Estimation of Ship Construction Costs

by

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B.S., Naval Architecture and Marine Engineering (2005)

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Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering at the
Massachusetts Institute of Technology
June 2006

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OUTLINE

LIST OF FIGURES

ACKNOWLEDGEMENTS:

I would like to express my sincere appreciation and many thanks to my thesis advisor, Professor Henry Marcus. His continued help, guidance, and trust throughout my tenure at MIT from acceptance to graduation will stay with me forever.

I would also like to thank Laurent Deschamps who ever so patiently and painstakingly helped me understand the detailed inner workings of the PODAC system and the benefits that it presents to ship cost estimating. It is also necessary to mention John Hootman and his other associates from NAVSEA who so readily gave their time and effort to explain the ship procurement process of the Navy.

Lastly I would like to thank Professor Howard Bunch from the University of Michigan for his information about PODAC and Professor Patrick Keenan from MIT for his help with the MIT Math Model.

To Lindsey…

ABSTRACT

Since the end of the Cold War naval procurement for the US Navy has seen a dramatic decrease. This decrease in defense spending has placed existing programs under more scrutiny than previous years. As a result there is less tolerance on the part of taxpayers and Congress for procurement cost growth. This Thesis attempts to examine the current method that the Navy conducts ship cost estimates and suggests changes in order to improve the confidence level and accuracy of the forecasts. An examination of how industry is conducting cost estimates was used as a comparison to the current Navy practices. Finally using only a weight based approach to ship cost estimating is insufficient. It is necessary to develop and use a model that incorporates other cost driving factors in order to develop estimates of sufficient quality at the preliminary design level.

INTRODUCTION

Since the end of the Cold War naval procurement for the US Navy has seen a dramatic decrease. This decrease in defense spending has placed existing programs under more scrutiny than previous years. As a result there is less tolerance on the part of taxpayers and Congress for procurement cost growth.

Government and especially the Navy have been known to take conservative steps when determining whether they need a re-evaluation of their practices. Ship cost estimating has evolved in industry to include new production processes and developments since the 80's. The Navy has not. As a result the Navy is estimating the cost of ships using processes that are part of the past during an era where vessels were being built at a much higher rate with less need for transparency and cost cutting.

An ability to perform effective, detailed, and reliable ship cost estimating could finally create a change in the way the Navy is able to negotiate its contracts. A greater understanding of the factors that drive costs can hopefully lead to a decrease in cost overruns for two reasons: First designers will be in a better position to quickly perform trade off studies and therefore develop a better understanding of how their designs affect cost. Second, with an ability to perform reliable cost estimates at the preliminary level, the Navy will be able to negotiate more favorable contract terms that could decrease costs.

In the past the Navy has used a weight based model to estimate costs. It has been shown that this is not a good and reliable method for estimating costs since weight is not the only factor driving costs. Thus this thesis attempts to examine how the Navy conducts its estimates and the limitations of the current method. Furthermore an examination of current industry ship cost estimating practices has been included suggesting ways that the Navy could improve its current models and practices. The MIT ship cost estimating model has been examined in order to determine its capabilities in estimating ship construction and life cycle costs. Finally some suggestions for decreasing ship construction costs have been included.

CHAPTER 1 - OVERVIEW OF US NAVY:

The US Navy, which is currently comprised of 283 vessels, is the most technologically advanced Navy in the world. The US government assigns a sizable amount of its budget each year to maintain this superiority. The president's budget for the US Navy for the year 2006 amounted to $133 billion. The projected increase for the budget in 2007 will be $4.4 billion. In 2005, the Navy devoted $7.6 billion to new ship construction projects of which 96% was allocated between four classes: the Arleigh Burke Class destroyer, the Nimitz Class aircraft carrier, the San Antonio Class amphibious transport dock ship, and the Virginia Class submarine.

Procurement cost growth in naval construction programs has been a longstanding problem that has plagued Navy officials and Members of Congress. Admiral Vernon Clark, Chief of Naval Operations (CNO), has expressed strong concern, if not outright frustration about the matter (7). Combined with the rising procurement costs, the Navy is also facing reduced budgetary constraints on ship procurement funding. The 2006 defense authorization bill (H.R. 1815) as reported by the House Armed Services Committee (H.Rept. 109-89) contains provisions that establish procurement cost caps on several Navy shipbuilding programs, direct the Navy to begin developing a lower cost destroyer, a lower cost nuclear-powered submarine, and create a new program for US shipyards aimed in part at improving the efficiency and cost effectiveness of the construction of Navy ships (7).

In order to fund cost overruns in its ship construction programs, the Navy has had to resort to "prior year completion" funding. This is essentially additional appropriations for vessels already under contract. Congress appropriated funds to cover a $2.1 billion increase in ship budget requirements for vessels that are currently more than 30% complete. The total appropriations are expected to surpass $3 billion by the time all vessels are complete since the cost estimates assume that shipyards will maintain current efficiencies and meet all their milestones. This would correspond to a cost increase range of 12% to 17% of the initial contract price (Figure 1). Over the past 5 years, about 10% of the Navy's ship construction budget of $52 billion has paid for cost growth for ships funded in prior years. The implication of these cost overruns is that it reduces the buying power of the budget for current construction and reduces the rate of modernization of the Navy.

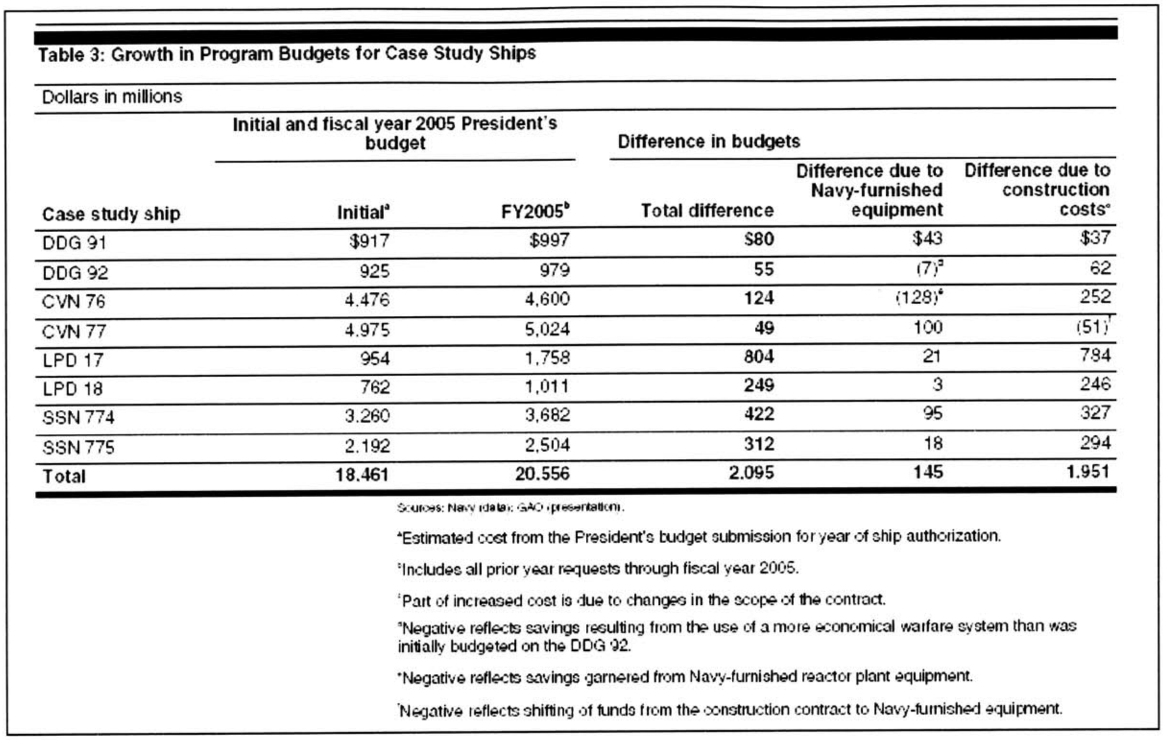


Table 3: Growth in Program Budgets for Case Study Ships

Dollars in millions

	Initial and fiscal year 2005 President's budget		Difference in budgets		
Case study ship	Initial[a]	FY2005[b]	Total difference	Difference due to Navy-furnished equipment	Difference due to construction costs[c]
DDG 91	$917	$997	$80	$43	$37
DDG 92	925	979	55	(7)[d]	62
CVN 76	4,476	4,600	124	(128)[e]	252
CVN 77	4,975	5,024	49	100	(51)[f]
LPD 17	954	1,758	804	21	784
LPD 18	762	1,011	249	3	246
SSN 774	3,260	3,682	422	95	327
SSN 775	2,192	2,504	312	18	294
Total	**18,461**	**20,556**	**2,095**	**145**	**1,951**

Sources: Navy (data); GAO (presentation).

[a] Estimated cost from the President's budget submission for year of ship authorization.

[b] Includes all prior year requests through fiscal year 2005.

[c] Part of increased cost is due to changes in the scope of the contract.

[d] Negative reflects savings resulting from the use of a more economical warfare system than was initially budgeted on the DDG 92.

[e] Negative reflects savings garnered from Navy-furnished reactor plant equipment.

[f] Negative reflects shifting of funds from the construction contract to Navy-furnished equipment.

Figure 1. Growth in Program Budget (4)

Reasons for Cost Overruns:

New production technologies and organizational improvements in shipyards have resulted in a continuous reduction in manhours/tonne over time. If time spent in dock is decreasing, then why is cost continuing to rise (Figure 2)?

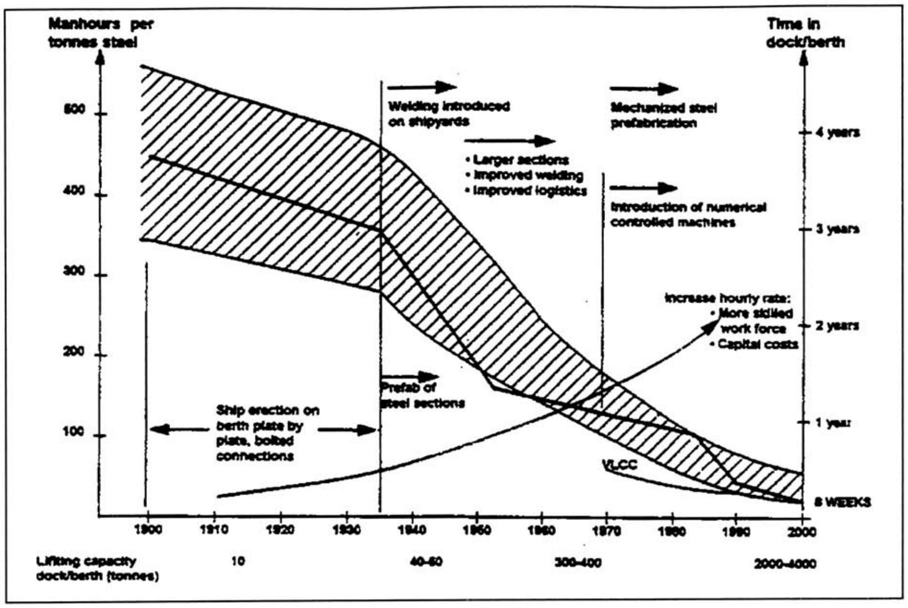
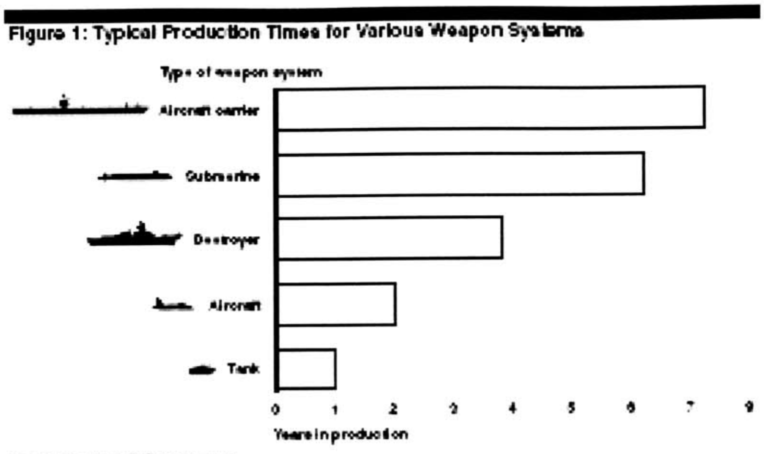


Figure 2. Shipyard Cost and Productivity (24)

1. Types of Shipbuilding Contracts

The nature of the shipping business in general lends itself to situations that place an excessive difficulty to effective cost estimation even to the most experienced ship cost estimator. Ship contracting is still at a time where it takes 9-14 years for a new class of surface combatants to be developed from concept design to delivery, when at the same time new technologies have a 3-5 year life cycle. It is therefore imperative to design vessels with a focus on technological convertibility. Figure 3 shows typical production times for various weapon systems.



Source: Navy data; GAO presentation

Note: A varying number of years of preliminary planning and early design work precede the start of production.

Figure 3. Typical Weapons Systems Production Times (4)

In most cases ship construction contracts are being agreed upon without the completion of detailed design. The reason for this is that detailed designs with a detailed cost estimate are very expensive and excessively time consuming. Shipyard work in terms of work specification is difficult to formalize and predict directly from intricate detailed ship designs. This presents a very large risk to both the buyer who might end up overpaying for a vessel and the seller who might have to incur exorbitant costs due to the lack of clear definition of the work at hand.

Two types of contracts have emerged that try to deal with the difficulty that naval acquisitions present to all parties involved in the transaction. The first is fixed price contracts. In this case the price is pre-arranged and agreed upon by both parties. Adjustments can be made in some cases but there is a definite ceiling price that if the shipyard surpasses, it agrees to pay all additional costs. The second is method is cost reimbursement contracts. The contract forces the government to pay all additional costs of completing a vessel if the shipyard can prove that the incurred costs were unavoidable. Generally cost reimbursement contracts are used for the lead ship and the fixed price contracts are used for the following vessels in the class due to the large amount of uncertainty present in a lead ship acquisition.

The contracts themselves however are not so clearly defined. They both have provisions that attempt to control cost and profit. These are called incentive fees. The shipbuilder and the Navy share the savings if the final cost is less than the estimated target, and they share the cost when the price exceeds the target. This process attempts to provide incentives for both parties to do their jobs efficiently. Either way, both contracts place an absolute emphasis on the need for a reliable cost estimate. Due to the absence of an effective cost estimating methodology, the contracts that are being used inherently create ways to force the buyer (in this case the Navy) to incur the major cost of overruns.

2. Labor and Materials Cost

Figure 4 shows the breakdown of the components of cost growth. It is apparently clear that labor and material surcharges which account for 78% of cost overruns are the leading cost burden that the US Navy has to manage.

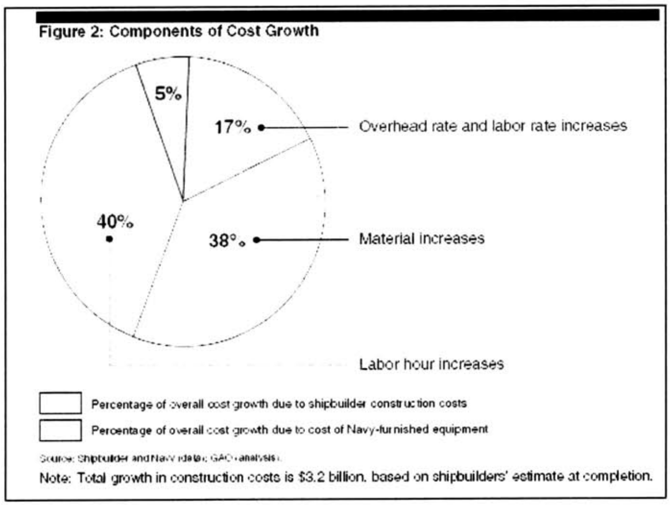


Figure 2: Components of Cost Growth

Source: Shipbuilder and Navy (data); GAO (analysis).
Note: Total growth in construction costs is $3.2 billion, based on shipbuilders' estimate at completion.

Figure 4. Components of US Navy Cost Growth (4)

For the vessels that were examined by GAO, the total cost growth due to increased labor hours totaled more than $1.3 billion. The main reasons for the cost growth can be seen in Figure 5. The repeated issue causing the delays was determined to be the lack of maturity of the design which directly led to rework. Examples of such issues include the LPD 17 where construction began as the design of the vessel continued to evolve. The vessel has faced the largest cost increases of all the vessels due to this fact. The DDG 91 and 92 suffered from severe reworking and delays due to the installation of the remote minehunting system which was a technology not fully developed at the time.

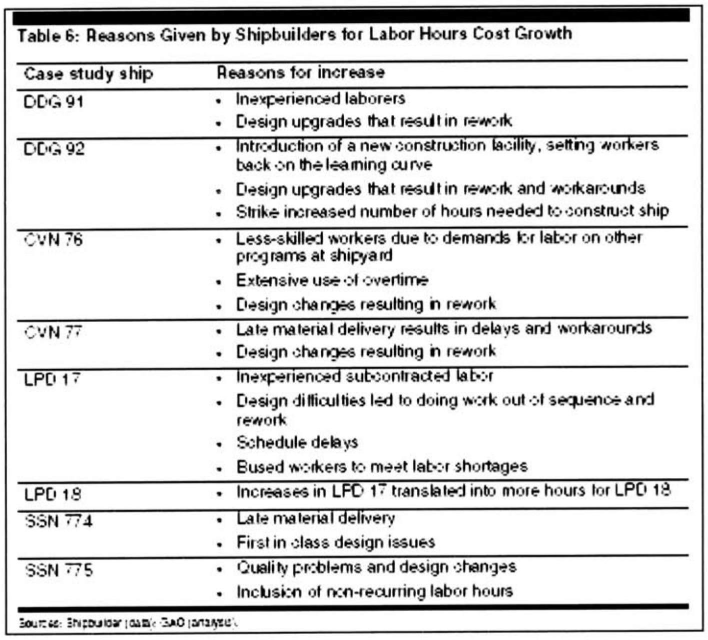


Table 6: Reasons Given by Shipbuilders for Labor Hours Cost Growth

Case study ship	Reasons for increase
DDG 91	• Inexperienced laborers • Design upgrades that result in rework
DDG 92	• Introduction of a new construction facility, setting workers back on the learning curve • Design upgrades that result in rework and workarounds • Strike increased number of hours needed to construct ship
CVN 76	• Less-skilled workers due to demands for labor on other programs at shipyard • Extensive use of overtime • Design changes resulting in rework
CVN 77	• Late material delivery results in delays and workarounds • Design changes resulting in rework
LPD 17	• Inexperienced subcontracted labor • Design difficulties led to doing work out of sequence and rework • Schedule delays • Bused workers to meet labor shortages
LPD 18	• Increases in LPD 17 translated into more hours for LPD 18
SSN 774	• Late material delivery • First in class design issues
SSN 775	• Quality problems and design changes • Inclusion of non-recurring labor hours

Sources: Shipbuilder (data); GAO (analysis).

Figure 5. Reasons for Shipyard Labor Hours Growth (4)

Overhead costs include a wide variety of costs incurred in the operation of the shipyard which are not directly chargeable to particular ship contracts. The overwhelming majority of overhead costs are time related. This leads to an understanding that by reducing construction time there are significant benefits, even if labor manhours don't decrease. The increased cost growth relating to overhead costs in this case are attributed to the decreased workload that US shipyards are facing which would absorb some of the operating costs.

Navy furnished equipment refers to the costs for technologies and equipment that the Navy purchases and has installed. Such equipment typically accounts for about 30% of the total budget for recent vessels. The growth of this significant cost sector has remained relatively low at 5% (Figure 4). The reasons for this is that the Navy benefits from economies of scale due to the affordability through commonality approach that it is beginning to use when procuring equipment in bulk. The Navy is however still far from creating an organized trans-vessel class commonality approach to its equipment acquisitions.

3. Underbudgeting and Price Increases

Underbudgeting and price increases have dramatically increased the levels of material cost growth. For the San Antonio, Nimitz, and Virginia class vessels, material cost was the most significant component of cost growth (Figure 6). DDG 91 had $22 million in material cost savings due to consolidation of Ingalls Shipyard with Avondale Shipyard under Northrop Grumman. Therefore materials were purchased for four ships at one time leading to a price decrease due to economies of scale.

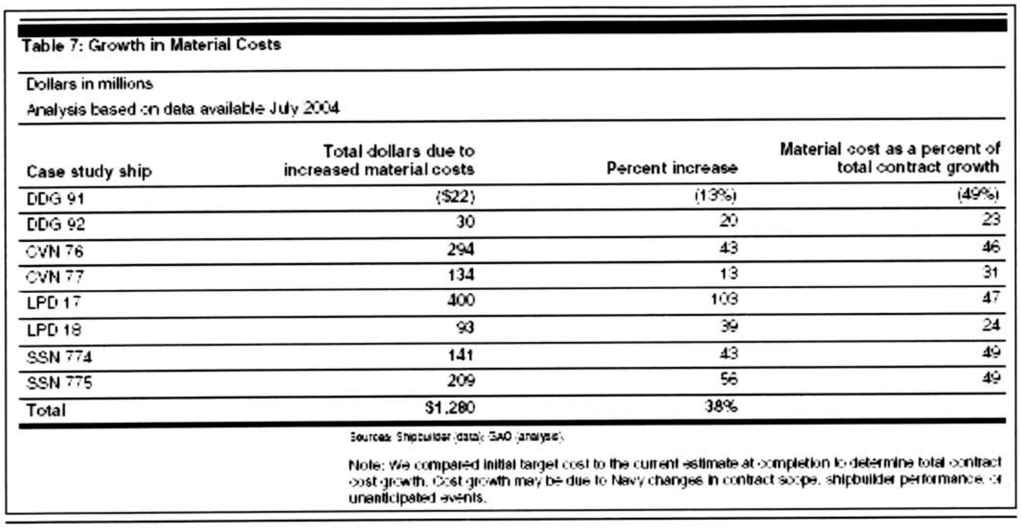


Table 7: Growth in Material Costs

Dollars in millions
Analysis based on data available July 2004

Case study ship	Total dollars due to increased material costs	Percent increase	Material cost as a percent of total contract growth
DDG 91	($22)	(13%)	(49%)
DDG 92	30	20	23
CVN 76	294	43	46
CVN 77	134	13	31
LPD 17	400	103	47
LPD 18	93	39	24
SSN 774	141	43	49
SSN 775	209	56	49
Total	$1,280	38%	

Sources: Shipbuilder (data); GAO (analysis).

Note: We compared initial target cost to the current estimate at completion to determine total contract cost growth. Cost growth may be due to Navy changes in contract scope, shipbuilder performance, or unanticipated events.

Figure 6. Growth in Material Costs (4)

The reasons for these cost increases rely heavily on the quality of the budget of the materials and the way the contracts are formulated. The first four Virginia class submarines' materials cost budget was $132 million lower than actual price quotes that were received by vendors and subcontractors. For the Nimitz class aircraft carriers, the materials cost budget was based on an incomplete materials list. Why? The reason again lies in the types of contract that are negotiated between the shipyards and the Navy. Since shipyards know that they will be reimbursed for change orders in contracts or price increases for high value specialized items, they underbudget their cost forecasts, win the contract to build and then simply pass on the higher cost back to the Navy.

Price increases of materials is another significant component of material cost growth. Factors that affect price increase are more than just national inflation levels. Inflation itself is an average number of a range of products that do not directly display the price increases that are faced by the naval construction industry. Changes in the supplier base since the end of the cold war due to the subsequent decreasing rate of ship production has resulted in industry consolidation. A lower number of suppliers has resulted in a lack of competition between subcontractors and a consequent increase in price. Over 75% of the ship material contracts for the Virginia class submarines have been from single source vendors. While on the LPD 17, the increase in cost of the subcontractors accounted for 70% of the increase in material costs (4).

CHAPTER 2 - COST ESTIMATION:

The cost of a vessel is the sum of all the labor and materials costs involved in the construction including any overhead costs. The final price of a vessel will include allowances for capital cost financing, inflation, and shipyard profit. Due to the particular nature of the shipbuilding industry and the high degree of variation between particular projects, the necessity of reasonably correct cost estimations is imperative. The complexity and cost of detailed ship design and the length of time between preliminary design and completion are the leading factors that determine the flexibility of contract between the Navy and the shipyard. This inherent flexibility and lack of definition is the leading cause for the increasing number of design change orders and final price escalation costs. Figure 7 shows a typical project timeline.

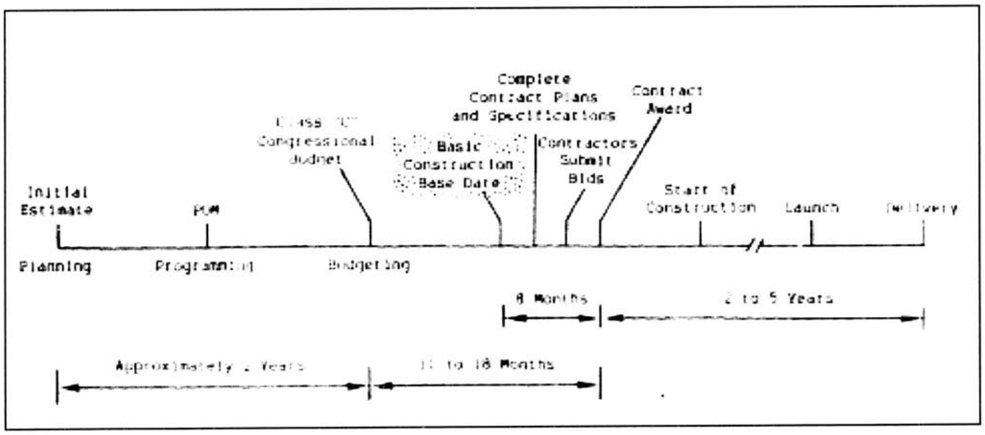


Figure 7. Typical Project Timeline (1)

Historically designers and shipyards have been able to categorize costs by consistent work breakdown structure such as hull structure, outfit, machinery, piping, electrical. Hull Structure is priced on hull weight and material type. More developed systems segregate different sections of the hull and develop different costs according to the production difficulty of the section. Major equipment is directly priced from the vendor. Other outfit systems are generally priced through parametric analysis and extrapolated historical data for the construction and installation of the system.

Cost estimates are required at all stages of design development. The importance of a good cost estimate particularly at the early levels of design can be crucial when comparing different design proposals. It is very easy to manipulate early cost estimating programs that use basic parameters as a basis and criteria for determining cost. The different types of cost estimates can be broken down into three general groups relating to stage of design: 1) Concept Design, 2) Preliminary Design, 3) Detailed Contract Design. Figure 8 shows a comparative cost comparison as the breadth and scope of each stage of cost estimation changes.

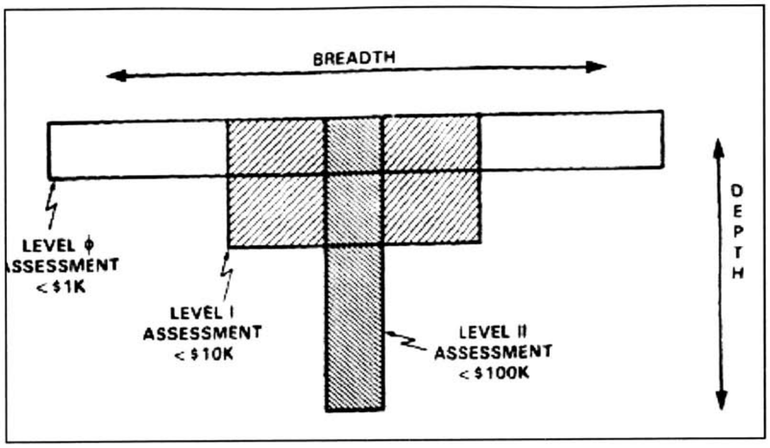


Figure 8. Cost of Scope of Various Cost Estimations (1)

A detailed explanation of each cost estimate according to stage will be presented in the following section. Figure 9 shows how cost analysis in the early design stages is in the enviable position of applying maximum effect for minimum cost (relative to project cost). Possible cost savings decrease dramatically as the project is defined more clearly. This relationship is particularly applicable with the introduction of advanced technologies in ship design. The greatest savings result from the introduction of innovations at the early stages of development. Incorporating new technologies at later stages when the design is already committed to a certain technology will result in increased labor costs and change orders.

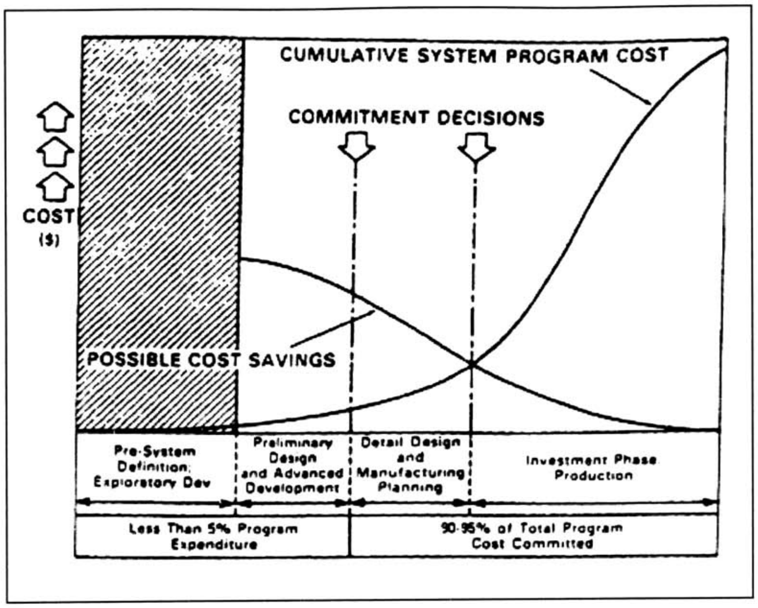


Figure 9. Cost of Design Change (1)

In the Concept Design stage, the purpose of the cost estimate is to create a very rough order of magnitude (ROM) cost estimate. At this stage basic ship type and parameters are presented and the mission and operational requirements are broadly defined. The cost estimate is used as a feasibility check on the project. At this stage the cost estimate is based on historically extrapolated data and basic parametric analysis.

The Preliminary Design stage is a very crucial design stage. At this phase, the methodology and validity of the cost estimate is imperative since it is at this point where the design will be evaluated against other options. It is therefore important for the designer to understand how his decisions will affect cost since major tradeoff studies are performed and major decisions about the future of the project will be made. This is a very powerful and exciting time of the design process, but also one that requires careful decisions and thorough understanding of the cost implications of each design choice. The two necessary components that must be addressed at this stage are: the initial capital cost for the construction of the vessel, and the net present value of the operating costs discounted throughout the life of the vessel.

The cost estimating methodology used at this preliminary stage depends on the type of project underway. If the vessel designed is radically different from all past designs using new technologies, new equipment, and composite materials, then the difficulty of making a realistic and reliable estimate will be compounded. This is because of the four main types of cost estimating methods that are available at this stage: 1) Analogy, 2) Parametric, 3) Extrapolation, 4) Expert Opinion.

The Analogy type uses a direct comparison between two similar systems. It is used in early stages of design and is inherently historically based. Its inability to account for new features and changes in productibility due to labor learning rate are its major flaws.

Parametric estimates base their predictions on design parameters such as ship size, weight, horsepower, etc. Such analyses use a mathematical relationship between input parameter and cost that is historically determined through regression analysis (i.e. Cost = f*(weight)). The cost estimator using this system must be knowledgeable enough to know when an adjustment factor is needed, and to know what the factor should be.

Extrapolation methods can only be used when there are return costs available for similar systems used in prior vessels (adjusting for inflation). The accuracy of the system is a function of the length of the extrapolation and the consistency of the factor being extrapolated. They should only be used if the project has progressed to such a level of definition. In the case of new technologies this type of methodology is difficult to assume.

Expert opinion can prove to be very effective but it can also be misleading. Personal involvement in projects carries with it the agenda that each person wants to follow. A person's occupation and position influences the forecast. Low estimates are generated by persons whose interests are served by low estimates. Examples could be the vessel designers, shipyards, subcontractors, and material vendors who want the vessel to be built. Similarly, high estimates are generated by persons whose interest is served by high estimates. In this case it could be the government cost estimator who does not want to be scrutinized by his superiors or some Congressional Committee when it turns out the project requires additional funds.

The value of an experienced cost estimator is that he has a better understanding of which particular CER is applicable to each situation. Since most CER's include empirically derived factors, it is necessary to have them used by someone who appreciates and understands their implications. This is particularly important if the new design uses new technologies which have not been used in the past. Furthermore, expert opinion is very useful in providing a rational crosscheck of the data that modern, complex, general, computer generated equations produce. It is therefore the appropriate combination of the value of judgment provided by the expert used in conjunction with estimating relationships that can result in better forecasts. A summary of the effectiveness of various types of cost estimates is shown in Figure 10.

TYPE OF COST ESTIMATE	PRECISION	COST	TIME	ABILITY TO REFLECT PROD'TN CHANGES	ABILITY TO REFLECT DESIGN CHANGES	DATA BASE COST	WORK WITH PODAC
Parametric	Fair	Low	Quick	Requires Factor	Requires Factor	Some	New Work Req'd
Engineering	High	Very Large	Slow	Yes	Yes	Large	Yes
Analog (Comparison)	Fair/Good	Medium	Moderate	Requires Factor	Yes	Some	New Work Req'd
Extrapolation	Fair	Low	Quick	Requires Factor	Requires Factor	Some	New Work Req'd
Expert Opinion	Fair-Low	Low	Moderate	Possibly	Possibly	Low	Possible
Performance Based	Unknown	Low	Quick	Requires Factor	Possibly	Some	Unknown
Re-use/Module	High	Low-Medium	Quick-Moderate	Yes	Yes	Large Startup	Yes

Figure 10. Comparison of Cost Estimates (25)

The final design stage before the project moves into construction is the Detailed Contract Design stage. In this phase the engineering methodology is used to determine costs. It is a timely, expensive and tedious process based on a detailed "bottom up" accounting of the required work and materials used to construct the ship. It is however, the most accurate method available. The costing information at this level of design provides the fundamental basis for the contract price rather than to create a design trade off analysis. The final technique that can be implemented is the introduction of re-use modules. This is a method that requires a strong detailed design structure that can formulate and categorize the vessel into modules and re-use elements. There are indications however that the Navy is moving towards a modularized production oriented approach to design. This will be discussed further in the following sections.

The difficulty of assigning an assumed final cost to a product 3 to 7 years before its materialization is logical; however, it is necessary to understand the factors that could result in cost changes in order to develop better methods of analysis to deal with them:

1. Technology Change
   - New processes
   - New materials
2. Social, Economic, and Political Situation
   - Changing workforce
   - Economic downturn and unrest
3. Shipyard Backlog
   - Heavy backlog causes confusion

- Few orders results in loss of learning

4. Labor Rates
    - Different for each shipyard
    - Unpredictable changes
5. Material Costs
    - Vendor base changes
    - Delayed shipments
6. Regulatory Structure
    - New rules
7. Inflation
    - Fluctuates unpredictably
    - Different rate for each item

The new cost estimating systems that industry and the Navy are developing are currently trying to incorporate factors that will deal with these issues that distort parameter estimates. One of the most important additions to the new system (discussed in Chapter 5) will be the uncertainty analysis which will assign a certain probabilistic distribution to each parametric regression equation (Figure 11). This will provide cost estimates with a certain range of probable outcomes. In this way it will be easier for the

Navy to plan and manage the level of risk associated with each project.

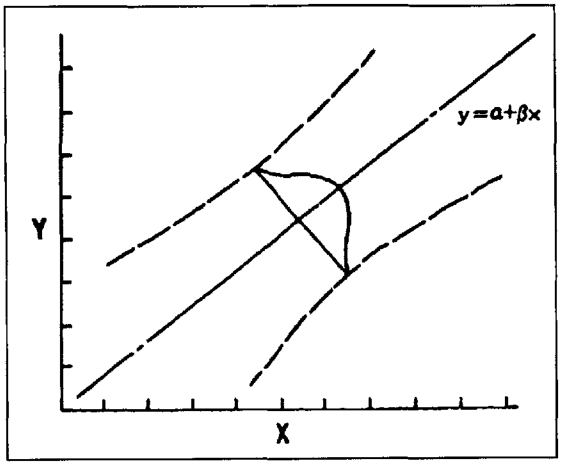
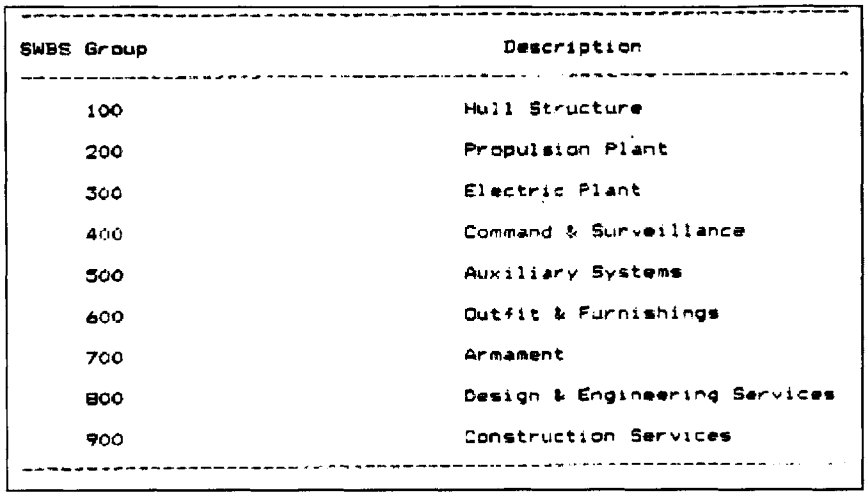


Figure 12. Addition of Risk in CER's (1)

Since cost estimates are often required well in advance of the contract design phase, the US Navy developed a method which is based on a single common parameter: weight. The basic construction cost of a ship is then directly determined, through the use of historically determined factors. These form cost estimating relationships (CER's) that are used to provide parametric analysis of ship construction costs. This method uses the Ship Work Breakdown Structure (SWBS) as a common means of communicating the level of technical definition between the designer, shipyard and cost estimator. Its definition varies in depth and breadth as a project moves through each design phase. The main components that make up the one digit SWBS group system are shown in Figure 13. The total weight of the ship is the sum of groups 100 through 700.



SWBS Group	Description
100	Hull Structure
200	Propulsion Plant
300	Electric Plant
400	Command & Surveillance
500	Auxiliary Systems
600	Outfit & Furnishings
700	Armament
800	Design & Engineering Services
900	Construction Services

Figure 13. One Digit SWBS Breakdown (1)

As the level of design increases, so does the level of group specification within the system. For example, a two digit weight group such as group 130 defines hull decks. On the three digit level, group 132 could be second deck. Engineers like using this type of classification system because it is system based. It is good for early stages of design and it lends itself to parametric extrapolation or analogy cost estimating methods.

Such an approach which results in a heavy reliance on weight as the surrogate of costs can be deceiving. Experience has shown that there are cost drivers other than weight that cannot be ignored. The DDG51 suffered from severe operational issues due to the use of a solely weight based cost estimate method. Designers believed that decreasing the beam by 2ft would decrease costs. The construction difficulty factor however, increased to such a level that the overall cost of the ship increased. Also operational issues arose due to the change since stretchers couldn’t fit in the 2ft narrower corridors.

Another issue with the SWBS classification is that it is system based rather than production based. The current system ignores the possibility of production friendly designs which would reduce costs. This is an issue that arises when designers try to optimize one aspect or system rather than the efficient production of the vessel as a whole. Figure 14 shows the effect of increasing the deck height of the DDG51 from 9ft to 11’2”. Since 6’5” is required for access of personnel, the DDG51 had only 2’7” available for distributive systems. This led to congested overheads, costly and difficult installation due to structural member penetration and the deviation from optimum pipe runs. The lack of available space meant that interference between systems was common which resulted in design changes in multiple systems. This fueled change orders and dramatically increased construction time and cost.

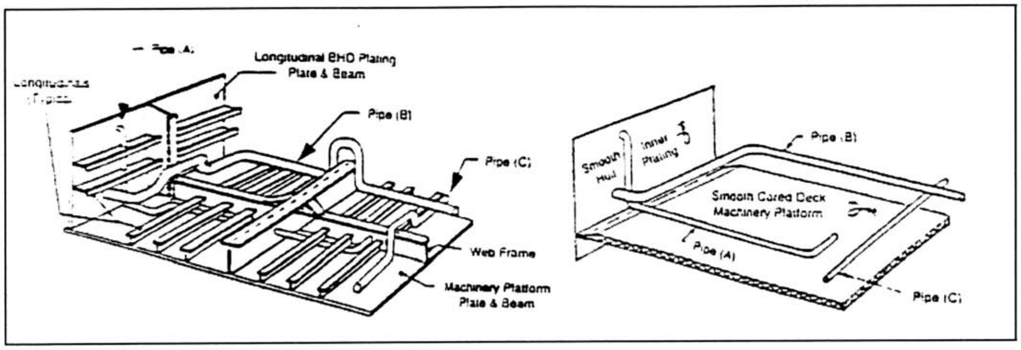


Figure 14. DDG-51 Design Issues (26)

CHAPTER 3 - DESIGN TO BUILD IMPROVEMENTS/ BUILD STRATEGY:

Product Work Breakdown Structure

The US Navy has been using a SWBS classification system for the past 60 years. It is a system that provides an initial approximation at an early stage of design; however, at the more detailed level it is necessary to incorporate new features that look at production methods rather than just a systems approach. Ships are built in subassemblies that are grouped by common characteristics. The Product Work Breakdown Structure (PWBS) classifies the different interim products that are assembled and subdivides the required work accordingly. These products benefit from cost and schedule savings because the work is sequenced into a convenient and functional order. This process is referred to as group technology. A typical example of its function is shown in Figure 15.

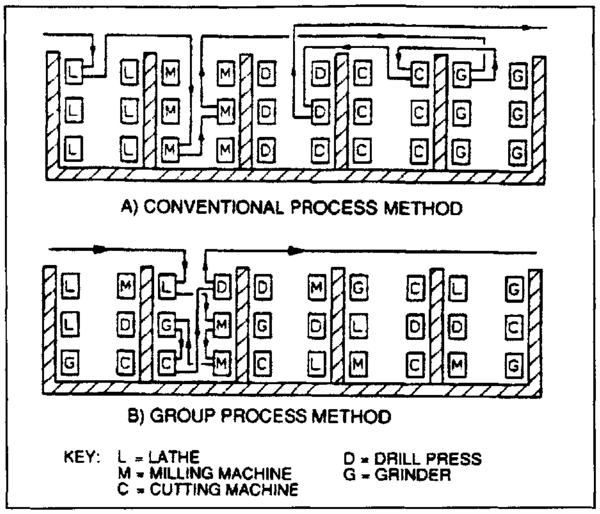


Figure 15. Efficiency of Group Technology (21)

This system of grouping resources efficiently can be expanded from subassembly to blocks to outfit zones in order to improve productivity and result in a more efficient use of a shipyard's resources. Since the PWBS system operates by creating interim products, the vessel is built according to zones and assembled at the final stage. (Figure 16)

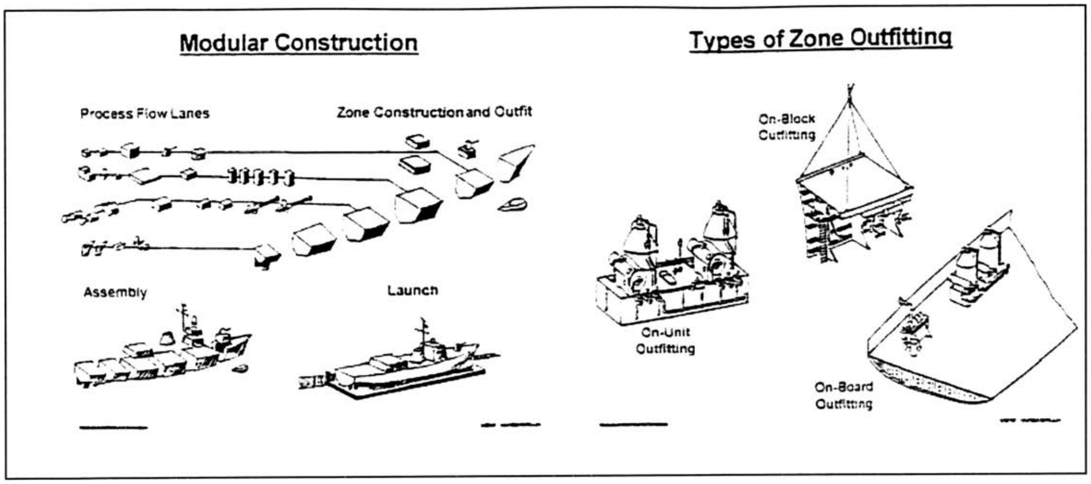


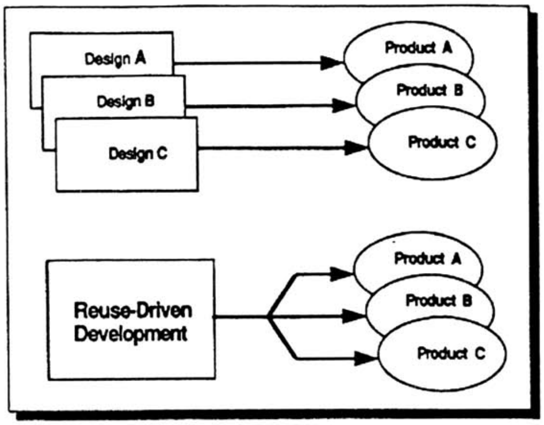
Figure 16. Modular and Zonal Construction (26)

A shipyard that uses this production sequence system needs to have ship designs that allow vessels to be subdivided efficiently in this way. In attempting to maximize productivity, the PWBS approach implies a significant amount of overlap of design, material procurement, and production. This is therefore placing added pressure on the already difficult position of the designer who now has to incorporate and anticipate the method and sequence of production.

Modular Construction:

The concept of modular construction is becoming more viable due to the changes that are occurring in the framework of the US Navy's procurement strategy. The Navy's

Affordability Through Commonality (ATC) program is an example of the effective use of reuse modules. The program attempts to standardize the number of different components of Naval Designs (such as using common pumps, pipe sizes, and plate thickness). Reuse modules are a logical extension of standard components of an existing system that can be incorporated in a new system. If an existing module can be described, classified, and priced within an interim PWBS, then that module or direct adaptation of it can be added directly into the new cost estimate. The cost of the module and the associated information will be added to the existing database of modules. Eventually it will be possible to define any design almost entirely by reuse modules at any level of the production line from subassembly to hull erection. (Figure 17)

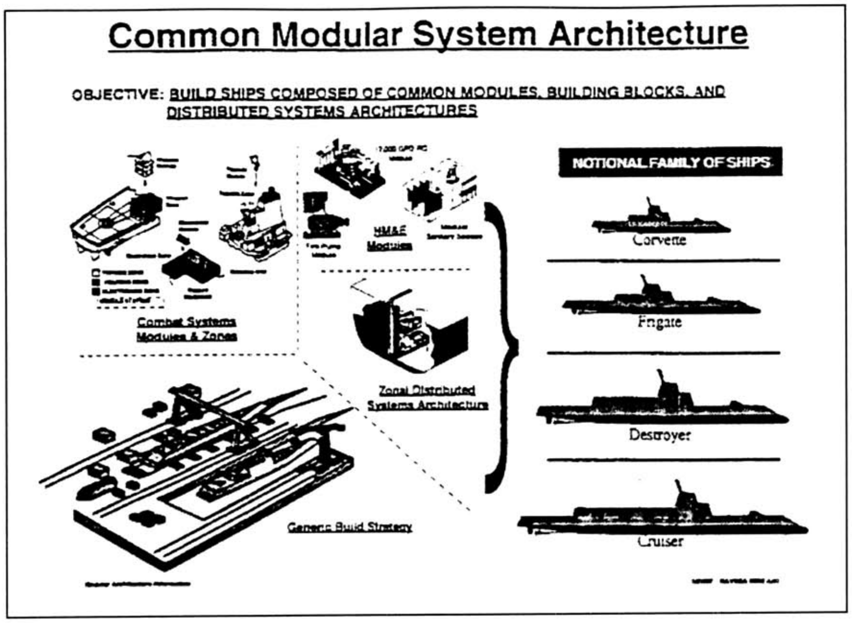


Source: Software Productivity Consortium

Figure 17. Converting to Re-Use Modules (25)

Using the new design and production organization methods can result in easier, faster, and cheaper ship procurement. Moreover, the time taken to make a comparative determination of the effects of a change in design and its consequent impact on cost will be reduced. The accuracy of the cost estimate will approach that of a detailed engineering estimate without the incurred cost and time lost to conduct the study. It will also give naval architects a better understanding of the cost implications of the design decisions that they make and ultimately result in producing lower cost vessels.

DDG51 vessels were built using modular construction but they were not designed with modular ship architecture thereby limiting the possible savings that would result from the advanced outfitting capabilities of the shipyard. Figure 18 shows how modular architecture and reuse systems can be incorporated, scaled, and used throughout different vessel classes.



Common Modular System Architecture

OBJECTIVE: BUILD SHIPS COMPOSED OF COMMON MODULES, BUILDING BLOCKS, AND DISTRIBUTED SYSTEMS ARCHITECTURES

Figure 18. Using Modular Architecture in the Navy (26)

The economies of scale that are reaped from pursuing such a focused and organized construction process cannot be understated or overlooked. Using similar modules for different vessel types improves shipyard productivity and decreases costs. Other benefits arise through the process of purchasing materials and equipment in bulk which again results in economies of scale. The Navy has attempted to incorporate an increasing number of subcontracting deals in order to decrease costs. Having multiple suppliers increases competition between the contractors which in turn should increase quality, service, and reduce acquisition cost. It will also let shipyards focus on the aspects of construction that they are more efficient or proficient at conducting. This would deal with the labor hour overruns due to the inexperience of the workforce shown in Figure 4. The UK Royal Navy uses such an approach to build its Type 45 destroyer (Figure 19).

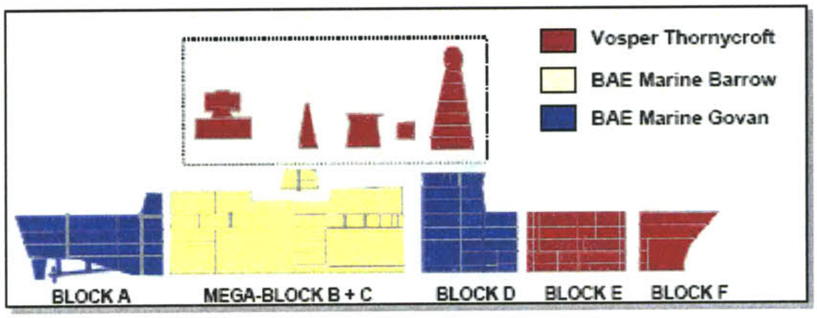
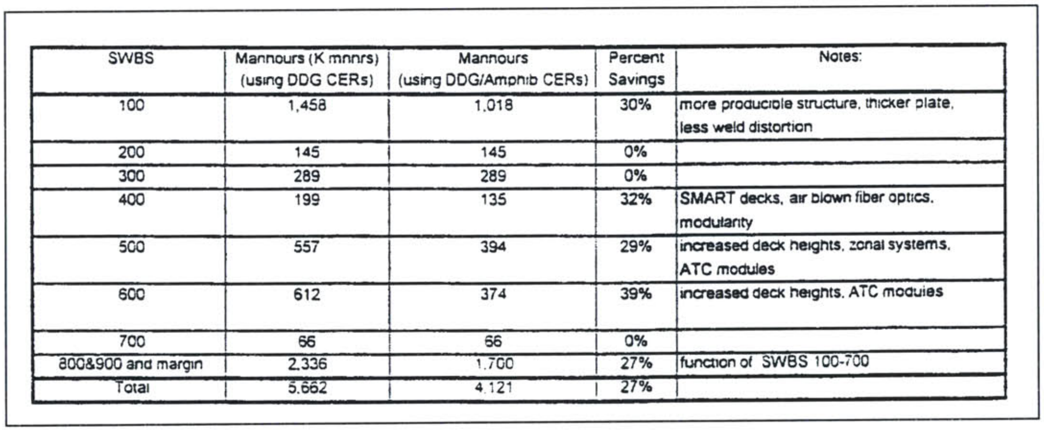


Figure 19. Modular Construction of UK Destroyer (12)

The possible savings that can be realized by switching to a modular production process can be pronounced. Figure 20 shows the cost savings expected for DD-21 due to the new design initiatives.



SWBS	Manhours (K mnhrs) (using DDG CERs)	Manhours (using DDG/Amphib CERs)	Percent Savings	Notes:
100	1,458	1,018	30%	more producible structure, thicker plate, less weld distortion
200	145	145	0%	
300	289	289	0%	
400	199	135	32%	SMART decks, air blown fiber optics, modularity
500	557	394	29%	increased deck heights, zonal systems, ATC modules
600	612	374	39%	increased deck heights, ATC modules
700	66	66	0%	
800&900 and margin	2,336	1,700	27%	function of SWBS 100-700
Total	5,662	4,121	27%	

Figure 20. Predicted Cost Savings (26)

Learning Curves:

Modularity and increased specialization decreases average construction cost as more similar vessels are produced. This is because ship construction labor costs decrease with experience as build strategy, manufacturing and production strategy, and management coordinate their efforts with a more efficient outcome. Therefore the CER's used for the original vessel have to be modified to take into account the effects of learning as series of several vessels of the same class are constructed in sequence.

The basic form of the learning curve is:

$\mathrm{Log}(y) = \mathrm{Log}(a)+b(\mathrm{Log}(x))$

where: y = Cost of x# of units

a = Cost of 1^{st} unit

b = Learning curve coefficient

The slope of the learning curve is the learning rate. So, for 2 units, $x = 2$, and $b(\mathrm{Log}(x))$ equal to the log of the slope. Thus,

$b = \mathrm{Log}(\text{slope}) / \mathrm{Log}(2)$

For a 90% slope, $b = \mathrm{Log}(0.9) / \mathrm{Log}(2) = -0.152$

Cost of Nth vessel = Cost of 1^{st} *N^(b)

The theory is that each time the total quantity of ships built doubles, the basic construction cost decreases by a constant percentage of the former cost. Therefore if the cost for the first year is 1, the cost for the second vessel will be 10% less i.e. 90% of the cost of the first. (Or using the equation, y = 2^(-0.152) = 0.9). The cost of the third vessel will be = 3^(-0.152) = 0.846, or 84.6% of the cost of the first vessel. Figure 21 shows how the effect of different learning curves decreases costs as output increases.

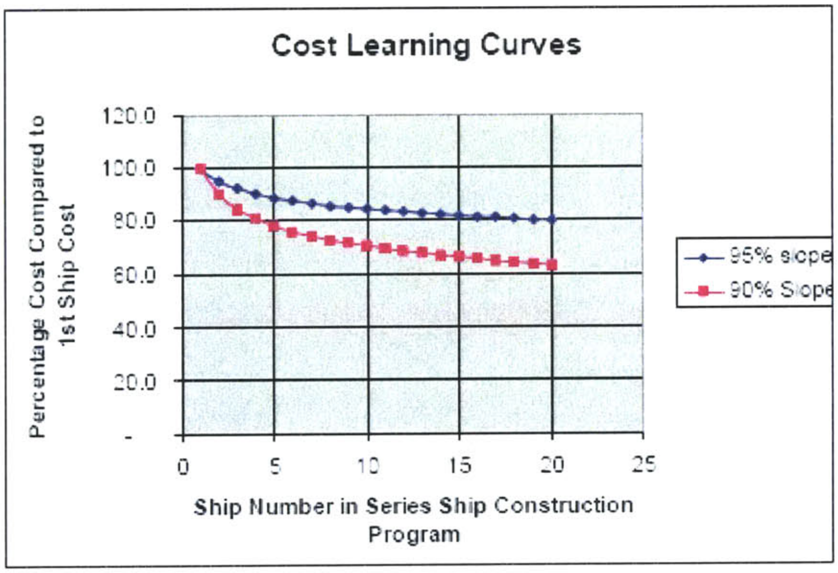
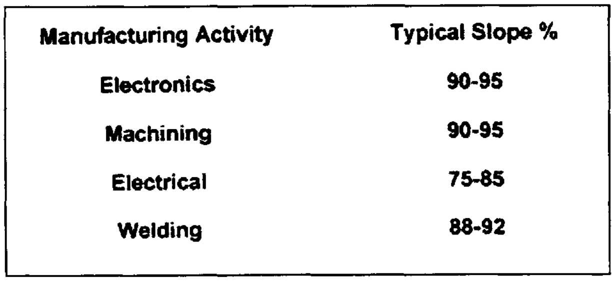


Figure 21. Effect of Learning on Cost (14)

Learning is different for each process that is being performed and varies depending on a variety of factors including system complexity, manufacturing technology, and construction time between completion and start of each following ship. Low skill level processes tend to exhibit low levels of learning since there is little or no reduction in the amount of labor with repeated performance of a certain task. Highly automated operations tend to also have slopes close to unity since machines do not increase their productivity through experience. Production innovation processes such as modulization and PWBS increase shipyard efficiency and decrease cost but it is not necessarily attributed to learning effects. The major region where learning makes a substantial difference is with highly skilled labor. This is because skilled labor can significantly improve its efficiency with experience. Figure 22 shows how different manufacturing activities exhibit differences in learning rates.



Manufacturing Activity	Typical Slope %
Electronics	90-95
Machining	90-95
Electrical	75-85
Welding	88-92

Figure 22. Typical Learning Rates (20)

Generally, if an operation requires 75% manual and 25% automation, slopes in the vicinity of 80% are common. If the ratio is 50:50, slopes are in the 85% region. If the ratio is 25:75 the learning rate is in the 90% region. Typical shipbuilding learning slopes tend to run between 80 and 85%.

There are instances when using learning curve correction factors is not appropriate. Such situations include:

- When ship construction is sporadic
- When the types of functions performed are inconsistent (custom products)
- When work is highly automated and production rate cannot increase further
- When rules and regulations limit the production rate
- When production quantities are small

Sporadic production, either due to low levels of orders, or labor issues such as extended strikes, results in breaks in production. The effects of such a time gap between resumption of construction can result in a stepped increase in cost upon resumption of construction as shown in Figure 23.

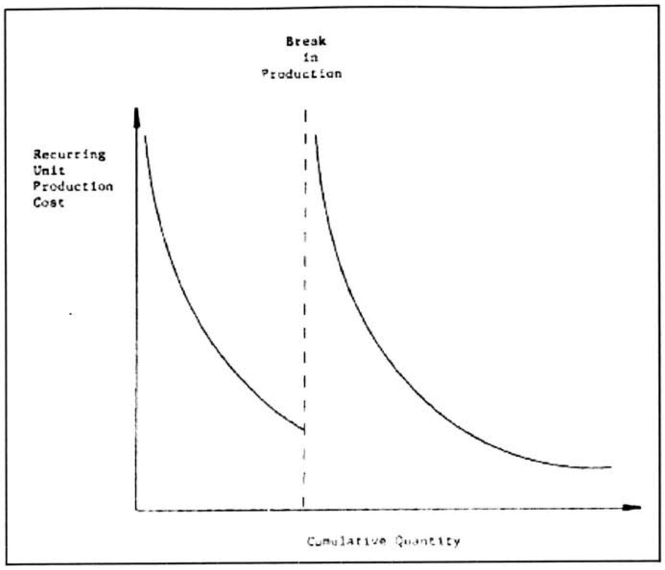


Figure 23. Effect of Break in Production (1)

Other instances where similar increases in cost can occur include major upgrades to facilities and changes to production processes since labor requires a certain amount of time to become accustomed to the new facilities and production methods. A typical example would be Philadelphia Kvaerner Masa yard. A major upgrade to the facilities increased the cost of construction because workers were not trained to use the new equipment. Significant design changes and technological upgrades to a class of vessels can also result in a loss of learning since the production process is inherently different. Thus CER’s that the Navy uses for ship cost estimating have to be used with extreme caution since they can result in significant variations between actual and predicted costs.

A major point of contention between the Navy and shipyards has been the costs of DDG 79 and the Virginia class submarines due to the cancellation of the order of 5 vessels over the past 10 years. During the cold war the US was constructing about 17 vessels per annum. Today, the number is down to less than 6. It is therefore necessary to re-evaluate and question whether it is applicable to use current correction factors for cost benefits that could arise from improvements in learning.

Benefits of Reduced Construction Time:

Korean shipyards proved that by pre-negotiating an exact delivery time with a detailed work breakdown structure and essentially outlawing change orders, it was possible to decrease construction time by 30%. Analysis of construction costs has shown that by decreasing the time taken from concept design to delivery by 50% it will be possible to decrease total costs by as much as 30% (19). Although it may be infeasible and undesirable to decrease costs by 50%, it is clear that the time value of money should play a much more important role in the decision making aspects of the naval procurement process. By having longer projects the Navy incurs the following costs:

1. Interest on capital
2. Interest on material inventory
3. Extra labor and material cost due to escalation factors (inflation)
4. Opportunity cost of facilities usage and cost of occupancy of facilities
5. Increased overhead costs
6. Cost of built-in obsolescence
7. Cost of rescheduling and planning

In short, as long as the vessel is held in drydock, the final acquisition cost will continue to rise. With post cold war reduction in military spending and the consequent decrease in procurement of naval vessels combined with a historical decrease in the Jones Act fleet, shipyards are not interested in decreasing manhours and/or project time.

Since shipyards rely on naval procurement to remain in business, they inherently work slowly, and produce expensive ships with as many extra change orders as possible. Thus the Navy has to re-evaluate the way it expects shipyards to operate if any benefits are to be made by using modern, highly efficient production methods. The existence of a PWBS system of construction has been in existence since the late 1980's. In fact the same shipyards that produce cost and time overruns for naval construction projects can build commercial vessels in a fraction of the time and cost. Figure 24 shows the speed that a commercial bulk carrier was built at Avondale shipyards by using a PWBS for vessel construction.

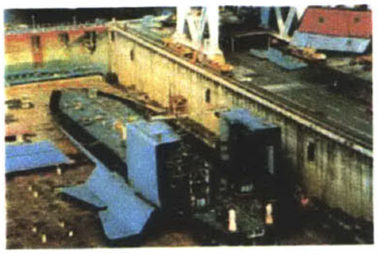


Fig. 3–56

Fig. 3-56. Erection, keel laying plus 11 workdays.

Fig. 3–57

Fig. 3-57. Erection, keel laying plus 13 workdays.

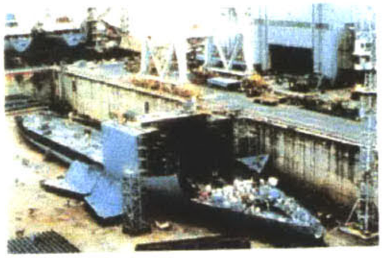


Fig. 3–58

Fig. 3–59

Fig. 3–60

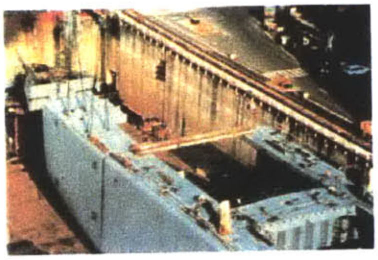


Fig. 3–61

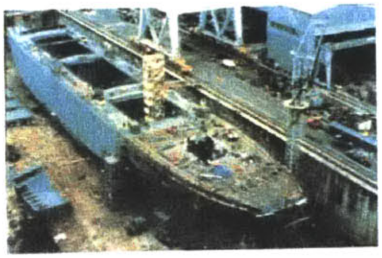


Fig. 3–62

Fig. 3–63

Fig. 3-58. Erection, keel laying plus 15 workdays.
Fig. 3-59. Erection, keel laying plus 19 workdays.
Fig. 3-60. Erection, keel laying plus 22 workdays.

Fig. 3-61. Erection, keel laying plus 22 workdays.
Fig. 3-62. Erection, keel laying plus 24 workdays.
Fig. 3-63. Erection, keel laying plus 24 workdays.

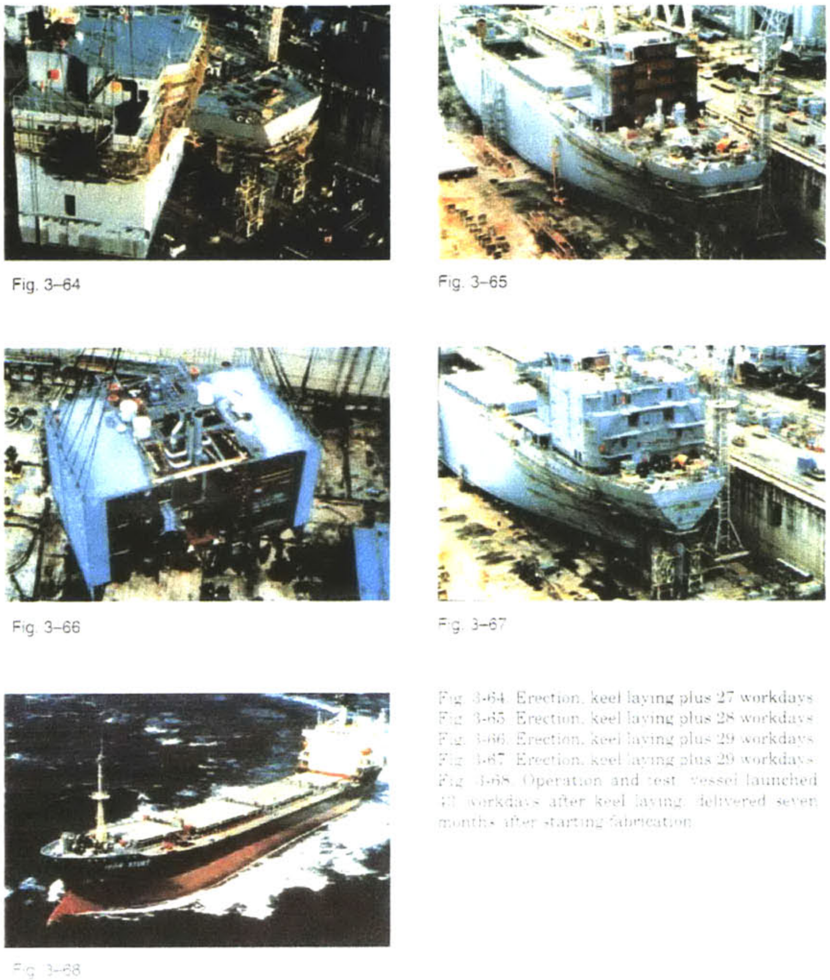


Fig. 3-64

Fig. 3-65

Fig. 3-66

Fig. 3-67

Fig. 3-64. Erection, keel laying plus 27 workdays.
Fig. 3-65. Erection, keel laying plus 28 workdays.
Fig. 3-66. Erection, keel laying plus 29 workdays.
Fig. 3-67. Erection, keel laying plus 29 workdays.
Fig. 3-68. Operation and test: vessel launched 43 workdays after keel laying; delivered seven months after starting fabrication.

Fig. 3-68

Figure 24. Construction using PWBS (21)

The vessel was launched 43 days after keel laying! US shipyards are still very far from attaining production levels experienced in Far East yards, which generally produce similar vessels at about 50% of the time. However, there is no reason that the same US yards cannot use the same production methods to build naval vessels.

In order to understand the value of a shorter construction period, it is necessary to conduct a present value analysis of future costs associated with longer construction periods. While it is relatively trivial to estimate the costs relating to labor, capital and material of a longer project, assigning a value to the added cost of built-in obsolescence is much harder. Built-in obsolescence itself is a knife with two edges. The elimination of change orders would probably result in an increase in short term re-conversion and upgrade of equipment; conversely, it has been shown that there are significant benefits that can be attained by shorter construction times without expensive, time consuming change orders.

Multi- Purpose Vessels

Navy mission requirements have become less focused and as a result, vessels have been designed with multiple capabilities. As a result, the navy is more flexible at any given time at the expense of capital and operating costs. By their nature multipurpose vessel designs incorporate performance penalties that are imposed by their various different requirements. It can be argued, that most vessels under typical missions perform only one main mission function. For example, during the Gulf War, the primary use of warships was surface to surface bombardment. Most vessels were equipped and manned to perform many other functions such as anti-submarine and surface-to-air warfare, but the capabilities were never used.

In naval ships the operating cost breakdown is 37% personnel, 21% maintenance, and 13% modernization (14). This emphasizes the need to reduce both manning and extra equipment. With more focused missions it is possible to reduce the crew size which would have dedicated personnel for each mission capability. Furthermore, specialization and training of the crew on primary and secondary mission requirements could improve operational proficiency and effectiveness.

Figure 25 performs a present value comparison of three different vessel configurations by mission. The multi purpose cost is significantly more expensive to construct and operate. Clearly, a more specialized mission oriented Navy would require more vessels and better operations management. A fleet increase of 35% comprising 60% type A and 75% type B vessels could be procured and operated at: (0.6*1.113+0.75*1.032) = 1.442C. This is about 82.5% of the cost of procuring and operating a smaller fleet of multiple purpose vessels.

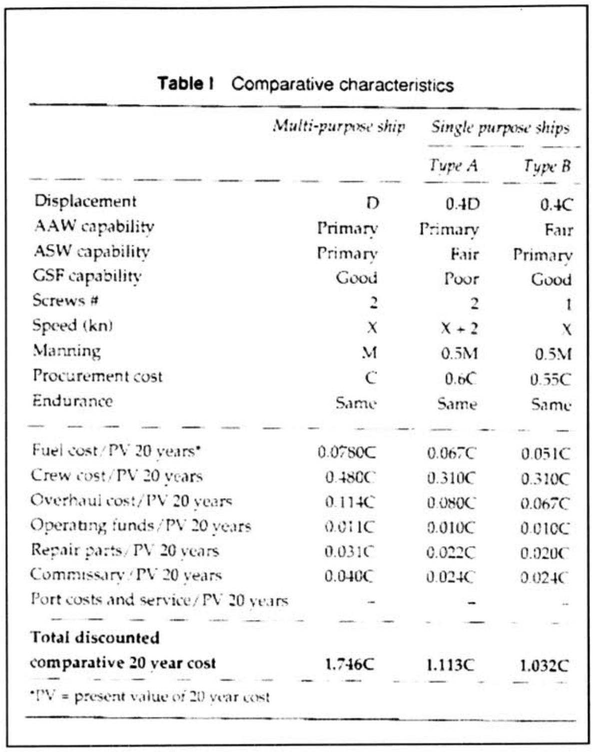


Table I Comparative characteristics

	Multi-purpose ship	*Single purpose ships*	
		Type A	*Type B*
Displacement	D	0.4D	0.4C
AAW capability	Primary	Primary	Fair
ASW capability	Primary	Fair	Primary
GSF capability	Good	Poor	Good
Screws #	2	2	1
Speed (kn)	X	X + 2	X
Manning	M	0.5M	0.5M
Procurement cost	C	0.6C	0.55C
Endurance	Same	Same	Same
Fuel cost/PV 20 years*	0.0780C	0.067C	0.051C
Crew cost/PV 20 years	0.480C	0.310C	0.310C
Overhaul cost/PV 20 years	0.114C	0.080C	0.067C
Operating funds/PV 20 years	0.011C	0.010C	0.010C
Repair parts/PV 20 years	0.031C	0.022C	0.020C
Commissary/PV 20 years	0.040C	0.024C	0.024C
Port costs and service/PV 20 years	–	–	–
Total discounted comparative 20 year cost	**1.746C**	**1.113C**	**1.032C**

*PV = present value of 20 year cost

Figure 25. A Single or Multi Purpose Navy (19)

Cost Estimating Relationships:

CER's are formulas that relate the cost of an item to the item's physical or functional characteristics. They can also compare the cost of an item to the cost of another item or group of items. They are historically derived through regression and parametric analysis. Since CER's are derived from physical data, it is necessary to understand how the data correlates to the problem that is being solved in each particular cost estimate. CER's vary in complexity and detail between the concept design stage and the detail design stage. Their significance lies in their ability to provide ship cost estimators with reliable results without the time and cost that would be incurred through the use of a detailed engineering analysis of a design. There are five main types of CER's:

- Manual - determined from external information such as vendors and subcontractors
- Calculated - determined and derived from actual previous ship cost data.
- Predictive - determined though regression from return data of multiple vessels over time, or from a common manufacturing method that is changing over time.
- Empirical - determined through statistical regression analysis of particular shipyard processes.
- Standard Interim Products - determined at each level of the PWBS. Existing CER's are grouped together into standard common interim products and modules called re-use packages.

CHAPTER 4 - NAVSEA 017 SHIP COST ESTIMATING SYSTEM:

NAVSEA 017 refers to the Naval Sea Systems Command Office of Cost Engineering and Industrial Analysis. The department prepares the Navy's ship cost estimates from the initial design feasibility study phase through production award and extends into actual contract execution for submission to the annual Department of Defense's shipbuilding budget.

The Shipbuilding and Conversion, Navy Appropriation (SCN) constitutes approximately 10 percent to 15 percent of the Navy's total annual procurement budget. The appropriation, as indicated by its name, includes the procurement of ships and craft to be newly constructed and major ship conversions (18). An SCN procurement item that has been authorized by Congress must be fully funded or the work on it must cease. This "end costed" policy assures that funds are always available for all reasonably expected costs through the ship construction. Exceptions to this policy include ship outfitting and post delivery costs. Also there are provisions that allow for cost escalation of shipyard costs due to inflation. In order for a ship cost estimate to be considered as a potential budget candidate the following conditions must be met:

- Written OPNAV cost and feasibility request must be in hand.
- Formal technical design inputs must be available.
- An approved acquisition strategy and shipbuilding schedule must be available.
- A cognizant Program Manager must be involved.

Cost estimates are to be prepared and submitted during each phase of the Planning, Programming and Budgeting system. These estimates are based on program acquisition strategy, technical definition and economic data available at the time of the estimate preparation. Clearly, the confidence and reliability of the estimates improve as the level of technical definition increases.

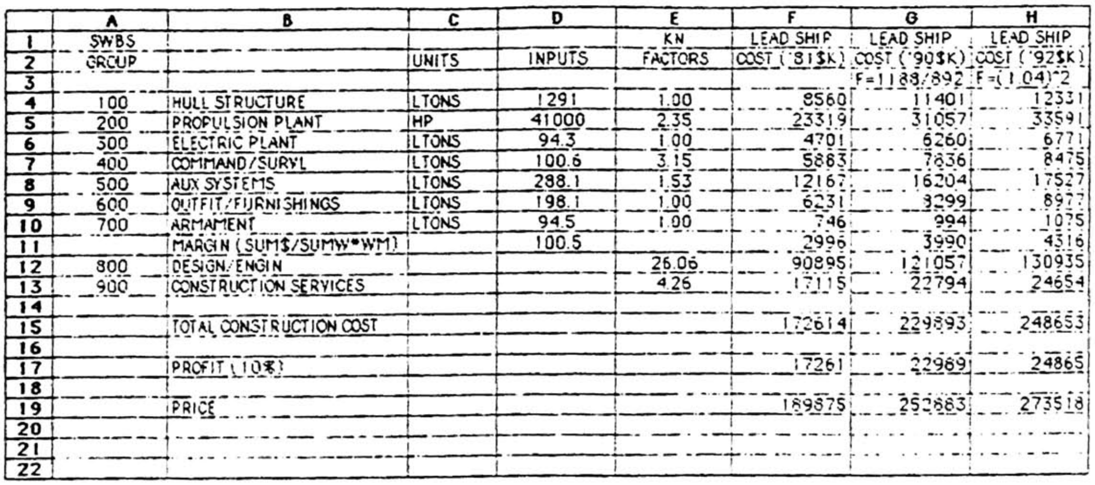
In the past, acquisition design was divided into four new ship design phases: Feasibility Study Phase, Preliminary Design Phase, Contract Design Phase and Detail Design Phase. For almost all major ship programs, NAVSEA would develop a ship design up to and including Contract Design. The intent of Contract Design was to provide a ship design that was sufficiently detailed and technically mature that a shipbuilder could use it to develop a cost proposal and ultimately sign a contract to develop the Detail Design and build the ship. Nowadays, NAVSEA only develops rough designs at the concept design level by the NAVSEA 05 division. This allows it to make an analysis of different alternatives that are submitted. If the specifications that the DoD requests are met, then the development of the ship design will be turned over to industry. The latter then performs feasibility, preliminary and contract designs.

The NAVSEA ship cost estimate classification system is shown in Table 1. The class "C" estimate is the ultimate goal of the ship cost estimating process. A class C is a commitment to Congress by the Navy that additional funds will not be required (exceptions being escalation factors due to inflation). The estimate is based on the three-digit SWBS system. The estimate also includes cost for government furnished material. The Cost Estimating Relationships (CERs) used to calculate the cost estimates are based on:

- an accepted weight estimate using bid information
- current weight estimate when using cost data from the contractor's latest Cost Performance Report (CPR)
- similar ship construction data of the prospective building yard(s) where new designs are being costed.

Class D estimates deal with ship conversions, modernizations, and Ship Life Extension Programs (SLEP). The estimate is comparable to that of a class C except there are provisions that deal with the uncertainties that occur with the repair and/or conversion. The requirements for this estimate include: a complete parts list, weights of equipment and material that is to be replaced, and a proposed list of ship alterations.

Class F estimates are prepared using information from feasibility studies based on single digit SWBS weights and only general guidance with respect to major electronics and weapons equipment. The cost estimate is in most cases a parametric extrapolation of a previous ship design. An example of such an ASSET model estimate is shown on Figure 26.



	A	B	C	D	E	F	G	H
1	SWBS				KN	LEAD SHIP	LEAD SHIP	LEAD SHIP
2	GROUP		UNITS	INPUTS	FACTORS	COST ('81$K)	COST ('90$K)	COST ('92$K)
3							F=1188/892	F=(1.04)^2
4	100	HULL STRUCTURE	LTONS	1291	1.00	8560	11401	12331
5	200	PROPULSION PLANT	HP	41000	2.35	23319	31057	33591
6	300	ELECTRIC PLANT	LTONS	94.3	1.00	4701	6260	6771
7	400	COMMAND/SURVL	LTONS	100.6	3.15	5883	7836	8475
8	500	AUX SYSTEMS	LTONS	288.1	1.53	12167	16204	17527
9	600	OUTFIT/FURNISHINGS	LTONS	198.1	1.00	6231	8299	8977
10	700	ARMAMENT	LTONS	94.5	1.00	746	994	1075
11		MARGIN (SUM$/SUMW*WM)		100.5		2996	3990	4316
12	800	DESIGN/ENGIN			26.06	90895	121057	130935
13	900	CONSTRUCTION SERVICES			4.26	17115	22794	24654
14								
15		TOTAL CONSTRUCTION COST				172614	229893	248653
16								
17		PROFIT (10%)				17261	22989	24865
18								
19		PRICE				189875	252883	273518
20								
21								
22								

Figure 26. Asset Model Output (20)

A class R estimate is a rough order of magnitude estimate. It is applicable for designs when the design information that is being used is not of feasibility standards quality. There is limited weight information known and the cost estimate uses old or generalized adjustment factors. Some examples are:

- a new design of an unconventional ship platform.
- a ship platform that is initially designed to carry many unconventional or developmental equipments.
- a ship designed beyond the current state of the art.

A class X estimate is applied to situations where the design is:

- not developed by the NAVSEA Cost Engineering and Industrial Analysis Division or the NAVSEA Ship Design Integration and Engineering Directorate, Cost Engineering Office, through the normal estimating process
- provided by other commands or agencies
- directed by higher authority.

TABLE 1. NAVSEA SHIP COST ESTIMATE CLASSIFICATION SYSTEM

Class	Basic Technical Input	Use
C	Completed Preliminary Design Three Digit Weights	Budget Phase (New Construction)
D	Scope of Work, Including Weights of Deletes & Adds SHIPALTS and Repairs	Budget Phase (Conversion)
F	Feasibility Study One Digit Weights	Planning/Programming Phase
R	Rough Order of Magnitude Less Than Feasibility Study	Planning Phase
X		A directed or modified estimate - an estimate not developed through the normal NAVSEA estimating process. An estimate established external to NAVSEA.

NAVSEA 05 uses a parametric ship design model called ASSET (Advanced Surface Ship Evaluation Tool). The model starts with an existing ship design, or parent ship, that is most closely analogous with the new ship concepts. The ASSET model iteratively changes the parent ship to reach a solution that accommodates the desired set of ship requirements. The design input provided to the cost estimator from ASSET is adequate to develop Class "R" cost estimates. The program also has the capability to be linked with the ACEIT (Automated Cost Estimating Integrated Tools) program which is a joint Army/Air force program supported by the Navy. It is also SWBS based in order to conform with NAVSEA standards but also includes indirect costs, escalation factors, and learning curves. The system can also output total life cycle costs for the vessel.

Once a design has been agreed upon, the development of the project is turned over to industry. The role of the Navy cost estimator then becomes that of a validation instrument of the contractors' cost models and estimates. This requires a large amount of interaction, communication, and cooperation between the contractor and the Navy personnel. Several issues of contention arise at this level of involvement due to the differences in estimating methods used by the Navy and all the different contractors that it uses. As a result, NAVSEA generally requires that all data is provided in SWBS form in order to be effectively and efficiently analyzed by 017. This is necessary because NAVSEA 017 still has to develop cost estimates of budget quality class C ratings for submission to Congress. 017 also requests that shipbuilders provide actual return cost data in order to keep the system updated.

The categories that constitute total end cost for a ship are show in Figure 27. The Major Category Codes (MCC) conform to the collection, accounting, and review systems used by NAVSEA. The categories can be separated into three groupings: shipbuilder portion, government furnished material (GFM), and general administrative. Construction plans, basic construction, and change orders (including shipyard profit which is about 10%) constitute the shipyard portion.

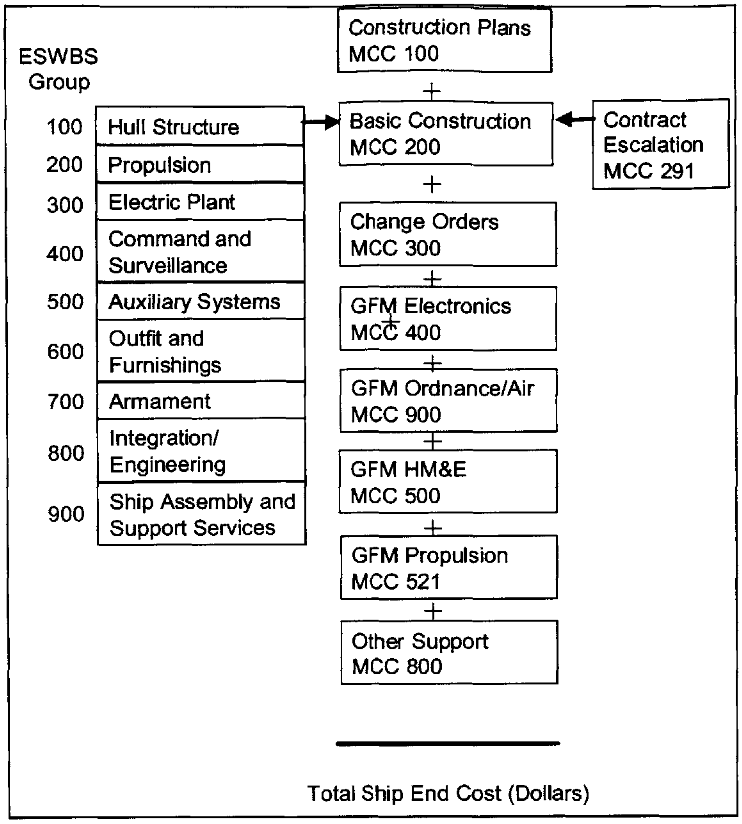


Figure 27. Total Ship Cost Categories (18)

Change orders have long been a region of difficulty for both the Navy and Congress. The existence of change orders is commonly due to the looseness of the initial award contract. The methods that such a change can take place are indicated in the federal acquisition regulation "changes" clauses. The reasons for change orders are the following:

- To include state-of-the-art improvements that come about during the lengthy construction periods of a ship,
- To correct deficiencies discovered in contract drawings or government furnished information which is the responsibility of the government,

- To correct differences between contract drawings and ship specifications,
- To incorporate safety items that emerge during construction,
- To incorporate improvements that are generated by the operational forces afloat, and approved for implementation,
- To have the shipbuilder repair or modify GFM,
- To change the contract ship delivery point, the contract date of delivery, or the method of shipment or packing.

There are about 3000 to 8000 change orders each fiscal year. The budgeted cost for change orders amounts to 10% for lead ships and 5% for follow ships. As it is in the interest of the shipyard to include as many change orders as possible, there is currently no incentive under the present system to see a decrease in their levels. As already mentioned in Chapter 1, change orders and the consequent increase in costs is a very significant number especially for lead ships. For the DDG-51 change orders accounted for over 17% of the total cost.

NAVSEA's use of CER's

Historically CER's were used to relate cost to SWBS weights under the following formula:

$$C = f * (\text{SWBS weight})$$

Where f represents a functional relationship relating material cost per ton and/or labor cost per ton. Other technical parameters are also used when better results are anticipated. These could include cost of energy generating systems that relate cost to power rating and weight. The following equation would be used:

$$C = (R/R_S)^{Kr} \quad X \quad (K_m \text{ x } W)$$

where
K_r = cost factor based on unit power rating
R = power rating (e.g., horsepower) of unit under consideration
R_S = power rating of "standard" unit
K_m = cost per unit of weight
W = weight of unit

These equations generate basic CER relationships. It is then in the discretion of the estimator as to what extent he is going to expand on or change the initial CER. Typical adjustments are made for inflation of labor and material costs as well as an incorporation of a historically acceptable level of risk. This process is far from an exact science and therefore requires judgment and experience. According to the level of detail of the data available from the contractor or shipyard, the estimator has to develop CER's according to the class of estimate that is being performed. The following estimating relationships are presented by NAVSEA as the suggested group relationships for class F estimates:

SWBS 100 - Hull Structure

Item	Labor CER	Material CER
GR 150, Deckhouse weight (Tons)	X MH/Ton (specific material)	$/Tons (specific)
GR 100, Remaining weight (Tons)	X MH/Ton (steel)	X $/Ton (steel)

Adjustments are made for different materials used:

Mild Steel (Tons)	X MH/Ton	X $/Ton
High-Yield Steel (Tons)	X MH/Ton	X $/Ton
High-Strength, High-Alloy Steel (Tons)	X MH/Ton	X $/Ton

For Submarines:

Pressure Hull Weight (Tons)	X MH/Ton	X $/Ton
GR 100, Remaining weight (Tons)	X MH/Ton	X $/Ton

SWBS 200 - Propulsion Plant

Item	Labor CER	Material CER
GR 220, Energy Generation System	MH/Unit, Rating, Ton, or Combination	Marine Vendor Input
GR 230, Propulsion	MH/Unit, Rating, Ton, or Combination	Marine Vendor Input
GR 240, Transmission Propulsion Systems	MH/Ton	$/Ton
GR 200, All Other	MH/Ton	$/Ton

SWBS 300 - Electric Plant

Item	Labor CER	Material CER
GR 310, Electric Power Generation	MH/Unit, Rating, Ton,	Vendor Input
GR 320, Power Distribution Systems (Tons)	MH/Ton	$/Ton
GR 330, Lighting System (Tons)	MH/Ton	$/Ton
GR 300, All Other (Tons)	MH/Ton	$/Ton

SWBS 400 - Command and Surveillance

Item	Labor CER	Material CER
GR 400, Command and Surveillance	MH/Ton	$/Ton

SWBS 500 - Auxiliary Systems

Item	Labor CER	Material CER
GR 510, Climate Control	MH/Ton	$/Ton*
GR 520, 530, 540, 550,	MH/Ton	$/Ton*
GR 500, All Other(Tons)	MH/Ton	$/Ton*

SWBS 600 - Outfit and Furnishings

GR 600, Outfit and Furnishings (Tons)	MH/Ton	$/Ton
GR 630, Painting	MH/Ton MH/Cubic Number	$/Ton

SWBS 700 - Armament

Since the majority of armament is GFM, the items are separately costed by the vendor or subcontractor. Shipyard costs are for installation of the equipment.

Item	Labor CER	Material CER
Guns (Units)	MH/Unit	$/Unit
Missile Launchers (Units)	MH/Unit	$/Unit
Torpedo Tubes (Units)	MH/Unit	$/Unit
GR 700, All Other (less weight of guns, etc.)(Tons)	MH/Ton	$/Ton

SWBS 800 and 900- Integration/Engineering and Ship Assembly and Support Services

The manhours and material dollars required for the work represented by these groups are a function of specification requirements, type of ship, and most significant, which shipyard is involved. The historical manhours and material dollars of Group 800 and 900 can be expressed as a percentage of the sum of historical manhours and material dollars for Groups 100 through 700 of the same ship.

Limitations of Weight Based System:

- **It cannot easily estimate cost differentials below gross levels of the work breakdown structure (WBS).** This precludes the method from being useful for trade-off studies of designs, materials, and manufacturing processes.
- **It cannot estimate cost differentials of outfit work performed at different stages of construction:** on unit,

on block and on board. Various established rules of thumb indicate that these cost differentials can vary from 300% to 500% or more.

- **It cannot estimate cost differentials due to configuration complexity,** such as compartment or system density (e.g. HVAC system installation in tight deckhouse) or location on board the ship (e.g. confining engine room installation versus easily accessible weather deck installation).
- **It cannot estimate cost differentials due to orientation of work** (e.g. less productive over head work versus more productive down hand work).
- **It cannot estimate cost differentials due to changes in build strategy,** including outsourcing the manufacturing of selected components to more productive, less costly vendors and suppliers.
- Since it operates mostly at high levels of the WBS, **it cannot easily translate or segment costs from one type of ship to another,** particularly ship types and hull forms not yet developed and built.

In typical government fashion, although it is clear that a Paleolithic cost estimating system is being used, little is being done to improve the current situation. The NAVSEA guide for the ship cost estimator (18) suggests that although "weight is the most commonly used parameter and has been shown in the past to provide good estimates, in the past the cost estimator has been encouraged to explore other available parameters to be used with, or in lieu of weight if improved results are anticipated". Although the reference manual states this fact, cost estimates conducted by the Navy are still primarily weight based.

How can weight be the single most important cost factor when different designs can have the same weight but completely different cost? The current approach inherently gives incorrect estimates especially when comparing competing preliminary designs because the system is not sensitive enough when evaluating the effects of subtle design changes.

The weight based model does not reflect or incorporate the effects of productivity changes or the process by which the vessel is built. An example is increasing the "shape" of a hullform by reducing the amount of parallel midbody. The change in actual steel structure weight may be insignificant in terms of the cost estimating relationships, resulting in no change in estimated cost.

However, eliminating several flat block modules will definitely result in a cost increase within a modular product oriented cost module such as PODAC. Figure 28 shows that cost not only changes with ship size but also with ship form.

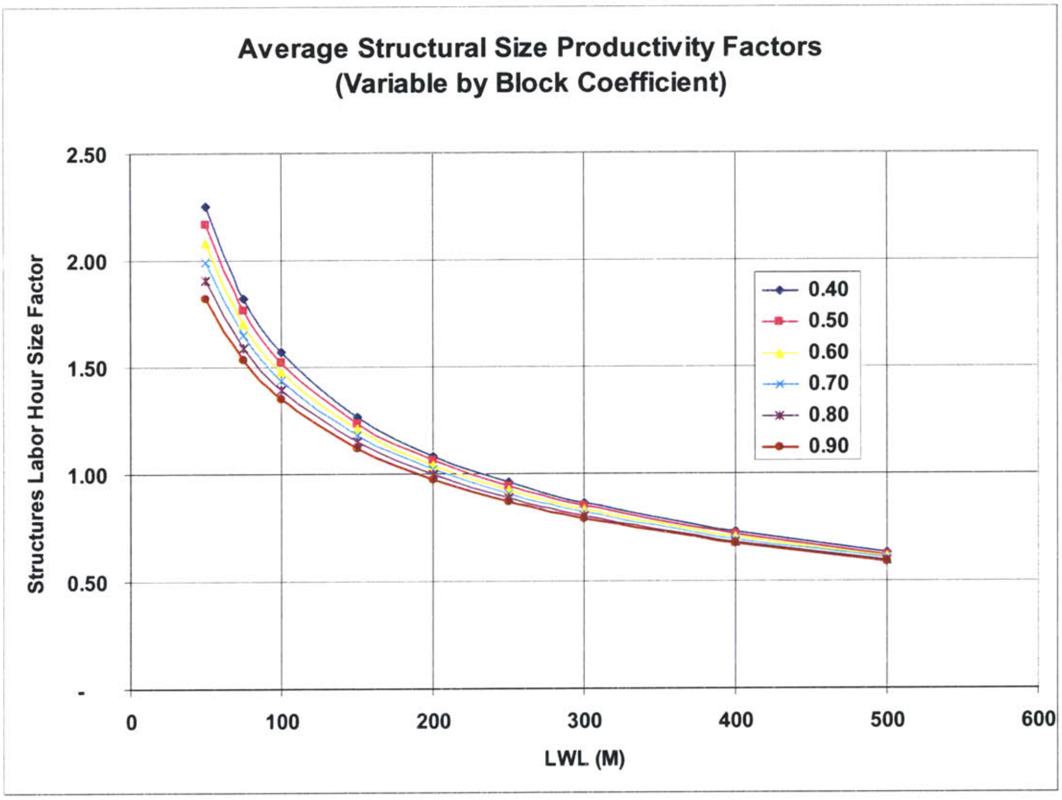


Figure 28. Index of Estimated Shipbuilding Costs (16)

The current estimating method makes no allowance or consideration of life cycle costs. This is major impediment when making trade off studies between different designs. Operating costs over the life of a vessel can amount to over 75% of total life cycle costs. Thus a cost estimating system that only focuses on initial acquisition cost without consideration for life cycle costs is inherently flawed. It is important and necessary that both designers be able to conduct reliable cost benefit analysis and design trade offs at the early stage of program development; and that mission leaders ensure that the mission requirements are realistic and can be met in an efficient and cost effective manor. In most cases a lack of visibility of the true problem or issue can lead to appropriation of unnecessary, ineffective, and operationally useless and/or expensive vessels.

In all fairness to the Navy, NAVSEA faces great difficulty in acquiring useful data from shipyards. In most cases the costs are bid data. The data is also gathered on the basis of a distributed system rather than on the basis of a production unit which forces the Navy to use a SWBS cost breakdown.

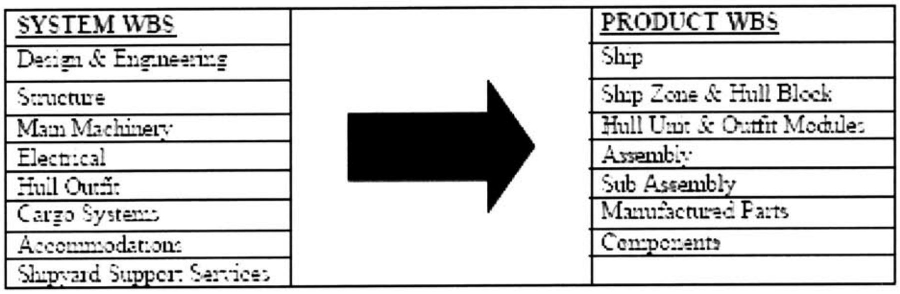
The next chapter will give insight into how industry has evolved its ship cost estimating capabilities in order to incorporate non weight based parameters into their forecasts.

CHAPTER 5 - PODAC:

The Product Oriented Design and Construction (PODAC) cost model was conceived as a means of developing a cost model that would employ a product oriented work breakdown system (PWBS) and group technology (GT). The system was developed by a joint government, industry, and academia consortium and the research funded by the Naval Surface Warfare Center (NSWC). The developing team was comprised of:

- Avondale Industries
- Bath Iron Works
- Ingalls Shipbuilding
- National Shipbuilding and Steel Company
- Newport News Shipbuilding
- University of Michigan
- Designers and Planners
- SPAR Associates
- NAVSEA

The new program was designed to address the long standing issue facing the traditional weight based models that were primarily linked to design features. The PODAC system incorporates algorithms that can determine the effects on cost of subtle design changes that have little or no impact on weight. It is a program that focuses on the production process of each interim product rather than on broad generalizations provided for by weight based CER's. Figure 29 shows how PODAC changes the viewpoint of a project from a System based to a Product based approach.

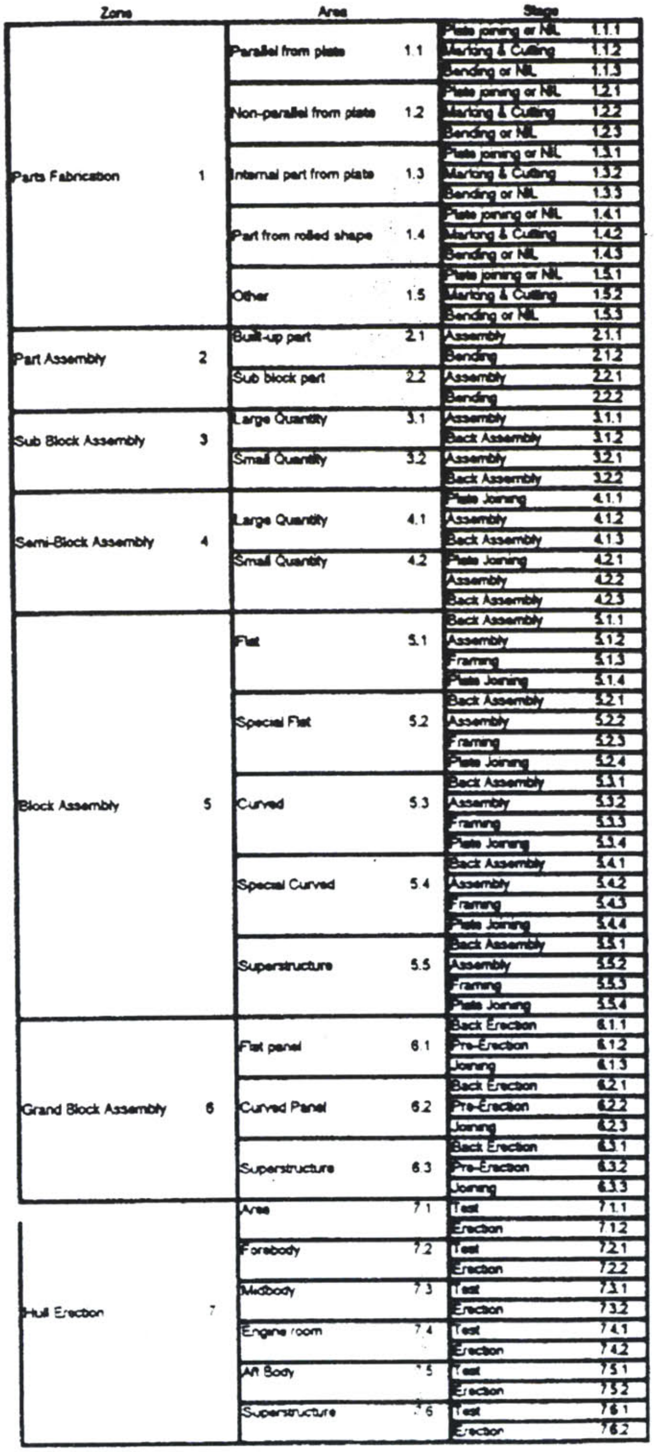


SYSTEM WBS	PRODUCT WBS
Design & Engineering	Ship
Structure	Ship Zone & Hull Block
Main Machinery	Hull Unit & Outfit Modules
Electrical	Assembly
Hull Outfit	Sub Assembly
Cargo Systems	Manufactured Parts
Accommodations	Components
Shipyard Support Services	

Figure 29. System vs. Product WBS (16)

The program has been operational since 1997 and has been successfully used in a wide range of programs both for government and industry specifications both domestically and internationally.

As already previously described, the system uses a PWBS system to define costs. The work is defined using three types of information: product structure, process, and work type. The hierarchical classification breakdown is shown on Figure 30. At each stage or process, interim products are defined by their specific work types that make up the finished product. In this way it is possible to assess the effects of design changes and innovations as well as to analyze their impact on the total life cycle cost of a vessel.



Zone		Area		Stage	
Parts Fabrication	1	Parallel from plate	1.1	Plate joining or NIL	1.1.1
				Marking & Cutting	1.1.2
				Bending or NIL	1.1.3
		Non-parallel from plate	1.2	Plate joining or NIL	1.2.1
				Marking & Cutting	1.2.2
				Bending or NIL	1.2.3
		Internal part from plate	1.3	Plate joining or NIL	1.3.1
				Marking & Cutting	1.3.2
				Bending or NIL	1.3.3
		Part from rolled shape	1.4	Plate joining or NIL	1.4.1
				Marking & Cutting	1.4.2
				Bending or NIL	1.4.3
		Other	1.5	Plate joining or NIL	1.5.1
				Marking & Cutting	1.5.2
				Bending or NIL	1.5.3
Part Assembly	2	Built-up part	2.1	Assembly	2.1.1
				Bending	2.1.2
		Sub block part	2.2	Assembly	2.2.1
				Bending	2.2.2
Sub Block Assembly	3	Large Quantity	3.1	Assembly	3.1.1
				Back Assembly	3.1.2
		Small Quantity	3.2	Assembly	3.2.1
				Back Assembly	3.2.2
Semi-Block Assembly	4	Large Quantity	4.1	Plate Joining	4.1.1
				Assembly	4.1.2
				Back Assembly	4.1.3
		Small Quantity	4.2	Plate Joining	4.2.1
				Assembly	4.2.2
				Back Assembly	4.2.3
Block Assembly	5	Flat	5.1	Back Assembly	5.1.1
				Assembly	5.1.2
				Framing	5.1.3
				Plate Joining	5.1.4
		Special Flat	5.2	Back Assembly	5.2.1
				Assembly	5.2.2
				Framing	5.2.3
				Plate Joining	5.2.4
		Curved	5.3	Back Assembly	5.3.1
				Assembly	5.3.2
				Framing	5.3.3
				Plate Joining	5.3.4
		Special Curved	5.4	Back Assembly	5.4.1
				Assembly	5.4.2
				Framing	5.4.3
				Plate Joining	5.4.4
		Superstructure	5.5	Back Assembly	5.5.1
				Assembly	5.5.2
				Framing	5.5.3
				Plate Joining	5.5.4
Grand Block Assembly	6	Flat panel	6.1	Back Erection	6.1.1
				Pre-Erection	6.1.2
				Joining	6.1.3
		Curved Panel	6.2	Back Erection	6.2.1
				Pre-Erection	6.2.2
				Joining	6.2.3
		Superstructure	6.3	Back Erection	6.3.1
				Pre-Erection	6.3.2
				Joining	6.3.3
Hull Erection	7	Area	7.1	Test	7.1.1
				Erection	7.1.2
		Forebody	7.2	Test	7.2.1
				Erection	7.2.2
		Midbody	7.3	Test	7.3.1
				Erection	7.3.2
		Engine room	7.4	Test	7.4.1
				Erection	7.4.2
		Aft Body	7.5	Test	7.5.1
				Erection	7.5.2
		Superstructure	7.6	Test	7.6.1
				Erection	7.6.2

Figure 30. PODAC PWBS Sections (PODAC)

Whereas in a SWBS cost estimating system CER's are generally defined through weight based relationships, in a PWBS system the definition of CER's changes with each level of definition. Examples of such evolution of CER definition is shown in Figure 31.

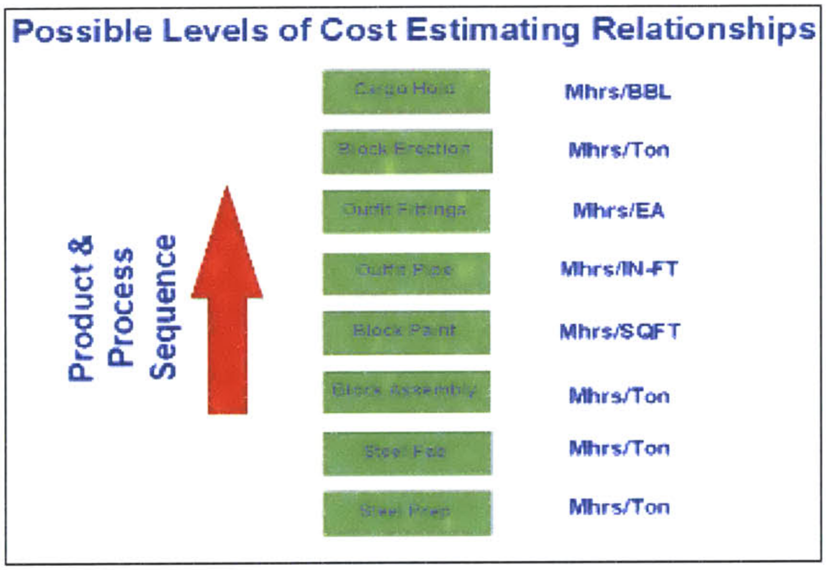


Figure 31. CER Change with PWBS Hierarchy (14)

Use of Empirical CERs in the PODAC Model

Empirical CERs are also used in the Parametric Module of the PODAC Cost Model to provide a top-down approach for estimating Basic Construction Costs at the Concept, Preliminary, and Contract stages of design:

- concept design level cost based on complexity factor (explained later in this report), displacement, and speed,

- preliminary design level cost based on complexity factor and system-based weight at the SWBS one-digit level,
- contract design level cost based on complexity factor and system-based weight at the SWBS two- or three-digit level.

A combination of traditional weight based CER's used in conjunction with complexity factors, process, and product based CER's form the backbone of the PODAC estimating system at every level of design.

1. Concept Design Level:

Price = Complexity Factor x [752 x $\mathrm{DISPL}^{0.835}$ x $\mathrm{SPEED}^{1.24}$]

*where Price is the sum of Labor Cost, Material Cost, All Indirect Costs, and Profit

Complexity Factor = Ship Type Factor x Size Factor

Ship Type Factor from Table 2

Size Factor = 32.47 x $\mathrm{DISPL}^{-0.3792}$

DISPL = full load displacement in long tons

SPEED = maximum sustained speed in knots

It is important to note that at the Concept Design level, there is no ability to distinguish between the various elements of price, such as labor and material costs.

Additionally, the price estimate determined using this approach was for U.S. Shipbuilding Programs, was for the first ship of a class, and did not include the cost for design and engineering. For naval ships, it did not include the costs of weapons or Navy program management.

SHIP TYPE	FACTOR
Tanker	0.80
Product Tanker Single Hull	1.13
Chemical Tanker	1.25
Double Hull Tanker	0.90
Bulk Carrier	0.86
Ore/Bulk/Ore Carrier	0.95
Reefer	1.16
Containership	0.96
Roll-On/Roll-Off	0.83
Car Carrier	0.61
Liquid Petroleum Gas Carrier	1.14
Liquid Natural Gas Carrier	1.12
Ferry - Aluminum High Speed	0.15
Ferry	1.25
Ferry - Aluminum SWATH	0.70
Passenger	3.00
Fishing	2.20
Harbor Tug	0.20
Naval Aircraft Carrier	6.00
Naval Combatant, Cruiser (Nuclear)	9.00
Naval Combatant, Destroyer	8.00
Naval Combatant, Frigate	7.00
Naval Amphibious, LHD/LHA	7.00
Naval Amphibious, LSD/LPD	5.00
Naval Auxiliary, Oiler	2.25
Naval Auxiliary, Tender	4.50
Naval Research	1.25
Naval Fleet Tug	1.00
US Coast Guard Icebreaker	4.50
US Coast Guard Buoy Tender	2.00

Table 2. Sample Ship Type Factors for Empirical CERs

Complexity Factor = Ship Type Factor (from table 2) x Size Factor

Size Factor = $32.47 \times \mathrm{DISPL}^{-0.3792}$

DISPL = full load displacement in long tons

2. Preliminary Design Level:

At the Preliminary Design level, the following weight-based CERs for Domestic Shipbuilding Programs can be seen to distinguish labor from material as shown in Table 3. Complexity Factors are derived from the Ship Type Factors and Size Factors as shown before in Table 2.

SWBS	DESCRIPTION	LABOR MANHOURS	MATERIAL DOLLARS
100	Structure	$\mathrm{CF} \times 177 \times \mathrm{WGT}_{100}^{0.862}$	$800 \times \mathrm{WGT}_{100}$
200	Propulsion	$\mathrm{CF} \times 365 \times \mathrm{WGT}_{200}^{0.704}$	$15{,}000 + 20{,}000 \times \mathrm{WGT}_{200}$
300	Electrical	$682 \times \mathrm{WGT}_{300}^{1.025}$	$25{,}000 \times \mathrm{WGT}_{300}$
400	Command and Control	$1{,}605 \times \mathrm{WGT}_{400}^{0.795}$	$40{,}000 \times \mathrm{WGT}_{400}$
500	Auxiliary	$\mathrm{CF} \times 34.8 \times \mathrm{WGT}_{500}^{1.24}$	$10{,}000 + 10{,}000 \times \mathrm{WGT}_{500}$
600	Outfit and Furnishings	$310 \times \mathrm{WGT}_{600}^{0.949}$	$5{,}000 + 10{,}000 \times \mathrm{WGT}_{600}$

Table 3. Empirical Preliminary CER Derivation

CF = Complexity Factor = Ship Type Factor x Size Factor

Size Factor = 32.47 x $\text{DISPL}^{-0.3792}$

DISPL = full load displacement in long tons

WGT_{X00} = weight of SWBS X00 in long tons

3. Contract Design Level:

At the Contract Design level, weight-based CERs for Domestic Shipbuilding Programs can also be seen to distinguish labor from material, as shown in Table 4. As before, Complexity Factors are derived from the Ship Type Factors and Size Factors.

SWBS	**DESCRIPTION**	**LABOR MANHOURS**
110	Hull Structure	CF x 4 x $\text{WGT}_{110}^{1.321}$
150	Superstructure	CF x 5,157 x $\text{WGT}_{150}^{0.384}$
161	Structural Castings and Forgings	CF x 314 x $\text{WGT}_{161}^{0.623}$
167/8	Structural Closures	60 x $\text{WGT}_{167/8}^{1.295}$
169	Special Purpose Closures	CF x 36 x $\text{WGT}_{169}^{0.969}$
170	Masts and Towers	CF x 149 x $\text{WGT}_{170}^{0.735}$

Table 4. Empirical Contract Level CER Examples

CF = Complexity Factor = Ship Type Factor x Size Factor

Size Factor = $32.47 \times \text{DISPL}^{-0.3792}$

DISPL = full load displacement in long tons

WGT_{XY0} = weight of SWBS XY0 in long tons

Similar Contract Design Labor CERs have been derived for SWBS Groups 2 - 6.

Improving Empirical CERs:

The suggested product-based and process-based Empirical CERs include the following, at the **Preliminary Design level of detail**. It is important to note that these Preliminary CERs are constructed by collecting data at the Contract and Detailed Design levels.

- STRUCTURE at the BLOCK level, with known block structural weight, number of parts, surface area, and joint weld length:

- manhours = f (number of parts) for preparation,
- manhours = f (number of parts) for fabrication,
- manhours = f (weight, surface area, weld length) for sub-assembly,

- manhours = f (weight, surface area, weld length) for assembly,
- manhours = f (weight, surface area, weld length) for erection.

- PIPING at the BLOCK level, with known block piping number of parts:
  - manhours = f (number of parts) for preparation,
  - manhours = f (number of parts) for fabrication,
  - manhours = f (number of parts) for sub-assembly,

    manhours = f (number of parts) for assembly.

- OUTFIT at the BLOCK level, with known block outfit weight and number of parts:
  - manhours = f (weight, number of parts) for on-unit outfitting,
  - manhours= f (weight, number of parts) for on-block outfitting,
  - manhours= f (weight, number of parts) for on-board outfitting.

- PAINTING at the BLOCK level, with known block surface area:
  - manhours = f (surface area) for block painting,
  - manhours = f (surface area) for final painting.

Sample Representations of Empirical CERs:

For Preliminary Design level CERs for LABOR in MANHOURS:

STRUCTURE manhours:

Preparation = f (Complexity Factor (CF), number of parts)

Fabrication = f (CF, number of parts)

Sub-Assembly = f (CF, weight, surface area, weld length)

Assembly = f (CF, weight, surface area, weld length)

Erection = f (CF, weight, surface area, weld length)

PIPING manhours:

Preparation = f (CF, number of parts)

Fabrication = f (CF, number of parts)

Sub-Assembly = f (CF, number of parts)

Assembly = f (CF, number of parts)

OUTFITTING manhours:

On-Unit Outfitting = f (CF, number of parts, weight)

On-Block Outfitting = f (CF, number of parts, weight)

On-Board Outfitting = f (CF, number of parts, weight)

PAINTING manhours:

Block Painting = f (CF, surface area requiring paint)

Final Painting = f (CF, surface area requiring paint)

SUPPORT manhours: = f (CF, displacement)

Complexity Factors:

There are several types of complexity factors that have been introduced into the PODAC system that adjust CER's. Several of these empirically derived complexity factors have been presented in the previous section. Complexity factors adjust CER equations according to each level of the hierarchy of the PWBS. The reason for this is that working conditions become increasingly more difficult, time consuming, and expensive as the work progresses from the workshop to on board installation. Ideally the most preferable place to do work would be:

- Under Cover

- At an easily accessible area
- Where less support services are required
- Where tools and equipment are readily available

Thus the most cost efficient place to construct and assemble the vessel is in the workshop. The least desirable work location is to do the work on board. On block work when the blocks are not too large (under 500 tons) are more convenient workplaces than onboard. There is added productivity if the blocks can be assembled under cover to eliminate the effects of weather conditions. Lastly on unit work, which involves the assembly of outfit modules, can produce cost savings since it is easier to access, assemble and outfit a unit on block rather than on board. Figure 32 shows comparative complexity factors assigned to different work sites.

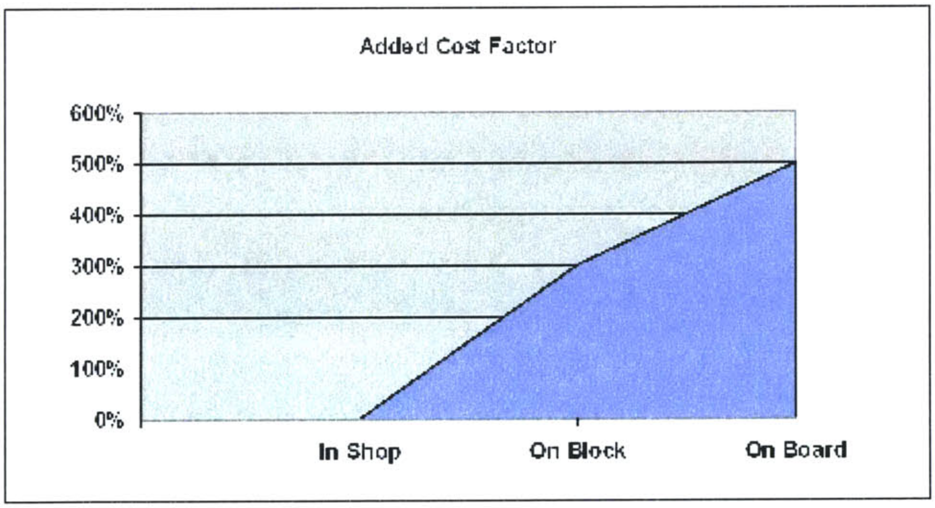


Figure 32. Complexity Factor by Work Stage (15)

Complexity factors differ not only by the location of the work, but by the type of work being performed at that particular location. For example down hand welding is much cheaper and more productive than overhead work at any stage of production. However, the CER's being used at each level of the PWBS cannot be the same for the same type of work being conducted due to the difficulty of access to the workplace. Figure 33 shows typical complexity factors that are assigned to different working sectors of a vessel.

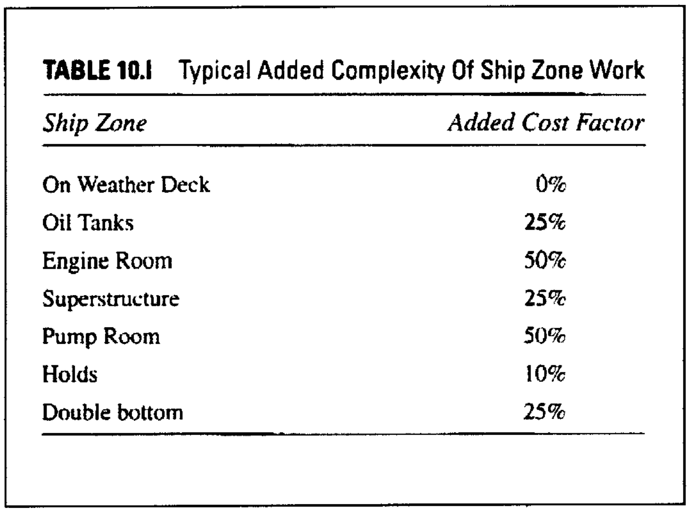


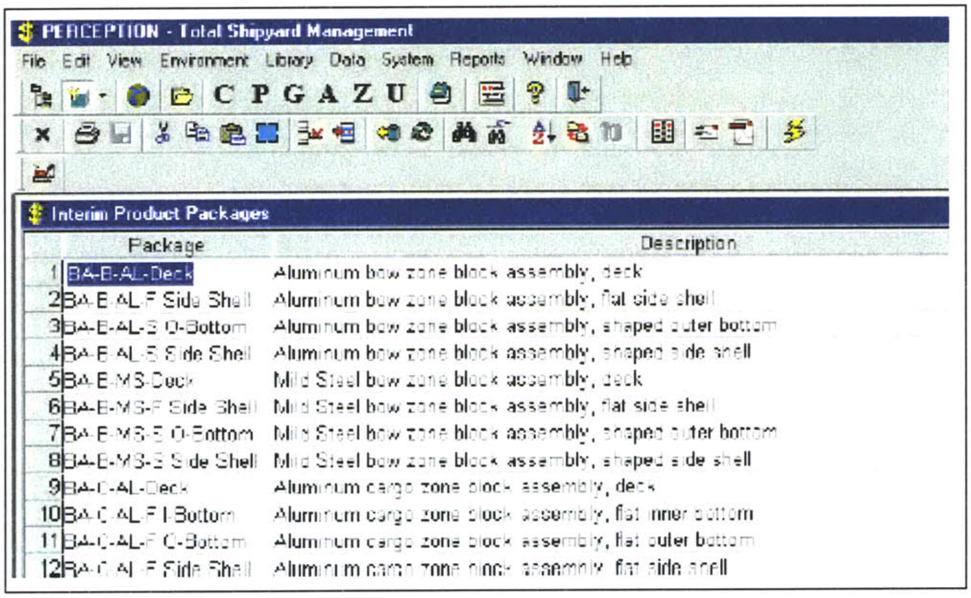
TABLE 10.1 Typical Added Complexity Of Ship Zone Work

Ship Zone	*Added Cost Factor*
On Weather Deck	0%
Oil Tanks	25%
Engine Room	50%
Superstructure	25%
Pump Room	50%
Holds	10%
Double bottom	25%

Figure 33. Complexity Factor by Work Area (23)

Interim Products (IP)

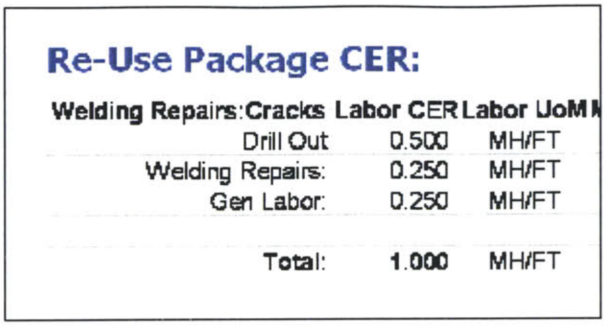
The CER's that are developed and incorporated into the new system are there in order to subdivide the vessel in a series of pre-costed, re-usable modules or packages of work to be conducted. Typical examples of standard work packages are shown in Figure 34. Standard work packages, just like CERs that are developed for different sections of the ship are categorized and organized in libraries within the system. The Cost estimator can then select the appropriate combination of CERs or work packages pertaining to the particular project.



	Package	Description
1	BA-B-AL-Deck	Aluminum bow zone block assembly, deck
2	BA-B-AL-F Side Shell	Aluminum bow zone block assembly, flat side shell
3	BA-B-AL-S O-Bottom	Aluminum bow zone block assembly, shaped outer bottom
4	BA-B-AL-S Side Shell	Aluminum bow zone block assembly, shaped side shell
5	BA-B-MS-Deck	Mild Steel bow zone block assembly, deck
6	BA-B-MS-F Side Shell	Mild Steel bow zone block assembly, flat side shell
7	BA-B-MS-S O-Bottom	Mild Steel bow zone block assembly, shaped outer bottom
8	BA-B-MS-S Side Shell	Mild Steel bow zone block assembly, shaped side shell
9	BA-C-AL-Deck	Aluminum cargo zone block assembly, deck
10	BA-C-AL-F I-Bottom	Aluminum cargo zone block assembly, flat inner bottom
11	BA-C-AL-F O-Bottom	Aluminum cargo zone block assembly, flat outer bottom
12	BA-C-AL-F Side Shell	Aluminum cargo zone block assembly, flat side shell

Figure 34. Examples of Work Packages (14)

Such reusable modules can be subdivided into reusable work packages that consume a standard amount of material, require a standard amount of work, and cost a standard amount of money. A typical example of such a process is shown on Figure 35.



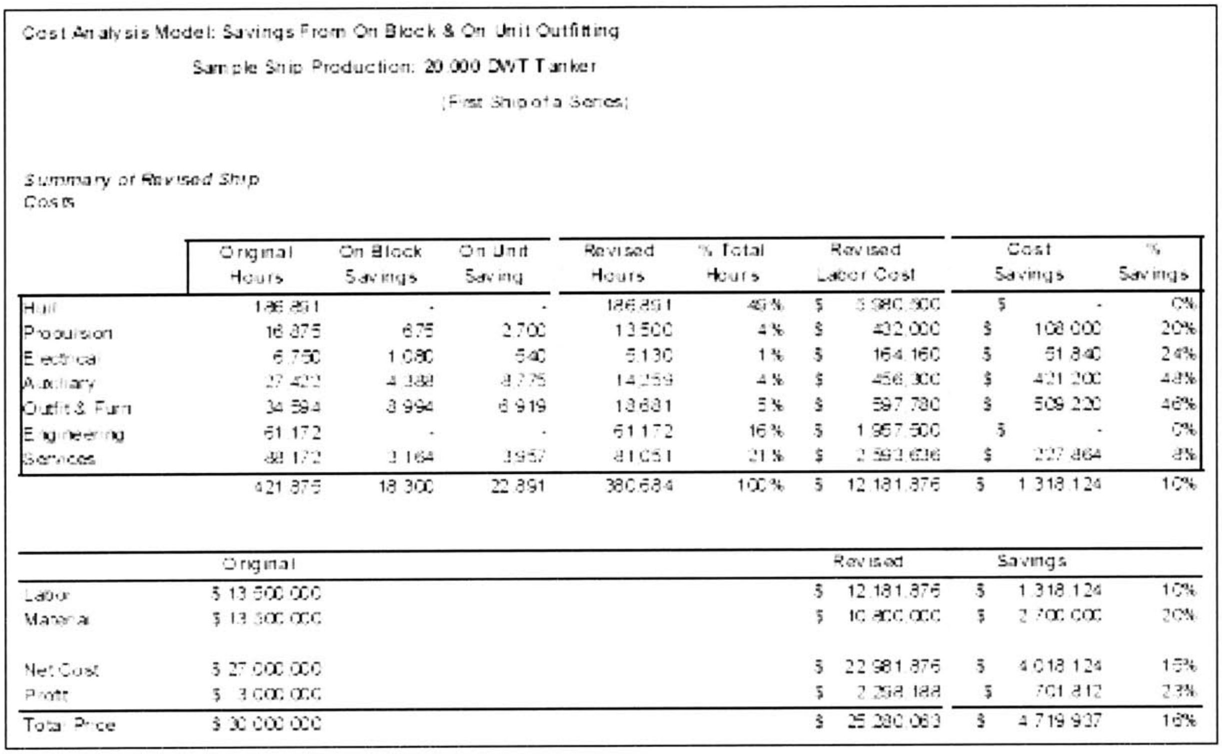
Re-Use Package CER:

Welding Repairs:Cracks	Labor CER	Labor UoM
Drill Out	0.500	MH/FT
Welding Repairs:	0.250	MH/FT
Gen Labor:	0.250	MH/FT
Total:	**1.000**	MH/FT

Figure 35. Example of Re-Useable Work Package (16)

In order for such a cost system to be effectively implemented in shipyards in order to maximize cost savings presented by pre outfitted, modular construction, it is necessary that the technical design information sent to the shipyard is tailored with such a build organization strategy in mind. Experience from the construction of the DDG-51 showed that although the shipyards had the capability to construct the vessel using modular methods and on block outfitting, the lack of design consideration to the generic build strategy resulted in excessive re-workings and a low level of productivity.

SPAR Associates conducted a study to determine the possible cost savings that could occur by the use of a modular, PWBS strategy built vessel that attempted to maximize cost savings through the use of minimal on board outfitting. Figure 36 shows a summary of the results. It is important to note the 16% cost savings realized by the implementation of such a generic build strategy.



Cost Analysis Model: Savings From On Block & On Unit Outfitting

Sample Ship Production: 20,000 DWT Tanker

(First Ship of a Series)

Summary of Revised Ship Costs

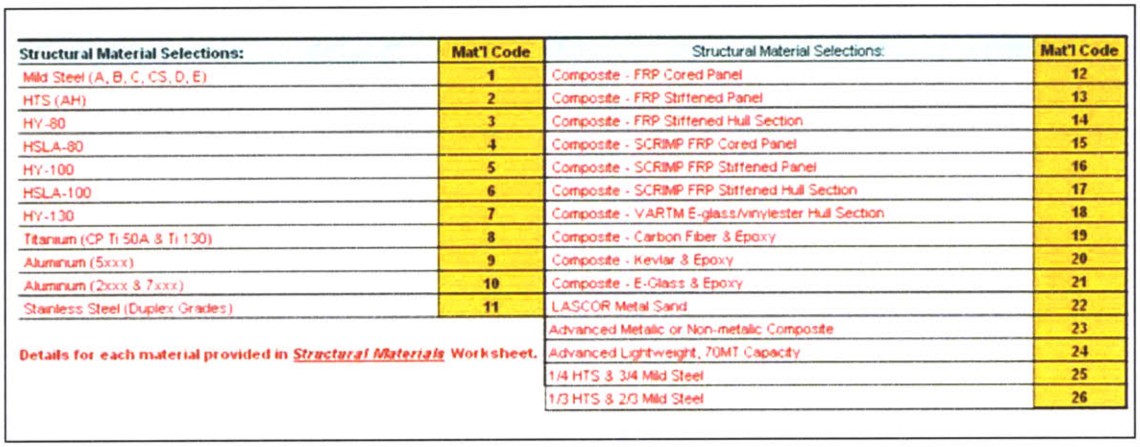
	Original Hours	On Block Savings	On Unit Saving	Revised Hours	% Total Hours	Revised Labor Cost	Cost Savings	% Savings
Hull	186,891	-	-	186,891	49%	$ 5,980,500	$ -	0%
Propulsion	16,875	675	2,700	13,500	4%	$ 432,000	$ 108,000	20%
Electrical	6,750	1,080	540	5,130	1%	$ 164,160	$ 51,840	24%
Auxiliary	27,422	4,388	8,775	14,259	4%	$ 456,300	$ 421,200	48%
Outfit & Furn	34,594	3,994	6,919	18,681	5%	$ 597,780	$ 509,220	46%
Engineering	61,172	-	-	61,172	16%	$ 1,957,500	$ -	0%
Services	88,172	3,164	3,957	81,051	21%	$ 2,593,636	$ 227,464	8%
	421,875	18,300	22,891	380,684	100%	$ 12,181,876	$ 1,318,124	10%

	Original	Revised	Savings	
Labor	$ 13,500,000	$ 12,181,876	$ 1,318,124	10%
Material	$ 13,500,000	$ 10,800,000	$ 2,700,000	20%
Net Cost	$ 27,000,000	$ 22,981,876	$ 4,018,124	15%
Profit	$ 3,000,000	$ 2,298,188	$ 701,812	23%
Total Price	$ 30,000,000	$ 25,280,063	$ 4,719,937	16%

Figure 36. Possible Outfitting Cost Savings (15)

Design Trade off Capabilities

An interesting feature of the new PODAC system is the incorporation of new hullforms such as catamarans, and trimarans into the database. The development of new CER's for different vessel classes and designs is very important as the Navy continues to design and purchase vessels with such configurations. Any added data into the system and CER libraries helps make the final ship cost estimation more realistic. Clearly submarine CER's cannot be used for destroyer class vessels. Similarly, steel monohull CER's cannot be used for composite trimarans. Figure 37 shows the variations of material CER's that are available with the new PODAC system.



Structural Material Selections:	Mat'l Code	Structural Material Selections:	Mat'l Code
Mild Steel (A, B, C, CS, D, E)	1	Composite - FRP Cored Panel	12
HTS (AH)	2	Composite - FRP Stiffened Panel	13
HY-80	3	Composite - FRP Stiffened Hull Section	14
HSLA-80	4	Composite - SCRIMP FRP Cored Panel	15
HY-100	5	Composite - SCRIMP FRP Stiffened Panel	16
HSLA-100	6	Composite - SCRIMP FRP Stiffened Hull Section	17
HY-130	7	Composite - VARTM E-glass/vinylester Hull Section	18
Titanium (CP Ti 50A & Ti 130)	8	Composite - Carbon Fiber & Epoxy	19
Aluminum (5xxx)	9	Composite - Kevlar & Epoxy	20
Aluminum (2xxx & 7xxx)	10	Composite - E-Glass & Epoxy	21
Stainless Steel (Duplex Grades)	11	LASCOR Metal Sand	22
		Advanced Metalic or Non-metalic Composite	23
		Advanced Lightweight, 70MT Capacity	24
		1/4 HTS & 3/4 Mild Steel	25
		1/3 HTS & 2/3 Mild Steel	26

Details for each material provided in *Structural Materials* Worksheet.

Figure 37. Material Options with PODAC (16)

The inclusion of such data has led to a new area of important design trade offs. That is the decision between choosing different materials for particular ship regions. The use of a re-use/ modular construction and design allows the designer or cost estimator to immediately determine the cost of using different materials for the whole vessel or for parts of it. Figure 38 shows the effect on weight of using different materials on a Trimaran hull.

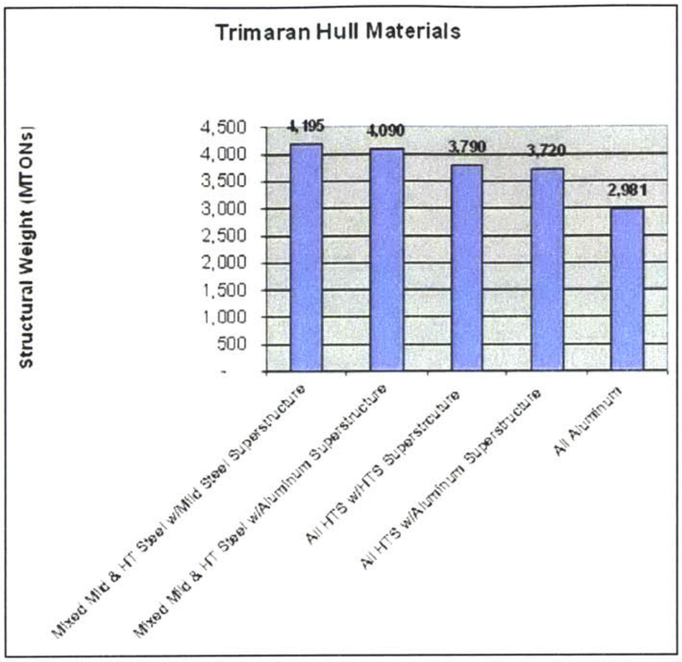


Figure 38. Material Trade-off Analysis (16)

As already stated rather repeatedly throughout this thesis, it is not enough to simply have a weight based analysis in order to determine costs. In an effort to produce lower costs, DDG-51’s deckhouse was built with thin plate. This resulted in excessive plate distortion due to the welding process. This distortion made the assembly of blocks highly labor intensive requiring the use of hydraulic rams. Figure 39 shows the clear benefit of using a non weight based system to analyze ship construction costs.

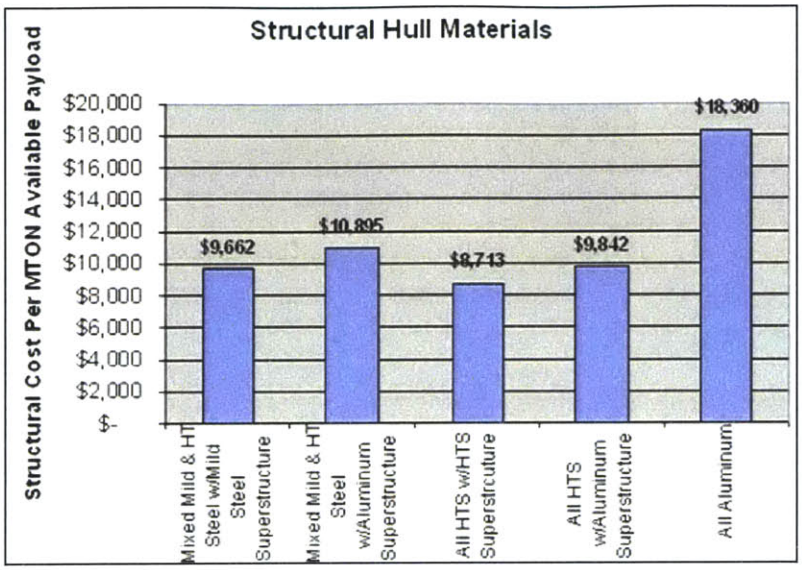


Figure 39. Construction Cost Material Trade-off (16)

Although Aluminium is the least cost solution as presented in Figure 38, it suffers from higher installation costs. The welding process is difficult, expensive, and requires highly trained labor. Aluminium also has a lower tensile strength than steel and therefore requires stronger structure to support the hull, equipment, and armament. This results in more structure and thus higher costs. The PODAC system has the capability with its comprehensive CER's to incorporate the build complexity and difficulty of production into its predictions.

Other trade-off studies that can be conducted by the new system include:

- Changes in equipment and related auxiliary systems e.g. AZIPOD propulsion versus geared diesel and rudder propulsion.
- Changes in subcontractors e.g. subcontracting the vessel pipe work.
- Changes in general arrangement or mission requirement.

Such trade-off capabilities allow the vessel designers an immediate understanding of the cost implication of their design decisions or changes. An understanding on the part of the designer as to why costs increase is a fundamental paradigmatic change in the thought process of ship procurement. It should definitely result in cheaper and faster vessel construction.

Risk Analysis

An important capability of the PODAC system is the ability that it presents the cost estimator to specify a range of possible costs for items or processes that are considered high risk. The greater the risk, the greater the probability that the cost estimate is not realistic.

Since it is impossible to exactly determine beforehand the type of probability distribution that can be applied to each process or CER due to the variability of real life issues, the program requires the input of an expected maximum and minimum value of cost. This essentially presents a series of triangular probability distributions. The program then combines the different probability functions into one single, complex distribution and the data is analyzed using Monte Carlo Risk. The data is then combined into a cumulative probability distribution of costs. Figure 40 shows an example of such a distribution.

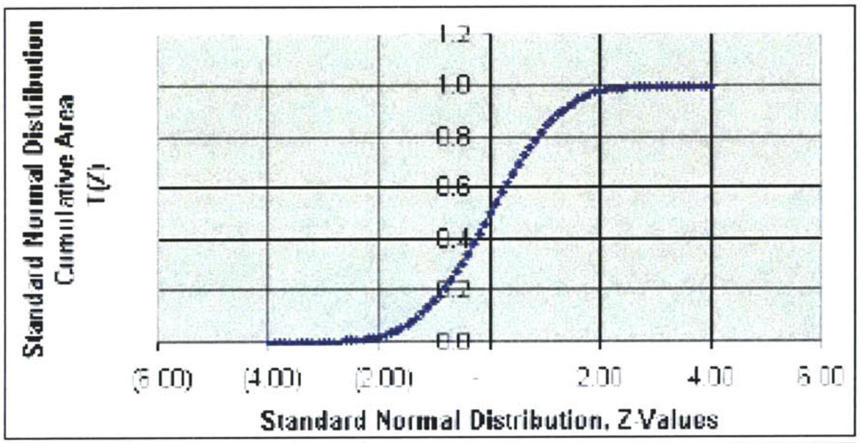


Figure 40. Cumulative Cost Distribution (14)

The existence of a probability distribution allows the estimator to develop a sense of confidence in the data that is produced, the probability that the estimate will be wrong, and what the range of possible cost will be about the expected prediction. The probability that cost does not exceed the estimators most likely cost estimate is presented in Figure 41.

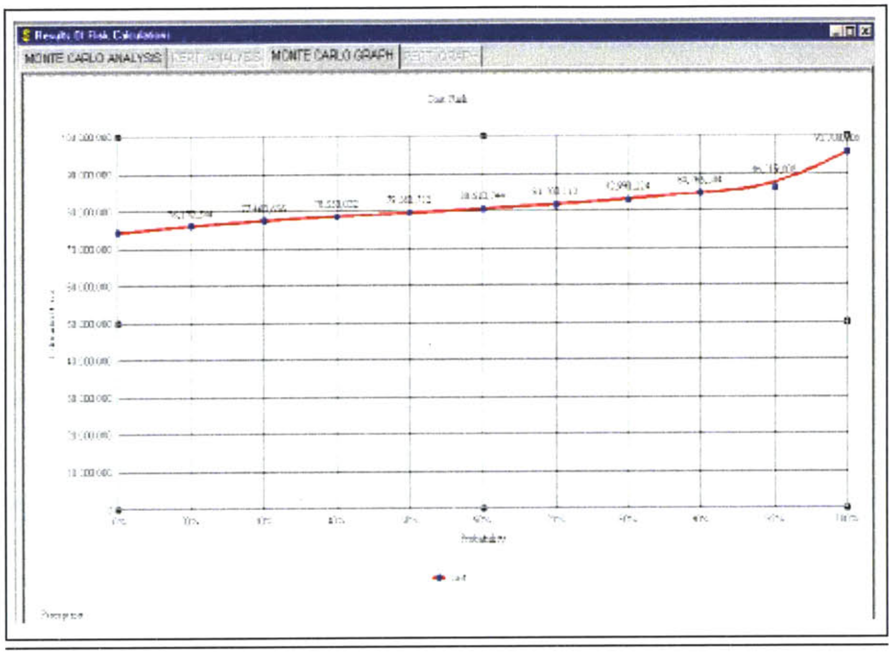


Figure 41. Probability Cost does not Exceed Estimate (14)

Life Cycle Costs

Life cycle costs can be essentially divided into four main stages: conception, acquisition, operation, and disposal. In order to correctly cost and evaluate a project it is necessary to make a prediction for each stage. Such costs have always been an area of concern for commercial ship owners. The reason is that ship owners are interested in the final bottom line of profit and return on investment. SPAR Associates' shipyard cost estimating program provides ship owners with design trade-offs that pertain to life cycle costs. The significance of operational and maintenance costs (about 75% of life cycle costs) has been already stated several times in previous sections. The cost estimating program allows the ship owner and the designer to immediately determine the required freight rate in order to have a certain return on investment (ROI) over a certain time period. Thus the design trade-off analysis can be expressed in terms of life cycle costs.

The importance of this added feature should not be overlooked by the Navy. Although naval acquisitions do not have a particular ROI requirement, they must satisfy a national security commitment at the least possible cost. It is therefore necessary for the Navy to understand the components of life cycle costs and how it is possible to reduce them. The Navy currently has several reporting systems such as the Ownership Architecture Retrieval System (OARS) for maintenance issues, COMET for personnel costs, which are all part of a Total Ownership Cost (TOC) breakdown. These systems deal with life cycle costs but they are not integrated between themselves in order to provide direct answers to design trade off questions at the design, costing, and acquisition decision level.

Problems:

Several issues have arisen due to the lack of coordination between the Navy, shipyards, and subcontractors. Designers building ships for the US Navy are using system based cost estimates which do not focus on the producibility of design. Shipyards are costing and building vessels with a product based approach; while the Navy is conducting its own cost operation using cost data provided by the shipyard in a product based format!

A cost estimate is only as good as the information supporting the estimate... if historical costs cannot be collected in ways that identify modular block costs, estimating by modular blocks can be difficult and will probably have a relatively high degree of risk in the accuracy and validity of the estimate. (14) It is therefore imperative that shipyards organize costs in ways that can directly benefit the cost estimating process.

CHAPTER 6 - MIT MATH MODEL

The MIT Math Model was developed in 1975 by Clark Graham while serving as the 13A course Associate Professor of Naval Construction in conjunction with 13A student R. Hamley. It was developed as an educational tool in order to assist 13A students with the ship cost estimating process for their ship design projects. It was adapted from the Navy Synthesis Model and called "Simplified Math Model for the Design of Naval Frigates". The model was revised and updated in 1984, 1986, 1988, and 1990. It is in excel format and designed to be a balance between simplicity, sophistication, and generality. It is relatively easy to understand and use and it is compatible with all personal computers.

Users of the model have to; however, understand its limitations. It is designed in order to be applicable to Naval Frigates, with a range of displacements from 2500 to 8500 tons. The model analyzes only conventional monohulls and assumes standard USN design practices. The system is limited to single screw vessels with diesel generator sets. The hull materials considered are mild steel hull with options for aluminium or mild steel superstructure. The system uses the USN SWBS weight breakdown system for weights. The empirically derived CER's are therefore primarily weight based. The model therefore has a limited scope without much flexibility for change. Having said that, its purpose is a teaching tool for naval ship design. The students are not presenting their designs to NAVSEA for appropriations from Congress, nore are they submitting detailed engineering designs to shipyards for construction. Thus at this level of preliminary design the model appears to be successful. Even the most modern (PODAC) systems still use parametric weight based empirical CER's from historical data (Chapter 5). Thus MIT's system is not using methods that far from standard industry practice at this level of design.

CHAPTER 7 - SHIP COST REDUCTION SUGGESTIONS:

1. Improve quality of Cost Estimates

    - Improve the current cost estimating method that the Navy is using incorporating improvements discussed throughout this thesis.
    - Conduct independent cost estimates in addition, support, and comparison of the Navy predictions to assure accuracy.
    - Conduct independent cost estimates of any change order work that is suggested by shipyards in order to determine accuracy and reliability.

2. Improve contract award process

    - Negotiate prices for construction of the lead ship separately from the pricing of detail design work.
    - Separate the pricing of lead ships from follow on ships. (4)

3. Improve management of programs

    - Require shipyards to submit monthly cost performance reports in order to allow project leaders to quickly become aware of cost driving factors.

4. Design Cheaper Vessels

Cheaper vessels can be designed and built in cheaper, simpler, and faster methods by using the following general guidelines:

- Maximum use of standard plate and stiffener sizes.
- Avoid using thin plate to avoid distortions
- Do not carry hull curvature into the structure inside of the hull plating
- Run strakes in the same direction as primary framing
- Design for maximum use of high productivity tools such as automatic welding
- Design bilge strakes with the same thickness as bottom plates
- Design to facilitate assembly and erection with structural units, machinery units, and piping units
- Make port and starboard units similar
- Eliminate camber and sheer
- Eliminate cruiser sterns and cambered transoms
- Maximize use of flat panels, straight frames, and reduce plate curvature
- Locate knuckles and chins at unit breaks
- Run chins parallel to keel (as much as possible)

- Simplify bow and stern shape by removing unnecessary curvature
- Allow for large deckspace to facilitate outfitting (9)

It is necessary however to be able to balance producibility with life cycle costs and performance. The ability to perform design trade-offs particularly at the conceptual and early stages of design, where decisions are generally established rather firmly, should be a top priority.

CONCLUSION

Introducing paradigmatic change in any business is difficult. Doing so is even harder for government. The introduction of integrated product teams between the Navy and the industry co-operating together from concept design to delivery can ensure a better consideration for acquisition and total life cycle costs.

Naval ship cost estimating has not seen any significant change since the 1980's. Cost is still estimated using outdated and inaccurate weight based ship cost estimating models whose assumptions and inability to reflect subtle design changes result in cost overruns.

The PODAC model attempts to deal with many of the issues cost facing the Navy today. Although the government essentially funded the project, cost estimations are not using the new systems. To a large extent this is probably because the results have not been clear in similar projects. It probably does not help that the design of the LPD-17, which ended up being grossly overpriced, included many PODAC principles. Also in order for the new program to be effective and produce realistic estimates, it is necessary for both industry and the Navy to practice operating and thinking in this new and different way. It will take some time to get accustomed and begin to have faith in a product based approach but I believe it will eventually happen for the Navy as it has happened effectively abroad.

The MIT Math Model is a useful engineering tool. For the purpose that it serves it is probably a reasonable method. Its estimates are not expected to be realistic given the limitations of the model. It should be examined whether it would be possible to acquire a cost estimating program such as the one developed by SPAR Associates in order to improve the accuracy of the cost estimates conducted at MIT.

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