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The Impact of Producibility on Cost and Performance in Naval Combatant Design

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ABSTRACT

Will the US Navy take producibility seriously in the next surface combatant? It is not easy to challenge yesterday's design paradigms and standards. Combatant ship designers have been conditioned to optimize performance and minimize risk. Producibility enhancements can cut cost, but some compromise in performance is expected, and change implies risk. A rational approach to producibility requires that we understand the total impact of producibility enhancements on cost, performance and risk. This understanding must be applied through concurrent engineering from the very beginning of the ship design process. Engineering and cost models must be reliable, practical and sensitive to the cost and performance impact of producibility enhancements. This paper describes a concept design case study which evaluates producibility enhancements in hull form and primary structure. A comparison is made between producible DDG design variants and DDG-51, but conclusions are directed at future combatant designs such as SC-21. Conclusions emphasize areas for further research and the need to address producibility in concept design as part of a total ship design approach using Navy-industry integrated product teams (IPT's).

INTRODUCTION

Efforts to improve the producibility of LPD-17, the Navy's newest amphibious ship design, have been enthusiastic and extensive. Product-Oriented Design and Construction (PODAC) principles were rigorously applied to LPD-17 resulting in a contract design specifying many hull form, general arrangement, machinery arrangement and structural producibility enhancements [1]. Despite this success, implementing producibility enhancements will require a determined team effort in future surface combatant designs where performance is traditionally given the highest priority.

Standards and design paradigms with a history of performance success are difficult to challenge because they represent decades of cumulative experience. Frequently their engineering basis and cost are not fully understood. Even when contract guidance drawings are used in a ship specification to provide contractors with some flexibility for production improvements, options at later design stages are severely limited by weight and stability budgets. We cannot afford to continue this thinking. We must understand the engineering basis and total life-cycle cost of our design requirements and we must apply this understanding from the very beginning of the design process, particularly when change offers the prospect of producibility improvement and cost reduction.

This paper assesses selected producibility attributes in hull form and primary structure, particularly those attributes which are effectively locked-in during concept design. It is intended as a case study examining producibility in the context of the design process, necessary design tools and the design team. Comparisons are made between a DDG-51 baseline (DDG1) and several "producible variants". Payload is held constant between the baseline and variants. Ship and system characteristics not directly related to the producibility enhancements being considered are changed only when absolutely necessary. Sustained speed, range, seakeeping and cost are assessed in the producible variants and compared to the DDG1 baseline. Conclusions are made regarding the various producibility enhancements. Process-based cost estimating is used to insure sensitivity to producibility changes usually absent in weight-based estimating methods.

An effort is also made to estimate the cost of correcting distortion. Distortion is an important cost factor in surface combatants, but currently it is not considered. Distortion and residual stress are particular problems in smaller surface combatants. It is estimated that flame straightening alone in DDG-51 has a direct cost of $340K per ship and a total cost (direct plus indirect) of $3.4M per ship [2].

This paper demonstrates that producibility improvements can offer significant potential for life cycle cost reduction without severely impacting performance, even when our paradigms may lead us to believe that their potential negative impact on performance is unacceptable. The key to success and confidence in making these trade-off decisions is having reliable and sensitive cost and performance models. Past combatant designs have not brought together the necessary expertise, modeling and analysis tools to concurrently consider life cycle performance and cost when assessing producibility enhancements. The use of Navy-industry integrated product teams (IPT's) starting in concept design offers the potential to effectively address producibility issues as part of a total system approach to naval ship design [3].

PRODUCIBILITY ENHANCEMENTS

The last 20 years have produced a tremendous collection of ship producibility studies and recommendations which have potential application in surface combatants [4]. This paper considers only a subset of these. Enhancements which effect primary structure include:

1. Make maximum use of standard plate and stiffener sections [5]. Use WT stiffeners vice W-T. WT stiffeners are produced by splitting a single W shape (I beam) along the center of the web to form two identical T's [6]. They are available in standard shapes from mills and distributors. W-T stiffeners are full-depth W shapes with one flange stripped off to form one deep-web T and two pieces of scrap. This process is usually done by the shipyard. The Navy typically specifies deep-web W-T shapes to minimize weight, but there is a 25% wastage in stripping W-T shapes and significant distortion of the member [7]. Shallower and more uniform WT web heights may also permit piping and cable runs external to stiffeners and frames. This would avoid costly cutouts and reduce pipe fitting and cable pulling during construction and maintenance.
2. Avoid thin plate to reduce distortion. Costs to correct distortion should be explicitly considered when specifying thin sections. Residual stress resulting from flame and mechanical straightening should also be considered.
3. Design plate thickness transitions to be less than 0.5" or 1.5t for structural continuity and to minimize fitup [8].
4. Do not carry hull curvature into the structure inside of the hull plating [9].
5. Coordinate the height of the keel, inner bottom and bilge radius [8].
6. Run strakes in the same direction as primary framing [10].
7. Design for maximum use of automatic welding and other high producibility tools [9].
8. Design bilge strakes with the same thickness as bottom plates [5].
9. Design to facilitate assembly and erection with structural units, machinery units and piping units [9].
10. Where possible make port and starboard units similar [5].

Enhancements which effect hull form include:

1. Eliminate camber and sheer [10].
2. Maximize the use of flat panels, straight frames and single plane curvature [8,10]. Where possible each unit should have a flat area on which the remainder of the unit can be built [5].
3. Locate knuckles and chines at unit breaks, 9-12" from bulkheads and decks. Where possible make chines parallel to the baseline to use as unit breaks [9,10].
4. Maximize straight and convex waterlines [10].
5. Simplify the bow and stem shape [10].
6. Design the transom stern to be flat with sharp corner connections to the shell. Eliminate the stern casting if possible [10].
7. Provide adequate deck height for efficient outfitting.

DESIGN VARIANTS

A total of 7 DDG variants are assessed for cost and performance. Combinations of producibility enhancements used in these variants are listed in Table 1.

Table 1

	Shell		TBHD	DKHS		Above WL Hull Form			
Variant	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
DDG1									
DDG2	X								
DDG3		X							
DDG4	X	X							
DDG5			X						
DDG6				X					
DDG7					X	X	X	X	X

Baseline Design

The baseline design (DDG1) which is used for comparison and as a starting point for all other variants is similar to DDG-51 Flight 1. The hull form and midship section for DDG1 are shown in Figures 1 and 2.

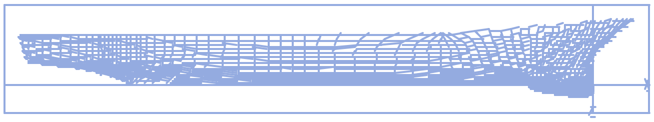

Figure 1

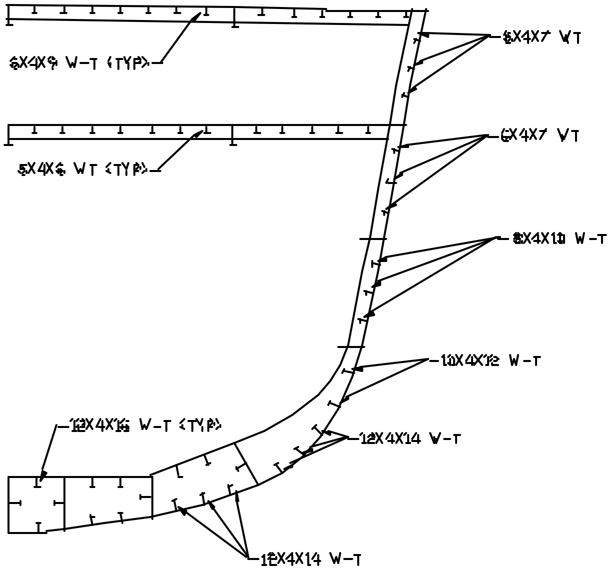

Figure 2

Baseline Hull Form. The DDG-51 hull form is designed to optimize seakeeping performance. It has significant double-curved camber and sheer, few flat panels or straight frames and little single plane curvature. Figure 3 shows a profile plot of Gaussian surface curvature for the baseline ship. Gaussian curvature is a product of minimum and maximum curvature and reflects the producibility of a surface. Gaussian curvature approaches zero as curvature in one or both of the principle curvature directions approaches zero. A surface with near-zero Gaussian curvature is considered a producible surface and is indicated by the black regions in Figure 3. Midships above the waterline in DDG1 is the only significant "producible" shell section.

Figure 3

Baseline Structural Design - Stiffeners. Most stiffeners in the hull and deckhouse of DDG-51 are specified as W-T shapes. The hull uses over 25 different W-T shapes requiring nearly 100,000 feet and 700 tons of W shapes to be deflanged. The flange material removed represents 25% of the weight of the original material and 170 tons per ship. This scrap must be handled and removed from the shipyard. Distortion and residual stress in the final W-T product cause distortion and fit-up problems later in fabrication and erection.

Baseline Structural Design - Plate Thickness and Distortion. There is significant variation in plate thickness in DDG-51 with relatively thin plate used in decks and in transverse and longitudinal bulkheads, particularly in the deckhouse. The use of high strength steel in thin sections increases payload fraction, directly and indirectly reduces ship displacement, reduces life-cycle fuel cost for a given payload and lowers VCG, but a major cost associated with these advantages is the significant increase in fabrication and maintenance problems associated with distortion. Waiting to correct distortion during unit fabrication or on-ship provides only limited results. In DDG-51, because of the high cost associated with changing the design, this is the only option remaining. In SC-21, distortion can and should be addressed in concept design.

Uniform scantlings, fewer thick to thin transitions, fewer attachments, and repetitive structural units (shapes and details) enable greater use of standard fixtures, hard tooling, controlled preheating, thermal tensioning, plastic prebending, dimensional monitoring, statistical process control, and distortion control based on modeling and empirical testing. A minimum plate thickness improves initial plate flatness and reduces distortion during stacking, transporting, shot blasting, preservation, fabrication and installation. Increased automation in the fabrication of standard units reduces overwelding, improves weld sequencing, and improves the accuracy of cutting, welding and fit-up. Strength is also improved by the reduction of crack initiation sites, structural misalignment and residual stress.

Distortion in DDG-51 is most severe in the 02 level deck, main deck, external deckhouse surfaces, bulkheads throughout the deckhouse and non-strength bulkheads on the DC deck. Numerous fixtures are used to control distortion during fabrication, transport and erection. The installation welding of outfitting items causes additional distortion. As vertical loads change during erection and ship launch, distortion reemerges, changes, and moves around. The effort and cost expended to control distortion including fixtures, straightening, damage to coatings, and disruption of other work, exceeds $3-5M per ship. Spot preservation never returns coatings to their original condition. This leads to corrosion and maintenance problems throughout the ship's life.

Methods used to control distortion are different at Ingalls Shipbuilding and Bath Iron Works (BIW), but the problems are the same and they result from the thin scantlings specified in the DDG-51 design. It is a design problem, but the weight and stability penalty associated with increasing these scantlings may exceed the cost savings associated with reducing distortion. It is essential that cost and performance impacts associated with distortion be understood in order to make rational structural design decisions.

Structural Variants

Structural variants DDG1 through DDG4 use the baseline hull form (Figure 1). In variants DDG2 and DDG4 W-T stiffeners are replaced with WT standard AISC shapes. Refer to Figure 4. A customized stiffener catalog is developed by evaluating section properties for all AISC W and WT shapes [6] and choosing a subset of shapes with good section modulus to weight ratios (moments are taken around the base to correspond with a panel neutral axis near the plane of the plate), local maximum values for stiffener depth, and reasonable values for flange thickness, flange breadth and web thickness. The total number of shapes selected is limited to ten. Variation in stiffener size in the producible variants is kept to an absolute minimum particularly when stiffeners are in the same panel or unit for fabrication.

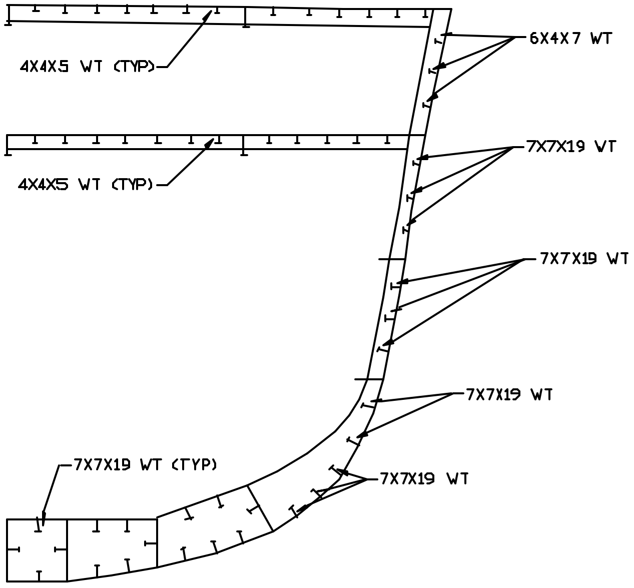

Figure 4

Baseline and variant structural designs are evaluated for structural adequacy using MAESTRO [11]. Figure 5 shows the MAESTRO model for the baseline design (DDG1). USN standard loads are used for the analysis. The weight change resulting from using WT stiffeners is relatively small allowing the baseline hull form to be maintained in variants DDG2 and DDG4 without seriously effecting performance.

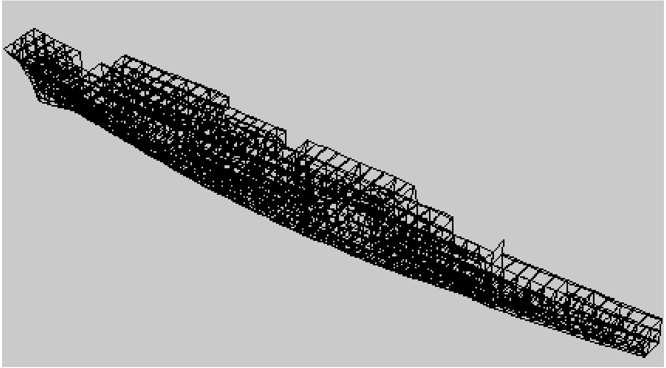

Figure 5

Table 2

Variant	LBP FT	BEAM FT	DRAFT FT	GMT/B	DISP LTON
DDG1	466	59.1	20.8	0.091	8557
DDG2	466	59.1	20.9	0.095	8618
DDG3	466	59.1	20.9	0.095	8619
DDG4	466	59.1	21.0	0.094	8685
DDG5	480	59.2	21.1	0.095	8987
DDG6	490	61.5	20.7	0.091	9278
DDG7	467	59.3	21.5	0.104	8784

Table 2 compares final ship characteristics for each variant. In variants DDG3, 4, 5 and 6 thin plating is replaced with thicker and more uniform sections. Large transitions are minimized and uniformity is increased. The impact of these changes is minimal in hull shell plating and most significant in decks, bulkheads and the deckhouse. Plate thickness is limited to two different sizes for the entire ship (1/2 inch and 7/16 inch). In variants DDG3 and DDG4 these changes are made in the hull plating and decks. The weight increase due to these changes is relatively small, stability improves, and the baseline hull form is maintained. In variant DDG5 the increased plating thickness in hull bulkheads results in significant added weight and the ship must be increased in length to maintain reasonable balance and performance. In variant DDG6, increased plating thickness in the deckhouse causes significant added weight and greatly reduces stability. This variant requires additional length and beam to balance with reasonable performance.

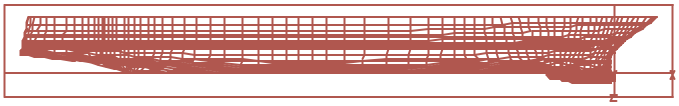

Figure 6

Hull Form Variant

In variant DDG7 hull form changes are made primarily above the design waterline (DWL) as illustrated in Figure 6. Hull form changes below the DWL are limited to fairing and adjustments necessary to accommodate the extensive above-waterline changes. All sheer and camber is removed. A chine is added just above the DWL, 12 inches below the second deck. Frames above the chine are straight and a large flat plate region is created aft and above the chine. The average hull deck height in DDG7 is 10.5 feet compared to 9 feet in DDG1. All deck panels are flat. Figure 7 shows the hull form with Gaussian curvature indicated (compare to Figure 3). Except for the transition between bow and midship regions, the entire hull above the waterline has single or zero curvature and is "producible" (black region). The producible region can be increased further by adding a knuckle at this transition. Hull form development and analysis is accomplished using FASTSHIP [12]. This hull form is incorporated into a balanced ship design using two raised-deck discontinuities in the otherwise flat sheer line as shown in Figure 8. Without sheer this stepping is necessary to maintain adequate freeboard forward, keep the weight increase to a minimum, and maintain adequate stability. Substantial reduction in deckhouse size is possible in this variant due to its larger hull volume.

Figure 7

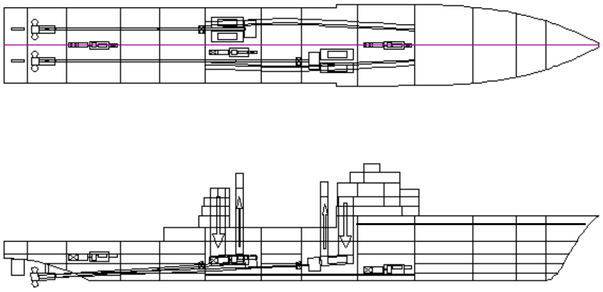

Figure 8

COST

Producibility improvements are frequently rejected because of the lack of data or reliable cost models to estimate their real cost impact. This is a major limiting factor in improving the producibility of US naval ships. Weight-based cost models are not sensitive to producibility enhancements and frequently predict cost penalties vice savings for valid cost-saving enhancements. A bottoms-up analysis of producibility enhancements requires a work content-based approach.

Cost Model

The National Shipbuilding Research Program (NSRP) has made a significant effort over the past decade to quantify and improve producibility. Their publications are a rich resource. NSRP 0405 attempts to identify a mutually acceptable technique for use by the Navy and industry in evaluating the construction cost of competing ship designs and design features [13,14]. This technique is based on the work content of the design rather than the weight of the design. The authors analyze methods used to estimate cost and enhance producibility in recent US Navy designs including T-AGS-45, SWATH-TAGOS, T-AGOS-19, FFG-7, SSN-21 and DDG-51. They interview key personnel at several shipyards and Supervisors of Shipbuilding. Based on this study they identify two basic techniques for evaluating producibility. The first is based directly on work content and material costs. The second identifies producibility criteria and uses expert opinion to informally assess producibility or to determine weighing factors for comparing alternative designs. This method does not directly calculate cost. NSRP 0405 endorses the work content-based approach as necessary to identify and effectively implement producibility improvements. It develops a set of cost-estimating computer programs as a basis and example of the work content-based approach. The major advantage of this method is that it provides an unbiased cost estimate necessary to evaluate new producibility concepts for which there is no historical data. The major disadvantage of this method is the level of effort and detail it requires to achieve a reliable cost estimate.

A more recent study, "Product-Oriented Design and Construction (PODAC)", continues the NSRP 0405 initiative [15]. The PODAC approach uses a combination of "re-use" modules and "zonal product" modules. A "reuse module" is any part of the ship (machinery space, deckhouse, bow), construction assembly, or interim product to which costs can be assigned, either by calculation or by return cost. A "zonal product" module is a unique portion or interim product of the ship for which costs must be calculated using a work content approach. These pieces are integrated to produce a total ship cost estimate.

Our study uses a combination of the NSRP 0405 and PODAC approaches. It uses the NSRP Cost Estimating Model [13,14] to estimate structural fabrication costs for interim products effected by the producibility enhancements being evaluated. These interim products are in structural groups 110 (hull shell and supports), 120 (hull structural bulkheads), 130 (hull decks), 140 (hull platforms and flats) and 150 (deckhouse). The model includes modifications recommended by Bunch [15], and an algorithm to estimate the cost of controlling distortion. Traditional weight-based methods are used to calculate cost for the rest of the ship. Fuel costs over the life of the ship are calculated based on hull resistance and a typical destroyer speed-time curve assuming 2500 underway steaming hours per year. All costs are discounted to 1995. The ships are synthesized and balanced using ASSET [17].

The NSRP model estimates work content based on type of process, shape, work orientation, stage and type of material. Labor cost is based on an a direct manhour rate of $40. Material cost is based on data obtained by Kriezis [16], Bloomquist's costs for W-T shapes [7] and private communications with shipbuilders and steel mills.

Cost of Distortion

Distortion and residual stress are particular problems in small surface combatants. It is estimated that flame straightening alone in DDG-51 has a direct cost of $340K per ship and a total cost (direct plus indirect) of $3.4M per ship [2]. There is no accepted method for predicting the extent or cost of distortion in complex ship structures. The most serious type of distortion in ship structures is buckling distortion which occurs during the fabrication and joining of stiffened plate panels. This distortion depends on may variables including material properties, pre-weld internal stress, welding voltage and current, welding sequence and physical restraints. Despite this complexity, welders, welding engineers and academic textbooks generally agree that, all other variables being optimal, the extent of distortion when welding stiffeners to plate and joining stiffened panels depends primarily on the plate thickness.

In order to make an approximate estimate of distortion expert opinion was solicited from US shipyards. An exponential curve was constructed relating extent of distortion as a fraction of plate area to plate thickness. The curve representing this relationship is shown in Figure 9. This curve was shown to shipyard workers involved in flame straightening and refined based on their input. This curve is used to estimate the area of plate requiring flame straightening. Direct manhours for flame straightening are estimated using Reference [18] data. The resulting relationship of direct labor manhours for flame straightening to stiffened panel plate thickness is shown in Figure 10.

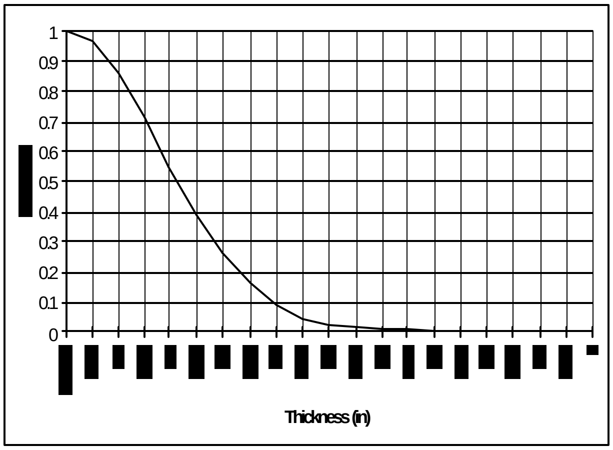

Figure 9

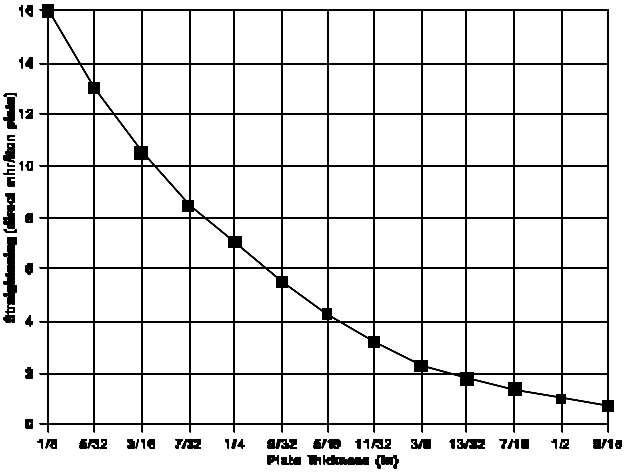

Figure 10

Reference [2] and subsequent conversations with the DDG-51 program office indicate that direct manhours to correct distortion account for only 10 percent of the total cost resulting from distortion. Ninety percent of the total cost results from disruption and represervation. All these factors are included in a simple algorithm to calculate the total cost of distortion as a function of plate thickness and area.

PERFORMANCE

Sustained speed, range, stability and seakeeping are evaluated for each variant. Radar cross-section (RCS) is assessed qualitatively with the intention of revisiting this assessment including the development of a topside design which specifically addresses RCS and producibility concurrently.

Sustained speed in calm water is calculated using Taylor Standard Series and in waves using a three-dimensional Rankine panel method. Seakeeping is assessed using Bales and McCreight indices [19,20] and the US Navy Ship Motion

Program (SMP). The Bales and McCreight indices provide a simple relative ranking based on hull principle characteristics and coefficients. SMP provides specific ship motion magnitudes.

RESULTS

Cost

Tables 3A and 3B provide cost results for the 7 variants considered. Table 3A summarizes results for those weight groups directly effected by the producibility enhancements being considered: shell and supports (SWBS 110), hull decks (SWBS 130), hull platforms and flats (SWBS 140), hull structural bulkheads (SWBS 120), deck house structure (SWBS 150), and total structure (SWBS 100). Group weight, material cost, and labor cost are included. Table 3B provides the results for the total ship including total weight and basic cost of construction (BCC) calculated using the process-based cost model and calculated using a traditional weight-based model. Table 3B also provides lifecycle fuel cost discounted to the base year of 1995. Fuel cost is added to BCC to provide a pseudo-lifecycle cost for variant comparison. A better comparison would be obtained by considering all life cycle costs.

Table 3A

	SWBS DIRECT					SWBS 100	
Variant	SWBS	LTON	MAT ($M)	MHR($M)	TOTAL ($M)	LTON	$M
DDG1	110,130,140	1196	1.14	6.03	7.18	3118	30.42
DDG2	110,130,140	1238	1.15	5.56	6.72	3173	29.96
DDG3	110,130,140	1239	1.18	5.47	6.65	3174	29.89
DDG4	110,130,140	1289	1.19	5.39	6.58	3239	29.82
DDG1	120	219	0.53	3.51	4.04	3118	30.42
DDG5	120	459	1.02	2.94	3.96	3508	33.24
DDG1	150	333	0.71	6.00	6.72	3118	30.42
DDG6	150	634	1.13	4.86	5.99	3734	34.24
DDG1	110,130-150	1529	1.86	12.03	13.89	3118	30.42
DDG7	110,130-150	1699	2.19	10.16	12.35	3291	28.73

Table 3B

	SHIP		WT-BASED	FUEL	FUEL +
Variant	LTON	BCC ($M)	BCC($M)	NPV$M	BCC ($M)
DDG1	8557	299.14	299.14	40.96	340.10
DDG2	8618	298.68	300.34	41.30	339.98
DDG3	8619	298.61	300.36	41.32	339.92
DDG4	8685	298.54	301.02	41.45	339.99
DDG5	8987	305.48	305.56	41.04	346.52
DDG6	9278	309.34	310.07	40.96	350.31
DDG7	8784	301.45	304.44	43.40	344.85

The use of a small standard set of WT shapes vice W-T shapes in the shell, hull decks and platforms in DDG2 results in a small increase in weight (2 % SWBS 100), a small decrease in BCC ($460K) and a small increase in fuel cost ($340K) for a net decrease in total cost of $120K. Fabrication cost for producing W-T shapes (and scrap) is included in the SWBS 110 material cost which is only slightly less than the cost of the heavier WT shapes. The WT shapes have a smaller surface area and require less blasting and coating than the W-T shapes. They also have fewer linear feet of end edges requiring less manual flame cutting, edge preparation and welding. Not considered in the model are WT cost benefits resulting from increased standardization, less distortion in the manufactured shapes, and potential benefits in outfitting. These savings could be significant. Overall, the use of WT shapes in the shell, hull decks and platforms should reduce life cycle cost.

Requiring a minimum 7/16 inch plate thickness in the shell, hull decks and platforms in DDG3 results in a 2 percent increase in SWBS 100 weight and a higher material cost. Labor hours are reduced through a 25% reduction in labor related to distortion (direct and indirect). The net effect is a small reduction ($530K) in BCC and a small increase in fuel cost ($360K) for a net decrease in lifecycle cost of $180K. Again, this does not consider the cost benefits resulting from increased standardization. DDG4 combines DDG2 and DDG3 enhancements with consistent cumulative results.

Requiring a minimum 7/16 inch plate thickness in hull bulkheads in DDG5 has a more dramatic impact. SWBS 100 weight increases by 390 tons compared to DDG1, requiring an increase in length of 15 feet (Table 2) in order to maintain a reasonable draft, sustained speed and range. This results in a net displacement increase of 430 tons. Although there are substantial labor savings achieved by minimizing distortion, these are not sufficient to prevent a $6M increase in BCC and lifecycle cost. The increase in length and resulting decrease in speed to length ratio minimizes the increase in fuel cost.

Requiring a minimum 7/16 inch plate thickness in the deckhouse in DDG6 has a similar weight impact compared to DDG5 with the added effect of a drastic reduction in stability. This requires an increase in beam of 1.5 feet and an increase in length of 25 feet in order to restore stability and maintain speed and range. This results in a net displacement increase of 721 tons. Distortion manhours are reduced by more than 75%, but this is not sufficient to avoid a net increase for the much larger ship of $10M in BCC and lifecycle cost.

Producibility enhancements in the hull form above the waterline in DDG7 have much more desirable and interesting results. Despite a 200 ton increase in displacement, a 4% increase in hull volume (hull deck height increased from 9 feet to 10.5 feet) is achieved for a $2M increase in BCC. Increased flat and single curvature panels in the hull reduce the manhours required for shaping and allow more automatic welding. The larger hull volume allows a substantial reduction in the deckhouse volume which is the best way of reducing distortion in the deckhouse. Manhour reductions due to reduced distortion in the deckhouse and improved producibility in the hull account for nearly $2M. This analysis does not consider the cost benefit in outfitting and maintenance for the increased deck height and increased standardization. These additional benefits in DDG7 are expected to be very substantial and need to be quantified.

Performance

A brief summary of the performance results is provided in Table 4. Sustained speed predicted using Taylor Standard Series (TSS) is nearly constant for variants DDG2, 3, 4 and 7. This is expected as these variants have nearly the same principle characteristics which are the basis of the TSS calculation. DDG 5 and DDG 6 are longer with lower speed to length ratio and higher sustained speed. Sustained speed trends are similar in waves except for DDG7 which has a somewhat different below-the-waterline hull form compared to the other variants. DDG7 has a slightly larger loss of speed in waves than the other variants consistent with degraded seakeeping performance. SMP results for pitch (Sea State 6) are shown for DDG1 and DDG7 in Figures 11 and 12. DDG7 shows slightly more pitch in head seas than DDG1. Other SMP results show similar minor degradation in DDG7 seakeeping. Bales and McCreight indices do not show this trend. Improved seakeeping indices for DDG 5 and 6 are due primarily to their larger displacement. None of the tools used in this analysis consider the impact of above-the-water hull form changes on resistance and seakeeping.

Table 4

	DISP	LBP	BEAM	DRAFT	SUST	SUST	RANGE	SEAKEEPING	
Variant	LTON	FT	FT	FT	KNOTS	(Waves)	NM	BALES	MCCR
DDG1	8557	466	59.1	20.8	29.7	29.3	3846	18.5	14.4
DDG2	8618	466	59.1	20.9	29.7	29.2	3815	19.3	14.4
DDG3	8619	466	59.1	20.9	29.7	29.2	3814	19.3	14.4
DDG4	8685	466	59.1	21.0	29.7	29	3802	19.4	14.4
DDG5	8987	480	59.2	21.1	30	29.6	3839	20.7	15.8
DDG6	9278	490	61.5	20.7	30.1	29.8	3847	22.3	17.4
DDG7	8784	467	59.3	21.5	29.4	28.7	3630	19.5	14.5

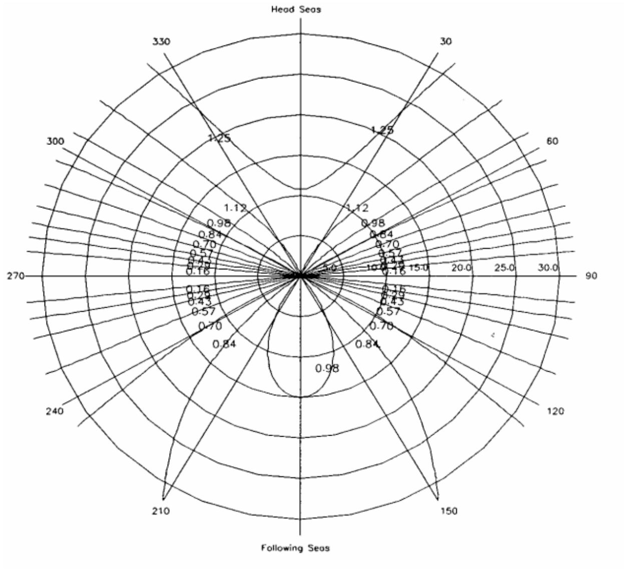

Figure 11

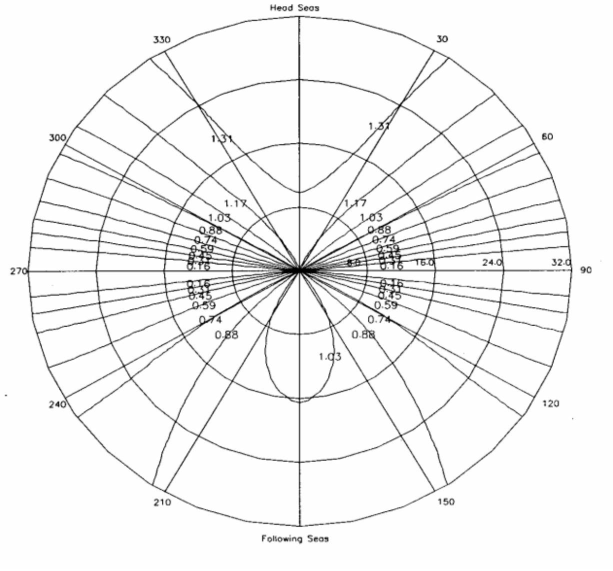

Figure 12

CONCLUSIONS

Producibility Enhancements

Conclusions concerning the specific producibility enhancements considered in this study are:

1. The use of standard WT shapes vice stripped W-T shapes provides modest direct-cost savings for a small increase in weight, and minimum performance impact with the potential for additional savings due to standardization and less distortion in the stiffeners.
2. Minimum plate thickness requirements to reduce distortion in the hull and hull decks can provide modest savings. Indiscriminate application of minimum thickness requirements can result in substantial increases in weight and significant ship impact with a net increase in cost despite substantial reduction in distortion.
3. Increased plate thickness should be considered for only the worse distortion trouble-spots in the deckhouse. Stability considerations cause significant ship impact which results in substantial cost increases.
4. The best way to reduce distortion in the deckhouse is to reduce the size of the deckhouse. This may require additional masts (possibly composite) to support sensors and weapon systems, but with a suitable hull design may also serve to reduce RCS.

5. Producibility enhancements in the hull form above the waterline can provide significant reduction in fabrication manhours. The performance impact of these changes appears to be small, but additional analysis is required to assess seakeeping and hull resistance in waves. Increased deck height may provide significant reduction in outfitting cost, but the current model is not sensitive to this change.

The Process

The most important benefit gained from this study is a greater appreciation for the need and the difficulties to concurrently consider performance, cost and risk from the very beginning of the design process. If any of these aspects is neglected or assessed incorrectly, the answer can simply be wrong! Just as weight-based cost models can be misleading, sophisticated but inaccurate or insensitive process-based models or performance models can require ten times the effort, and be just as wrong. A significant obstacle to a rational total-ship design process is the lack of convenient and effective cost and performance models, and the inaccessibility of the best expertise to solve particular aspects of the design problem.

Specific limitations identified in this study include:

1. The need for early-stage design and production models and expertise to accurately estimate work content and cost. These models must be sensitive to critical variables effecting cost, performance and risk including fabrication details, increased standardization and the cost of distortion. Potential shipbuilders have the best data and the most complete appreciation for their unique production processes to formulate a shipbuilder-unique (vice generic) build strategy and accurately estimate work content and cost.

2. The need for accurate models and expertise to predict and control distortion. Increased standardization and automation enable the practical application of these tools. Laboratories, academia and contractors have the best expertise in this area [21].

3. The need for accurate models and expertise which consider the above-waterline hull form to assess seakeeping and resistance in waves. Non-linear seakeeping programs are on the cutting edge of technology. Navy laboratories, academia and contractors have the best expertise in this area.

4. Measures of ship performance (MOP's) are not the ultimate measure of military effectiveness. Measures of Effectiveness (MOE's) which consider ship performance on specific missions in specific operational scenarios must be considered. The Navy and Navy laboratories provide the best expertise to determine and assess these MOE's.

5. The need for accurate life-cycle cost data, models and expertise which are sensitive to critical design variables such as fabrication detail and sequencing. The Navy, ship repair contractors and shipyards have the best expertise in this area.

These are only examples of the broad range of problems, models and expertise necessary to assess producibility enhancements in a naval combatant design. Although the necessary expertise and many of the necessary tools exist to apply to this problem, they do not exist in one place! The Navy cannot do this analysis alone. They must apply the best expertise available to the many and varied aspects of the problem (Figure 13). The use of Integrated Product Teams (IPT's) including DoD, Navy, shipbuilders, contractors and academia offers the greatest potential for solving a problem of this scope [3]. Huthwaite's Third Truth states: *Multifunctional teams are the key to solving the total design equation* [22]. Figure 14 illustrates a notional approach for executing naval ship design. It specifies the use of IPT's from the beginning of concept design. Unfortunately, bringing industry onboard at the start of concept design poses significant logistic and contractual problems.

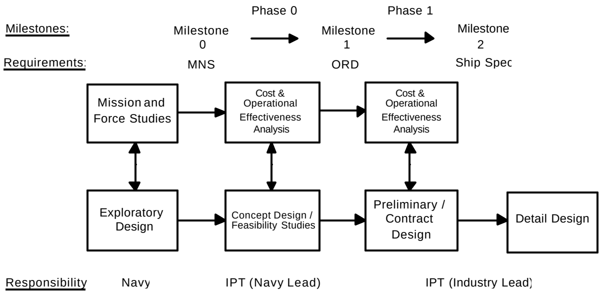

Figure 13

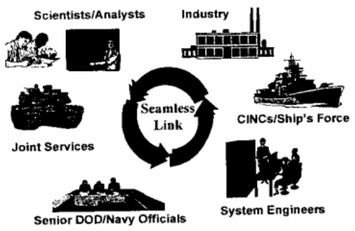

Figure 14

Collocation is important to the effectiveness of IPT's, but it is difficult and costly to assemble geographically-dispersed experts for extended periods of work. One potential solution to these logistic problems is the concept of "virtual collocation" and the "Design Team of the Future"

[23]. Various electronic media can be used as a means of expressing the design, capturing design knowledge, structuring design arguments and organizing presentations and team interaction. Many of the elements for this vision already exist: CAD workstations, 3-D models, product databases, computer-integrated video teleconferencing, groupware and international broadband digital networks [24].

Ensuring fair and open competition actually poses more of a challenge than the logistics of collocation. Providing for innovative and flexible contractual arrangements with necessary incentives while maintaining an even contractual playing field is a difficult and long-standing problem. A potential solution may be to award multiple concept design contracts with multiple IPT's at Milestone 0, competing for downselection to one or two teams at Milestone 1, and final selection at Milestone 2.

We must take producibility seriously in our next surface combatant and all future ships. Our best experts (Navy, industry, academia) working in an environment of collaboration and trust must be utilized in a rational ship design process that is not restricted by past design standards and paradigms. We can no longer afford performance at all cost. We must effectively assess and consider life cycle cost, performance and risk from the very beginning of the design process and we must implement the results of this analysis in our future surface combatants.

We must do this together.

REFERENCES

[1] Fireman, H. et al., "LPD-17: In the Midst of Reform", *Naval Engineers Journal*, May 1995, pp. 267-282.

[2] Cole, B., "Cost of Non-Fairness of Thin Plate Steel Decks and Bulkheads During Construction of New Ships for the US Navy", NJC/NCEMT Workshop: Navy Needs for Prediction and Control of Distortion and Residual Stresses in Fabrication of Welded Components, 1994.

[3] Keane, R.G. and Tibbitts, B.F., "A Revolution in Warship Design: Navy-Industry Integrated Product Teams", *Journal of Ship Production*, Vol. 12, No. 4, November 1996, pp. 254-268.

[4] Bunch, H., "Catalog of Ship Producibility Improvement Concepts", *Journal of Ship Production*, Vol. 11, No. 3, August 1995, pp. 203-207.

[5] *Manual of Steel Production*, American Institute of Steel Construction, October 1994.

[6] Bong, H.S. and W. Hills and J.B. Caldwell, "Methods of Incorporating Design-for-Production Considerations into Concept Design Investigations", *Journal of Ship Production*, Vol. 6, No. 2, 1990, pp. 69-80.

[7] Blomquist, P., "Tee-Beam Manufacturing Analysis: Producibility of Panel Stiffening Element", *Journal of Ship Proction*, Vol. 11, No. 3, August 1995, pp. 171-186.

[8] Bethlehem Steel and A&P Appledore and JJ Henry, *Design for Production Manual*, Vol III, NSRP #0236, UMRTI #73531, 1985.

[9] Kraine, G. and S. Ingvason, "Producibility in Ship Design", *Journal of Ship Production*, Vol. 6, No. 4, 1990, pp. 255-267.

[10] Lamb, T., *Engineering for Ship Production, NSRP #0219, UMTRI #72960*, 1986.

[11] *MAESTRO*, Method for Analysis, Evaluation, and Structural Optimization, computer code distributed by Proteus Engineering for Owen Hughes, Version 7.0.

[12] *FASTSHIP*, computer code distributed by Proteus Engineering, Version 4.37.

[13] *Producibility Evaluation Criteria Cost Estimating Computer Programs - Manual*, NSRP Project 0398, December, 1993.

[14] *Development of Producibility Evaluation Criteria*, NSRP Project 0405, December, 1993.

[15] Bunch, H. et al., *Product Oriented Design and Construction (PODAC) Cost Model Development*, ONR Report, May, 1995.

[16] Kriezis, G., "Standardization in Ship Structural Design", *Journal of Ship Production*, Vol. 7, No. 1, 1991, pp. 37-46.

[17] *ASSET*, Advanced Surface Ship Evaluation Tool, NSWC Carderock, US Navy, Version 3.3, June 1993.

[18] Mason, Bob, "Accuracy Control at Newport News Shipyard", presentation given at a Workshop in Strategies to Control Distortion and Residual Stress in Naval Shipbuilding, sponsored by The National Center for Excellence in Metalworking Technologies and the Navy Joining Center, August 30, 1995.

[19] Bales, N.K., "Optimizing the Seakeeping Performance of Destroyer Type Hulls", Thirteenth Symposium on Naval Hydromechanics , Tokyo, Japan, October, 1980.

[20] McCreight, W.R., "Estimating the Seakeeping Qualities of Destroyer Type Hulls", DTNSRDC/SPD-1074-01, January, 1984.

[21] Michaleris, P. and DeBiccari, A., "A Predictive Technique for Buckling Analysis of Thin Section Panels Due to Welding", *Journal of Ship Production*, Vol. 12, No. 4, November 1996, pp. 269-275.

[22] Huthwaite, B., *Strategic Design, A Guide to Managing Concurrent Engineering*, Institute for Competitive Design, 1994.

[23] Design Team of the Future Conference, Massachusetts Institute of Technology, December 4, 1996.

[24] Ishii, H. et. al., "Iterative Design of Seamless Collaboration Media", MIT Media Lab, 1996.