MULTIOBJECTIVE SHIP DESIGN OPTIMISATION FOR LIFECYCLE: Applications to the Design of Tankers and Passenger Ships

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   - Holistic Ship Design Optimisation
   - Multi-objective Optimisation
   - Risk based Ship Design
   - Life Cycle Approach to Ship Design

2. Multi-objective Optimisation of Tanker Design

3. Multi-objective Optimisation and Life Cycle Approach to Passenger Ship Design (RoPax and Cruise Ships)

4. Conclusions- The Way Ahead
Important Design Optimization Notions (1)

- **Holism** *(philosophical notion, from Greek ὅλος, meaning entire, total)*- *adj. holistic*
  
- The properties of a system cannot be determined or explained by looking at its component parts alone; instead of, *the system as a whole determines the behaviour of the part components, i.e. interactions between the components cannot be neglected.*

- “The whole is more than the sum of the parts” *(Aristotle ‘Metaphysics’)*

- **Multi-objective ship design optimisation** may be interpreted as the *mathematical implementation* of the holistic approach to ship design.

- **Risk:** *the quantifiable likelihood (mathematical probability) for the upset of an acceptable state or of a worse-than-expected state condition.* *Safety* may be defined as “*a societally acceptable state of risk***.”
Important Design Optimization Notions (2)

- Major design optimization objectives (...objective/merit functions, criteria, indices...)
  - Performance/Efficiency
  - Cost (building, operational, life-cycle cost)
  - Safety >>> ('design for safety' and 'risk-based design')
  - Environmental protection (oil outflow, gas emissions, ...noise)

- Major design optimization constraints
  - Safety regulations
  - State of market (demand, supply, cost of steel, fuel, etc)
  - Other, more case specific

- Considering the risk of an investment in a new shipbuilding, the design of which should be holistically optimized, we might interpret the Holistic Ship Design Optimisation also as a generic Risk-based Ship Design Optimisation, in which the risk of an investment with specific profit expectation is minimised, or the profit maximised for an acceptable risk.
**Important Design Optimization Notions (3)** — Typical assessment *criteria-indicators* for *holistic ship design optimization*

- **Required Freight Rate (RFR):** The freight rate per ton of transported cargo which covers all expenses, with a remainder sufficient for a reasonable return on the shipbuilding investment. Actual freight rates are set by the market and fluctuate during ship’s life cycle.

- **Net Present Value (NPV):** is the sum of the present values of all cash flows (in and out) discounted at a rate consistent with the ship investment's risk. *The RFR is the freight rate producing discounted cash flows with zero NPV, i.e. the break even rate.*

- **Building Cost, Yearly Operational Cost, Life Cycle Cost** (including scrapping/dismantling; ‘Design for Life Cycle’)


- **Gross Cost for Averting Fatalities (GCAF) =ΔCost of applied Risk Control Options (RCOs)/ ΔRisk of fatalities of human lives (in terms of Potential Loss of Lives PLLs)**

- **Net Cost of Averting Fatalities (NCAF) = ΔCost-ΔBenefit/ΔRisk**

- **Attained Subdivision Index (A):** the probability of ship’s loss (capsize and/or sinking) due to side collision and flooding

- **Required Subdivision Index (R):** is set by regulation as a function of ship size and People On-Board POB (effect of extent of live boats).....A > R

- **EEDI and EEOI:** Energy Efficiency Design and Operational Indices acc. to MEPC-IMO (CO2 emissions per deadweight ton-miles)

- **Oil Outflow Index (OOI) = the % of carried oil which is statistically expected to be released to the marine environment over ship’s life cycle due to collision and grounding damages (MARPOL-IMO)**
Holistic Design Optimisation - Generic Problem

**INPUT DATA GIVEN BY OWNER REQUIREMENTS AND/OR PARENT HULL**
- Deadweight, payload
- Speed
- Maximum Draft
- Initial Arrangement
- etc..

- **VARIATION OF DESIGN PARAMETERS**
  - Hull form
  - Arrangement of spaces
  - Arrangements of (main) outfitting
  - Structural arrangements
  - Network arrangements (piping, electrical, etc)
  - etc…

Parametric Model of Ship Geometry and Outfitting

**Design Optimization**

**OUTPUT DATA**

**OPTIMISATION CRITERIA**
- Maximization of Performance/Efficiency Indicators
- Minimization of Environmental Impact Indicators
- Minimization of Building and Operational Costs
- Maximization of investment profit
- Minimization of investment risk
- etc…

**CONSTRAINTS**
- Regulations set by society
- Market demand/supply
- Cost for major materials, fuel and workmanship
- Other, case dependent constraints

Output
Generic Ship Design Optimization
Software Platform of NTUA-SDL

Design Optimization

- Concurrent Evaluation of Multiple Objectives
- Design Realization
  - Hull form, Internal compartmentation, Structure, Machinery Spaces
- External Shape
  - Resistance, Propulsion, Seakeeping, Intact Stability
- Internal Arrangement
  - Survivability, Capacities, Weights, Machinery layout
- Global Properties
  - Cost
- Design Pool

Has the Pareto Frontier Formed?

Selection of the Best Compromise

Yes

No

Knowledge Base
- Technical & Economical Databases, Regulations

Owner’s Requirements and/or Parent Hull

Variation of Design Parameters

Control of Constraints

Optimisation Criteria
- Evaluation of Multiobjective Function
BEST plus – a novel AFRAMAX oil tanker design
a joint NTUA-GL-FS development

BEST (Better Economics with a Safer Tanker)®
The problem, the challenges and the way ahead

- Oil tanker design was lately driven mainly by production aspects. The product has changed little.
- A recent analysis (SAFEDOR) for large oil tankers documented that the risk to environment is dominated by collision, grounding and fire.
- In response, GL and the National Technical University of Athens (NTUA) teamed up in 2008 and developed a novel AFRAMAX tanker design concept.
- The design was called BEST – Better Economics with a Safer Tanker – and it won the Greek Lloyd’s List Shipping Award for technical innovation in 2009.
- GL also received feedback from shipyards and operators regarding the desired features of the new design and now focuses on, compared to traditional designs, less extreme layout variations.
- The novel BEST+ design enhances the attractiveness of the initial concept by also integrating hydrodynamic optimisation of the hull form.
Create Objectives

Check MARPOL Requirements

Calculate Lightship & DWT

Check MARPOL Requirements

Create Hullform

Create Capacity Plan

Create Design Variable Vector

Read Design Variables Vector

Read Parameter Values

Create Structural model

Check Required Scantlings

Calculate Steel weight Distribution

Calculate Lightship & DWT

Check MARPOL Requirements

Create Objectives

Resistance Code (SHIPFLOW, CFD etc.)

Create calculation grid

Calculate Total Resistance

MULTIOBJECTIVE SHIP DESIGN OPTIMISATION

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Joint NTUA GL project

BEST
Final Optimization Flowchart BEST+
Integrated FS-NAPA-POSEIDON Platform

Optimization Flowchart

Optimization Control (FFW)

- Hull Form Generation
  - Tank Computation
    - Cargo Hold Mass Computation
      - Total Mass Computation
  - (Economic) Target Evaluation

- Max. Speed Computation
  - Stability, Trim, Draft Computation
    - Oil Outflow Index Computation
      - EEDI Computation

- hydrodynamic response surface file
  - COT compartmentation file
  - hullform IGES file

FFW
NAPA
POSEIDON

A. Papanikolaou
MULTIOBJECTIVE SHIP DESIGN OPTIMISATION
Implementation 1: Parametric Model in NAPA – GA of Reference Ship
Initial Studies of AFRAMAX Tanker Pareto Frontier Designs
Latest developments: 5x3 COT AFRAMAX tanker designs vs. 6x2 COT traditional (ref. ship) and improved designs (BEST+, 6x2)

Second Optimization (150X30 Designs, Design Speed 15knots)  
RFR vs. Oil Outflow

5X3 Twin Skeg (4500 variants)
BEST+

I.D 2590 (a)
I.D 2515 (a)
I.D 3210 (b)
I.D 1431 (b)
I.D 4567 (b)
I.D 4416 (b)
I.D 4247 (b)
I.D 559 (b)
I.D 2111 (b)

6X2 Reference

Improvement of 34.7% in OOI
Possible compromise
Multi-criteria Decision Making by Utility Functions Technique – Equal Weights (1)

<table>
<thead>
<tr>
<th>Case</th>
<th>6x3 Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design ID</td>
<td>1710 (#1)</td>
</tr>
<tr>
<td>Cargo.Vol</td>
<td>129804 (+2%)</td>
</tr>
<tr>
<td>Oil.Outflow</td>
<td>0.007777 (-23%)</td>
</tr>
<tr>
<td>Wst.cargo.area</td>
<td>10908 (-2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>6x3 Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design ID</td>
<td>2122 (#2)</td>
</tr>
<tr>
<td>Cargo.Vol</td>
<td>135950 (+7%)</td>
</tr>
<tr>
<td>Oil.Outflow</td>
<td>0.00942 (-6%)</td>
</tr>
<tr>
<td>Wst.cargo.area</td>
<td>11013 (-1%)</td>
</tr>
</tbody>
</table>

Reference Design

| Cargo.Vol     | 126765 |
| Oil.Outflow   | 0.01006|
| Wst.cargo.area| 11077  |
Multi-criteria Decision Making by Utility Functions Technique – Unequal Weights (2)

Case | 6x3 Flat  
Design ID | 2069  
Cargo.Vol | 137494 (+8%)  
Oil.Outflow | 0.0111 (+10%)  
Wst.cargo.area | 10894 (-2%)  

Case | 6x3 Flat  
Design ID | 2122 (#2)  
Cargo.Vol | 135950 (+7%)  
Oil.Outflow | 0.00942 (-6%)  
Wst.cargo.area | 11013 (-1%)  

Reference Design  
Cargo.Vol | 126765  
Oil.Outflow | 0.01006  
Wst.cargo.area | 11077
Implementation 2: Friendship Framework System® AFRAMAX Tanker GUI
Details of parametric models and design parameters: the structural design model

General Arrangement created from FFW ....

... and structural template model ...

... translates into structural CSR model in Poseidon*

including arrangement of
• girders
• stiffeners
• cutouts
• plates
• compartments

* slop tanks not modelled
A continuous ramp is used to link the inner bottom with varying heights near COT no 1.
Local hull form optimisation with FFS: CFD simulation within BEST+

- **SHIPFLOW** by FLOWTECH
  - Well established and validated
  - Robust and relatively fast

- **Zonal approach**
  - Potential flow analysis
    - Free trim and sinkage
    - Non-linear free surface boundary conditions
  - Boundary layer computation
  - RANSE simulation
    - Overlapping grid technology
Hydrodynamics of final hull at 13, 14, 15 and 16kn

Design draft = 13.7m

Scantling draft = 14.8m
Final hull form visualisation
Speed-power curves (incl. sensitivities)

Study on added resistance in waves

Scantling draft = 14.8m
Design draft = 13.7m
The BEST plus team

from left to right: Prof. Apostolos Papanikolaou, NTUA; Dr. Stefan Harries, Friendship Systems, Dr. Pierre. C. Sames, GL, Mattia Brenner, Friendship Systems, Prof. George Zaraphonitis, NTUA, Marc Wilken, GL
Feasibility Prospects

- The proposed designs can be readily built at slightly higher cost (initial investment) and are economically very attractive to operate (significantly reduced freight rates).

- The introduction of raised double-bottom height in the forward part of the ship (and possibly raised deck by a linear sheer) is very simple and yet has a great potential as RCO (Risk Control Option); considering the frequency of grounding incidents in the bow region it appears to be an attractive safety measure to be quickly adopted.
Risk-based Passenger Ship Design Optimisation
EU project GOALDS

The presented case studies focus on the conceptual/preliminary stage by optimising the main dimensions, hull form and internal compartmentation of a RoPax and a cruise ship.
The problem and the challenges

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MULTIOBJECTIVE SHIP DESIGN
OPTIMISATION

Comparable max. data
Titanic capacity (max): pass 2435, crew 892
total 3,327

Allure of the Seas
capacity (max): Pass 6,296, crew 2,394
total 8,690
Conducted Optimization Studies

To investigate the impact of the GOALDS probability of survival formulation on the design and operational characteristics of ROPAX and Cruise ships, a series of sample ships has been selected to be re-designed for:

- **enhanced survivability** (minimum risk for Potential Loss of Lives), considering also
  - building cost,
  - efficiency in operation
  - and lifecycle cost
GOALDS Optimization Studies

- Two Cruise ships
  - Large
  - Medium
- Four RoPax
  - Large
  - Medium
  - Small (2 ships)
- Design teams
  - Shipyard
  - University Laboratory
  - Shipowner
  - Class Society
  - Flag Administration
Optimization Platform NTUA-SDL: Integrated NAPA & mode FRONTIER

ModeFRONTIER

Input File
(Design Variables)

NAPA
(Parametric Model)

Output Files
(Objective Functions,
Constraints etc.)
Basic Features of the Parametric Model

• Initialization phase (Clear the NAPA database, read input variables)
• Definition phase
  1. Create the hullform and internal arrangement
  2. Define loading conditions
  3. Define openings, cross-connections, escape routes
• Evaluation phase
  1. Evaluate geometric constraints
  2. Calculate lanes length and transport capacity
  3. Estimate resistance and propulsion power
  4. Calculate intact stability
  5. Calculate A-SOLAS 2009 and A-GOALDS
  6. Calculate economic indicators
  7. Calculate Potential Loss of Life (PLL)
• Print output files
Original Design: Medium Size RoPax/FINCANTIERI-NTUA
## Main dimensions, Medium Size RoPax

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendicularels</td>
<td>162.85 m</td>
</tr>
<tr>
<td>Subdivision length</td>
<td>182 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>27.6 m</td>
</tr>
<tr>
<td>Subdivision draught</td>
<td>7.10 m</td>
</tr>
<tr>
<td>Height of bulkhead deck</td>
<td>9.80 m</td>
</tr>
<tr>
<td>Number of passengers</td>
<td>2080</td>
</tr>
<tr>
<td>Number of crew</td>
<td>120</td>
</tr>
<tr>
<td>Gross tonnage</td>
<td>abt. 36000</td>
</tr>
<tr>
<td>Deadweight</td>
<td>5000 t</td>
</tr>
<tr>
<td>Lane meters</td>
<td>1950 m</td>
</tr>
<tr>
<td>R index (SOLAS2009)</td>
<td>0.79804</td>
</tr>
<tr>
<td>A index (SOLAS2009)</td>
<td>0.80305</td>
</tr>
<tr>
<td>A index (GOALDS)</td>
<td>0.82666</td>
</tr>
</tbody>
</table>
Medium size ROPAX: parametric model, change of beam
Medium size RoPax: Setup of the optimization problem

Optimization Variables (range)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>L&lt;sub&gt;REF&lt;/sub&gt;</td>
<td>157m - 167m</td>
</tr>
<tr>
<td>B&lt;sub&gt;REF&lt;/sub&gt;</td>
<td>27.5m - 28.2m</td>
</tr>
<tr>
<td>T&lt;sub&gt;REF&lt;/sub&gt;</td>
<td>6.8m - 7.2m</td>
</tr>
<tr>
<td>DBT&lt;sub&gt;HT-AFT&lt;/sub&gt;</td>
<td>2.3m - 2.8m</td>
</tr>
<tr>
<td>DBT&lt;sub&gt;HT-MID&lt;/sub&gt;</td>
<td>1.5m - 2.0m</td>
</tr>
<tr>
<td>DBT&lt;sub&gt;HT-FWD&lt;/sub&gt;</td>
<td>1.4m - 1.9m</td>
</tr>
<tr>
<td>DK&lt;sub&gt;1 HT&lt;/sub&gt;</td>
<td>2.3m - 2.6m</td>
</tr>
<tr>
<td>DK&lt;sub&gt;2 HT&lt;/sub&gt;</td>
<td>2.1m - 2.3m</td>
</tr>
<tr>
<td>DK&lt;sub&gt;3 HT&lt;/sub&gt;</td>
<td>3.0m - 4.2m</td>
</tr>
<tr>
<td>DK&lt;sub&gt;4 HT&lt;/sub&gt;</td>
<td>5.4m - 5.8m</td>
</tr>
</tbody>
</table>

Number of Passengers: 2080
Persons in lifeboat N<sub>1</sub>=660
Persons in excess of N<sub>1</sub> N<sub>2</sub>=1540

Objective Functions

- \( \text{min}(PLL_G) \)
- \( \text{min}(\text{Econ. Impact}) \)

Constraints

- \( A_{\text{SOLAS}} > R_{\text{SOLAS}} \)
- \( PLL_G < PLL_{G-\text{INIT}} \)
- \( \text{Intact Stability Requirements} \)
- \( \text{GM} < 3.5m \)

Number of Feasible Designs: 423
Number of Unfeasible Designs: 124
Medium size RoPax, Optimization results
Medium size RoPax, Optimization results
Medium size RoPax, Optimization results
Medium size RoPax, Optimization results

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## Comparison of Original and Optimized Design

<table>
<thead>
<tr>
<th>Metric</th>
<th>Original</th>
<th>Design 467</th>
<th>Diff.</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Reference (m)</td>
<td>162.845</td>
<td>167.000</td>
<td>4.155</td>
<td>2.55%</td>
</tr>
<tr>
<td>Beam (m)</td>
<td>27.600</td>
<td>28.200</td>
<td>0.600</td>
<td>2.17%</td>
</tr>
<tr>
<td>Draught Subdivision (m)</td>
<td>7.029</td>
<td>6.922</td>
<td>-0.107</td>
<td>-1.52%</td>
</tr>
<tr>
<td>Height to bulkhead deck (m)</td>
<td>9.800</td>
<td>10.250</td>
<td>0.450</td>
<td>4.59%</td>
</tr>
<tr>
<td>DWT (t)</td>
<td>5253</td>
<td>5424</td>
<td>170.500</td>
<td>3.25%</td>
</tr>
<tr>
<td>Lightship (t)</td>
<td>14000</td>
<td>14356</td>
<td>356.100</td>
<td>2.54%</td>
</tr>
<tr>
<td>Lanes Length (m)</td>
<td>1950</td>
<td>2011</td>
<td>60.870</td>
<td>3.12%</td>
</tr>
<tr>
<td>CAPEX (m$)</td>
<td>0.000</td>
<td>2.180</td>
<td>2.180</td>
<td></td>
</tr>
<tr>
<td>Gross Economic Impact (m$)</td>
<td>0.000</td>
<td>5.900</td>
<td>5.900</td>
<td></td>
</tr>
<tr>
<td>GMS (m)</td>
<td>2.123</td>
<td>2.516</td>
<td>0.393</td>
<td>18.51%</td>
</tr>
<tr>
<td>GMP (m)</td>
<td>1.933</td>
<td>2.455</td>
<td>0.522</td>
<td>27.01%</td>
</tr>
<tr>
<td>GML (m)</td>
<td>2.768</td>
<td>3.316</td>
<td>0.547</td>
<td>19.77%</td>
</tr>
<tr>
<td>A SOLAS</td>
<td>0.823</td>
<td>0.882</td>
<td>0.060</td>
<td>7.27%</td>
</tr>
<tr>
<td>A GOALDS</td>
<td>0.827</td>
<td>0.884</td>
<td>0.057</td>
<td>6.95%</td>
</tr>
<tr>
<td>PLL (SOLAS)</td>
<td>4.006</td>
<td>2.656</td>
<td>-1.350</td>
<td>-33.69%</td>
</tr>
<tr>
<td>PLL (GOALDS)</td>
<td>3.914</td>
<td>2.617</td>
<td>-1.298</td>
<td>-33.15%</td>
</tr>
<tr>
<td>A SOLAS</td>
<td>0.823</td>
<td>0.913</td>
<td>0.090</td>
<td>10.94%</td>
</tr>
<tr>
<td>A GOALDS</td>
<td>0.827</td>
<td>0.917</td>
<td>0.090</td>
<td>10.88%</td>
</tr>
<tr>
<td>PLL (SOLAS)</td>
<td>4.006</td>
<td>1.968</td>
<td>-2.038</td>
<td>-50.87%</td>
</tr>
<tr>
<td>PLL (GOALDS)</td>
<td>3.914</td>
<td>1.883</td>
<td>-2.031</td>
<td>-51.89%</td>
</tr>
</tbody>
</table>
Optimization of Panamax Cruise Ship
STX FRANCE-NTUA
# Main dimensions, Panamax Cruise Ship

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculare</td>
<td>269.140 m</td>
</tr>
<tr>
<td>Subdivision length</td>
<td>288.663 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>32.200 m</td>
</tr>
<tr>
<td>Subdivision draught</td>
<td>7.85 m</td>
</tr>
<tr>
<td>Height of bulkhead deck</td>
<td>10.60 m</td>
</tr>
<tr>
<td>Number of passengers</td>
<td>3000</td>
</tr>
<tr>
<td>Number of crew</td>
<td>1000</td>
</tr>
<tr>
<td>Gross tonnage</td>
<td>abt. 92000</td>
</tr>
<tr>
<td>Deadweight</td>
<td>8700 t</td>
</tr>
<tr>
<td><strong>R index (SOLAS2009)</strong></td>
<td>0.82152</td>
</tr>
<tr>
<td><strong>A index (SOLAS2009)</strong></td>
<td>0.82412</td>
</tr>
<tr>
<td><strong>A index (GOALDS)</strong></td>
<td>0.84656</td>
</tr>
</tbody>
</table>

*) Based on calculations for the starboard side only, resulting in smaller $A$ values than the actual, due to the position of the corridor and the associated down-flooding openings.
Panamax Cruise Ship: formulation of the optimization problem

Optimization Variables
• Beam
• Draught
• Height of Dk 2
• 4 variables controlling the length of MFZ no 1, 2, 4 and 5
• 4 variables controlling the length of the w/t compartments within these zones.

The ship’s length is a depended variable, derived from the sum of lengths of the main fire zones.

Number of Feasible Designs: 508
Number of Unfeasible Designs: 173

Objective Functions
\[ \min (PLL_G) \]
\[ \min \text{(Econ. Impact)} \]

Constraints
• \[ T_{ROLL} > 16 \text{sec} \]
• \[ PLL_G < PLL_{G-INIT} \]
• Intact Stability Requirements
• \[ T_D < 7.8 \text{m} \]
• \[ -1.0 \text{m} < trim < 0.25 \text{m} \]

\[ A_s - R_s \geq 0.0075 + \frac{1 - A_s}{10} \]
Panamax Cruise Ship, Optimization results

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MULTIOBJECTIVE SHIP DESIGN OPTIMISATION
Panamax Cruise Ship, Optimization results

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MULTIOBJECTIVE SHIP DESIGN
OPTIMISATION
Panamax Cruise Ship, Optimization results

A. Papanikolaou
Panamax Cruise Ship, Optimization results
## Comparison of Original and Optimized Design

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<tr>
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<th>Original</th>
<th>Design 636</th>
<th>Diff.</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length BP (m)</td>
<td>269.140</td>
<td>269.14</td>
<td>0.000</td>
<td>0.00%</td>
</tr>
<tr>
<td>Beam (m)</td>
<td>32.200</td>
<td>32.900</td>
<td>0.700</td>
<td>2.17%</td>
</tr>
<tr>
<td>Draught Subdivision (m)</td>
<td>7.850</td>
<td>7.798</td>
<td>-0.052</td>
<td>-0.66%</td>
</tr>
<tr>
<td>Height to bulkhead deck (m)</td>
<td>10.600</td>
<td>10.600</td>
<td>0.000</td>
<td>0.00%</td>
</tr>
<tr>
<td>CAPEX (m$)</td>
<td>0.000</td>
<td>2.657</td>
<td>2.657</td>
<td></td>
</tr>
<tr>
<td>Gross Economic Impact (m$)</td>
<td>0.000</td>
<td>-0.110</td>
<td>-0.110</td>
<td></td>
</tr>
<tr>
<td>GMS (m)</td>
<td>2.440</td>
<td>2.989</td>
<td>0.549</td>
<td>22.50%</td>
</tr>
<tr>
<td>GMP (m)</td>
<td>2.143</td>
<td>2.724</td>
<td>0.581</td>
<td>27.11%</td>
</tr>
<tr>
<td>GML (m)</td>
<td>2.143</td>
<td>2.724</td>
<td>0.581</td>
<td>27.11%</td>
</tr>
<tr>
<td>T-Roll (sec)</td>
<td>19.83</td>
<td>18.14</td>
<td>-1.69</td>
<td>-8.52%</td>
</tr>
<tr>
<td>A SOLAS</td>
<td>0.818</td>
<td>0.900</td>
<td>0.082</td>
<td>10.02%</td>
</tr>
<tr>
<td>A GOALDS</td>
<td>0.865</td>
<td>0.933</td>
<td>0.068</td>
<td>7.86%</td>
</tr>
<tr>
<td>PLL (SOLAS)</td>
<td>2.120</td>
<td>1.162</td>
<td>-0.958</td>
<td>-45.19%</td>
</tr>
<tr>
<td>PLL (GOALDS)</td>
<td>1.569</td>
<td>0.781</td>
<td>-0.788</td>
<td>-50.22%</td>
</tr>
</tbody>
</table>
Comparison of Required Subdivision Indices

\[ R_{\text{index}} = \begin{cases} 
0.9 & \text{for } pob < 1,000 \\
0.97 & \text{for } pob \geq 6,000 
\end{cases} \]

\[ R_{\text{index2}} = 1 - \left( \frac{2300}{5 \cdot pob + 20000} \right) \]

Pending final discussions/approval by IMO
Conclusions on passenger ship results

- Ship design is a complex process, and it is difficult to capture all design details within a parametric model.

- The obtained results in terms of stability and economic impact must be treated with some caution with respect to employed semi-empirical estimations of ship properties and cost.

- The obtained results indicate that there is room for a significant increase of the Required Subdivision Index in comparison with the requirements of SOLAS 2009.

- The implemented optimization methodology is a valuable tool to:
  - the designer in the exploration of the huge design space,
  - administrators/regulators in defining reasonable levels of ship’s survivability that can be achieved cost effectively.
Almost five (5) decades after the introduction of the Computer-Aided Ship Design and Optimisation in the 60ties, with the landmarking contribution of *em. Prof. Horst Nowacki*, we can certainly say that *today’s state of the art, knowledge and technology in the field allows comprehensive holistic multi-objective optimisation approaches to the design of a ship as a system* (and its individual components or for individual objectives/functions) *for her entire life cycle*, leading to ships of *enhanced efficiency, safety, comfort and environmental protection* to the benefit of society, world and national economies and of the shipping industry.

It should be noted, however, that the *implementation* of the required relevant optimisation procedures *needs still to be developed for a long list of practical cases by experienced software programmers* supported by ship designers (*ideally by naval architects*), which will be a demanding R&D task for the decade(s) to come.
References

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FRIENDSHIP SYSTEMS 10 Years Anniversary
16. October 2013, Berlin

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