathbf{p}^{k1}$, $\mathbf{p}^{k2}$, $\mathbf{p}^{k3}$,

(c) direct interpolation.

Ad (2) Derivatives $\mathbf{G}^1$ and $\mathbf{G}^2$ of $\hat{g}(p)$ - Taylor expansion:

(a) Surface $\hat{g}(\eta, \xi) = \boldsymbol{\alpha}^T \mathbf{a}$

$$\boldsymbol{\alpha} = \{1, \eta, \xi, \ldots\ldots\ldots\ldots, \eta^2\xi^2\} = \{\alpha_i\}$$

$$\mathbf{a} = \{a_1, \ldots, a_9\}; \text{ where } \eta, \xi = -1, 0, 1.$$

(b) Nodal $\hat{g}(.)$values in nine (3x3) regular points $\mathbf{p}^{kJ}$

$$\mathbf{g}^N = \{\hat{g}_1, .., \hat{g}_j, \ldots, \hat{g}_9\}$$

(c) Determination of coefficients **a:**

$$\mathbf{g}^N = \mathbf{C}\,\mathbf{a}; \quad \mathbf{C} = [\alpha_i(\eta_j, \xi_j)]; \quad \mathbf{a} = \mathbf{C}^{-1}\mathbf{g}^N$$

(d) The $\hat{g}$-surface reads:

$$\hat{g}(\eta, \xi) = \boldsymbol{\alpha}^T \mathbf{C}^{-1} \mathbf{g}^N = \mathbf{N}^T \mathbf{g}^N;$$

$$\mathbf{N} = \{N_i\} = \mathbf{C}^{-T} \boldsymbol{\alpha}$$

(e) Derivatives in η-ξ coord. system are stored in vector

$$\mathbf{G}_{,\eta\xi} = \{ \hat{g}_{,\eta} \ \hat{g}_{,\xi} \ \hat{g}_{,\eta\eta} \ \hat{g}_{,\eta\xi} \ \hat{g}_{,\xi\xi} \}.$$

They are calculated from the relation

$$\mathbf{G}_{,\eta\xi}\ (\eta,\xi) = \mathbf{B}(\eta,\xi)\ \mathbf{g}^N\ ;$$

$$\mathbf{B}\ (\eta,\xi\ ) = \begin{bmatrix} N_1(\eta,\xi)_{,\ \eta} \ .. \ N_i(\eta,\xi)_{,\ \eta} \ ..... \ N_9(\eta,\xi)_{,\eta} \\ .... \\ N_1(\eta,\xi)_{,\ \xi\xi} \ .. \ N_i(\eta,\xi)_{,\ \xi\xi} \ ... \ N_9(\eta,\xi)_{\xi\xi} \end{bmatrix}$$

(f) Derivatives $\mathbf{G}_{,xz} = \{\hat{g}_{,x} \ \hat{g}_{,z} \ \hat{g}_{,xx} \ \hat{g}_{,xz} \ \hat{g}_{,zz}\}$

using Taylor expansion around point x_K, z_K

$$\mathbf{g}^N = \mathbf{g}^K + \mathbf{D}\ \mathbf{G}_{,xz}$$

$$\mathbf{g}^K = g^K\{\ 1,.., 1\};$$

$$\mathbf{D} = \begin{bmatrix} (x_1-x_K) & (z_1-z_K) & \frac{1}{2}(x_1-x_{K)}^2 & (x_1-x_K)(z_1-z_K) & \frac{1}{2}(z_1-z_K)^2 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ (x_i-x_K) & (z_i-z_K) & \frac{1}{2}(x_i-x_{K)}^2 & (x_i-x_K)(z_i-z_K) & \frac{1}{2}(z_i-z_K)^2 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ (x_9-x_K) & (z_9-z_K) & \frac{1}{2}(x_9-x_{K)}^2 & (x_9-x_K)(z_9-z_K) & \frac{1}{2}(z_9-z_K)^2 \end{bmatrix}$$

(g) Finally from

$\mathbf{G}_{,\eta\xi} = \mathbf{B}\,\mathbf{g}^{N}$

the relation for derivatives $\mathbf{G}_{,xz}$ can be obtained:

$\mathbf{G}_{,\eta\xi} = \mathbf{B}\,(\mathbf{g}^{K} + \mathbf{D}\,\mathbf{G}_{,xz})$

$$\mathbf{G}_{,xz} = (\mathbf{B}\,\mathbf{D})^{-1}\,(\mathbf{G}_{,\eta\xi} - \mathbf{B}\,\mathbf{g}^{K}) = (\mathbf{B}\,\mathbf{D})^{-1}\,\mathbf{B}\,(\mathbf{g}^{N} - \mathbf{g}^{K}).$$

(4) Linearisation of surface at $\hat{g}^{i}$ (p) = 0

→ set of nm planes for each substructure i:

$$\hat{g}_m(\mathbf{p}) = \alpha_m z + \beta_m x + \gamma_m ;\quad m=1,.., nm$$

with coefficients α_m , β_m, γ_m corresponding to

- tangent plane on $\hat{g}(\mathbf{p})$ in point $(\mathbf{p}^m)$ in outer linearization,
- secant planes connecting $\mathbf{p}^{10}$, $\mathbf{p}^{20}$, $\mathbf{p}^{30}$, $\mathbf{p}^{m}$ in inner linearization

(5) Section modulus linearisation

- substructure areas $\mathbf{X} = \{x_i\}$ → intermediate variables,
- section modulus linearized into the form

$$z_i(\mathbf{X}) = z_i(\mathbf{X}^0) + (\mathbf{X}-\mathbf{X}^0)^T \mathbf{Z}^i_{,\mathbf{X}} = z_i(\mathbf{X}^0)\,(1 - (\mathbf{X}-\mathbf{X}^0)^T \mathbf{b}^i)$$

where:

$$\mathbf{Z}^i_{,\mathbf{X}} = -\, z_i(\mathbf{X}^0)\,\mathbf{b}^i \;;\; \mathbf{b}^i = \{b_j\}^i = \{b^i_j\} \;;$$

$$b^i_j = -\left[(d_j^{\,2} + \delta I_i) / I(\mathbf{X}^0) + d_j / (A(\mathbf{X}^0)\, d_i^{max}) \right];$$

d_j distance from N.A. to the centroid of substr. j;

d_i^{max} maximal distance of substr. i from N.A. ;

A(.) is ship cross section area ; I(.) is ship moment of inertia,

(6) Global feasibility constraint for substructure i

$$\hat{g}_m(\mathbf{p}^i) = \alpha^i_m\, z_i(\mathbf{X}^0)[1 - (\mathbf{X}-\mathbf{X}^0)^T \mathbf{b}^i] + \beta^i_m\, x_i + \gamma^i_m \;\geq 0$$

i = 1,.., NS (substructures)

m = 1,.., nm (planes)

Final form for Simplex tableau

$(\mathbf{D}^1 - \mathbf{D}^2)\,\mathbf{X} \geq \mathbf{D}^3$; where for i, j=1,.., nv ; m= 1,..,nm ;
k= (i-1) nm + m

$\mathbf{D}^1 = [D^1_{ki}]$; where $D^1_{ki} = \beta^i_m$;

$\mathbf{D}^2 = [D^2_{kj}]$; where $D^2_{kj} = \alpha^i_m\, z_i(\mathbf{X}^0)\, b^i_j$;

$\mathbf{D}^3 = \{D^3_k\}$; where $D^3_k = -\alpha^i_m\, z_i(\mathbf{X}^0)\,[1 + \mathbf{X}^{0T}\mathbf{b}^i] - \gamma^i_m$;

(7) Additional standard design constraints

$$I\,(\mathbf{X}) \geq I_{min}$$

$$z_i\,(\mathbf{X}) \geq (z^{DECK})_{min}\ ;$$

$$z_i\,(\mathbf{X}) \geq (z^{BOTT})_{min}\ ;$$

$$h_{min} \leq h_{N.L.}(\mathbf{X}) \leq h_{max}$$

2. DESIGN PROBLEM SOLUTION

- **Program OCTOPUS** uses the procedure with the following calculation blocks:

(A) Response / feasibility analysis modules **(CREST)**,

(B) Decision making - synthesis modules **(DeMak)**

(C) Interaction / visualization programs

-structural model/response(MAESTRO **MM/MG**)

-optimisation model **(DeVIEW)**

MODULE	OCTOPUS
(1a) STRUCTURAL MODEL	MAESTRO files generated by program MM and used in OCTOPUS (s/r CRINDAT)
(2) LOAD MODEL	Class.Soc (CRS) Loads + designer given loads generated automatically by OCTOPUS s/r CRLOAD
(1b) MINIMAL DIMENSIONS	Minimal dimensions by OCTOPUS s/r CRMIND
(3a) RESPONSE CALCULATIONS - - PRIMARY STRENGTH (u- displ.; stresses σx, τ)	Extended beam theory (cross section warping fields in bending and torsion, normal stresses, respective shear flows) - program LTOR
(3b) RESPONSE CALCULATION - -TRANSVERSE STRENGTH (displacements v, w, θx stresses σy)	FEM calculation using - beam element with or without rigid ends - stiffened panel macroelements - program TOKV

MODULE	OCTOPUS
(4) FEASIBILITY CALCULATION (Normalized Safety Factor)	Calculation of macroelement feasibility using library of safety criteria in program PANEL (C – capability; D – demand)
(5) RELIABILITY CALCULATION (not used in this example)	FORM approach to panel reliability. Upper Dietlevsen bound as design attribute
(6) DECISION SUPPORT PROBLEM DEFINITION (interactive)	Constraints: User given Minimal dimensions Library of criteria (see 4) Objectives: Minimal weight, Minimal cost Maximal safety
(7a, b,c) OPTIMIZATION METHOD	Decision making procedure using a) Global MODM program GLO b) Local MADM module LOC c) Coordination module GAZ
(8a,b,c) PRESENTATION OF RESULTS	a) VB Environment, b) Program MG, c) DeVIEW graphic tool

V. Zanic - Optimization of Thin-Walled Structures

❑ Definition of variables in GLOBAL and LOCAL optimizers

Local variables for substructure s =1,..,NS

$\underline{\mathbf{x}}^{s} = \{\underline{x}_i\}^{s} = \{t_{plating}, n_{stiffeners}, h_{web}..\}^{s}$,

Substructure areas are intermediate (global) variables,

$\mathbf{X} = \{x_s\}$; where $x_s = x_s(\underline{\mathbf{x}}^{s})$,

Project k is defined as

$\boldsymbol{P}^{k} = \{\underline{\mathbf{x}}^{1},..,\underline{\mathbf{x}}^{NS}, \mathbf{x}_{fixed}\}^{k}$.

❑ Global level MODM optimization (level 1 - ship cross-section)

- OCTOPUS metamodeling of global constraint surface

- DS problem: Determine $\mathbf{X} = \{x_s\}$

  minimizing $\mathbf{c}^{T}\mathbf{X}$

  s. t. $\mathbf{D}\,\mathbf{X} \geq \mathbf{d}, \mathbf{X} \geq \mathbf{X}_{min},$ s = 1,..,NS,

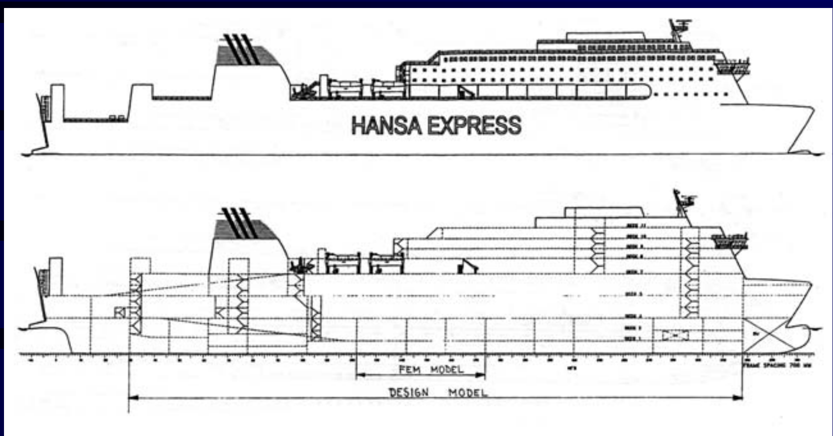
❑ Solution strategy: revised dual Simplex algorithm.

❑ Local coordinated MADM (level 2 – substructures)

- Determine nondominated designs $\underline{\mathbf{X}}^N$ with preferences:
  $\mathbf{a}(\underline{\mathbf{x}}^s) = \{a_1(\underline{\mathbf{x}}^s) = $ min. weight, $a_2(\underline{\mathbf{x}}^s) = $ min. cost,
  $a_3(\underline{\mathbf{x}}^s) = $ max. safety, $a_4(\underline{\mathbf{x}}^s) = $ min. distance to $x_s\}$
- Designs must satisfy $\underline{\mathbf{X}}^{\geq}$ **(feasibility)** requirements:
  bounds $\underline{\mathbf{x}}^s_{max} \geq \underline{\mathbf{x}}^s \geq \underline{\mathbf{x}}^s_{min}$,
  constraints $\mathbf{g}(\underline{\mathbf{x}}^s) \geq 0$,
- Global-local criterion $x_{MAXs} \geq x_s(\underline{\mathbf{x}}^s) \geq x_{MINs}$.
  (x_{MINs} and x_{MAXs} from global optimization $\mathbf{X}=\{x_s\}$).

3. OPTIMIZATION EXAMPLE

Optimization problem : large RoPax structural design,



PRINCIPAL DIMENSIONS	
Length overall	221.2 m
Length between perpendiculars	207.0 m
Breadth max. o.f	29.0 m
Depth to bulkhead deck	9.8 m
Depth to deck 5	16.4 m
Design draft	7.0 m
Scantling draft	7.4 m
Lanemeters	3500 m
Speed at design draft with 4 engines at 85%	24.5 Kn

(Benchmark: MAESTRO analysis+design based on SLP)

❑ Design Problem Identification:

Design objectives $a_{1\text{-}3}(.)$: min. weight, min. cost, max. safety

Free design variables $\underline{X} = \{\underline{x}^1,..,\underline{x}^{NS}\}$ are scantlings; nv =264

Constraints $g(\underline{X}) \geq 0$;ng ≈ 49000 from DnV Rules

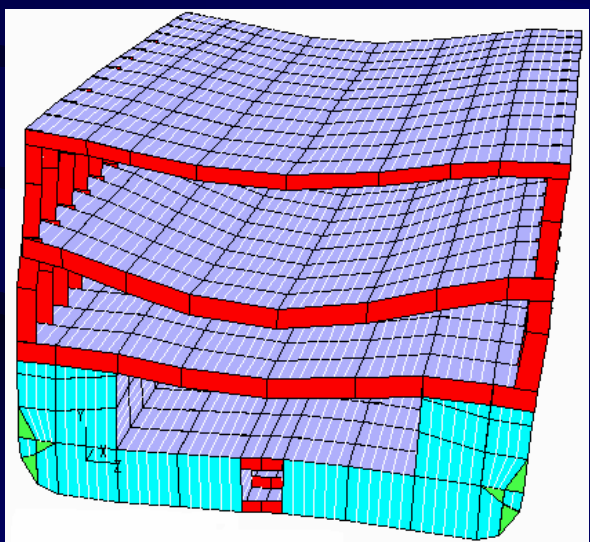
Prototype P^0 scantlings from Yard documentation
Proposal 1 design (P^1) was obtained using SLP
Proposal 2 design (P^2) was obtained using DeMak.

Frame spacing and topology fixed to P^0 design values.

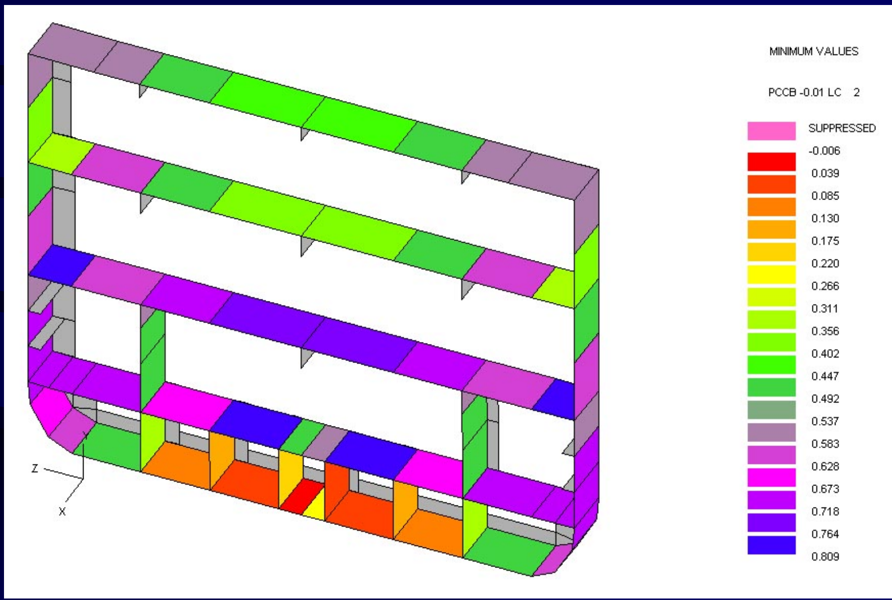
❑ Mathematical Models used in design procedure:

(1)MAESTRO 3-D FEM model-concept/preliminary design

- Non symetric loading – sym-antisym loads decomposition
- Control structure 3 bulkhead spacings; Fr. 123-171



(2) **OCTOPUS model** of cross section for concept design.



- **Longitudinal strength:** vertical bending moment at middle of the ship Moment was equal to the sum of the still water bending moment and 59% of the wave bending moment (DnV) for the dynamic load cases.

- **External loads:**

- *Water pressures* DnV Rules.
- *Deadweight loading* In dynamic load cases mases multiplied by corresp. acceleration factors (DnV Rules).
- *Cargo loads:* upright and heeled condition
- *Water ballast:* mass and pressure in heeling ballast tanks.
- *Self weight*
- *Load cases* based on given loading conditions and DnV

❑ Applied Load Cases

LOAD CASE	Description
LC 1	Full load on decks + dynamic / Scantling draught / SAGGING
LC 2	Full load on decks + dynamic / Scantling draught / HOGGING
LC 3	Full load on decks except D1 + dynamic / Scantling draught / SAGGING
LC 4	Full load on decks except D1 + dynamic / Scantling draught /HOGGING
LC 5	Ballast condition /Draught 5.8 m / HOGGING
LC 6	Full load on decks + dynamic / Heeled condition / SAGGING
LC 7	Full load on decks + dynamic / Heeled condition / HOGGING

❑ Prototype Analysis:

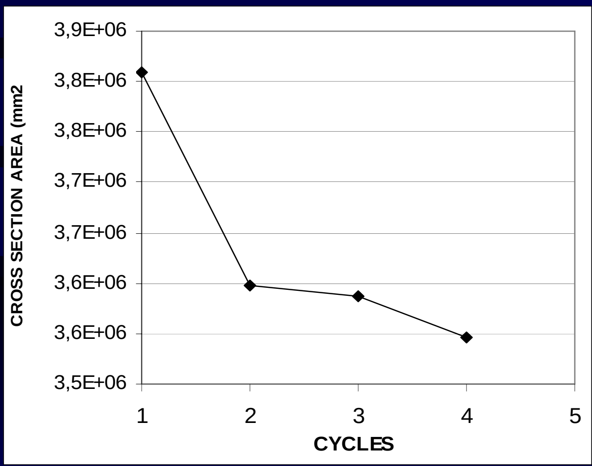
- Prototype P^0 has problems in double bottom, tank side and the middle of deck 5.
- Starting point P^0 checked using module for approx. initial sizing + preliminary optimization

→Due to the good prototype starting point was not modified.

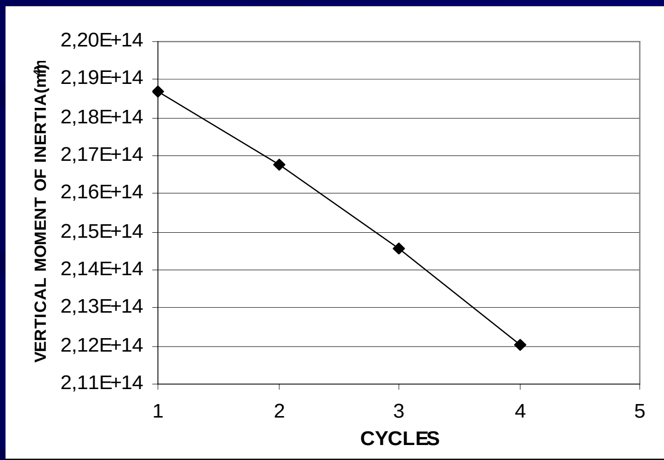
❑ Optimization Process

- P^0 design optimization → proposals P^c
- Standardization of stiffener profiles, flanges on girders or frames

❑ Optimisation history plots

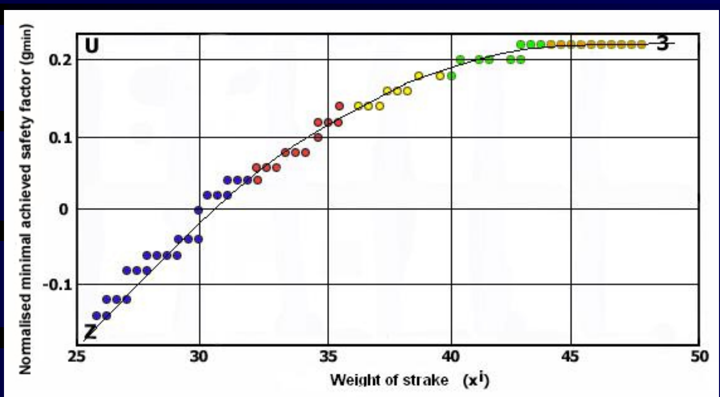


History of Cross Section Area

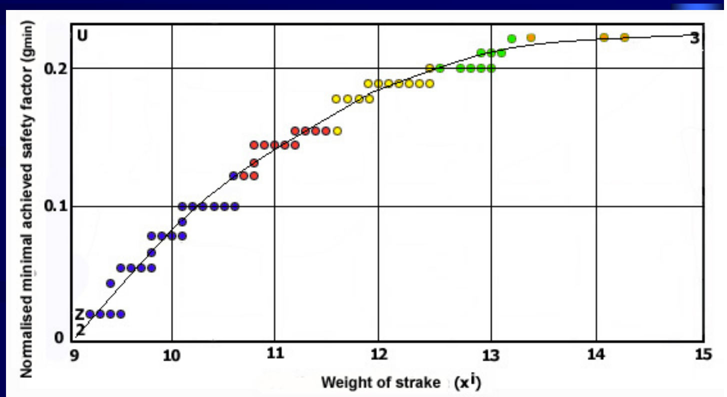


History of Vertical Moment of Inertia

❑ Substructure design variants (module DeVIEW)



Plot of the Nondominated Designs for Strake 2



Plot of the Nondominated Designs for Strake 36

- Smooth and regular nondominated hypersurfaces were obtained for all substructures in complex Ro-Pax structure.

- 40 substr. safety criteria used for each of 7 load cases

- Reliable FEM response model

→→ The obtained results, seem to confirm the assumptions of the quadratic approximation used.

❑ Optimization results

MODEL	Web frame spacing s_w (mm)	Weight of optimization model (t) W_{start} W_{opt}	Weight per length $w_L = W_{opt} / L_{FEM}$ (t / m)	Savings before final standard. $\frac{W_{start} - W_{opt}}{W_{start}}$	Weight* of design model $\approx k_x * A_x * w_L$ (t)	Increased deadweihgt = decreased steel weight (t)
PROTOTYPE ***P^0***	**2800**	**1355**	**40.33**	**-**	**5646**	**-**
PROPOSAL1 ***P^1***	**2800**	**1355** **1220**	**36.31**	**9.97%**	**5083**	- 563 t
PROPOSAL2 ***P^2***	**2800**	**1355** **1258**	**37.44**	**7.16%**	**5241**	- 405 t

Comments

- After SLP optimization (10 cycles) the P^1 design had the mass 563 t less than prototype P^0
- Structure P^2 was optimized by DeMak through 4 design cycles. It has the mass 406 t less than P^0
- Saving was quite significant result since prototype P^0 was very good design done by experienced designers.
- P^1 weighs somewhat less than P^2. Reasons:
  - OCTOPUS design used standard scantlings (tables),
  - additional safety criteria + higher safety
- OCTOPUS required less effort

4. CONCLUSIONS

Presented results show:

- Weight savings were obtained by simultaneously resolving structural problems of given prototype and increasing safety. It is contrary to some prejudices.
- Obtained plate and frame/girder thicknesses were automatically standardized in *PROPOSAL 2*. It is standard Yard procedure and inherent to OCTOPUS.
- Criteria that are procedures or tables or have disconected feasible domains can be easily included