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Reducing Detail Design and Construction Work Content by Cost-Effective Decisions in Early-Stage Naval Ship Design

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The Office of the Under Secretary of Defense, Acquisition, Technology, and Logistics (AT&L) recently presented analyses of cost and schedule growth on Major Defense Acquisition Programs (MDAPs) over the last 20 years (2013, 2014). For naval ships, AT&L (2013) concluded that contract work content growth (not capability growth) dominates total cost growth statistically. In addition, costs-over-target are significant and reflect poor cost estimation or faulty framing assumptions. AT&L (2014) also concluded prices on fixed-price contracts are only "fixed" if the contractual work content remains fixed, but this is often not the case. We show that under-sizing the ship during concept design studies increases ship outfit density and adds complexities to the design. These early-stage design decisions on sizing the ship are a major contributor to unnecessary work content growth later in Detail Design and Construction (DD&C) that cannot be eliminated no matter how productive the shipbuilder. However, new ship design methods are being developed and integrated with legacy physics-based design and analysis tools into a Rapid Ship Design Environment (RSDE) that will enable a more rational process for initially sizing ships. We also identify the need for early-stage design measures of complexity and ship costing tools that are more sensitive to these measures, and propose solutions that will aid decision-makers in reducing DD&C work content by making cost-effective design decisions in early-stage naval ship design.

Keywords: economics (design); economics (shipbuilding); computers in design

1. Background

The U.S. Navy and shipbuilders have been trying to improve the naval ship design, acquisition and construction (DAC) process for decades. Yet, too many new ship acquisition programs continue to exceed programmed cost and schedule. Many of the DAC process improvements have been imitations of what foreign shipbuilders have been doing. Many times we replicate behaviors of these foreign role-model shipbuilders with no real understanding whether this will change our performance. Other DAC process improvements have been motivated by articles about "best" practices and they are adopted because they have been labeled "best" without knowing how these practices might affect the economics. Reinertsen (1997) emphasizes there is a different way to make these choices: Do more of the things that help us achieve our objective. If our objective is affordability, we must determine which things in the infinite list of things we could possibly do will actually help us reduce the cost and time to design, acquire and construct a naval ship. The tool to use for maximizing the affordability objective of a complex system is an economic model. Reinertsen (1997) adds that the desire in creating an economic model is to identify how to manipulate the input variables to minimize or maximize the output. In the case of naval shipbuilding, we must understand how changes in the inputs ("hands-on" labor hours, "white collar" labor hours, material costs, product performance, schedule) change the output (affordability). When this is done systematically we can identify relationships between input and output. These relationships may tell us that certain inputs have more impact than others on our

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goal of affordability. There must be effective economic models to measure affordability from the beginning of design development.

2. The problem

AT&L (2013) in its analyses of cost and schedule growth on major defense acquisition programs (MDAPs) over the last 20 years concludes:

> *Premature contracting without a clear and stable understanding of engineering and design issues greatly affects contract work content stability and cost growth. . .Early work content stability on a contract predicts lower total cost, work content, and schedule growths. . .Contract work content growth dominates total cost growth statistically, but costs-over-target also are significant and worrisome. Cost-over-target reflects poor performance, poor estimation, or faulty framing assumptions and generally is bad. . .*

2.1. Contract cost growth on development contracts (Milestones B–C, in Fig. 1)

For Navy ships (1970–2011), AT&L (2013) found a statistically significant undefinitized contract action (UCA) effect. UCA pertains to any contract action for which the contract terms, specifications, or price is not agreed upon before performance is begun under the action. Thirty-nine percent of the ship development contracts had a UCA, and they generally add 41% points to total cost growth. AT&L warned it could indicate an area of caution and attention for the Navy.

AT&L (2013) showed that UCAs had a measurable increase on total contract cost growth and also on cycle time in development by increasing schedule growth. For ship development contracts, UCA effects were significant. Although it can take some time for problems on development contracts to be revealed, these results confirm the view that a well-understood and well-defined contract at the outset tends to perform better in the long term.

2.2. Contract cost growth on early production contracts (Post Milestone C, in Fig. 1)

For ship early production contracts, AT&L (2013) analyses showed that, as expected, the effect of work content growth is statistically significant, and schedule growth is also a large contributor to total cost growth. Interestingly, there was no UCA correlation with total cost growth for ship production. For Navy early production contracts, the statistics are clear for total cost growth from 1992 to 2011:

> *The dominant statistical correlate of total cost growth was work content growth (as reflected in a higher contract target cost), which explained 95% of the variation in the data.*

Beyond analysis, experience also leads AT&L to assert that basic acquisition fundamentals work. Premature contracting without a clear and stable understanding of engineering and design issues greatly affects contract work content stability and cost growth. In addition, first principles indicate that concurrent production when designs are unstable can impose added retrofit costs for early production products.

The example that AT&L (2013) used to show early production contract cost growth (growth from initial contract budget base) due to "work added later" was a DDG 51 contract. Many associated with surface combatants know that the Navy's surface combatants are extremely sophisticated. However, it is generally accepted that U.S. Navy combatants designed in the last few decades are more complicated and densely outfitted than their predecessor classes.

Building on the results from last year's report, AT&L (2014) analyses show that prices on fixed-price contracts are only "fixed" if the contractual work content remains fixed, but this is often not the case. To a great degree, the Navy is the only customer for new military vessels (i.e., a monopsony-type market). AT&L (2014) emphasized they are continuing the effort to change the acquisition culture from one focused on accepting costs as a given to one where each element of cost is assessed as to how it can be reduced without reducing value received.

Research by AT&L is continuing in an effort to understand what causes increases in cycle time of programs. The complexity and capability of our warships and weapons systems have increased dramatically contributing to large increases in cycle time. Thus, cycle time appears longer compared with that of many decades ago, but the real driver appears to be system complexity. AT&L (2014) points out that some outliers are enormous; these probably represent more of a problem than the general increasing trend, again due to complexity.

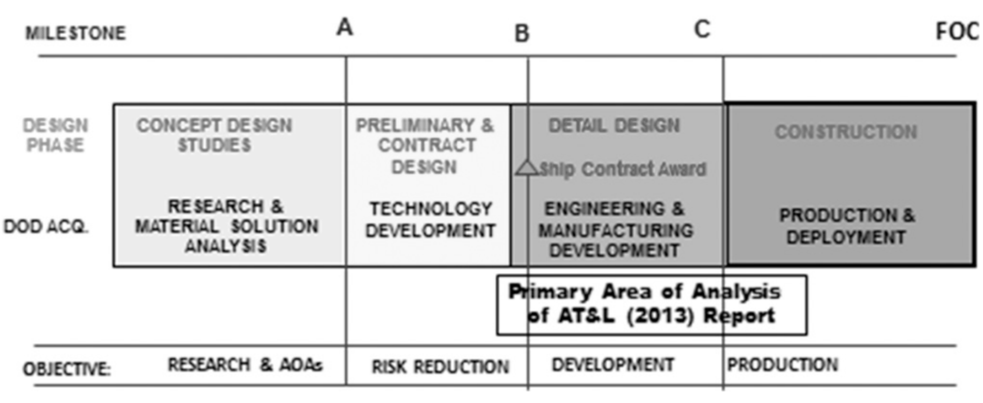

Fig. 1 Ship design and acquisition process compared to the defense acquisition process

2.3. Naval ships unnecessarily cost too much to design and build

U.S. Navy surface combatants are highly effective warships. However, Keane and Tibbitts (2013) describe from first-hand experience that the size of the hulls on a number of surface combatants was arbitrarily constrained during ship design based on false cost premises. As a result, these ships have unreasonably high outfit density factors and thus were overly complex (difficult) to design and construct. Therefore, it took a lot longer and cost a lot more to design and construct the early ships of these classes.

As shown in Fig. 2 (Keane 2012), ships with higher densities and normalized first-ship production hours per long ton follow a trend that is a function of their basic ship outfit density (light ship weight minus ship structure weight divided by total volume) and the type of ship. For example, lower left commercial designs are not much more than empty tanks; Hybrid designs are not far behind; Auxiliary/Amphibs Designs have a lot of empty hangar/well deck space; and combatant designs have virtually no “empty air” spaces. Future ship design points are clearly speculative and prone to growth. So, what is an unreasonable density factor, and what is an overly complex design? The challenge for the early-stage ship design engineer is how to quantify and compare capability on such a chart, capability which is mission driven and different for each element of force architecture. However, experienced design engineers should be able to identify outliers like the DDG; also, during concept design studies, it is important to see the relative changes and trends in alternative ship concepts. One can readily see by looking at Legacy Hulls (Return Data) in Fig. 2, in general, ships with greater outfit densities tend to have higher production man-hours.

AT&L noted that cost growth on development contracts correlates strongly with cost growth on subsequent early production contracts. This finding is substantiated by Fig. 3 which shows man-hours for lead ship Detail Design (defined as “development” by AT&L). Note how much variation there is within the surface combatants. (Both of these figures are from a presentation by the NAVSEA Cost Group, which was given at a meeting of the Ship Design Committee of the Society of Naval Architects and Marine Engineers in June 2007.) Also, recall the significant UCA effect that AT&L found for ship development contracts. UCA’s can be considered an indicator of work content that was imbedded in the basic ship design during the earlier stages of design.

In a recent National Shipbuilding Research Program report (NSRP, 2011), U.S. shipbuilders summarize impressions of successful foreign design and shipbuilding practices. The report identifies many differences our shipbuilding industry has recognized as contributing to increased shipbuilding costs but has been unable to change. These include early design decisions that lock in density (like the early DDG 51 decision to constrain length which drove high density), ever increasing technology being added to ships (usually increasing demands for space, weight, power, and cooling), drives to reduce ship manning through automation and low maintenance materials selection, etc.

The NSRP report specifically mentions numerous criticisms of U.S. naval ships for having poor general arrangements (such as missing and even under sized compartments like fan rooms) and poor systems engineering of piping and ventilation systems (such as inefficient and complicated routing). These design issues have been problematic for quite a while and across a range of naval ships designed over a number of decades (Keane & Tibbitts 2013). They relate directly to ship density and the resulting complexity. Even with the most efficient manufacturing processes, poorly engineered systems driven by an overly dense ship design will result in higher construction costs as well as a lower quality and operationally a more expensive ship. The ship designer needs to

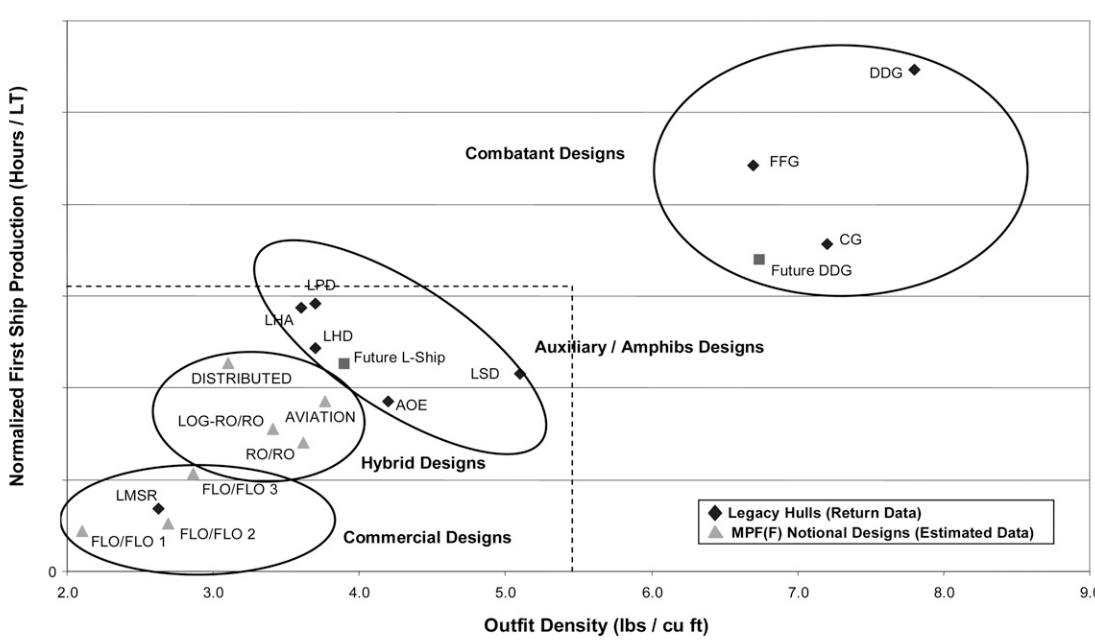

Fig. 2 Ship production hours versus outfit density factors

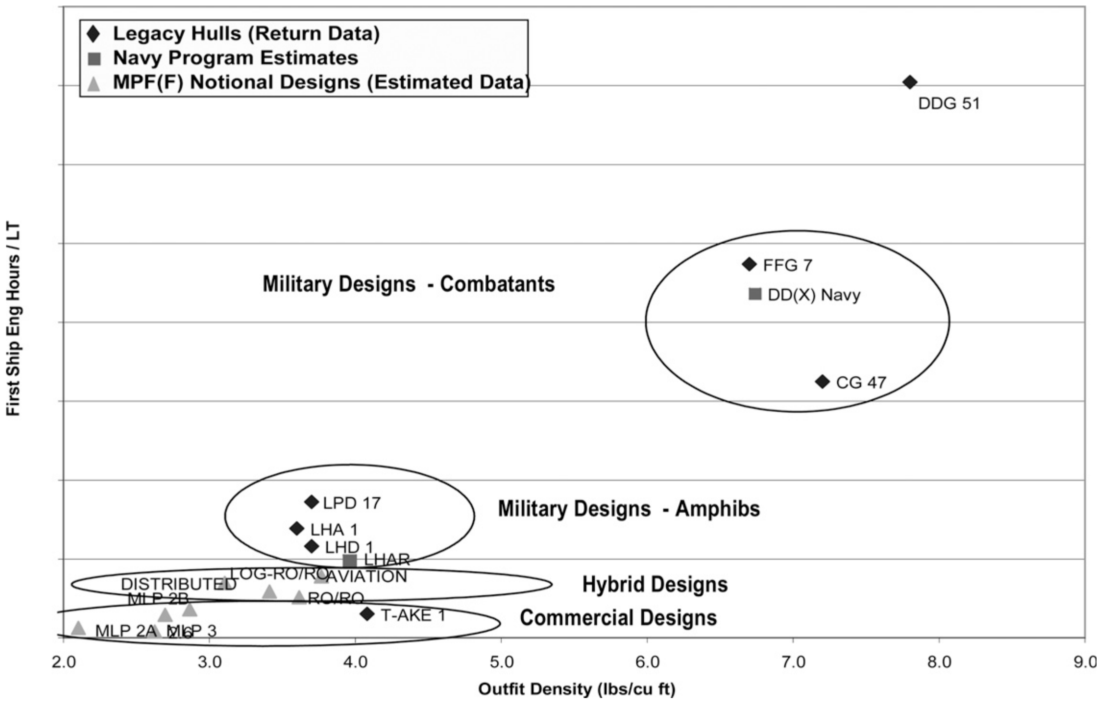

Fig. 3 Detail design engineering hours versus ship outfit density factors

have early-stage integrated design tools and higher fidelity costing tools to convince decision-makers that bigger can be better, not necessarily more costly.

3. A solution: Design out complexity early

In a sophisticated system like a naval ship, an integrated measure of product complexity at the total ship level is difficult to establish. There is no doubt that a wider application of complexity assessment particularly in early-stage ship design has an immense potential. There are a number of approaches to measuring different aspects of complexity for use in different stages of design. It is not clear how these diverse measures can be used to assess the complexity of different ship design concepts during the design space exploration (DSE) phase (PreMilestone A in Fig. 1) and to include a ship complexity assessment methodology within an integrated design environment for evaluating design alternatives in the early stage of the design process.

Caprace and Rigo (2010) note that complexity often tends to be used to characterize a product or system with many parts that are interrelated in complicated arrangements (analogous to a naval ship). They also explain that the design process itself is complex. This complexity stems from time varying design requirements (so stability of requirements up front becomes of significant importance) and the voluminous solution spaces that need to be explored (so rapid DSE is critical). They contend that some decisions made at the early design stages often fail to deliver results that meet the expectations of the ship operators. They attribute many of these failings to design engineers' lack of understanding of complexity and not addressing complexity during early-stage design. This serious design deficiency can result in a number of costly changes and even in a redesign. We contend that ship complexity is a root cause of the UCA effect that significantly contributed to cost growth of ship development contracts.

In addition, Caprace and Rigo (2010) list several factors that influence product complexity such as the number of components, the number of interactions/connections, the number of assembly operations, the number of subassemblies, the number of branches in the hierarchy, the number of precedence levels in the hierarchy, the type of interactions/connections, the properties of interactions/connections, the type of components, geometry, shape, material, production process, size, density, accessibility, weight, and so forth. A total ship design complexity measure would have to be a combination of these factors that could be used to reduce the global complexity of the ship during the concept design phase.

3.1. Complexity in ship concept design

If one created a total ship complexity measure, it is not unreasonable to expect more capable ships to have a higher complexity value (e.g., combatants compared to auxiliaries). The issue then becomes what is an unreasonable complexity measure for a defined capability (or performance). The challenge is to achieve the same capability (or performance) with lower complexity.

Gaspar et al. (2012) describe a hierarchical architectural approach to addressing system complexity. This hierarchical approach decomposes a system into subsystems and uses the architecture of a system and its subsystems to better understand total system complexity. This assumes a system can be divided into a finite number of subsystems, each of which may be further subdivided. One representation of the architecture of a naval ship is its ship arrangements. At the total ship level, it is the General Arrangements of the compartments representing the major functions performed aboard ship and their interrelationships. Each compartment is further arranged within, but some compartments include subsystems from a number of ship systems.

For early ship concept design, however, it is a challenge to get a general arrangement let alone arrangements of individual compartments, and arrangement of distributed systems is seldom explored. The objective of using a measure of complexity in concept design is to get to cost, half of which is driven by the ship and half by mission systems. Thus, there is a need to be able to model complexity of mission systems as well as the platform. The complexity of mission systems, however, is the subject of another paper.

Experience has shown (NSRP 2011) that ship arrangements developed during the early stages of design were often carried through detail design without any attempt at optimization. In fact, since most navy ships are undersized, Keane (2012, 2013) points out that the ship arrangement is too often in flux long into detail design, and design engineers are hard pressed just to find enough space for everything. As mentioned above, the decisive task of concept design is the voluminous solution spaces involving hundreds or thousands of alternative ship concept designs that need to be evaluated. The improvement that is required is in the methodology of exploring this huge concept design solution space. The methodology must take into account simultaneously the complexity of the alternative concept designs in terms of ship arrangements including enough space for vital outfitting components such as HVAC, pipes, electrical cables, and so forth. It is therefore necessary to include the methodology and an adequate measure of total ship complexity inside the integrated design environment for early-stage design, including relating total ship complexity to costs.

3.2. Ship density as a measure of complexity

Possible measures of complexity previously mentioned are size, density, accessibility, and weight. Weight is a parameter that is commonly used in early ship concept design and in costing concept designs. However, weight is not an adequate measure of ship complexity. Size, density, and accessibility are better measures and are somewhat interrelated. The parameter density measures how tightly systems and equipment are arranged within a hull structure. Ship density is readily calculated for hundreds or even thousands of ship concept designs when exploring and evaluating the huge design solution space in early ship design.

Ship density is a reasonable general measure of the ability to arrange a ship from general arrangements in early-stage design through in depth modeling in detail design. In general, the larger the size and the lower the density the easier it is to arrange a ship. Grant (2008) shows that ship density is a good measure of ship complexity. He presents evidence of the "first in-class performance drop-off" phenomenon that suggests excessively dense designs increase the complexity of a design by increasing the quantity and intensifying the severity of problems encountered in the initial build effort. Complexity translates to increased first-ship costs.

In addition, Grant (2008) presents figures similar to those of Figs. 2 and 3 that show the first Virginia class submarine cost less per long ton than the first seawolf class submarine. He notes this is significant because the Virginia class is the first fast-attack submarine design to break the trend of increasing shipbuilder costs per long ton with each subsequent design. It is also the first submarine to break a similar trend of increasing density with each subsequent design. The critical conclusion of Grant's research is that density reduction in many cases is a preferred alternative to weight or size reduction when decision-makers seek options for lower cost submarine designs.

Grant's research mainly focuses on submarine design and procurement, but he emphasizes that the general concepts are applicable to surface ship designs and may be applied more broadly. Based on an examination of density as it relates to cost, Grant concludes:

1) weight-reduction efforts to reduce cost have often resulted in the opposite effect;
2) unnecessarily dense designs inevitably result in increased cost, schedule, and performance risks; and
3) density measures are sufficient approximations of how tightly systems and equipment are arranged within a ship.

He ends with the conclusion that density represents a significant and previously underemphasized driver of historic submarine cost growth in excess of inflation.

4. Impact of outfit density on ship construction work content

European ship designers and shipbuilders are actively promoting the benefits of designing larger hulls to better accommodate equipment and outfit systems. Gelling and Goossens (2008) explicitly explain the Damen Schelde Naval Shipbuilding approach of arranging a ship in a way that modularity, standardization, and simplification of components can be readily employed from the beginning of concept design. Modularity and standardization are not new concepts to naval ship design (Abbott et al. 2008). Abbott (2010) has been recommending these for many years. They all emphasize it is possible to eliminate unnecessary work content and Damen actually presents data validating reductions in production, operations, and maintenance costs. A pillar of Damen's design philosophy is "oversizing" the hull (Keane 2013). Damen has demonstrated that all of these efforts result in a reduction of man-hours, material cost and construction time, resulting in a reduction in recurring construction costs.

A larger hull also increases the opportunities to better accommodate service-life allowances for weight and stability for future upgrades. Gelling and Goossens (2008) emphasize that by making installation of equipment and systems easier for the shipbuilder, a larger hull offers opportunities to reduce construction work content and provides the benefits of improved access to systems during operations and maintenance activities.

Qualitatively, it might be expected that when on-board spaces become very dense with equipment and systems, workers have more and more difficulty accessing their work areas and their relative productivity becomes degraded. Impacts of unnecessarily high outfit density are:

- Design tends to have more interferences in early ships of the class resulting in delays, rework, and added costs.
- Design changes to later ships of the class result in more interferences reducing learning curve improvements.
- Work sequencing is more difficult to plan and schedule, increasing the time and cost to plan and perform the work.

- Negative impacts compound when combined with weight saving thin steel:
  - Distortion and distortion removal impacts on the outfitting strategy (delayed installation of damageable items, paint, and insulation).
  - Delays to items that need paint and insulation complete behind them before their installation.
  - Constraints on penetration locations resulting in inefficient routing of distributive systems.

4.1. A process-based cost model

In the late 1990s, the U.S. Navy and the shipbuilding industry worked together and developed a cost estimating tool that is sensitive to manufacturing processes. Trumbule et al. (1999) acknowledged that the product oriented design and construction (PODAC) cost model is a cost estimating tool that accurately reflects the cost of ships being built in modern ship production facilities. They noted that the cost estimating approach inherent in the PODAC cost model provides the analyst with insight into the cost of the intermediate products and the processes by which they are produced. This allows ship designers to understand the cost impact of design alternatives, and shipbuilders to understand and evaluate the cost of production processes and facility changes. The PODAC cost model was developed to produce cost estimates using actual shipbuilding costs compiled from libraries of returned costs. The model operates parametrically at approximately the 3-digit U.S. Navy ship work breakdown system (SWBS) level and provides a wide variety of selections for ship systems, equipment and machinery, crew size, type of materials, and ship production considerations. SWBS is used only for placing costs into recognized categories and does not indicate any method for estimating costs. The cost model uses many other metrics (area, volumes, power, manning, etc.), not just weight. The PODAC cost model has been successfully validated across a range of commercial and naval ship types. Although NAVSEA has not validated the PODAC cost model, validations have been conducted on a number of cost estimates made outside the U.S. Navy and they have proven to be credible.

The PODAC cost model provides features for estimating nonrecurring design and engineering and recurring ship construction costs and schedules for lead ship and follow ships for a multiple ship acquisition program. The PODAC cost model also produces cost risks based upon estimates of expected engineering and shipbuilder capabilities and expertise as well as estimates of relative design complexities and expected build strategies. A full discussion of how the cost model performs cost risk evaluations is available in the user manual that can be downloaded from the SPAR web site.

Finally, the PODAC Cost Model produces estimates of shipyard manpower requirements broken down by basic trades/crafts groups. This output is a good cross check of the estimated labor hours and planned schedules for the anticipated available levels of shipbuilding manpower. For early concept design where few design details are available, the cost model substitutes values based on statistical survey analyses of existing ship designs. Subsequent sections present some of the results of these ship design statistical analyses.

4.2. Shipbuilding productivity factor

While there is a concept of a standard cost for performing a specific element of work, the actual cost will always vary depending on the who, when, and where of the work to be performed. A shipyard that has the right equipment and facilities, a skilled work force, a competent planning and management team will almost always perform the work more quickly and less expensively than the shipyard that is compromised in one or more of these areas. In addition, a standard cost may identify expected costs for work under "normal" circumstances, but the actual cost will likely be higher if the work area is congested, confined and/or difficult to reach.

There are other technical issues that need to be considered. Working to a poorly engineered design will always be more costly than working to one that is well done and easier to build. An extension to this is whether or not the design is available when the work is scheduled to begin. For example, if pipe routes are not complete, their penetration locations may not be included in the steel plate cutting data and the holes will need to be cut and reinforced manually in the field. If foundation designs, pipe routes, and other details are not available when blocks are being outfitted in the shop, these items will need to be installed onboard the ship under more costly conditions, often by cost factors of 3–5 times. These factors have been quoted by shipbuilders in Japan, Korea, and Northern Europe for commercial ships, typically much less complex (and less dense) than naval vessels. Hence, it is reasonable to suggest that the higher density naval vessels would suffer much higher cost factors during latter stages of construction.

Labor hour savings from early-stage outfitting is a key objective of an effective build strategy, and it is dependent on timely design availability. Therefore, for a cost estimate to be realistic the following issues need to be considered and their effects included:

- Availability and capability of facilities
- Experience and skill level of work-force
- Quality of planning and early-stage outfit scheduling
- Experience and competence of management
- Efficiency of business practices
- Relative design complexity and producibility
- Quality of design and engineering
- Magnitude and timing of change orders

All of the aforementioned issues influence the relative level of productivity for the shipbuilder working on a given contract. The PODAC Cost Model provides for several types of productivity factors:

- For technical support
- For structural manufacturing and assembly work
- For outfit manufacturing and assembly work
- For material costs

The Cost Model provides indications of cost differences between shipyards of various sizes and the impact upon higher costs expected from shipyards building naval ships. For the notional shipyard, each of the aforementioned productivity factors equals 1.00. The factor is greater than 1.00 for a less productive shipyard, and less than 1.00 for a more productive shipyard.

4.3. Selected shipbuilding productivity factors

During the development of PODAC in the late 1990s, relative productivity was researched from a number of different sources. The study also compared data obtained from various commercial shipyards and several projects involving Northern European shipyards. Additional productivity factors were compiled and reported by Koenig et al. (2003) for East Asia. The key point is that different productivity factors are used in the cost model depending on the type of ship (commercial, naval auxiliary, combatant, etc.) and the expected cost performance of the shipbuilder. More information can be found in the user documentation for the PODAC cost model.

4.4. Ship density affecting construction labor productivity

In 2009, a cursory study was made to determine if there is a cost benefit to reducing the relative density of ship outfit systems. Intuitively, it might be expected that when on-board spaces become very dense with equipment and systems, the workers have more and more difficulty accessing their work areas and their relative productivity becomes degraded. Of course, when productivity levels decrease, labor hours and costs increase. This condition is less of a problem if the equipment and outfit systems can be installed earlier on block where accessing work is much less of a problem than if the work were done on-board.

A very crude measure of the producibility of an early-stage ship design is ship outfit density. Grant (2008) defines a number of measures of ship outfit density. Two are ratios of ship outfit weight (or light ship weight minus ship structure weight) divided by either total molded volume or floodable volume of the hull (also known as volume of displacement). For the Cost Demonstration described in the next section, ship outfit density is calculated as follows:

$$\text{Ship Density Factor} = \sum(\text{SWBS200} - 700\,\text{mt weights}) \\ / \text{ Ship m3 Volume of Displacement } \nabla$$

The research of Grant (2008) and Figs. 2 and 3 provide reasonable evidence that labor costs do increase with density. The PODAC Cost Model developed a labor productivity factor (the higher the factor, the more labor hours that are estimated) that is a direct function of outfit density. Figure 4 shows this labor productivity factor as an approximate correlation of the impact of outfit density on labor productivity. The exponential equation in Fig. 4 exhibits what appears to be the most realistic relationship for the ship types selected for the study described in the next section. A productivity factor (labor hour multiplier) of 1.00 applies to expected outfit labor productivity for the less complex ship designs (e.g., tankers and bulk carriers) and forms the basis for many of the cost model cost estimating relationships (CERs). The higher the density, the greater is the productivity factor that is applied to the standard model outfit CERs.

NAVSEA (2005) defines a CER as a technique used to estimate a particular cost or price by using an established relationship with an independent variable. If one can identify an independent variable (driver) that demonstrates a measurable relationship with contract cost or price, one can develop a CER. That CER may be mathematically simple in nature (e.g., a simple ratio) or it may involve a complex equation.

Figure 4 is a critical factor in developing the cost estimate and is evidence of the many statistical surveys that have been made and that influence the conclusions. There is more information provided in the PODAC cost model's user documentation that shows actual production hours for different ships compared to their density factors. The documentation correlates these data with productivity factors that have been used in developing realistic cost estimates over the past 15 years. By plotting actual return hours against density factor for each weight group of SWBS 200–700 groups, there is some correlation between

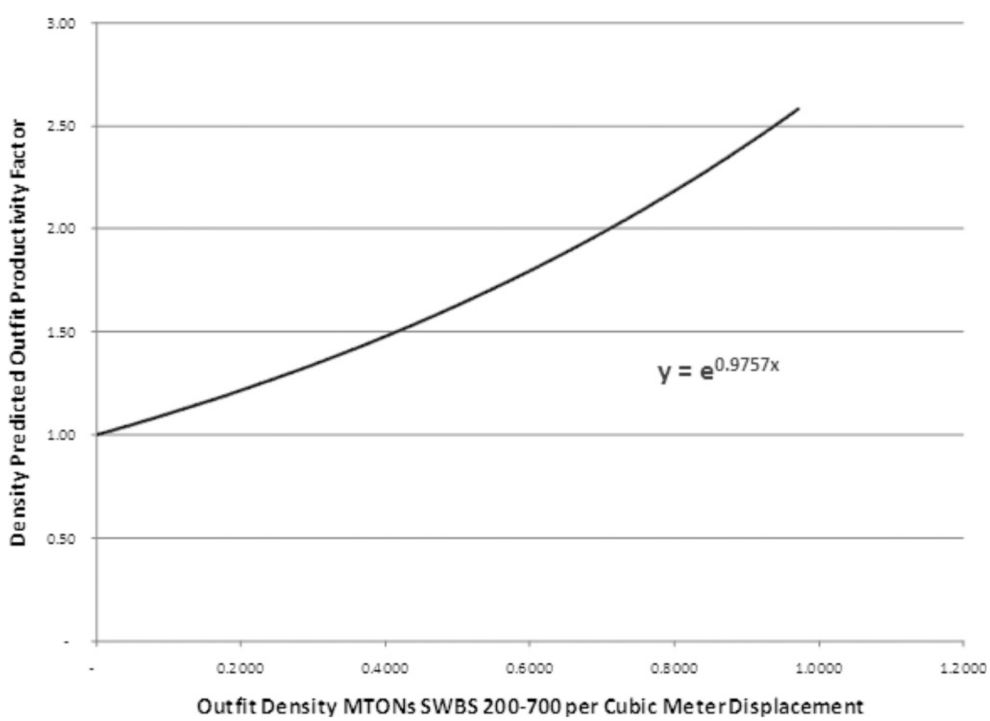

Fig. 4 Predicted impact of outfit density on labor productivity (SWBS 200 to 700 only)

Table 1 Ship characteristics of 150-meter 30-knot notional surface combatant

150 meter 30 Kt Surface Combatant			
Hull			
LOA, Length Overall	150.00	M	
LWL, Length Waterline	–	M	
Beam, Molded	16.42	M	
Depth, Molded	10.72	M	
Draft, Design Full Load, Molded	5.63	M	
ACCOMMODATIONS			
Commissioned Officers	19		
Noncommissioned Officers	18		
Enlisted	201		
	238		
MACHINERY CONFIGURATION	QTY	kW Each Max Service Speed	
Gas Turbine Direct Drive w/ CPP-LW2500 Plus	2.00	–	kW
Supplemental Power—Medium Speed diesel w/Gear Box	2.00	3,000	kW
ELECTRIC GENERATION AND DISTRIBUTION			
Ship Service Generator	4.00	1,200	kW
SPEED AND ENDURANCE			
Speed (Max)	30.00	KTS	
Speed (Cruise)	14.00	KTS	
Range (Max)	4,500	NM	

higher-density and higher labor cost. A range of ship types from commercial to combatants was considered, although there is a lack of data on USN surface combatants. The details of these actual labor costs are not available and no doubt are influenced by other factors besides density such as change orders and other engineering and production issues.

Figure 4 normalizes the trend correlation for a productivity factor that begins with the least dense designs (e.g., large volume cargo ships) and increases for the more complex, denser vessels such as combatants. The user of the PODAC cost model may select an outfit productivity factor that includes other considerations beyond just outfit density. As discussed earlier, these considerations may include the impact of expected quality of production engineering, production capabilities, and general shipyard labor performance.

5. Impact of ship density on cost demonstration

A cursory rough-order-of-magnitude (ROM) study was made to determine if there is a work content benefit to reducing the relative density of ship outfit systems. This study used SPAR's "Patrol Boat/Frigate Series" cost estimating model based on the PODAC cost model. A baseline frigate of 150 m length overall (LOA) was selected with the ship characteristics listed in Table 1. These ship characteristics fit well within the limits of the Patrol Boat/Frigate Series cost model.

5.1. Ship design statistical data

Figures 5 and 6 show a plot of full load displacement versus LOA and hull slenderness ratio (SLR) versus full load displacement. The survey data were collected from many ship designs, ranging from patrol boats to destroyers, domestic and foreign, and provide the basis for cost model default design values. Then, as more design details are made available, the actual design values can be entered to over-ride the default values provided by the cost model. The use of statistical values has been very helpful in early stages of design. We acknowledge these statistical values do not necessarily result from rigorous design analyses and introduce uncertainty related to curve fitting, but they have proved to be "close enough" to see the relative trends in costs. This notional ship design was used to simulate what happens when the hull is lengthened and how that affects cost.

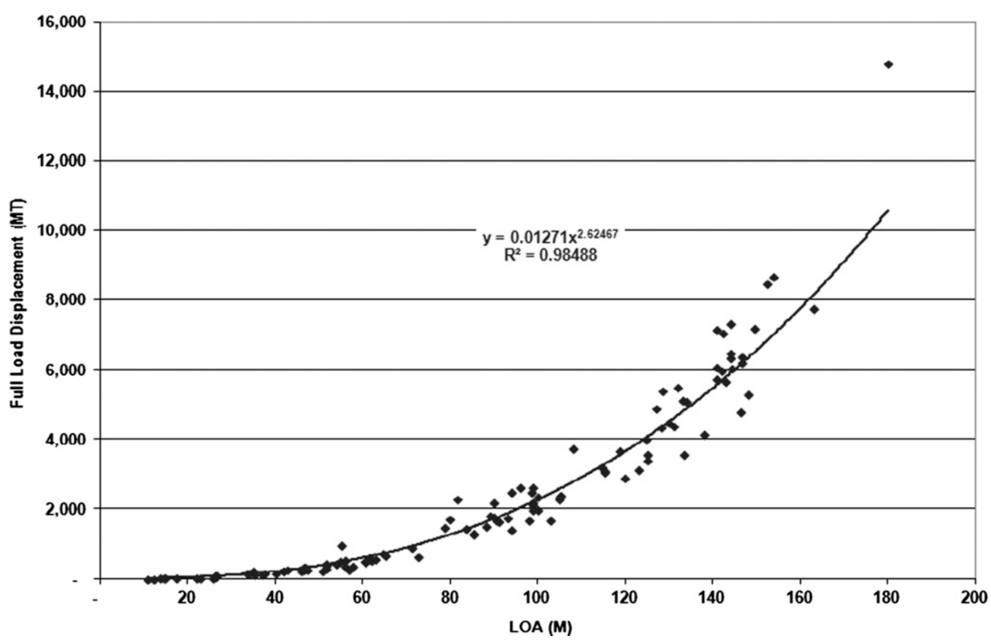

Fig. 5 Patrol boats, cutters, and frigates full load displacement versus length overall

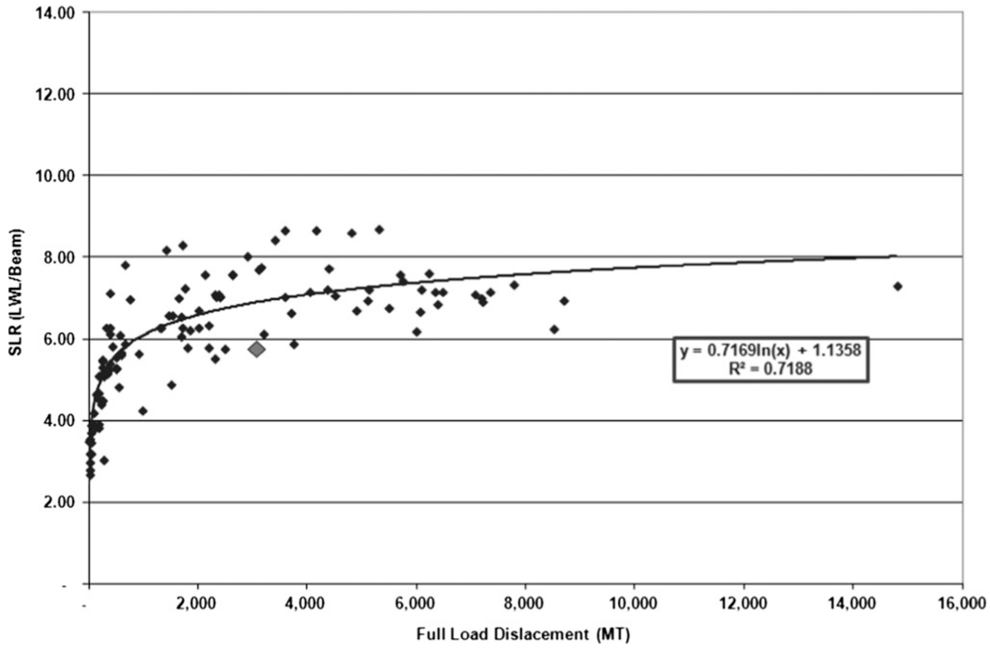

Fig. 6 Patrol boats, cutters, and frigates slenderness ratio (SLR) versus displacement

Figure 7 shows the statistical survey of propulsion power (kW) versus the product of speed times displacement (Kts $\times$ ∇). This simple propulsion power relationship does not consider the effects of hull SLR upon power requirements. Figure 8 shows the relationship.

Choosing one of the fitted curves in Fig. 8, the following formula may be applied to estimate the propulsion power:

$$\mathrm{kW} = [2.7708 \times e\hat{} - 0.296\,\mathrm{SLR}] \times \mathrm{Kts} \times \nabla$$

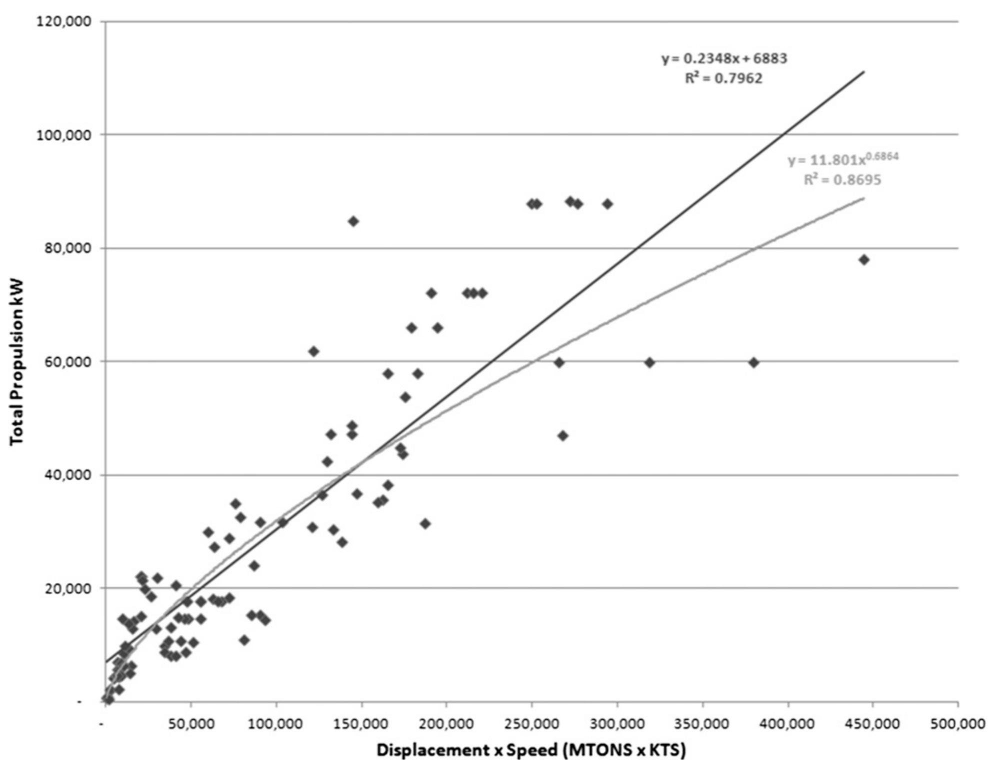

Fig. 7 Propulsion requirement versus displacement $\times$ speed

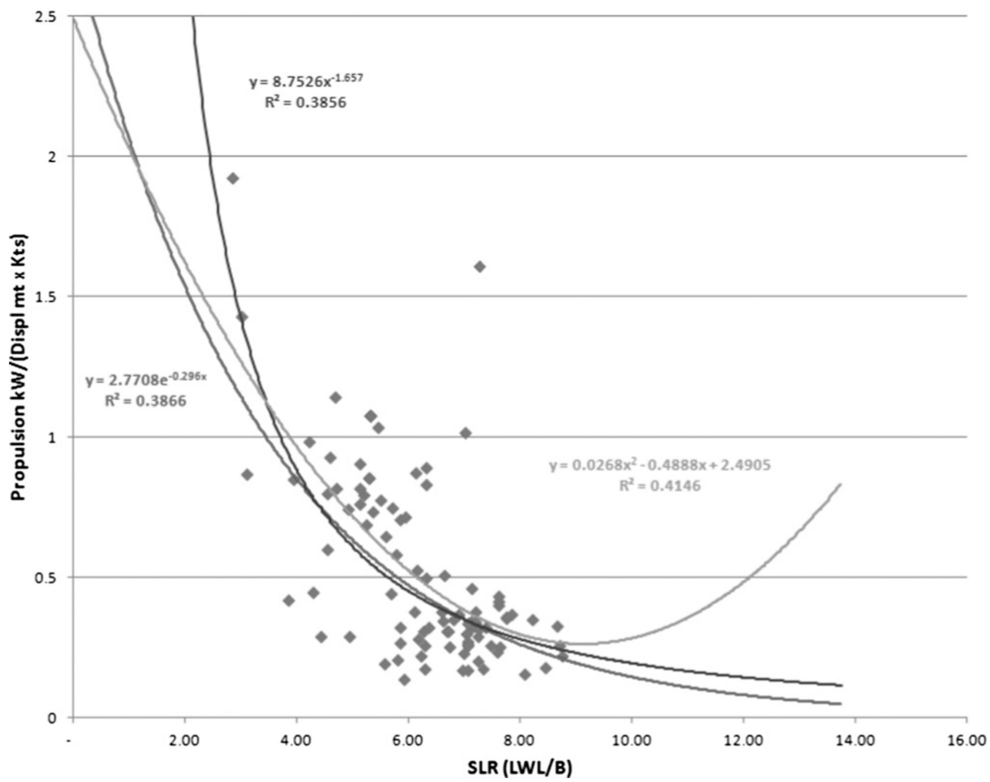

Fig. 8 Propulsion requirements versus SLR

Note that the curve clearly will not reduce to zero kW when SLR reaches a very high value. Frictional hull drag will become more dominant and cause the power requirement to increase as the hull gets longer and longer.

5.2. Effects of changing hull length

The study incrementally stepped through LOAs from 135 m up to 180 m; 150 m was selected as the baseline. As shown in Fig. 9, propulsion was left a variable, since an increase in the hull SLR (LWL/Beam) would enable less power to maintain the same speed. Although the propulsion system kW changed with each increment of LOA, electrical systems were kept more or less constant (same electric generation) for each increment. Auxiliary systems were left to follow the general requirements of the propulsion system. Some piping systems such as bilge and ballast were left to change with the size of the hull. It was assumed that general outfit for each increment remained the same except for items such as hull insulation and coatings. Ship structure was left to change with the change in LOA except superstructure systems were kept the same throughout the study as were the accommodations outfit. We emphasize that the baseline is not an actual ship, but a notional ship used to study the density effects on cost.

Figure 10 shows the changes in outfit density and the corresponding changes (about 10%) in the labor hour multiplier—the higher the multiplier, the more "should cost" labor hours. Note that lengthening the hull can result in lower labor hours due to the lower labor hour multiplier. It needs to be said that there is some uncertainty in the prediction method for the labor hour multiplier. Also, productivity problems with high-density outfit spaces can be somewhat reduced in design with outfit packaging techniques and in planning with maximum early-stage outfitting. Nevertheless, these best shipbuilding practices are beneficial for a lower-density ship as for a higher-density ship.

Figure 11 shows the reduction in labor hours and cost due to the potential improvements in productivity with lower outfit density. Most of the reduced labor hours are due to smaller propulsion systems that offset the increase in labor hours to manufacture and assemble the larger hull. We recognize that propulsion plants do not necessarily come in linear sizes, but it is noted that the CERs for SWBS Group 200 (propulsion)—are some of the highest CERs, much higher than those for SWBS Group 100 (structures).

There are other effects on cost not modeled in this study, such as the degree of preoutfitted hull blocks, use of modular system components and equipment, and relative producibility of the detailed engineering. In addition, for U.S. Navy ships, longer, more slender hulls must be evaluated to ensure technical feasibility in meeting damage stability requirements. Finally, one could also respond that the modeled labor savings by making the hull longer are not that significant. Unfortunately, many of the CERs used in the study are a smear of work on-ship and a blend of on-block and on-board that tends to minimize productivity problems. The biggest savings for making the hull bigger is for enabling onboard work to be more productive. Again, much more research needs to be done to compile better labor hour (work content) data relative to density, especially for U.S. Navy ships.

The simple model used for this study can be tweaked further to provide better results. This study really is just a start. On the other hand, the analyses do show a potential for more focused development of new design characteristics. There may

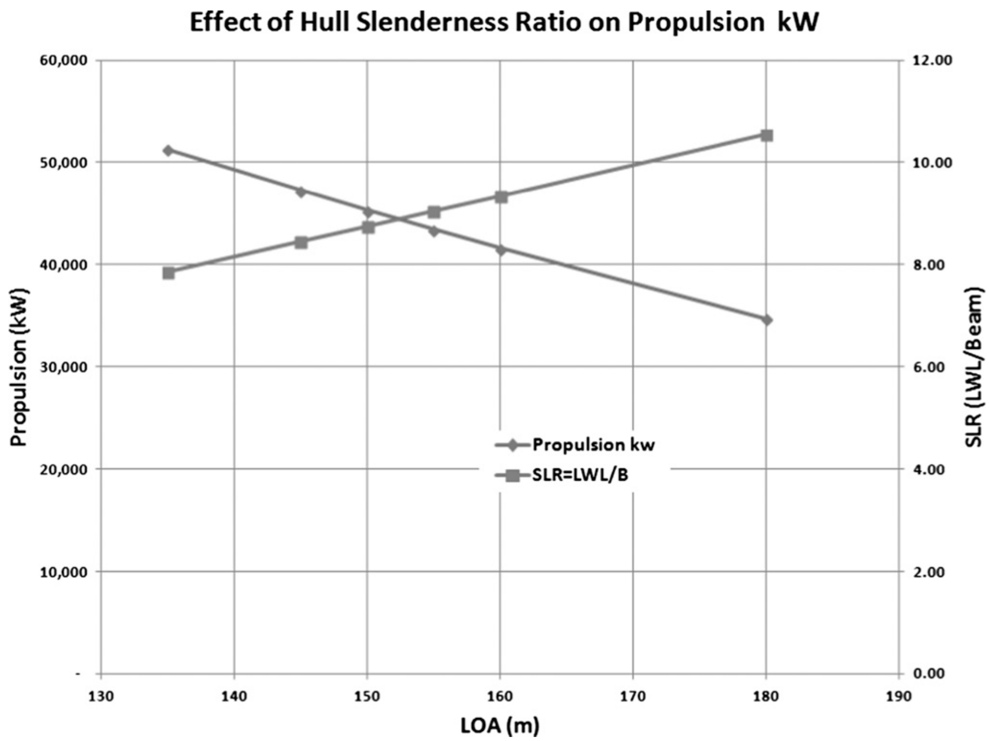

Fig. 9 Total propulsion power (kW) and hull SLR versus length overall (LOA)

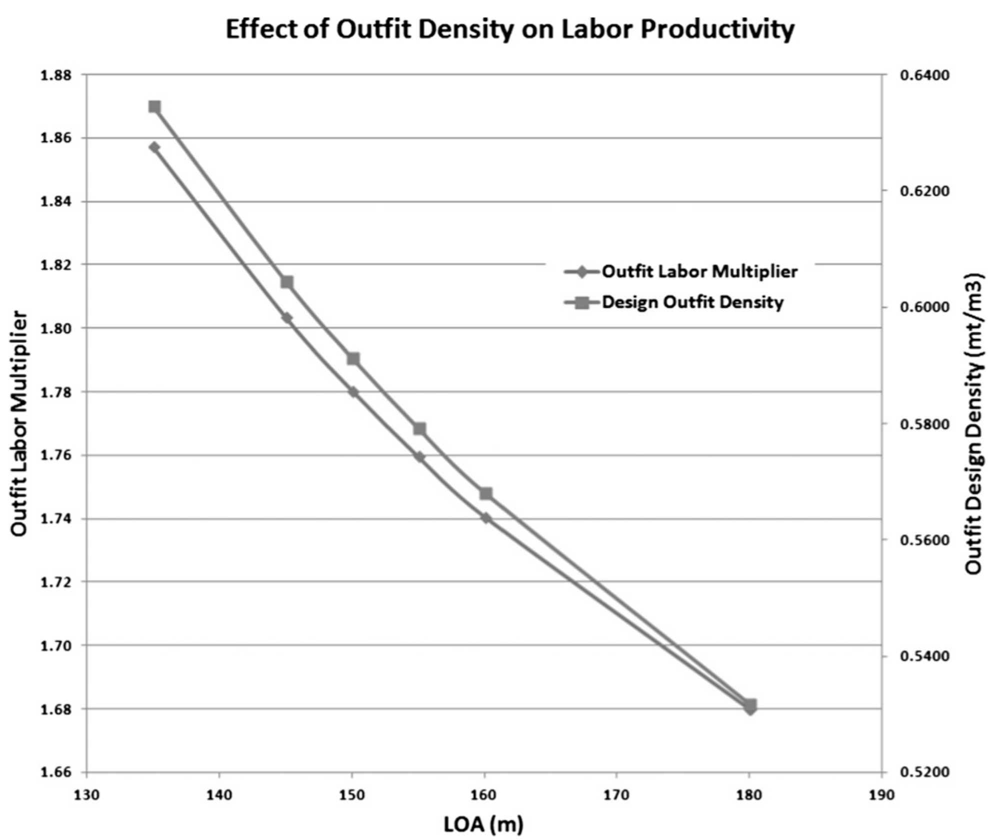

Fig. 10 Outfit density and outfit labor multiplier versus LOA

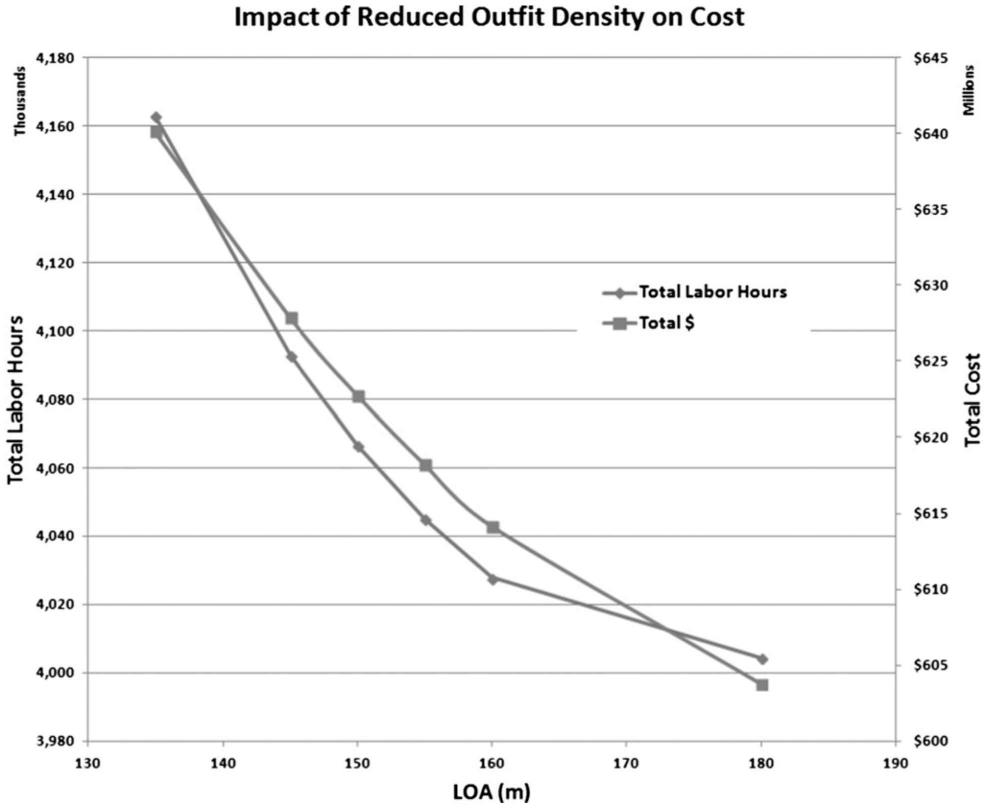

Fig. 11 Total hours and cost versus LOA

be an optimum selection of characteristics that will minimize construction labor hours or cost while still maximizing mission requirements. Density impact on work content and cost is important to model early in the development of a design. Evaluating work content or complexity in a design has merit as an integral part of the early ship design cycle. We cannot emphasize enough that there is a lot more research required for developing more analytical methods to relate the many independent variables (cost drivers) to shipbuilding work content or costs for more cost-effective early-stage design decisions.

6. The way ahead

AT&L (2013) found that contract work content growth dominates total cost growth statistically. Previously, Keane (2012) and Keane and Tibbitts (2013) identified that unnecessary, unidentified work content can be locked in a ship design in the initial sizing of the hull during ship concept design studies. And based on benchmarking studies of U.S. shipyards, first marine international (FMI 2005) estimated that a U.S. destroyer contains 50% more work content than a comparable modern international destroyer. FMI contended that a significant portion is due to the density and general complexity of U.S. vessels. Combined with the results of the ROM study described above, the major findings are:

- Density impact on work content or labor hours is important to model early.
- Further research needs to relate density/build strategy/design maturity/etc., to shipbuilding work content or costs so that cost models can be more effectively utilized for early design decision-making.
- These higher fidelity cost models need to be integrated with existing Navy early-stage ship design tools.

Although the process-based PODAC cost model was developed for NAVSEA (Trumbule et al. 1999), and NAVSEA has utilized a design for producibility methodology applying a build strategy in early design (Bunch et al. 2006), these have been ad hoc initiatives. Therefore, these need to be assimilated within NAVSEA's early design stage integrated design environment. With additional development and integration into early-stage ship design tools, these could be used by ship concept design engineers to compare the work content of early-stage ship designs. The PODAC Model could be the analytic model to actually drive simulations of how a ship concept will be designed and constructed.

As previously described, there are many benefits offered by incorporating higher fidelity cost models with early-stage ship design tools. Even though the ROM study defined above was based on a simple parametric design analysis, it was still effective at comparing work content of crude alternative designs. The PODAC cost model, which models how ships are actually designed and constructed, could be even more effective when integrated with the Navy's early-stage ship design tools. As shown in Fig. 12, these include the ship synthesis model ASSET (Advanced Ship and Submarine Evaluation Tool), the design analysis product model LEAPS (Leading Edge Architecture for Prototyping Systems), the newly developed integrated design environment RSDE (Rapid Ship Design Environment), and other physics-based design and analysis tools.

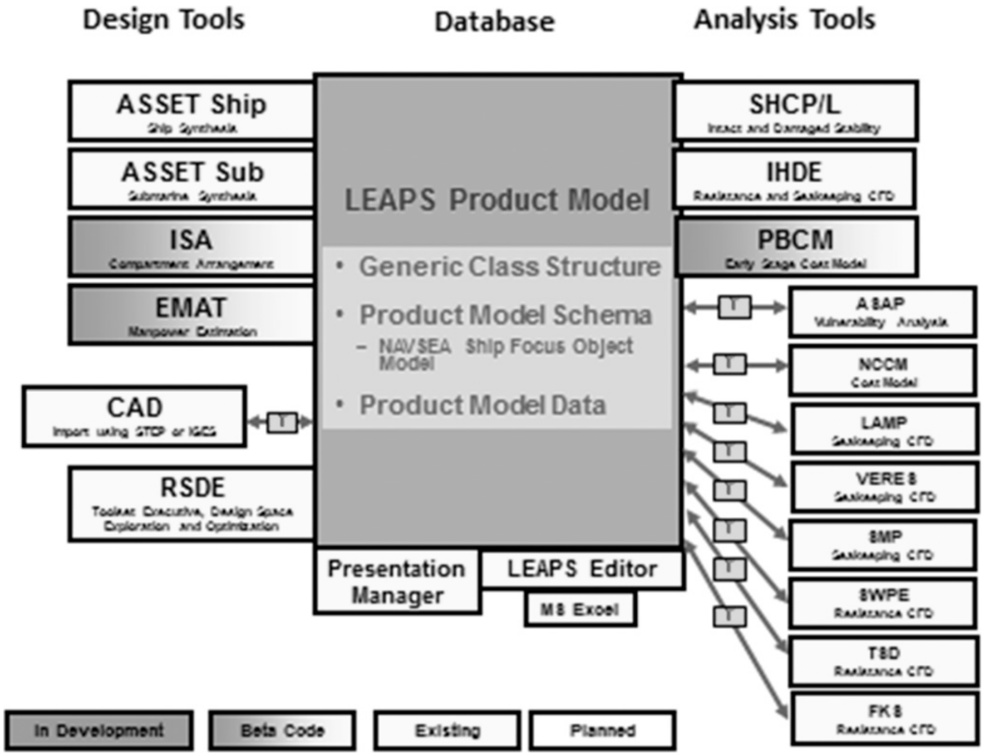

Fig. 12 Rapid ship design environment (RSDE) and LEAPS product model

RSDE is being developed under the Computational Research and Engineering Acquisition Tools and Environments (CREATE™)-Ships Project, which was initiated in 2008 by the DoD High Performance Computing Modernization Program (HPCMP). RSDE provides a graphical user interface (GUI) to DSE and multidiscipline synthesis and optimization. RSDE is a multiuser environment and will serve as a decision aid through visualization of the trade space.

This would allow the PODAC model to extract ship characteristics (weights, volumes, machinery specs, etc.) from ASSET so that the model could produce estimates of work content with very little additional user information. One of the ideas behind the integration of the PODAC model into LEAPS would be to make work content an integral part of the ship design optimization system.

In addition to process models like PODAC permitting quick assessments of work content, risk, and other design trade-offs, they can also be used to evaluate alternative build strategies for improved ship producibility. Combining process models like PODAC with different build strategies, these models could automatically generate estimated engineering and shipyard production manpower comparisons to evaluate work content of alternative design-build approaches.

7. Conclusions

Decision-makers want detailed cost analyses complete with confidence factors, but in early-stage design, time and other resources are limited, yet the solution space is enormous. Although there are available cost data, the data are by no means comprehensive. The limited analysis presented here is just a start, but shows promise for further work. The labor productivity factors in the PODAC cost model have been very useful in assessing whether or not estimates need to be increased to accommodate designs that are more complex and denser. Results from using PODAC have been well received and recipients appreciate the insight that is provided.

There are many benefits of incorporating process-based cost models like PODAC into the CREATE™—Ships RSDE configuration. These models must be very flexible and provide many default characteristics of a ship design if they are not available; then they can be easily over-ridden with actual design information as the design evolves. The defaults must be based on comprehensive statistical analyses of surface ships and their various characteristics. This will enable work content to be evaluated from the earliest design stages with minimal design details. As the design is developed, the estimates converge to firmer values and less risk.

One of the ideas behind the integration of a PODAC type model into LEAPS is for the model to store results back into the LEAPS database, thereby making work content an integral part of the ship design optimization system, RSDE. The PODAC type model will enable a very wide range of design/engineering options to be explored with immediate impact upon work content.

Ship design outfit density computations should be related directly to outfit productivity. ASSET can calculate these factors which should be grouped by ship type and plotted against man-hours for detail design and construction. There should be actual man-hour data for a wide range of ships that can be organized into a relational data base. This is not an exact science, but a reasonable conclusion can be made that the higher density ships do require more labor hours. The content of what is being assembled is something that does affect the labor cost, but in general, labor productivity does appear to decrease as density increases. The results of the study described above may need to be modified with further investigation and analyses, but the results are pointing in the right direction. Establishing ship density factor as the first-order ship producibility discriminator during requirements determination and concept design studies will significantly contribute to reducing detail design and construction work content by cost-effective decisions in early-stage naval ship design.

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