Reducing Total Ownership Cost: Designing Inside-Out of the Hull

Robert G. Keane, Jr., Ship Design USA, Inc.

ABSTRACT

Over the past 25 years, the Naval Sea Systems Command (NAVSEA) has had a number of initiatives to implement modular design and construction but has experienced only limited success (Abbott, 2008). These initiatives included the Ship Systems Engineering Standards (SSES) Program, Affordability Through Commonality (ATC) Program, Product-Oriented Design And Construction (PODAC), Total-ship Open System Architecture (TOSA), Continuing Baseline Designs, Concept Formulation (CONFORM) and the Navy's Mid-term Sealift Technology Development Program (MSTDP). The Maritech and National Shipbuilding Research Program (NSRP) funded comprehensive shipbuilder studies such as Product Work Breakdown Structure (PWBS) or zonal design and construction and MASE (Maritech Advanced Shipbuilding Enterprise) Project 21 (Develop and Implement "World Class" U.S. Material Standards and Parametric Design Rules to Support Commercial and Naval Auxiliary Ship Construction).

These initiatives were all well intended and produced valuable results. Yet, the Navy continues to experience unique, one-of-a-kind, complex Detail Designs with the resulting cost and schedule problems. Why aren't the valuable results of these many research projects on modular or zonal design and construction being fully implemented? One reason may be that the fundamental early stage ship design process has not changed. The early stage ship design process does not deal with the ship in terms of modules or zones and the process itself is not structured for re-useable design modules. However, a number of improvements to the early stage design process are being developed. These include design tools which are being developed under the Computational Research & Engineering for Acquisition Tools & Environments (CREATE)-SHIPS Project, and a series of Ship Design Process Workshops. What does all of this have to do with reducing Total Ownership Costs?

PROBLEM: NAVAL SHIPS UNNECESSARILY COST TOO MUCH TO OWN

The problem is obvious. Naval ships cost too much to acquire, operate, maintain and repair, and modernize. Yes, new systems to meet new requirements in order to overcome new threats contribute to increased costs. However, these do not explain the appalling cost growth on recent ship acquisitions. This issue has been studied by various organizations over the years. One of the common conclusions is that the lack of design maturity or design stability is a significant contributor. In addition, a number of ship classes in the Fleet have experienced unnecessary in-service costs which can be attributed to poor technical decisions during design. The author has written on what needs to be done to improve naval ship design. This paper concentrates on a fundamental change in the early stage ship design process to ensure that the right decisions are made and that design stability is reached much earlier in the design process.

GAO Study of Cost Growth Cites Lack of Design Maturity Leading to Design Changes. A February 2005 report by the independent Government Accountability Office

(GAO) addressed the long-standing problem of cost growth in the Navy's shipbuilding programs. The GAO found that for the eight ships they assessed, the total cost growth on these ships could reach $3.1 billion or more. The following excerpt from the GAO report, "Improved Management Practices Could Help Minimize Cost Growth in Navy Shipbuilding Programs," validates that we have lost the recipe for design, acquisition, and construction of cost-effective warships:

> *"Increases in labor hour and material costs account for 78 percent of the cost growth (during detail design and construction) on the eight ships we reviewed ….Shipbuilders cited a number of direct causes for the labor hour, material, and overhead cost growth in the eight ships. The most common causes were related to design modifications, the need for additional and more costly materials, and changes in employee pay and benefits. For example, the lack of design maturity when introducing new technologies led to rework, increasing growth in labor hours for most of the ships. The design of ship systems...continued to evolve even as construction proceeded. As a result, workers were required to rebuild completed areas of the ship to accommodate design changes…"*

Navy Needs To Be More Disciplined In Shipbuilding. The Navy needs to take charge, better define its needs, and assume more responsibility with contracting and shipbuilding, according to Vice Admiral Paul Sullivan, who was at that time Commander, Naval Sea Systems Command (COMNAVSEA), in an interview with Defense Daily on 16 May, 2007:

> *"We have to return to our roots; we are in charge...if we can't fix price a contract on a lead ship then maybe we didn't reduce the risk enough before we started ...Then you have to ask yourself the question: Should we have started that contract in the first place? Should we have matured the design more and [driven] the risk out?..."*

GAO Study of Shipbuilding Criticizes Navy Practice of Starting Construction Without A Stable Design (GAO, 2009). To ensure design and construction of a ship can be executed as planned, commercial shipbuilders and buyers do not move forward until critical knowledge is attained. To minimize risk, buyers and shipbuilders reuse previous designs as much as possible and attain an in-depth understanding of new technologies included in the ship design. Before construction begins, shipbuilders complete key design phases that correspond with the completion of a three-dimensional product model.

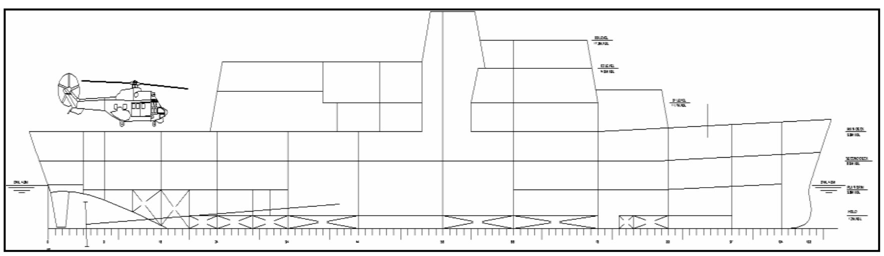
> *"Navy programs often do not employ these [commercial] best practices...New designs often make little use of prior ship designs. As a result, a full understanding of the effort needed to execute a program is rarely achieved at the time a design and construction contract is negotiated...Complete information on the systems that will be installed on the ship may not be available, leading to changes that ripple through the design as knowledge grows. Starting construction without a stable design is a common practice and the resulting volatility leads to costly out-of-sequence work and rework...Congress has recently encouraged greater technology maturity and design stability at key points, but required reporting does not directly address completion of a three-dimensional product model."*

HOW WE GOT TO WHERE WE ARE TODAY

Lack of Stable Design. Basic ship design is pretty straight forward. The ship designer must estimate the weight of the ship and everything that goes in the ship and support the weight with the underwater volume of the hull, and distribute the weight and underwater volume such that the ship floats upright and meets the mobility performance requirements. If you get either the weight or volume wrong, there are serious consequences which are virtually impossible to fix in later design phases. Our current practice, Figure 1, of designing or fixing the hull form first and then trying to fit everything in that hull – "Outside-In Design" – has caused significant unbudgeted increases in cycle time, acquisition costs, and ownership costs. This is the primary reason why ship arrangements are unstable, that is constantly changing, well into Detail Design.

"Outside-In Design": Start with Hull Form, Then Cram Everything into Hull

- Hull is sized and shaped based on early design weight estimates and area/volume estimates,



- and big assumption volume is "arrangeable"

Figure 1. Current Navy Practice: "Outside-In" Design

Other major TOC adverse impacts of such early-stage unstable designs are:

(1) non-optimum hydrodynamic hull form designs which significantly increase energy consumption and the fuel bills for the Fleet;

(2) difficulty in maintaining and repairing ships due to space limitations and the "tightness" of the ship arrangements;

(3) insufficient service-life allowances for weight and/or space, thus increasing modernization costs;

(4) significant reductions in terms of years of the economical service-life of ships;

(5) possible operational restrictions due to the inability to develop robust designs where ship performance is minimally sensitive to variations in operations.

Let us look at some actual data on real designs.

Shown in Figure 2 for the first ship of a class are Detail Design engineering hours per long ton versus ship density in pounds per cubic foot for a range of naval ship designs. Look just at the legacy hulls. The whole world knows that U.S. Navy surface combatants are outstanding Warships. However, since the size of the hull was constrained during design, they have unreasonably high density factors. As a result, it took a lot longer and cost a lot more to design and build the early ships of these Classes. The same is true for

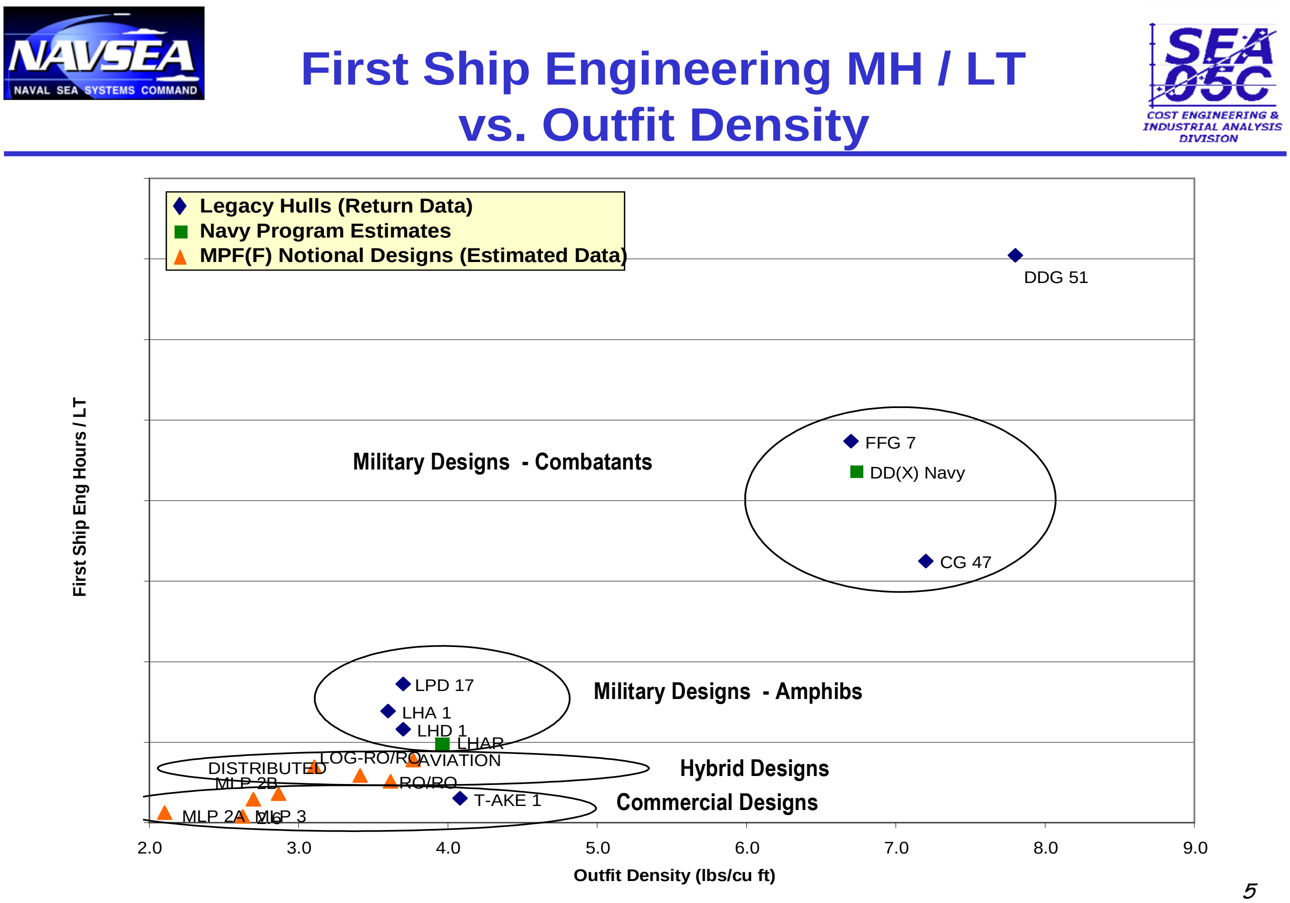


Figure 2. Detail Design Engineering Hours versus Ship Outfit Density Factors

production hours as shown in Figure 3. Both of these figures are from a presentation by the NAVSEA Cost Group, which was given to the SNAME-ASNE Joint Ship Design Committee meeting in June 2008. One can readily see that ships with greater density increase production costs. It should be emphasized that ships with greater density also increase ownership costs. One would think that this is intuitively obvious. Then, why does it happen so often? An answer to this question is addressed later. For now, let us just say that the ship designer needs to have the early stage design tools to convince decision-makers that bigger is better, not necessarily more costly.

Example of Discipline in Shipbuilding. One of the supposed principles of Acquisition Reform was to emulate efficient commercial practices. What are the commercial ship design practices for sizing the hull? Shown in Figure 4 is an excerpt from the National

Shipbuilding Research Program (NSRP) Project 21, which used a totally different methodology of “Inside-Out Design”.

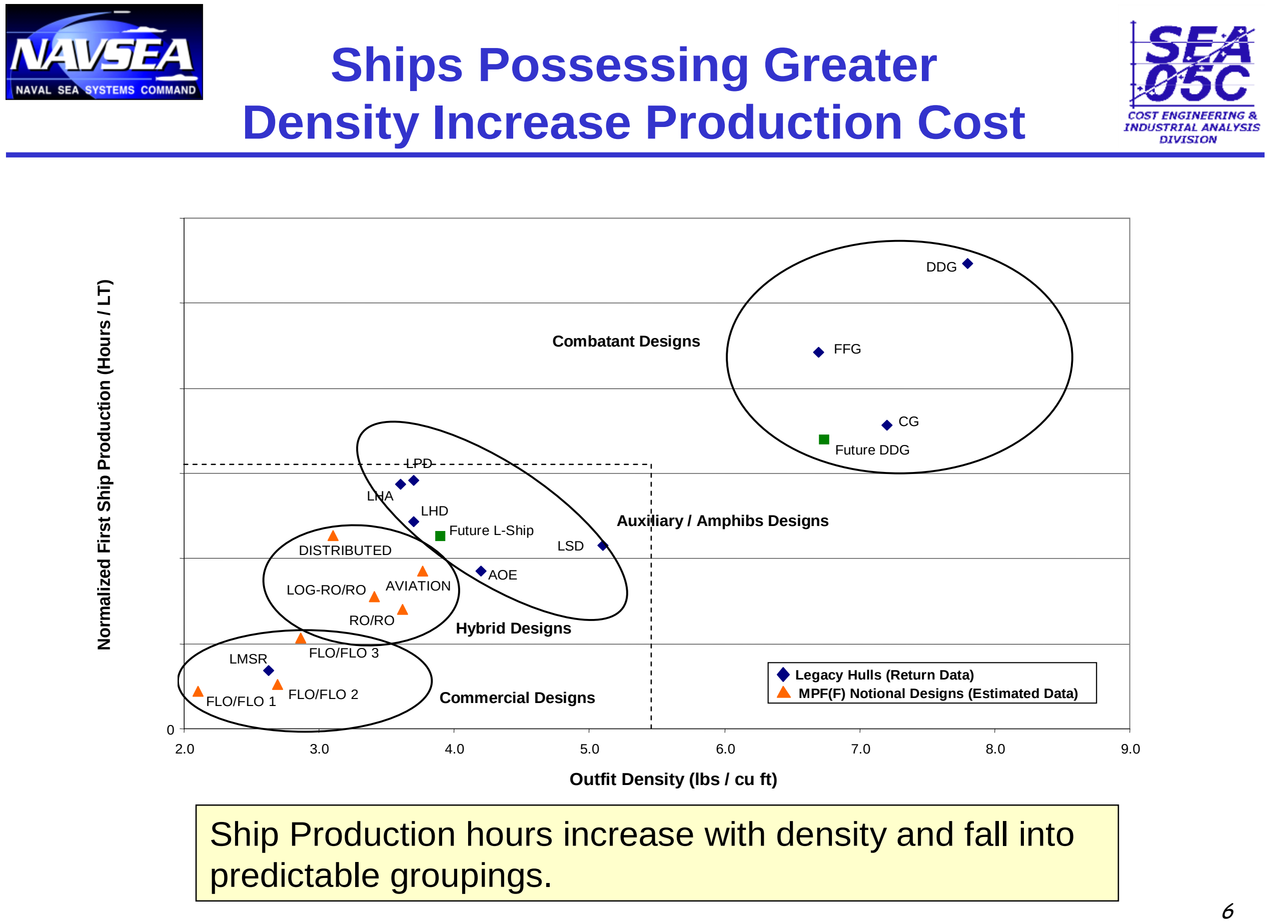


Figure 3. Ship Production Hours versus Ship Outfit Density Factors

The Project 21 methodology includes whole-ship and zone-specific parametric design rules, families of standard interim products, and design for production principles. These process improvements used prior work performed under the Navy’s Mid-Term Sealift Technology Development Program (MSTDP). The design tools developed under Project 21 were to enable shipyards to significantly reduce the cycle time for Contract (Functional) Design and Detail (Transition and Zonal) Design for commercial ships like a cargo ship. However, a cargo ship is a homogeneous product, whereas a warship is very non-homogeneous. Thus, Project 21 was to apply the results for commercial ships to a Navy auxiliary ship; however, Project 21 was terminated before this task was completed. Nevertheless, NAVSEA had a highly successful experience in the early 1990’s with Inside-Out Design on the Strategic Sealift Program (LMSR). Since the Surface Ship Navy continues to either ignore or forget this successful experience, it is worthwhile to review the successful acquisition outcomes of the Strategic Sealift Program.

"Inside - Out Design": Create internal arrangement, then fit hull form to functional spaces: NSRP Project 21

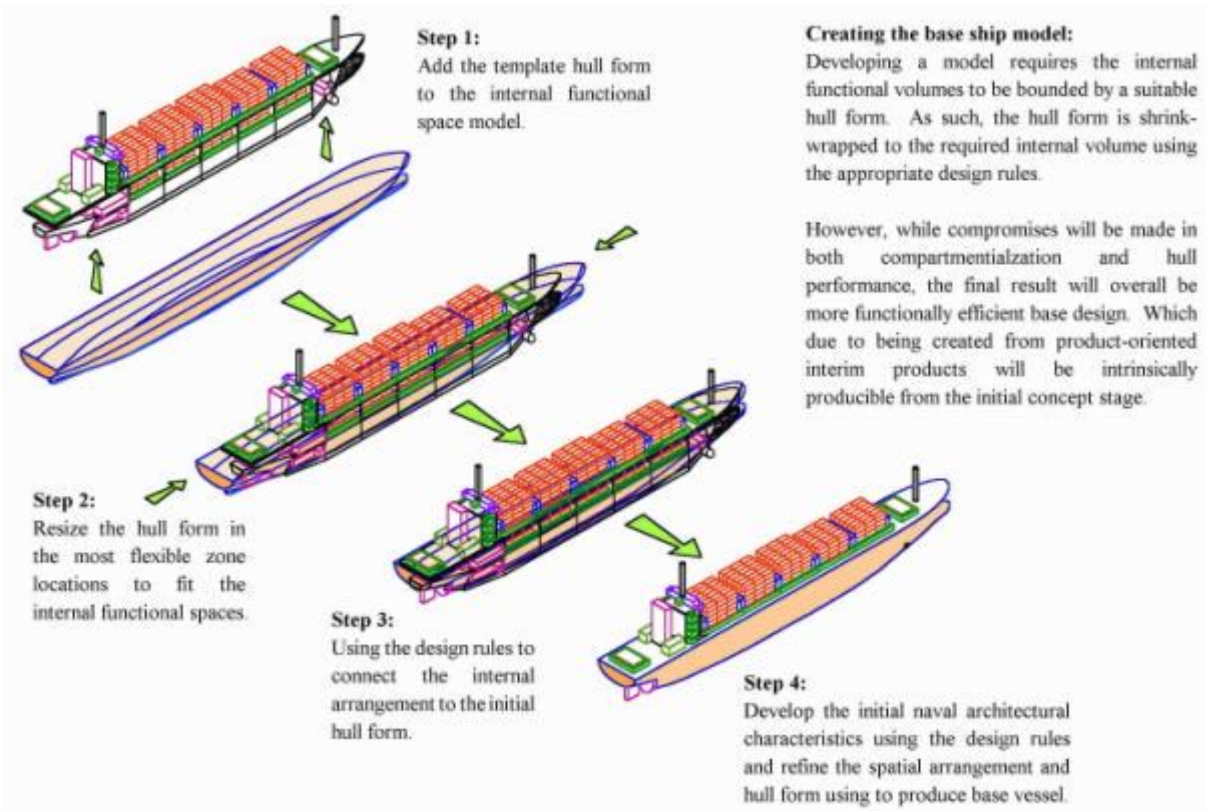


Figure 4. Current Commercial Practice: "Inside-Out" Design (NSRP Project 21)

One of the pillars of success started with a community-wide workshop for identifying the critical needs for integrating Design for Producibility into the naval ship design process. The NAVSEA Design for Producibility Workshop had a significant impact on the Mid-Term Sealift Technology R&D Program, previously mentioned, being focused on producibility in lieu of high-speed. This led to the ERAM or Engine Room Arrangement Module project. The collaborative, multi-disciplinary ERAM team explored new tools, processes and technologies including Hierarchy of Building Blocks. The ERAM participants which included shipbuilders, design agents, major vendors and NAVSEA engineers took this new knowledge and experience back to their organizations. This resulted in significant producibility innovations being implemented in the Strategic Sealift Acquisition Program. Innovation without implementation is really not innovation!

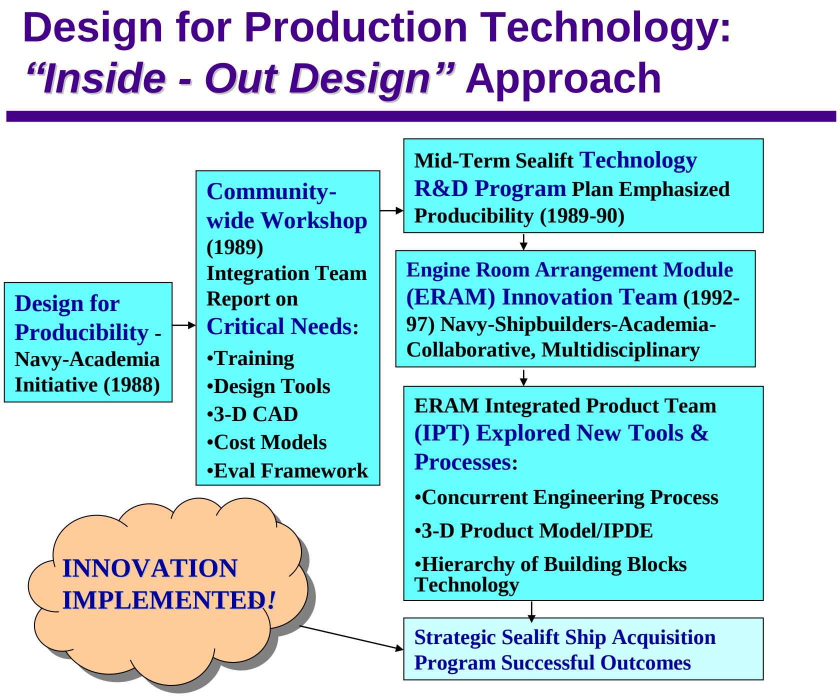


Figure 5. NAVSEA Design For Production Innovation

Table 1 lists the results for the Engine Room Arrangement Module for the Strategic Sealift new construction lead ship. Establishing the engine room arrangement significantly contributed to stabilizing the general arrangements early in design and resulted in reduced costs and reduced cycle time. Critical to these reductions is the amount of outfitting work done off-vessel in a more efficient environment.

Table 1 Producibility Advantages of Sealift Engine Room Arrangement Module

Producibility Depends on Stable Ship Arrangements

- Sealift (LMSR-Engine Room Arrangement Module only)
  - Engine room cost reduced 57% (from $58M to under $25M)
  - Design time reduced 45% (from 27 weeks 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

Figure 6, another NAVSEA Cost Group plot from its presentation to the Ship Design Committee, shows the Cost Performance Index, or CPI, for the lead ship of a number of naval surface ship acquisitions. (The Defense Acquisition University states that CPI is computed by dividing the Budgeted Cost for Work Performed (BCWP) by the corresponding Actual Cost of Work Performed (ACWP). This metric is an Earned Value Management (EVM) performance factor representing cost efficiency.) One can readily see that the Strategic Sealift or LMSR is the most successful ship acquisition program in many years. This plot also shows that many acquisition programs invest a lot of production hours for a little bit of progress, especially at the end of construction. The author contends that a thorough analysis of the shipbuilding change order activity on these programs would reveal instability in the ship arrangements long into Detail Design.

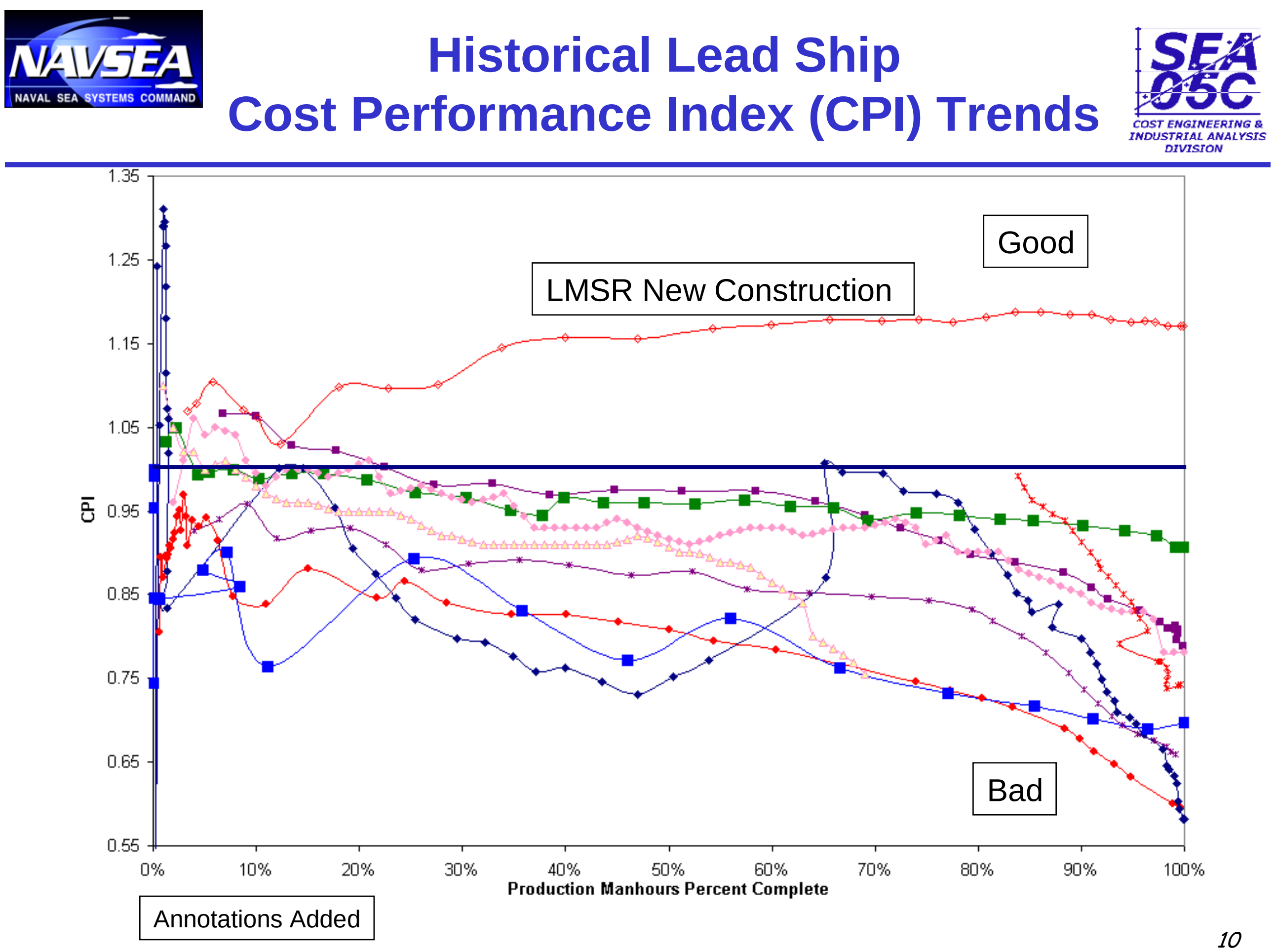


Figure 6. Lead Ship Cost Performance Index Trends for U.S. Navy Acquisitions

Lack of Design Maturity. As shown in Figure 6, virtually all ship programs had less than successful acquisition outcomes. The GAO excerpt above noted that one of the reasons for unbudgeted cost and schedule growth is the lack of design maturity. Not addressing design issues early in the design process usually has adverse impacts also on in-service or ownership costs. On the other hand, conducting robust engineering during the early stages of design can have a significant positive impact not only on costs and schedule but also on improving the warfighting capabilities of Navy ships. The following quote from Admiral Halsey's Chief Meteorologist is appropriate:

> *"...In time of war, when combat objectives rise above all other priorities, it is not the rule to bestow grave concern on incidental dangers. Planes do not stay grounded and fleets do not run scared because of ugly weather if in doing so they jeopardize military or naval missions."*
>
> 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*

Fleets cannot run scared because of ugly weather. In this case CDR Kosco is referring to the typhoon that did more damage to Halsey's fleet in a few hours than the whole Japanese Navy did in over three years – three ships capsized, more than 800 sailors were lost, and virtually all of Halsey's airplanes were damaged. In the ocean battlespace, the ocean is a constant 24/7 threat. One could say we have learned a lot since WWII, and that is true. But decision-makers should be reminded that when NASA was putting a man on the moon in 1969, the naval engineering community was just beginning to be able to predict rigid body motions of ships in confused seas as shown in Figure 7.

The rigid body motions that ship designers are interested in are large amplitude motions in the ocean battlespace which affect the ability of the ship to perform its missions in moderately high sea states and which threaten the survivability of the ship in severe sea states. These include:

- Susceptibility to capsizing
- Structural integrity
    - Primary structural loads from ship motions
        - Including structural fatigue from hundreds of thousands of load cycles over life of ship
    - Secondary loads from wave impacts
        - Including whipping of primary structure that can also affect its fatigue life

ONR, NAVSEA, NSWCCD and academia have collaboratively devoted a lot of intellectual capital to integrating seakeeping into the naval ship design process. However, much more needs to be done. Specifically, structural fatigue problems due to the high operational tempo of the Fleet and our inability to address secondary loads during early stage design needs urgent attention.

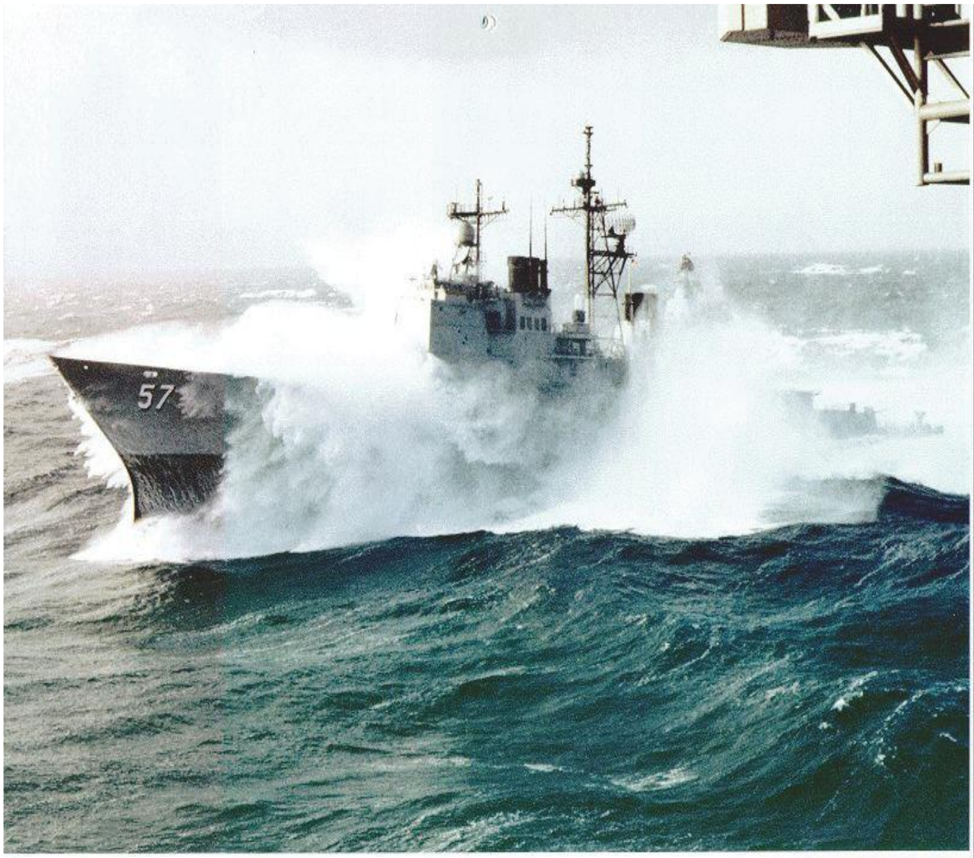


Figure 7. Warfighting in the Ocean Battlespace

In the past and even more recently, structural design engineers have used rule-based empirical methods to estimate seaway loads for early stage design. Remember that structural weight is more than 60% of light ship weight, so if the ship design engineer does not get it right up front, an inaccurate weight estimate has major impacts later in design and in-service. In fact, for all surface combatants in the Fleet today, no analytical computations or Seakeeping model tests were done during Preliminary or Contract Design (PD/CD) to determine seaway loads. Highly random wave-induced loads were a simplified set of hydrostatic loads.

Table 2 outlines the rule-based approach which was used by highly experienced design engineers for the structural design of the three major classes of surface combatants in the Fleet over the past thirty years: CG 47/52, DDG 51 and FFG 7. Table 3 lists the subsequent structural problems after these ships were in-service. The lack of design maturity or robust design of ship structures can be attributed to the use of rule-based quasi-static seaway loads. However, at the time the three classes were designed, the only way to explore the large variations of seaway loads which the ships would encounter in-service was by time consuming, costly seakeeping model tests. These tests were not conducted. In all three cases, the hull forms were either specified (CG 47 was limited to re-using the DD 963 hull form) or designed first and fixed throughout the design.

Table 2

Seaway Loads for Design of Surface Combatants: Rule-Based

- Structural Design of FFG 7, CG 47, DDG 51 Classes
  - Interested more in extreme loading conditions than in actual working loads
  - Worked with simplified loading envelopes
    - establish maxima of various load conditions
    - which have reasonable probability of occurring simultaneously
  - Deterministic analysis of bending moments and shear forces resulted in scantlings for maximum load expected
  - Highly random wave-induced loads acting on structural members was a simplified set of hydrostatic loads under extreme sea conditions
  - This gross simplification was thought to be adequate for conventional hull girder designs (longitudinally-stiffened, steel monohull)

No Analytical Computations nor Seakeeping Model Tests During PD/CD to Determine Seaway Loads

Table 3 In-Service Structural Problems of Surface Combatants

Lack of Physics Based Tools: Increased Ownership Costs

- FFG 7 Class
  - Hull girder doubler plates & ballast added due to weight growth
  - Extensive deckhouse fatigue cracking (seaway load cycles)
- 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 have exceeded design loads**
  - Design loads based on standard rule-based loads
  - Model test data support operational loads

Ownership Costs: $100M's in repairs and sustaining service-lives
Warfighting Capabilities: months not in service, operational restrictions

All three classes experienced serious structural problems as listed in Table 3. The predominant problem was fatigue cracking. Seaway loads model tests were run after the problems were experienced in-service. Obviously, operational loads exceeded the rule-based design loads. Due to the lack of physics-based tools for use in early design, the fleet had to spend $100M's to repair these problems. Equally important, these warships were out of service for months and operational restrictions were imposed. In addition, in order to maintain a 313-ship fleet, the service-life of existing ships must be extended, some well beyond 30 years. And the hull structure is the determining factor for service-life. As previously noted, the CG 47/52 Class design was constrained to the DD 963 hull form. The DDG 51 Class hull form design was constrained in length, beam, and height between decks. All three were also constrained in displacement (weight). These were typical of "Outside-In Design". To make these three ship designs feasible, a lot of weight had to be taken out of each design, particularly in ship structures. Constraining the CG 47 hull form to the DD 963 did not save that many Detail Design and Construction manhours for the lead ship and contributed to the substantial CG 52 Class structural problems which had to be fixed later in-service.

No validated analytical tools exist for predicting secondary loads and current model testing methods take too long to be effective in early stage design. Table 4 lists issues with other important design tools. For example, the Ship Hull Characteristics Program (for intact and damage stability) also uses rule-based quasi-static approaches that recently have been found to be inadequate for certain hull forms.

Table 4

Issues with current assessment methods

- Analytical/computational tools for prediction of extreme, non-linear motions have been in development for years
- Model experiments conducted in random waves require long test run times to ensure that critical wave events which are probable in the seaway have been encountered
- Panel test pressures to structural design loads – experimental to analytical methodology not well defined
- Intact and Damage Stability computations (like Ship Hull Characteristics Program-SHCP) need to account for variations of waterplane area in waves
- No appropriate computer prediction tools to assess damaged ships (progressive flooding, structural integrity)

Root Cause of Wrong Technical Decisions Leading to TOC Increases. Before addressing what the Navy needs to do to resolve these design methodology deficiencies, let us try to answer the previous question: Why do decision-makers make the wrong technical decisions concerning hull size so often? Friedman (2004) notes that in the 1970's some in the Navy..."*tacitly assumed that ship size could be equated to ship cost..."* even though..."*the central assumption, that size and cost inevitably go together, is often false."* Friedman speculates that this strategy was based on the supposition that "*only a shrunken ship would be sellable"* to the politicians and operational commanders.

Friedman emphasizes that "*modern warships are much more volume - than weight critical: they need every usable cubic foot of volume they can get.*" Nevertheless, this philosophy of constraining the size of the hull continues even to today.

The single factor that makes a lot of this not intuitively obvious is the use of a one-dimensional weight-based cost estimating tool. Many times this tool leads to the wrong design decision; that is, a ship with a smaller hull is a less costly ship because the hull weighs less and therefore costs less. Ship designers need cost estimating tools that are based on how ships are actually designed and constructed, not how much they weigh. The new multi-objective design optimization math of fuzzy logic, genetic algorithms, and neural networks could have applications here.

Table 5

Deficient Cost Engineering Tools

- NAVSEA standard cost models have limited effectiveness during early stage ship design
- Weight based Cost Estimating Relationships provide limited insight when making subsystem tradeoff decisions
- Legacy ship cost models are particularly limited when estimating cost of software intensive systems
- Design for Producibility changes that are cost effective result in increased cost estimates in weight-based model

WHERE WE NEED TO GO

The critical impact of ship design on acquisition programs is recognized by senior Navy leadership, our shipbuilders, and independent benchmarking organizations. Although some recognize that the greatest leverage is design and engineering, there have not been, in the author's view, commensurate investments in sustaining and advancing our naval ship design capabilities. This is particularly true for ship design tools.

Early stage design is a critically important phase because decisions that lock in the construction and ownership costs are made during this phase. Important details are addressed during Contract Design, but major decisions regarding the basic architecture of the ship and ship systems are made during Concept and Preliminary Design. The greatest return on invested time would be from defining the Concept and Preliminary Design Process in greater detail.

Ship Design Process Modeling. Deciding the appropriate level of design process definition is a major challenge that must be addressed at the beginning of each design phase. Designing the ship design process is a process in itself. Design of a specific ship is a non-repetitive process that warrants careful process design. In addition to determining the appropriate level of process detail, ship design planning must consider how best to decompose the overall design process. Care must be taken to avoid optimizing one sub-process to the disadvantage of another sub-process and possibly to the overall integration process. We need to find some way to preserve what we have learned without discouraging the engineers from doing new things. However, constant changes in the design must also be controlled. The secret to doing this is to concentrate on the right level of the process architecture (Reinertsen, 1997).

In 2007 at the Navy's Center for Innovation in Ship Design (CISD), a small Navy-industry-academia team with over 200 years of naval ship design and shipbuilding experience conducted a workshop on the Initial System Architecting sub-process, which begins the Preliminary Design (PD) phase of the naval ship design process. The architecture of the ship is almost invisible to most, yet it has an extraordinary impact. As the CISD team applied the framework to "leaning" the critical initial phase of the Preliminary Design process, it became evident that early attention to the ship physical architecture would pay big dividends. Architecture in this sense goes beyond basic general arrangement to include the philosophy of mission systems and auxiliary systems distribution and connectivity, survivability, the impact of build strategy on the arrangement, and other systems engineering considerations.

The Initial System Architecting sub-process was selected because this is the first allocation of major shipboard functions throughout the ship, where the total-ship system architect determines whether there are sufficient ship resources (space, weight, power, etc.). It is driven by the general arrangement task. Large blocks within the ship are allocated, defining the area and volume, location, adjacency, and separation requirements for the major systems of the ship. If done well, the development of the various systems can be accomplished during subsequent design phases with minimal rework to the total-ship functional layout--a stable design.

The team achieved the objective of the CISD workshop and a much improved Initial System Architecting future state sub-process was developed. The future state sub-process would better meet the sub-process objective of developing an initial ship configuration and size with a much higher degree of confidence, meaning one that does not grow significantly during follow design phases or does not overly constrain design solutions. In order for the design to meet schedule and cost requirements with minimal rework in later stages of design and production, a stable design for production must be established as soon as possible. And the first critical step in establishing a stable design is locking in the ship arrangements; that is, subsequent subsystem detail design would not require redesign of the ship arrangements and thus the total ship. Other characteristics of the future state sub-process that emphasize earlier integration are:

- Developing a minimal cost design, not minimal size, volume, weight, etc.
- Sizing the ship to reduce costs due to complexity and increased volumetric density.
- Recognizing that functional arrangements must be developed and optimized before hull form is sized and set.
- Defining architectures of major ship systems and interfaces of new technologies and systems.
- Identifying specific technical uncertainties, as well as the consequences of the uncertainties and how to address them during Preliminary Design (PD).

- Using architecture to partition high technical risks and define design margins for resulting interfaces.
- Identifying fallbacks for technical uncertainties if consequences of uncertainties cannot be satisfactorily resolved during PD.

Ship Design Process Architecture. Many emphasize the need for dramatically changing the pre-production design process to a more modular architecture. These pre-production processes need to apply standardization to material, equipment, design methodology, cost estimating methodology, interim product definition, functional arrangements, zone/modular designs and whole-ship designs.

Reinertsen (1997) emphasizes the key to designing a process which must be both disciplined and flexible is structure; that is, standardize the lower levels of the process architecture. When we design a design process, we want to create standardized building blocks that are defined primarily at their interfaces, rather than by their internal procedures. By standardizing the process interfaces, we can evolve the internal structure as necessary to meet changing requirements. When the external properties are controlled, we can change internal methods without unraveling the entire design process.

Starting in 2008, as shown in Figure 8, a series of Ship Design Process Workshops sponsored by ONR, NAVSEA and CREATE-SHIPS have been held to create these standardized building blocks. The building blocks documented independently thus far are integrated topside design, machinery arrangements, vulnerability, and hull design sub-processes. A lot has been learned about external dependencies and connecting these sub-processes into the bigger ship design process. The conclusion from the 5th Workshop is that Combat Systems is 70% of the challenge. Therefore, at the next Workshop, Combat Systems sub-processes will be emphasized to better understand the interdependencies with HM&E sub-processes.

Lessons Learned Validation. The success of VIRGINIA in controlling and even reducing acquisition costs validates that process architecture has much to do with stabilizing the arrangements early in design. This was a key lesson learned from the highly successful VIRGINIA class design-build-sustain strategy, which the Chief of Naval Operations (CNO), Admiral Roughead, in February 2010, emphasized that all acquisition programs should leverage.

The Navy and Electric Boat (EB, 2002) understood that no single metric can reflect the success of a program, but the fraction of design completion at the start of construction is a strong leading indicator. Incompleteness of a design at the start of construction increases uncertainty and, thus, the likelihood that late changes will be necessary. Design changes after construction start have created significant cost increases in the past. The Navy and Electric Boat recognized that the incompleteness of the earlier submarine designs when construction was started caused most of the cost increases. The Navy and Electric Boat therefore dedicated themselves to a stable design baseline, to complete all ship arrangements and to greatly increase the fraction of the Detail Design completed by the start of construction compared to previous classes.

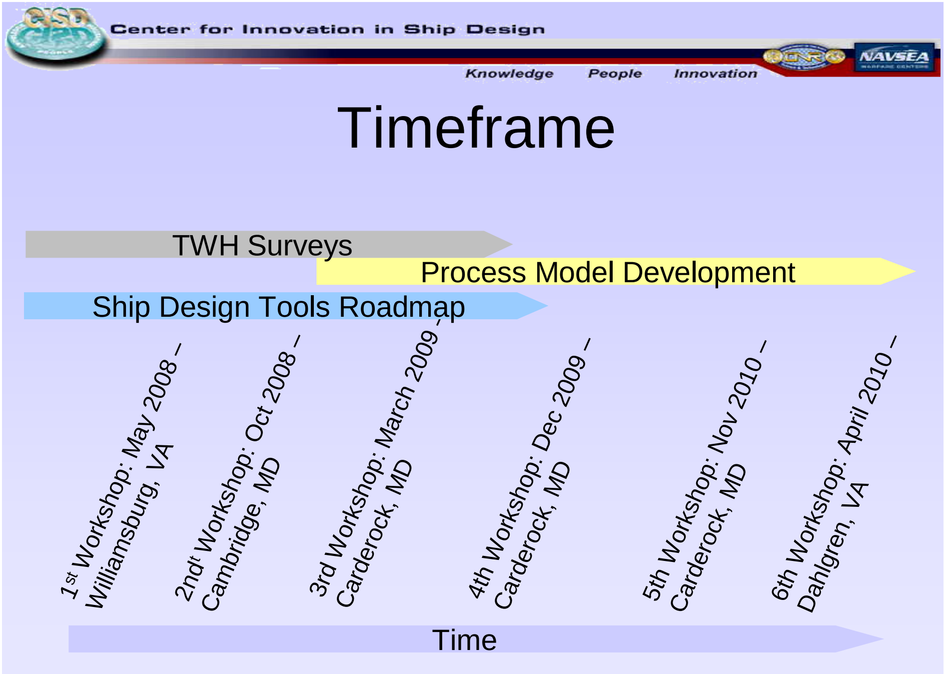


Figure 8 Ship Design Process Workshops

In fact, they divided the complex development process into phases called "Product Areas". Product Area I (PA-I) was the Arrangement phase. Based on the Technical Requirements, in PA-0, the teams were responsible for producing ship arrangements that were developed and analyzed by all relevant disciplines including shipbuilders and customer engineers and operators. Arrangements were approved for producibility, operability, and maintainability.

We Shape Our Tools and Our Tools Shape Us. In addition to the emphasis on the ship design process, there is a symbiotic, or cooperative, mutually beneficial, relationship between design tools and process. The principal objective of a recent study by shipbuilders under the Maritech ASE Project #21, Parametric Design Rules to Support Commercial and Naval Auxiliary Ship Construction, was to demonstrate how a significant reduction in design and engineering cycle time and man-hours can be achieved through a more effective use of design tools and a different approach to the design - build process. While current design and engineering processes are labor intensive and relatively lengthy, even with the latest design tools, there is considerable scope to reduce the design and, as a byproduct production, cycle time and man-hour expenditures. This has been made possible because of the move towards a product-oriented build philosophy. However, this change requires a significant change in the pre-production processes, starting with concept design.

The CREATE-SHIPS Project, which is sponsored by the DoD High Performance Computing Modernization Program Office, is a major step in that direction. The CREATE-SHIPS Project objective is to design out defects, and to optimize the total-ship design, while meeting acquisition schedules. At the heart of the CREATE-SHIPS Project is developing and deploying scalable physics-based computational engineering software products to:

- Enable major improvements in DoD acquisition engineering design and analysis processes
- Replace empirical design based on historical data and experimental testing with physics-based computational design validated with experimental testing
- Detect and fix design flaws early in the design process before major schedule and budget commitments are made
- Develop optimized designs for new concepts
- Begin system integration earlier in the acquisition process
- Increase acquisition program flexibility and agility to respond to rapidly changing requirements
- Enhance the productivity of the DoD engineering workforce
- Establish an organic capability to develop and deploy physics-based computational engineering software within the DOD

Need for Architectural Design Tools. The current naval ship design practice of specifying selection or design of the hull form first, then, forcing all necessary systems to fit within the physical hull confines - "outside-in" design (Keane et al, 2007) - is totally inconsistent with the product-oriented design and construction (PODAC) process of the Maritech ASE Project 21. Decomposing into subsystems creates a logical structure with bounded subsystems that can be more easily analyzed, designed, built, and maintained. The design of a non-homogeneous warship requires highly computational architectural analysis tools like the Intelligent Ship Arrangements (ISA) tool (Daniels, 2010). ISA is being developed by the University of Michigan, and is funded by ONR and the CREATE-SHIPS Project. A ship design engineer with a tool like ISA can rapidly consider a wide range of arrangements in terms of overall location, adjacency, separation, access, area requirements, area utilization, and compartment shape. The system architecture is quite general to facilitate its evolution to address additional design issues, such as distributive system design, design for production, and design for ownership. Investment in the Intelligent Ship Arrangements - ISA - tool and other architecture tools needs to be accelerated.

In addition, Systems Engineering methodologies being developed by DDR&E at the Systems Engineering Research Center (SERC) at the Stevens Institute of Technology need to be integrated into the early ship design process. Requirements-driven, model-based, uncertainty-analysis tools are being developed to analyze the possibility of conflicting requirements of various components of existing systems with the objective of simplifying the process of design - build. The true value of these methodologies is to give the design engineers the tools they need to rapidly analyze the requirements, model the uncertainty and complexity for estimating ship's weight and volume, and thus stabilize the ship arrangements much earlier in the design - build process. These will contribute to NAVSEA's ability to deliver major, complex projects on time and within budget.

Need for Higher Fidelity Modeling in the Ocean Battlespace. As highlighted by the Maritech ASE Project 21, the ship structure architecture has a significant impact on an efficient design - build process. In addition, the ship designer's over reliance on rule-based structural design has resulted in costly construction and in-service changes. However, next generation High Performance Computers (2020) will provide exciting opportunities to develop and deploy very powerful physics-based application codes which will utilize accurate solution methods, model all the effects we know to be important, complete computations in the time frame of early stage design, and find/fix design flaws early in the process.

Therefore, there is an urgent need for a new multi-disciplinary approach to early stage structural design. Our vision, as depicted in Figure 9, is a physics-based software development project in the framework of an Integrated Structural Design Environment (ISDE). Table 6 lists the many benefits of ISDE and higher fidelity modeling.

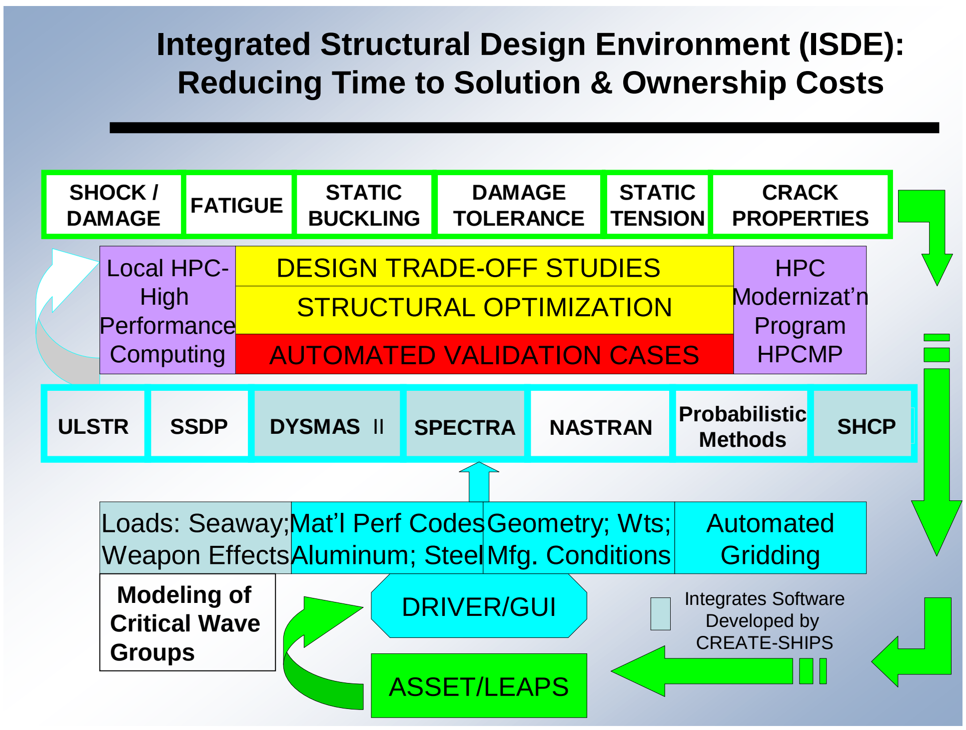


Figure 9. Integrated Structural Design Environment (ISDE)

ISDE is a concept conceived by NAVSEA, NSWCCD, and industry. With ISDE, ship design engineers would be able to more rapidly and reliably predict ship structure size and weight early in design. In the meantime, however, individual elements of ISDE would be used in early ship design in lieu of rule-based or empirical design methods. Under the auspices of the CREATE-SHIPS Project, NAVSEA and NSWCCD are rebuilding the NAVSEA early stage ship design environment (Kassel, et al, 2010) by integrating more physics-based modeling (Wilson, et al, 2010) with the ship synthesis model, ASSET (Advanced Ship and Submarine Evaluation Tool), and the ship design analysis product model, LEAPS (Leading Edge Architecture for Prototyping Systems). ISDE would integrate structural analysis tools and provide a more complete Platform Modeling capability in the Ocean Battlespace.

Table 6

Benefits of Modeling Warships in the Ocean Battlespace

Physics based software products developed as part of an Integrated Structural Design Environment (ISDE) being used throughout the Navy, other Government organizations, and industry for:

- Timely Design and Construction of New Ships with Extended Service-Life
- Maintenance and Repair Decisions for Sustaining Service-Life of Ships In-Service
- Operator Guidance for Reduced Ownership Costs of Ships In-Service
- Development of high strength, light weight, low maintenance steel and aluminum alloys

THE WAY AHEAD

In a 14 July 2009 interview with the Boston Globe, Dr. Carter, OSD (AT&L), stated:

> *There are many, many causes of screwed-up programs and people are always looking for common denominators. But self-deception is probably the greatest common denominator, where people march along, knowing that there's something wrong, nobody wanting to speak up, everybody hoping it will get better somehow. And eight years into a program you can find a program that has worked its way into that kind of corner. The job is to make everybody realize they have a common problem and work toward solutions. It's an everyday occurrence.*

If the Navy continues with what it has traditionally done by first starting with the hull form and constraining the design - "outside-in design", there is little possibility of significantly reducing Non-Recurring Engineering (NRE) and shipbuilding cycle-times and costs. The Way Ahead is to demonstrate how a significant reduction in design and engineering cycle time and man-hours can be achieved through a more effective use of design tools and a different approach to the Design-Build-Own Process; that is, creating the baseline ship by: **(**1) matching the internal volumes to the hull form; (2) then finalizing the baseline design - "inside-out design". Designing inside-out of the hull is a proven methodology for significantly reducing the Design-Build cycle times and the total ownership costs of new ships.

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