Optimizing design processes to drive down total ownership cost

By Victoria Dlugokecki and Lisa Hepinstall
All of these “design for” buzzwords have, at one time or another, come to the forefront of the marine industry as ship owners continue to face the challenges of designing, building, operating, and maintaining government and commercial ships over their full life cycle. Our purpose here will be to take you on our journey, as engineers, down the path to enabling lower-cost ship designs.

In 1986, one of the pioneers of modern day United States shipbuilding, Tom Lamb, published a seminal book. Engineering for Ship Production, A Textbook was developed through the National Shipbuilding Research Program (NSRP), and in the book, Lamb states, “Today’s ship designer has both the opportunity and the obligation to design ships so that the minimum total cost is achieved. However, this opportunity cannot be seized by the ship designer in isolation. It is only possible through an awareness of the facilities and production techniques and methods used in the shipyard that will build the design.” Every young ship engineer or designer should subscribe to this fundamental practice. It is the basis for the design for production (DFP) philosophy.

Traditional design for production is primarily concerned with reducing acquisition cost at the individual shipyard’s level, but this is only a portion of the total life cycle cost of a ship. While it varies from commercial ship class to ship class, or from navy platform to navy platform, acquisition cost may only account for 30 to 40% of the total cost to own and operate a vessel over its life cycle. The remaining 60-70% of life cycle cost represents operating and support costs. Maintenance and energy costs represent a major portion of these operating and support costs. It is estimated that early stage design decisions drive 75% or more of ship construction and life cycle cost, so design for maintenance, and other energy efficient design initiatives (such as design for performance), together with DFP can significantly reduce the cradle to grave cost impacts to ship owners.

DFP in manufacturing
The concept of DFP has had strong connections with manufacturing industries, including the automotive, aviation, information technology, electronics, and defense sectors for many years. DFP is not new to the shipbuilding industry. International shipyards emphasize design producibility, whereby ship designs are tailored to leverage shipyard production attributes and avoid constraints. The U.S. shipbuilding industry also has had decades of exposure to the concepts of DFP. One of the earliest references that we have found on the subject is from the 1979 REAPS Technical Symposium, held in San Diego, CA. REAPS stood for Research and Engineering for Automation and Productivity in Shipbuilding.

The REAPS program was a U.S. shipbuilding industry/Maritime Administration cooperative effort whose goal was the improvement of shipbuilding productivity. It was a precursor of the current NSRP, which is a collaboration of U.S. shipyards focusing on common issues with a goal of reducing the cost of building, operating, and maintaining navy and commercial ships. NSRP has invested heavily in the implementation of DFP principles in U.S. shipyards. While there are many definitions of DFP, they all focus on reducing the cost of production by minimizing work content, simplifying fabrication, and rationalizing material choices. The achievement of the ultimate goal is possible through an awareness of the facilities and production techniques and methods used in
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the shipyard that will build the design. Examples of DFP guiding principles that help reduce design and construction waste, thus lowering the overall cost of shipbuilding, are shown in Table 1.

**Design for maintainability**

Considering that vessels will have a service life of between 20 and 50 years—20 to 25 years is more typical for commercial ships, and aircraft carriers can have service lives of 45 to 50 years—design decisions made early in the ship design process will impact costs for decades. Design for maintainability (DFM) can be defined as designing for “the relative ease and economy of time and resources with which a ship can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair” (from the DOD handbook *Designing and Developing Maintainable Products and Systems*). Examples of some DFM guiding principles are shown in Table 1. As can be seen, there are many synergies between DFP and DFM, including standardization and simplification of the design and/or design components. Another common area is inspection and test, which is done initially by the building shipyard, and then by operators and maintainers throughout the life cycle.

There is a misconceived notion that designing for maintainance will automatically increase the acquisition cost of the ship. While that proves true in some cases, there are many DFM best practices that can be implemented without impacting initial cost. Ensuring accessibility of components is one of these key considerations. Another is considering equipment removal and equipment removal routes to simplify maintenance activities during the ship’s life cycle.

**Design for performance**

While design for performance may not be part of our lexicon yet, all of the work that both commercial and government ship owners are doing regarding fuel efficiency is to drive performance. In addition to saving fuel costs for the operator, fuel efficiency is a green initiative that benefits the environment through reduced greenhouse gases and conservation of natural resources.

Through the International Maritime Organization, the Energy Efficiency Design Index (EEDI) was made mandatory for new ships and the Ship Energy Efficiency Management Plan for all ships at MEPC 62 (July 2011) with the adoption of amendments to MARPOL Annex VI. The EEDI is a non-prescriptive, performance-based mechanism that aims at promoting the use of more energy efficient/less polluting equipment on ships. The EEDI is expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase. Ship designers are using many strategies to achieve improved vessel efficiency, reduce fuel consumption, and lower emissions through design. Some of these include hull form optimization, structural optimization, the use of advanced machinery technologies for engines and other equipment, and the use of energy saving devices.

**In the real world**

The indoctrination of the DFP and DFM philosophy for one of the authors started when she hired into the Initial Design and Naval Architecture Department at National Steel and Shipbuilding Company (NASSCO) in 1997. NASSCO (now General Dynamics NASSCO) was in the process of formalizing their DFP policy through an NSRP project, which was published as a design for production manual, 2nd edition, following the NSRP work done by Newport News Shipbuilding in the development of their design for production manual in 1985. Structural engineers performed longitudinal and transverse frame spacing tradeoff studies during initial structural design concept development. The elimination of one longitudinal saved not only the associated material cost, but reduced the fitting and welding cost on every cargo deck, every accommodation deck, and every transverse bulkhead. But it wasn’t just that; it also saved on bulkhead cutouts, collars, and brackets. Concept arrangements were developed in concert with the concept structural design and the concept level build strategy. Arrangements considered optimum block lengths and plate straking philosophies. Before a pencil was laid on paper (or a mouse was clicked in CAD), engineers considered the shipyard’s facility capabilities and preferred material considerations. It was second nature. Accessibility for production welding also was a key
Bollinger Shipyard’s DFP and DFM efforts are reducing total ownership costs for both their commercial and government customers, including the USCG’s fast response cutters, currently under construction at Bollinger’s Lockport, LA shipyard.

**Table 1: Guiding Principles**

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<thead>
<tr>
<th>Design for Production Guiding Principles</th>
<th>Design for Maintainability Guiding Principles</th>
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<tbody>
<tr>
<td>Design for facility, workstation, and equipment capabilities</td>
<td>Design for desired level of maintenance</td>
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<tr>
<td>Minimize number of parts</td>
<td>Design to the ship’s mission and operating/maintenance environment</td>
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<tr>
<td>Standardize parts</td>
<td>Design for accessibility</td>
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<tr>
<td>Standardize material types</td>
<td>Maximize use of standardization</td>
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<tr>
<td>Minimize lifting and handling of parts</td>
<td>Minimize skills and training requirements</td>
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<tr>
<td>Minimize/optimize welding</td>
<td>Simplify diagnostic, testability, and verification</td>
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<tr>
<td>Simplify layout and measuring</td>
<td>Simplify the design and maintenance requirements</td>
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<tr>
<td>Minimize fabrication/assembly complexity</td>
<td>Use modular or unit packaging</td>
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<tr>
<td>Optimize for outfitting and assembly</td>
<td>Maximize interchangeability</td>
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<tr>
<td>Apply shipyard standards</td>
<td>Minimize impact to repairer’s morale</td>
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<tr>
<td>Simplify the engineering and design process</td>
<td>Reduce the potential for ship repair errors</td>
</tr>
<tr>
<td>Optimize for inspection and test</td>
<td>Minimize lifting and handling</td>
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consideration during structural design. Engineers and designers who come from a production background, or are exposed to shipyard production processes are more likely to produce “production-friendly” designs.

But it wasn’t only arrangements and structure getting DFP visibility in early design phases. The naval architects worked hand-in-hand with machinery/piping and other outfitting counterparts to ensure a buildable design. Were maintenance envelopes (at least for major machinery items at first) considered in the general arrangement? Was there enough space to run, in particular, large diameter piping, like ballast, firefighting, and main engine exhaust in the preliminary design? Did structural arrangements allow for minimized piping penetrations through transverse frames, or at least account for them to eliminate the need for collars and/or reinforcements? Was there a plan for running distributive systems in the arrangement—pipe chases, wire raceways, vent trunks? If the initial arrangements didn’t account for these items early on, it would only add cost during later design phases.

Continuing on their DFP journey, the authors facilitated the development of a standard DFP process, along with the development of DFP manuals for three mid-tier shipyards in the 2007 NSRP project entitled “Design for Producibility (DFP) for Mid-Tiered Shipyards,” which was a shipyard-led, collaborative research project including Bollinger, Atlantic Marine (now BAE Southeast Shipyard), and Todd Pacific Shipyards (now Vigor Shipyard). The purpose of the project was to incorporate DFP methodologies into the shipyard’s design process to enable simplification of the ship design process and vessel construction requirements. The individual shipyard’s DFP manuals provided designers with shipyard preferred design features and materials along with detailed facility capabilities to ensure that future designs would lower shipbuilding costs.

The project was fortunate in that each of the participating shipyards had current new-building ship construction contracts in their yards at the time, each at different stages of engineering/construction. Cost savings and cost avoidance opportunities were identified including relocation of equipment located across block breaks, and the use of flanged plate in lieu of welding for minor bulkhead subassemblies. Through their continued new construction efforts, including multiple classes of offshore supply vessels and the United States Coast Guard’s fast response cutter, Bollinger has been expanding their DFP processes and documentation efforts, including electronic delivery of DFP guidance to their engineers and designers.

The NSRP is not the only organization focused on lowering shipbuilding cost through DFP and DFM initiatives. The Center for Naval Shipbuilding Technology (CNST) is a Navy ManTech Center of Excellence, chartered by the Office of Naval Research (ONR) to identify, develop, and deploy advanced manufacturing technologies that reduce the cost and time to build and repair navy ships. In 2008, CNST awarded General Dynamics Electric Boat (EB) a multi-phase project as part of the shipyard’s DFP initiative. One of the phases focused on two key DFP areas: cost-based design
drivers and manufacturing best practices for design standards. EB recognized that it is crucial for the design and engineering community to understand manufacturing capabilities, best practices, shop floor lessons learned, and costs associated with product development and operations at the earliest stages of design. The results of the project also enabled design personnel to be aware and take advantage of new manufacturing equipment capabilities through the use of rule-based, cost-based, standardized designs to improve the process for ships’ systems. In another recent CNST DFP-focused project, Marinette Marine Corporation was awarded a project to develop a producibility optimization handbook, with a specific focus on improving manufacturing processes for littoral combat ship (LCS) construction.

The next logical step for the authors was to look at the significant life cycle costs associated with maintenance activities. As the project coordinator for a major CVN availability while at Atlantic Marine, one of the authors learned first-hand the maintenance challenges associated with aging ships. Tank access, equipment and piping system access, troubleshooting, and lock-out/tag-out activities all were significant maintenance cost drivers. The authors participated in another NSRP project, this time focused on DFM. This project formalized nearly 1,000 DFM cost reduction opportunities identified through more than 35 workshops with ship repair personnel from shipyards throughout the U.S. Those cost reduction opportunities that had very little impact on acquisition cost were categorized as best practices and formalized as design guidance that engineers and designers can immediately implement in their ship designs to lower total ownership cost. Examples include such items as:

- minimize the number of tanks in the vessel
- do not locate equipment in the bilge area
- minimize the amount of piping and other outfitting in the bilge area
- allow accessibility for maintenance between equipment and structure, piping and structure, and so forth
- consider equipment removal paths early in the design, and keep them clear of piping, vent, cable, and other outfitting
- minimize the use of enclosed foundations. If an enclosed foundation is required, include openings in the structure for basic access
- minimize equipment and other items located on weather decks
- minimize the length of cable exposed to the weather by locating the deck / bulkhead penetration as close to the equipment as possible.

Other cost reduction opportunities identified through the project, while having the potential to reduce life cycle costs, had acquisition cost impacts and are required to go through a cost benefit analysis to prove out their life cycle cost savings. The following list of design features and material selection were all identified through the project. While increasing acquisition cost, these have actually been specified by various ship owners for vessels with the intent of reducing maintenance costs:

- piping on the weather deck shall be stainless steel
- sea water cooling system piping shall be CuNi
- permanent pad-eyes shall be provided for removal of thrusters. A pad-eye registry shall be created including location, safe working load, test load, and test date
- vertical ladders shall be provided inside the machinery casing as necessary to permit access to all levels
- a deck washing system shall be provided
- stainless steel fasteners shall be used on the weather deck
- marine-type LED lighting fixtures shall be used throughout the vessel
- sewage tanks shall have stiffeners on the outside of the tank.

While the use of a 3D product model for design is certainly not new, more and more ship designers are using the model to review for DFP and DFM features in the design. One of the authors can remember a summer internship at Gibbs and Cox in the 1980s, sitting at a light table and looking at a stack of 2D design drawings—one for structure, one for equipment, one for piping, one for HVAC, one for electrical, and so forth—trying to determine if there were any interferences in the design. Use of a 3D product model has eliminated this tedious effort and enabled a deeper vetting of the design while it is still in the design stages. Review of the design for production aspects, like welding access, is just one of the benefits of having a 3D product model. Integration of the structural design with outfitting design is also facilitated with the use of the model. For instance, a common complaint by repair personnel is that tank accesses are blocked either by piping or other outfitting in the area. Clearances around manholes is one of the items typically checked during a review of the 3D product model. Other important DFM features that can be checked with the model are access to equipment and access to outfitting items.

Was there a plan for running distributive systems in the arrangement—pipe chases, wire raceways, vent trunks?
Corrosion is a major maintenance cost driver. By making early design decisions and material selections, designers are able to reduce or slow down corrosion over the vessel’s life cycle. An example of an early design decision that reduces maintenance cost is to increase the use of bulb flats, given their preservation-friendly characteristics. The lack of sharp edges facilitates both surface preparation and coating activities. Typically, they are specified for corrosion prone structure, including tank tops, where condensation within the tank accelerates corrosion, and on weather decks, where the sea environment accelerates corrosion. In addition, vessels like offshore support vessel designs will typically include bulb flats as structural members in tanks with highly corrosive contents. It is not just structural corrosion that drives cost. Owners are specifying corrosion-resistant piping materials, particularly for sea water systems and for weather deck applications.

In the long run
Cost-conscience commercial owners realize the long run benefits of DFM decisions, in spite of selected acquisition cost increases. The navy also recognizes these benefits but is often constrained by “color of money” issues and tightened cost controls. The FY2014 President’s Budget Submission for the Department of the Navy noted that almost $6.9 billion was spent on ship maintenance for FY2012. That represents a 60% increase over the FY2006 actual cost of ship maintenance ($4.3 billion). Decision makers in the navy also realize that a large majority of the 289 ships in commission today will still be in the fleet 10 years from now, and they are faced with the need to support a growing maintenance demand with reduced budgets, requiring them to focus their efforts on reducing ship maintenance costs.

For example, within the submarine community, Electric Boat has extended its “design build” philosophy to “design build sustain” in an effort to include the interests of the maintainers and the operators in the design of their vessels. They’re successfully implementing DFM principles in their Virginia class Reduction of Total Ownership Costs program as well as their design efforts for the OHIO Class Replacement program.

Ship designers are pursuing many avenues in their quest for energy efficient designs. One area they are looking at very early in the design process is hull form optimization. By optimizing the ship’s principal characteristics around a service speed that has been rationalized for the ship’s operations, designers can significantly lower fuel consumption and the generation of CO₂ over the life cycle of the vessel. Using the vessel’s anticipated operational profile (different operation drafts, trim and speed combinations) during hull form optimization enables another level of fuel efficiency to be achieved, particularly for vessels with multiple off-design conditions. In addition, many of the world’s leading model basins are focusing on the use of advanced computational fluid dynamic analyses for hull form designs that minimize hull resistance and increase propulsion efficiency.

Another way to improve fuel efficiency is through optimization of the structural design of the vessel with the purpose of achieving a lighter weight design. This can either impact the draft of the vessel, resulting in lower power requirements, or increase the available deadweight, improving the general transportation efficiency by enabling the vessel to carry more cargo. The use of higher-strength steels is becoming common practice in the design of many commercial ships, including tankers, bulk carriers, and containerships. The use of composites and aluminum for high-speed craft and vessel superstructures is also used as a weight saving strategy. Both of the navy’s LCS class designs include the...
use of aluminum—the superstructure for Lockheed Martin’s Freedom class and the entire vessel for Austal’s Independence class. The superstructure for the DDG 1000 Zumwalt class destroyers is composite. In addition to improving stability, enabling additional payload and/or increased ship speed, the corrosion-resistant properties of composites should reduce maintenance cost over the ship’s life cycle.

Energy saving devices are another area for investigation that ship designers can specify to improve fuel efficiency. Many of these energy saving devices focus on improvement of propulsion efficiency, like pre- and post-swirl devices or ducts for propellers. Recently, however, there has been increased effort in devices that reduce hull resistance, like air lubrication systems for the hull. Lastly, designers can look at equipment that saves energy, like solid-state lighting (SSL).

The navy is pursuing energy efficiency advances through the use of energy saving devices. Two of these already in the implementation phase are stern flaps and SSL. Stern flaps have been proven to save fuel costs through increased propulsion efficiency. They also reduce exhaust emissions and increase ship speed and endurance. Stern flaps are currently installed (or are being installed) on cruisers, destroyers, and certain amphibious ship classes. SSL (LEDs) improves energy efficiency, saving fuel at sea and saving shore power in port. Further adding to its operating and support cost savings, SSL also improves lamp life span, in turn driving down maintenance and sparing costs, and the removal of mercury-containing fluorescent tubes drives down handling and storage costs. ONR first piloted SSL on submarine platforms, and in 2012, with more than 600 LED lighting fixtures, USS Chafee became the first United States Navy ship to be fitted with all-LED lighting.

Not only is the navy modifying existing vessels with fuel savings technologies, new vessel concept design exploration is focusing on energy and the environment. In summer 2013, General Dynamics National Steel and Shipbuilding Company, Huntington Ingalls, and VT Halter Marine Incorporated were each awarded contracts for T-AO(X) studies. The T-AO(X) is a new class of navy fleet replenishment oilers. The energy conservation studies focus on areas of interest such as hull and propeller optimization, waste heat recovery, high efficiency lighting, and the potential use of voyage and trim optimization tools. The T-AO(X) industry studies also included an analysis of potential maintenance-related design features to reduce operating and support cost and enhance the crew’s productivity. DFM features referenced in the studies include machinery removal routes, distributive system trunks, tank interiors free of structural members, and consolidated over-board discharges.

The ship design community in the U.S. is continually progressing through a “design optimization continuum,” typically based on the specific challenges facing each ship program. As ship owners become more holistic in their acquisition strategies, the impetus to drive down total ownership cost will shift to the ship design and shipbuilding community, whereby design optimization strategies will translate into competitive leverage. Regardless of the design optimization strategy, the authors have found that fundamental success drivers common to all design optimization processes include the establishment of clear, unambiguous goals, coupled with a design team that incorporates the use of deck-plate shipbuilding and ship repair expertise.

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