DESIGNING OUT COMPLEXITY EARLY: A PATH TO FLEXIBLE WARSHIPS

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“Outside-In Design” – Start with Hull Form, Then Cram Everything into Hull

- Hull is sized & shaped based on:
  - Early design weight and area/volume estimates
  - Big assumption volume is “arrangeable”
  - Big assumption limiting hull size limits ship costs

Ship Arrangements unstable through Detail Design
First Ship Engineering MH / LT vs. Outfit Density

- Legacy Hulls (Return Data)
- Navy Program Estimates
- MPF(F) Notional Designs (Estimated Data)
- FFG 7
- DD(X) Navy
- CG 47
- LPD 17
- LHA 1
- LHD 1
- LHR
- LOG-RO/RO AVIATION
- DISTRIBUTED
- MLP 2B
- MLP 2A
- MLP 3
- T-AKE 1

Military Designs - Combatants
Military Designs - Amphibs
Hybrid Designs
Commercial Designs
Ships Possessing Greater Density Increase Production Cost

Ship Production hours increase with density and fall into predictable groupings.
Adverse Impacts of “Outside-In” Design

- Inefficient Hydrodynamic Hull Form Designs increase Fleet fuel bills and environmental emissions
- Overly weight and stability sensitive designs require exotic, costly, lightweight materials
- Difficulty in maintaining and repairing ships
- Insufficient service-life allowances thus increasing modernization costs
- Reductions in years of economical service-life of ships
- Operational constraints due to lack of robust designs

“Shipboard distributed systems such as...structure...in wide disrepair throughout the surface force.” Balisle, 2010
Use of Rule-Based Methods in Early Ship Design: Seaway Loads

- Structural Design of FFG 7, CG 47, DDG 51 Classes
  - Interested more in extreme loading conditions than actual loads
  - Worked with simplified loading envelopes
  - Deterministic analysis resulted in scantlings for maximum load expected
  - Highly random wave-induced loads were set of simplified hydrostatic loads under extreme seas

No Analytical Computations nor Seakeeping Model Tests During PD/CD to Determine Seaway Loads
Lack of Physics-Based Design Tools: Increased Ownership Costs

- FFG 7 Class
  - Hull girder doubler plates & ballast added
  - Extensive deckhouse fatigue cracking

- CG 52 Class (with VLS)
  - Serious hull cracking and buckling problem
  - Extensive superstructure fatigue cracking

- DDG 51 Class
  - Bow structure buckling and cracking issue

- Operational loads exceeded rule-based design loads

$100M’s in repairs and sustaining service-lives
WHERE WE NEED TO GO

According to an old proverb, if we do not change our direction, we might end up where we are headed.
● **Ship design and design for production:**
  – Develop a rationalized standard design approach that includes new methods and reduces design cost.
  – Establish design for production standards, including in the earliest design stages.

● **Dimensional and quality control:**
  – Promote awareness of the schedule impacts and true costs of non-value-added work.
  – …improve dimensional and distortion control through ship design, block breakdown, welding and other technologies.

● **Production and process engineering:**
  – Develop a training and certification program...
  – Introduce a production engineering requirement for future designs.
● **Pre-erection outfitting, outfit installation and module building:**
  - Optimize the design and pre-production processes to inherently define outfit modules and support advanced outfitting.
  - Increase the use of outfit modules.
  - Define and measure outfit manning density.

● **Manpower, organization of work, and job and skills flexibility:**
  - …increase the levels of flexible working, and make more use of multidisciplinary teams.
  - Fully implement workstation organization and product-oriented operations.

**SD&MT Panel Challenge: Design Out Complexity Early - Provide A Path To Flexible Warships**
Flexible Warship Initiative (FWI)

Long-term collaboration between Navy-Industry-Societies

- Navy’s Program Executive Office (PEO) Ships
- Global Shipbuilding Executives Summit (GSES)
  - GSES I - VI
- America Society of Naval Engineers (ASNE)
  - ASNE Day 2010 - 2015
- Society of Naval Architects and Marine Engineers (SNAME)
  - Ship Design Committee (SDC)
  - Naval Ships SD-8 Panel
- Navy’s Center for Innovation in Ship Design (CISD)

Team A established at GSES VI, ASNE Day 2015
Three Tasks Assigned to Team A

1. Identify first order Principles for Design of Flexible Warships
   – analysis of foreign naval ships
   – experience of former US shipyard executive
2. Assess design tool needs for Design Space Exploration (DSE) of Flexible Warships
   – software development work of DoD High Performance Computing Modernization Program (HPCMP) Computational Research & Engineering Acquisition Tools & Environments (CREATE) – Ships Project
3. Propose an approach for addressing distributed systems during DSE for Flexible Warships
   – SNAME SDC/SD-8 workshop to identify design tools and process improvements
Analysis of Foreign Flexible Warships: Danish Standard Flexibility (STANFLEX)

- Foundation on which to build future flexible warships:
  - business practices, requirements, and interfaces
- Danish Navy collaborated closely with shipyard in a public/private partnership
- Requirements stabilized early, faster & cheaper production
- Modules only half of a successful Flexible Warship
- Key is sizing ship infrastructure to support future upgrades
  - significant service-life allowances for power, cooling, structure, weigh, networks (cableways) and space
  - design margins begin with twice as much as usual

Danes Embraced Flexibility Culture by **Focusing on the Sea-Frame**
Foreign Flexible Warships: Damen SIGMA (Ship Integrated Geometrical Modularity Approach)

- Dutch SIGMA class based on the following major principles:
  - “Oversized” hulls reduce installation, operation & maintenance costs
  - Systematic structural layout of standard 24-ft compartments with common modular spaces for ops, habitability, facilities, & payload
  - Mix of military and commercial standards
- Damen concluded it is not ship size but complexity due to high compactness of systems that leads to extreme costs
- Cost of a hull larger than initially anticipated is easily recovered by cost effective installation of systems
- Longer, more slender hull reduces fuel consumption, offers space for cost-effective maintenance & modernizations

**Flexibility more than pays for itself:**
“STEEL IS CHEAP, AIR IS FREE!”
Principles for Design of Flexible Warships
P. Jaquith, former shipyard executive

- **Focus on Design Space Exploration (DSE)**
  - transform from focus on point designs & accepting first solution

- **Address Cost in Early DSE**
  - look at engrg, matls, and production together as all design driven

- **Reduce Work Scope & Variation in Basic Design**
  - world-class shipbuilders focus on early stage design

- **Introduce “Commonality” in Basic Design**
  - build designs on off-the-shelf equipt & production interim products

- **Define Systems & Arrangements in Basic Design**
  - utilize experienced engineers for defining principal systems & arrgts.

- **Analyze Alternative Arrangements in Basic Design**
  - achieve required performance with reduced work content & variation

- **Develop New Cost Estimating Methods & Metrics**
  - based on work content & alignment with std. production processes
Design Tool Needs for Design Space Exploration (DSE) of Flexible Warships

- Model “flexibility” in concept design for sizing ship
- Relate “flexibility” to Cost Estimating Relationships (CERs)
- Integrate these with Navy early stage ship design tools:
  - **Rapid Ship Design Environment – RSDE**: Ship Concept DSE & Optimization
  - **Advanced Ship & Sub Evaluation Tool – ASSET**: Ship Synthesis Model
  - **Leading Edge Architecture for Prototyping Systems – LEAPS**: Design Analysis Product Model
  - **Integrated Hydrodynamics Design Environment – IHDE**: Hull Form DSE & Optimization
  - **Integrated Structural Design Environment – ISDE**: Ship Structure DSE & Optimization

**CREATE-Ships Products Critical to Flexible Warships**
### Elements of Ship Construction Costs for Flexible Warships

<table>
<thead>
<tr>
<th>Basic HM&amp;E Systems Costs (Standard Shipbuilding CERs)</th>
<th>+ CER Adjustments for Military Requirements</th>
<th>+ Add Military Systems</th>
<th>X Adjustments for Productivity</th>
<th>+ Cost Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mil-Spec Material</td>
<td>• Weapons Systems</td>
<td>• Engineering Quality</td>
<td></td>
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<tr>
<td>• Gen-Spec Reqts.</td>
<td>• C4ISR</td>
<td>• Commonality</td>
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<tr>
<td>• Redundancies</td>
<td>• Special Coatings</td>
<td>• Constr. Stage</td>
<td></td>
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<tr>
<td>• CBRN Requirements</td>
<td></td>
<td>• Outfit Density</td>
<td></td>
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<td>• Arctic Service Requirements</td>
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**Flexible Designs:** Can move work to more productive construction stages
Design Space Exploration (DSE) via HPCMP CREATE-Ships RSDE

From... Limited Investigation of relatively few Design Points

To... Full Investigation of Concepts throughout the Design Space

Explore Levels of Flexibility/Producibility During DSE

Generating The Space

Exploring The Space

Evaluating The Space

Visualizing The Space

Explore Levels of Flexibility/Producibility During DSE
Ship Design Characteristics for Assessing Complexity - SNAME SDC/SD-8 Workshop

- Design Complexity Characteristics for Ship Concept Design
  - Technical maturity, extent of commonality, number of components and systems
  - Ship densities by ship types and systems (e.g., power)
  - Complexities of design strategy/approach, e.g.,
    - multiple competitive early designs by shipbuilders
    - use of legacy designs
  - Imposed design constraints, e.g.,
    - limit size of ship or dimensions of hull
  - Architectures and ease of routing of Distributed Systems

Ship Density, Systematic Commonality, Distributed Systems Critical to Right Sizing Flexible Warships
Shortcomings In Distributed Systems Design Tools - SNAME Workshop

- ASSET does not dedicate space for Distributed Systems
- Design rules limit innovations in Distributed Systems
- Lack of trade-offs between architectures
- Lack of area & volume data of existing Distributed Systems
- Inconsistent as to when M&S of Distributed Systems begins
- Questions about validity of physics-based M&S tools
- Greater trade-off between ship arrangement definition and large number of alternative ship concepts during DSE

Lack of Knowledge about Distributed Systems in Early Stage Ship Design
Distributed Systems Design Tools
Recommendations - SNAME Workshop

- Obtain data on Distributed Systems space for existing ships
- Modify ASSET to include space allocations for Dist. Sys.
- Include a ship arrangement design capability in ASSET
- Integrate In RSDE/LEAPS more physics-based M&S Tools for Distributed Systems, including Ship Structures
- Develop Dist. Sys. design margins & service-life allowances
- Establish exit design definition criteria for Distributed Systems at each stage of design & production planning
- Obtain labor-hour data for routing Dist. Sys in dedicated space vs practice of routing them in overly dense spaces
- Include a Distributed Systems Engineer in the design team along with Topside Design & Ship Arrangement Design Engrs
Solution: Design Out Complexity Early During Design Space Exploration (DSE)

- Expand education & training of acquisition personnel in the Principles for Design of Flexible Ships during DSE

- Incorporate in DSE tools measures to compare levels of flexibility of alternative warship concepts
  - Ship Densities, Distributed Systems, Ship Arrangements, Design Margins, Service Life Allowances

- Incorporate in work content/cost models ship density, design maturity, systematic commonality, other productivity factors

- Integrate these higher fidelity process-based work content/cost models with Navy early stage ship design tools

A Path to Flexible Warships easier to build, operate, maintain & modernize throughout their full service-life
Back Up
Reducing Total Ownership Cost (TOC)
Designing Inside-Out of the Hull

Bob Keane
7 March 2013 (Updated)

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Root Cause of Wrong Technical Decisions: “Outside-In” Design

- Some in the Navy...”tacitly assumed that ship size could be equated to ship cost...”
- ”the central assumption, that size and cost inevitably go together, is often false.”
- Based on supposition that “only a shrunken ship would be sellable”
- “...modern warships are much more volume - than weight critical...”
- Nevertheless, this philosophy of constraining the size of the hull continues even to today.

Friedman, U.S. Destroyers: An Illustrated Design History, 2004
“Inside Out Design”: Create internal arrangement, then fit hull form: NSRP Project 21

Step 1: Add the template hull form to the internal functional space model.

Step 2: Resize the hull form in the most flexible zone locations to fit the internal functional spaces.

Step 3: Using the design rules to connect the internal arrangement to the initial hull form.

Step 4: Develop the initial naval architectural characteristics using the design rules and refine the spatial arrangement and hull form using to produce base vessel.

Stable Arrangement Leads to Stable Design – Start with Architectural Templates
Producibility Depends on Stable Arrangements

- Sealift (LMSR-Engine Room Arrangement Module only)
  - Engine room cost reduced 57%
  - Design time reduced 45% (from 27 to 15 weeks)
  - Manufacturing man-hours reduced by 40%
  - Design process supported 18-month build strategy
  - 20% reduction in piping, cabling & equipment realized
  - 60% increase in level of standardization
  - Doubled amount of equipment installed off vessel
  - Off vessel testing increased from 5% to 40%

Lead ship delivered on time & within budget
Historical Lead Ship Cost Performance Index (CPI) Trends

LMSR New Construction

Annotations Added
Damen Philosophy of Standardization in Ship Design and Production

- Development of standard systems & construction details with necessary attention and time
- Risks in performance & performance predictions are hugely decreased
- Engineering time saved and risk limited by using proven systems and construction details
- Standardized systems and constructions are improved based on feedback from customers
SIGMA - Ship Integrated Geometrical Modularity Approach

- A systematic modular design series
- Developed by Damen Schelde Naval Shipbuilding
- SIGMA class is based on the following major principles:
  - Oversized hulls, to reduce installation and maintenance cost
  - Systematic structural layout
  - Mix of military and commercial standards

Damen’s philosophy: Standardized patrol boats and naval vessels, Gelling and Goossens, 2010
Oversized Hull - Philosophy

- Not ship size but complexity of ship and selected equipment and systems that dominate cost
- High compactness of systems with minimum installation space leads to large installation cost
- Therefore, cost of larger hull is easily recovered by cost effective installation of systems:
  - a modular environment in which commonality and clustering of systems are optimized
  - integrated planning results in high accuracy during ship construction
  - very efficient and cost-effective outfitting
Cost Drivers Based on Weight

Surface Combatants

Steel = 50% of weight
C4I = 50% of cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>WT (LT)</th>
</tr>
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<tbody>
<tr>
<td>Hull</td>
<td>8%</td>
<td>50%</td>
</tr>
<tr>
<td>Propulsion &amp; Electric</td>
<td>13%</td>
<td>18%</td>
</tr>
<tr>
<td>C4I &amp; Armament</td>
<td>50%</td>
<td>11%</td>
</tr>
<tr>
<td>Auxiliary Systems</td>
<td>8%</td>
<td>14%</td>
</tr>
<tr>
<td>Outfitting</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>Integration/Engineering</td>
<td>8%</td>
<td>0%</td>
</tr>
<tr>
<td>Ship Assembly &amp; Support</td>
<td>8%</td>
<td>0%</td>
</tr>
<tr>
<td>Total (100-700)</td>
<td>84%</td>
<td>100%</td>
</tr>
<tr>
<td>Total (100-900)</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>
Cost Benefits of Oversized Hull – Interest to PM & Shipbuilder

- Oversized hull might be considered a disadvantage, as it will be heavier and more expensive.

- Reality however is considerably different:
  - Hull of a surface combatant represents only approx. 8% of total building cost
  - An oversized hull of 20% in length will increase total building cost only by approx. 1-3%

- Limited extra cost for larger hull is easily recovered by significant savings on labor for installation of equipment

Steel is cheap – Air is free!
Other Benefits of Oversized Hull – Interest to Owner-Operator

- Oversized hull is more slender which improves seakeeping performance

- Oversized slender hull also reduces resistance:
  - Model tests of Damen Fast Crew Supplier show reductions of 12% in fuel in calm water, 18% less in Sea State (SS) 3 and 22% less in SS 4
  - Over one month it used 200 gallons less fuel per day - saving US$ 850 per day, US$ 300K per year

- Relatively empty hull offers adequate access space for cost-effective maintenance and repair

- Available space in oversized hull very useful during future upgrading of ship
Systematic Structural Layout

- Consists of standard compartments with extensive repetition of standardized elements
- Modular spaces are incorporated for operations, accommodation, technical facilities and payload
- Interconnected through spacious straight central main passageway
- Modular spaces are connected to a “municipality utilities” like arrangement of system connections with standardized components
  - power, air cooling, automation and fluids with similar foot-print layout in each compartment
Damen Schelde Naval Shipbuilding
SIGMA class

7 – 14 sections of length 7.20 m
(12 x 600 mm / 4 x 1800 mm)
1½ or 2 module combination

Length o.a. 52-105 m
Breadth o.a. 9-14 m

Naval Patrol 9113

Combat System  Auxiliary systems  Propulsion  Accommodation  Support spaces
Mix of Military and Commercial Standards

• Applicable standards are openly discussed with customer to find the right balance

• Often decided on commercial equipment installed to operate reliably under naval conditions

• Example is shock-proof floors on which commercial equipment can be installed
  – similar shock resistance as MilSpec equipment at a much better price
“There are many, many causes of screwed-up programs...But self-deception is probably the greatest common denominator...knowing that there's something wrong, nobody wanting to speak up, everybody hoping it will get better somehow...job is to make everybody realize they have a common problem and work toward solutions...”

Dr. Carter, AT&L, 2010: “Screwed-up Programs”
To Efficiently Produce And Own A Warship

- More physics-based analyses and geometry fidelity in Ship Concept & Preliminary Design
- More product-oriented design environment with design templates in Concept Design
- More resources in early stage design and pre-M.S. A – CONFORM Program
- Address design issues early in design process
Vision for Physics-Based Design

Physics based software products being used for:

- Timely Design and Construction of New Ships with Extended Service-Life
- Maintenance and Repair Decisions for Sustaining Service-Life of Ships
- Operator Guidance for Reduced Ownership Costs of Ships In-Service
“...In time of war, when combat objectives rise above all other priorities ...Planes do not stay grounded and fleets do not run scared because of ugly weather...”

CDR George Kosco, ADM Halsey’s Chief Meteorologist, *Halsey’s Typhoon: The True Story of a Fighting Admiral, an Epic Storm, and an Untold Rescue*, 2008
The Way Ahead: Designing Inside-Out of the Hull

- Developing minimal cost design, not minimal size.
- Sizing ship to reduce costs due to complexity and increased volumetric density.
- Reusing design templates of major ship systems
- Recognizing functional arrangements must be developed before hull form is sized and set.
- Using architecture to partition high technical risks and defining design margins for resulting interfaces.
- Utilizing more physics-based design tools in early ship design.

A new approach to the Design-Build-Own Process
Beware of Spurious Correlations

Number of people who drowned by falling into a pool correlates with Films Nicolas Cage appeared in

- 140 drownings
- 120 drownings
- 100 drownings
- 80 drownings

- 1999: 6 films
- 2000: 4 films
- 2001: 2 films
- 2002: 2 films
- 2003: 4 films
- 2004: 0 films
- 2005: 0 films
- 2006: 0 films
- 2007: 2 films
- 2008: 2 films
- 2009: 4 films