Updating MIT's Cost Estimation Model for Shipbuilding

By

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ABSTRACT

This thesis project will update the MIT ship cost estimation model by combining the two existing models (the Basic Military Training School (BMTS) Cost Model and the MIT Math Model) in order to develop a program that can accurately determine both a ship's acquisition cost as well as its life cycle cost. Using United States Coast Guard resources, this project will also address various aspects of the ship design process which have a direct effect on the cost of building a ship. This will include, but not be limited to, the cost estimation process, determining which design decisions have the biggest impact on the ship's total cost, common pitfalls in the design process that lead to increases in cost, and lessons learned that have helped minimize the cost of a ship.

INTRODUCTION

This thesis project will update the MIT ship cost estimation model by combining the two existing models (the Basic Military Training School (BMTS) Cost Model and the MIT Math Model) in order to develop a program that can accurately determine both a ship's acquisition cost as well as its life cycle cost. Using United States Coast Guard resources, this project will also address various aspects of the ship design process which have a direct effect on the cost of building a ship. This will include, but not be limited to, the cost estimation process, determining which design decisions have the biggest impact on the ship's total cost, common pitfalls in the design process that lead to increases in cost, and lessons learned that have helped minimize the cost of a ship.

This paper will discuss a number of concepts that are used in the cost estimation process. These concepts include Ship Work Breakdown Structure (SWBS) groups and how they can be used to help with cost estimation, cost estimating relationships, the differences between lead and follow ship costs and factors that determine them, life cycle costs and their components, and how they tie into the big picture of Coast Guard and Navy cost estimation. These concepts will then be revisited during the discussion of the current cost models in use at MIT.

While the actual cost estimating relationships that are used by the programs will not be published, the means in which they are applied will be discussed at length in order to provide the reader with a good understanding of both the old and new cost models work.

CHAPTER 1: BASIC PRINCIPLES OF COST ESTIMATION

When calculating the cost of a vessel one must consider the costs of both labor and construction materials in addition to any overhead costs that may be incurred during the project. Shipyards typically have to deal with a highly variable product which makes bidding on contracts especially difficult. With minimal profit margins and little time available to make bids, it is crucial that reasonably accurate cost estimations are developed. Making matters even more difficult is the fact that due to the complexity and cost of a detailed ship design, and the large amount of time between the creation of a preliminary design and when that design is finally seen through to completion, there are often a significant number of design change orders which can cause dramatic increases to the cost of the final product. (1)

New construction contracts often begin without detailed production drawings. This makes it very important for shipyards to have a means of developing accurate cost estimations. Shipyards typically maintain a catalog of historical costs that are tracked by a consistent work breakdown structure (WBS). This catalog typically has a list of common ship systems that includes hull structure, piping, electrical, paint and furnishings. This list is further augmented by ancillary shipyard services required for production support. The U.S. Coast Guard and the U.S. Navy both use a well known WBS called the Ship Work Breakdown Structure (SWBS). (2)

1.1 SWBS Groups

Using the SWBS system, material in a ship is broken down into seven major categories, or SWBS groups. The sum of the weights of the seven major SWBS groups (plus the weight of the margin) is the total lightship weight for the ship. SWBS numbers have three digits in them which are used to define material contained in that specific group. The first digit in a SWBS group number describes the most basic category to which a particular piece of material belongs.

SWBS 100 (Hull Structure)- Group 100 refers to the assembled main hull body with all structural subdivisions. This group includes shell plating, longitudinal and transverse framing, platforms, masts, all of the interior and exterior decks, and the superstructure. Additionally all doors and closures fall into this group.

SWBS 200 (Propulsion Plant)- Group 200 refers to those major components installed primarily for propulsion and the systems necessary to make these components operable. This group contains engines, turbines, boilers and energy converters, main condensers and air ejectors, shafting, bearings and propellers.

SWBS 300 (Electric Plant)- Group 300 refers to the power generating and distribution system installed primarily for ship service and emergency power and lighting. This includes generators, switchboards, lighting, and cables used for power distribution.

SWBS 400 (Command and Surveillance)- Group 400 refers to all equipment and associated systems installed to receive information from off-ship sources, to transmit to off-ship receivers and to distribute information throughout the ship. It also refers to sensing and data systems required for navigation and weapon fire control. This group also includes interior communications systems as well as countermeasure and protective systems.

SWBS 500 (Auxiliary Systems)- Group 500 refers to those systems required for ship control, safety, provisioning and habitability. All auxiliary systems including heating, ventilation, air-conditioning, refrigeration, plumbing, firemain, freshwater, rudders, steering gear, winches, capstans and cranes used for anchor stowage, as well as fuel and diesel oil filling are included in this group.

SWBS 600 (Outfit and Furnishings)- Group 600 refers to the outfit equipment and furnishings required for habitability and operability, which are specifically included in other Hardware Elements. Hull fittings, boats, boat stowage and handling, ladders and gratings, nonstructural bulkheads and doors, storerooms, furnishings for living, office, medical and dental spaces, and galley equipment are all included in this group.

SWBS 700 (Armament)- Group 700 refers to armament and related ammunition handling, stowage, and support facilities; and cargo munitions handling, stowage, and support facilities. Guns, their mounts and all weapons launching devices are included in this group. The costs of expendable ordnance or attached air assets are not included in Group 700.

In addition to the seven main groups that breakdown a ship's weight, there are two other SWBS groups that are used in the cost estimation process: groups 800 and 900.

SWBS 800 (Integration/Engineering)- The integration and engineering element refers to the engineering effort and related materials associated with the design and development of the ship. The work included in this group includes the development and maintenance of drawings, production engineering, mass properties engineering, design support, quality assurance, integrated logistic support engineering, repair planning, and preparation and planning for special purpose items and systems.

SWBS 900 (Ship Assembly and Support Services)- The ship assembly element refers to work associated with ship construction and testing which is not included in the aforementioned groups. The elements in this group include staging, scaffolding and cribbing, temporary utilities and services, molds, patterns, templates, jigs, fixtures, special production special tools and test equipment, dry-docking, contractual and production support services, insurance, trials, tests and inspection, and delivery.

Table 1, taken from the Advanced Naval Vehicles Concept Evaluation Final Report (3), expands upon the contents of each of the aforementioned SWBS groups detailing a more complete list of the material that fits into each category.

Group	Description	Definition
1	Hull structure	Shell plating or planking; longitudinal and transverse framing; innerbottom plating; platforms and flats below lowermost continuous deck; fourth deck; third deck; second deck; main deck or hangar deck; forecastle deck (including platforms, flats, and decks between main and gallery deck); gallery deck; flight deck; landing platforms and special purpose decks above weather deck (includes catapult troughs); superstructures; foundations for main propelling machinery; foundations for auxiliaries and other equipment; structural bulkheads; trunks and enclosures; structural sponsors; armor; aircraft fuel saddle tank structure; structural castings, forgings, and equivalent weldments; sea chests; ballast and buoyancy units; doors and closures, special purpose; doors, hatches, manholes, and scuttles, nonballistic; doors hatches, manholes, and scuttles, ballistic; masts and king posts; compartment testing.
2	Propulsion	Boilers and energy converters; propulsion units; main condensers and air ejectors; shafting, bearings, and propellers; combustion air supply system; uptakes and smoke pipes; propulsion control equipment; main steam system; feedwater and condensate systems; circulating and cooling water system; fuel oil service system; lube oil system.
3	Electric plant	Electric power generation; power distribution switchboards; power distribution system (cable); lighting system - distribution and fixtures.
4	Communication and control	Navigational system and equipment; interior communications systems; armament control systems; countermeasure and ships' protective systems (except electronic); electronic systems including electronic countermeasures.
5	Auxiliary systems	Heating system; ventilation system; air-conditioning system; refrigerating spaces, plant and equipment; gas, NEAF, cargo piping, oxygen-nitrogen, aviation lube oil systems; plumbing installations; firemain, flushing, and sprinkler system; fire extinguishing systems; drainage, trimming, heeling, and ballast systems; freshwater system; scuppers and deck drains; fuel and diesel oil filling, venting, stowage, and transfer systems; tank heating systems; compressed-air systems; auxiliary steam, exhaust steam, and steam drains; buoyancy control system (flooding and venting - submarines); miscellaneous piping systems; distilling plant; steering gear system; rudder; winches, capstans, cranes, and anchor-handling system; elevators, moving stairways, and cargo handling equipment; operating gear for retractable elevating units; aircraft elevators; aircraft arresting gear barriers and barricades; catapults and jet blast deflectors, hydrofoils and lift systems.
6	Outfit and furnishing	Hull fittings; boats, boat stowage and handling; rigging and canvas; ladders and gratings, nonstructural bulkheads and nonstructural doors; painting; deck covering; hull insulation; storerooms, stowages, and lockers; equipment for utility spaces; equipment for workshops; equipment for galley, pantry, scullery, and commissary outfit; furnishings for living spaces; furnishings for office spaces, electronic, and radar; furnishings for medical and dental spaces.
7	Armament	Guns, mounts, and launching devices; ammunition-handling systems; ammunition stowage; special weapon stowage and handling.
8	Design and engineering services	Design and engineering services.
9	Construction service	Staging, scaffolding, and cribbing; launching; trials and docking; temporary utilities and services; material handling and removal; cleaning ship services.

Table 1: SWBS Group Descriptions (3)

NATO also uses a SWBS 000 group designated for General Guidance and Administration. Group 000 contains elements which accommodate a wide variety of applications. The major subgroups within Group 000 include combat capabilities, strategic and special capabilities, operation support capabilities, ship system management, ship system performance, subsystem characteristics, general requirements for design and construction, integrated logistics support requirements and quality assurance requirements. Only the costs for development and preparation of general requirements should be carried in this group. Costs to execute ship acquisition and maintenance should be entered in the appropriate elements of groups 100-900. (4)

Group specifications within the system increase as the level of design increases. One digit SWBS groups pertain to very general categories as was demonstrated by the descriptions above. The SWBS 100 group covers all of the elements pertaining to hull structure which is a very broad grouping of material. The two digit SWBS 130 group represents all of the elements pertaining to the hull decks and the three digit SWBS 132 group refers only to the second deck. Similarly in the SWBS 300 group, 300 represents the electric plant, 330 the lighting system, and 332 the lighting fixtures. It is important to note that the more specific groups (two and three digits) are all subsets of their parent groups. Everything in the 332 group is an element of the 330 group, and likewise everything in the 330 group is contained in the 300 group.

This classification system is convenient because it is system based, and this is preferred by engineers. The SWBS classification system provides a format by which a shipyard can collect and organize historical data to determine costs. These costs can then be used to estimate the pricing of new work. Both of the cost models used at MIT use SWBS groups as a means of breaking down a ship's weight in order to ultimately produce cost estimates. These models and their applications will be covered at greater length in a later chapter.

1.2 Cost Estimating Relationships

A series of Cost Estimating Relationships (CERs) are used in conjunction with the SWBS groups to produce cost estimates. CERs are an extremely useful tool as they provide a basic means for estimating costs despite dealing with a number of material products, parts and components in addition to multiple labor processes and support services. Costs can be estimated both at very high levels (such as during concept stages of design) and at very low levels (such as from detail bills of material). Therefore CERs must come in many different levels of detail. There are also CERs available that can provide greater accuracy than possible from available design information alone, but without the precision of what might be obtained after detail design and engineering has been completed. (2)

A CER is a formula that is able to relate an item's cost to its physical or functional characteristics. It can also be used to relate an item's cost to the cost of another item or group of items. Examples of how CERs are set up include representing the cost of labor for steel block assembly in terms of man hours per ton, the material cost for piping in terms of dollars per meter, or the labor hours spent on shipyard services as a fixed percentage of the total production hours. (2)

CERs are typically developed directly from a measurement of a single physical attribute for a given shipbuilding activity, and that activity's cost. Some CERs may be developed for a number of physical attributes. CERs may also be developed to determine a variety of costs and cost-related parameters. These include estimates for labor hours, material costs, overhead, number of items, and weight.

Most CERs are defined in terms of simple linear relationships such as 25 man-hours per long ton of an individual SWBS group, or 20 dollars per foot of cable laid on a ship. There are other CERs that can contain far more complicated formulations. High-level CERs can exhibit non-linear relationships to accommodate the costs across a wide range of applications and a variety of detail requirements. An example of a more complicated CER is represented below.

$$SteelCost = 0.00255\Delta^{0.99}$$

This section will discuss five different types of CERs: Manual CERs, Calculated CERs, Predictive CERs, Empirical CERs and Standard Interim Product CERs. Manual CERs are developed using external information that can be provided by vendor or subcontractor quotations. Calculated CERs are determined from a set of return cost data from a single ship that is based on an actual cost expenditure and its associated measurable parameter. An example of this is labor hours per square feet of painted area. Predictive CERs are derived from return costs from multiple ship sets, or from the costs collected from a given manufacturing process where costs might exhibit a pattern of change over time. The predictive CER is the trend value of unit cost expected to apply for the given contract application. (2)

Empirical CERs are developed by collecting a number of physical attributes for a given shipbuilding activity as well as their associated cost. These attributes can include ship type and size, part weight, part area, part perimeter, joint weld length, number of processes applied and/or the number of parts involved. If this data is collected for a number of ships built in the same shipyard, a statistical analysis may then be used to determine the statistical significance of the parameters. This allows for the development of equations with coefficients and exponent values for the activity CER. The equation coefficients and exponent values generated are shipyard-dependent and will reflect the level of productivity for the activity for that shipyard alone. (2)

The final type of CER is the Standard Interim Product CER. An interim product is defined as any output of a production work stage that can be considered complete in and of itself. It can also be presented as an element within any level of a product work breakdown structure (PWBS). As shipyards move towards adopting standard interim products as the primary basis for building ships, interim products themselves can form the means for developing high-quality cost estimates. The interim product cost estimate package consists of a set of cost items and/or cost item CERs, each describing labor and/or material costs. The labor costs may be broken down into the product's sequence of manufacturing and its assembly stages. They may also include indirect cost efforts such as project supervision and material handling as well as related direct costs such as testing.

The interim products can be defined at any level of the PWBS. The higher the level, the more ship type-specific they are likely to be. These interim products effectively become complex high level CERs because they can include any number of cost items and these cost items may be parametric to any number of different defining characteristics. The use of the standard interim product as a means for cost estimation is sometimes referred to as a "re-use package" that can operate within a variety of applications. The package can be used repeatedly if needed when developing a project cost estimate. (2)

Cost estimators face the challenge of determining what type of CER is appropriate at any given stage of the design process. Detail CERs are of little value when few details are known. Similarly, high-level CERs are not feasible when their assumptions are no longer applicable to a particular problem. Furthermore, the CER must be able to identify the cost driver for the scope of the work being estimated. The cost driver is the controllable ship design characteristic or manufacturing process that has a predominate effect on cost. The real problem becomes determining where one obtains the necessary data used to develop realistic or appropriate CERs that can be meaningfully applied at any given time during the design evolution process. (2)

A cost estimate is only as good as the information that supports it. For shipyards, historical cost information is invaluable for developing cost estimates for new work. Historical information needs not only to be accurate, but it must also be collected in such a way that it can be effectively used in the cost estimating process. For example, if a certain shipyard uses modular blocks as a primary means of construction, there will be significant problems if historical costs cannot be collected in such a way that is able to identify modular block costs. As a result, there will be a relatively high degree of risk in the accuracy and validity of the estimate. It is crucial that a shipyard have a cost planning and data collection system in place that is capable of organizing costs in such a way that they correlate directly to the cost estimating processes that are used by that particular shipyard.

Shipyards must collect both labor costs as well as material costs when compiling data for their catalogs. Labor costs, which are directly related to labor hours, are collected from time charges to production work orders. Material costs are collected from purchase orders and from stock transactions when applicable. Shipyard work orders are generally organized around work type and stage of construction, while material is often catalogued by ship system. The correlation of material to work orders can be obtained from issues of material to work orders or the requisitioning of bills of material to the PWBS. (2)

In order to benefit the cost collection process, work orders should identify the scope or the physical (material throughput quantity for which the work is being done). For example, a work order might prescribe a budget of a hours to assemble b material items that are constructed with an average size of c. The labor hours and material costs can then be summarized through the PWBS. The units of measure at a given level of the PWBS will be the most meaningful and therefore the cost driver for that level. The unit of measure for steel fabrication might be based upon the joint weld length, while the unit of measure for block erection might be best described in terms of the total number of parts or the total weight of the entire block.

Despite the fact that high-level CERs broken up by ship systems are required for concept and preliminary design estimating, modern ship production methods no longer allow costs to be collected directly by ship systems. Production management software systems that are utilized by many shipyards are now only able to develop CERs by measuring actual costs against known work order throughput parameters (meter of weld, square meter of plate, number of pipe spools, etc.). Many of these shipyard systems have little or no means to transform these product- and process-oriented CERS into the desired high level, ship systems and mission oriented CERs. (2)

With so many different components, ships are complex products to say the least and they are normally designed system by engineered system. However, manufacturing does not maximize its cost efficiency and schedule performance if the work is planned and executed by system. Group technology and zone sequence scheduling are examples of executing work by interim product (units, blocks and modules) and by stage (fabrication, assembly and erection). These examples of work objectives transform the SWBS into a parallel PWBS. The transformation occurs when the systems-oriented ship design information is processed for necessary work instructions by production engineering. (2)

In order for a shipyard to provide accurate production cost data that is SWBS-oriented, some reverse transformation is required. Some of the shipyard production management systems have the capability to transform product- and process-oriented work orders so that ship systems costs are able to be collected. Methods have been devised for allocating or distributing costs that are effective, although somewhat approximate. One approach used is to allocate costs based upon a planned breakdown of budget by ship systems involved in the work order. When time charges are entered, they are then distributed automatically on a pro-rated budget basis back to the applicable ship systems. Typically such work orders are restricted to a single type work process. As a result the allocation can be a fair and reasonable representation of the actual work performed on each system.

A second approach used is having the estimator compile and analyze detailed production data and then correlate the resulting costs to functional characteristics of the ship. For example, the electrical costs can be summarized and related to the ship-wide electrical load, measured in kilowatts. A CER such as this may be directly useful for estimating cost at the concept and preliminary stages of design. A third approach is to develop systems-based CERs from shipyard work standards applied to the ship system's bill of material. (2)

1.3 Learning Curves

Once the CERs are determined and in place it becomes necessary to look at the cost of a ship in several respects. First, how much is it going to cost to build the initial ship in a given class (the lead ship)? Then, once the construction of the first ship is completed, how much is it going to cost to build subsequent ships of the same class (the follow ships)? It is often accepted that the production of multiple products benefits from a learning curve. This means that for a series of ships being built, each subsequent ship labor cost should decrease due to continued improvements introduced over time in the build strategy and the manufacturing processes and refinements used in production. Additionally, the use of blocks, modules and other standard interim products used in construction as well as increased specialization decreases the average construction cost as more similar vessels are produced. As a result the CERs that are used for the original vessel have to be modified to take into account the effects of learning as a series of vessels of the same class are constructed in sequence.

Each process that is performed is affected by learning to different degrees. The degree varies depending on a number of factors that include a system's complexity, the manufacturing technology being used on the system, and the time between the completion of one ship and the start of construction on the next. Low skill level processes tend to exhibit low levels of learning as there is little or no reduction in the amount of labor despite repeated performance of the task. Highly automated operations also tend to experience little or no reduction in efficiency because machines are unable to increase their productivity through experience. Innovative production processes such as modulization and the PWBS are able to increase a shipyard's efficiency and decrease costs, but this is not necessarily attributed to learning effects. The major area where learning has a significant influence is in tasks that involve highly skilled manual labor. This is due to the fact that skilled manual labor significantly improves its efficiency through experience and repetition. Table 2 shows how different manufacturing activities may exhibit different slopes in their learning rates. The slopes listed are measured in percentages. A slope of 100% means that there is no learning involved in the process, and therefore the efficiency cannot be improved upon through learning.

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

Table 2: Typical Learning Rates (1)

If in a particular operation there is a three to one ratio between manual and automated labor, a slope in the vicinity of 80% is common. If the ratio between manual to automated labor is one to one, the slopes are typically in the 85% region. If the ratio is three to one in favor of automated labor, it will generally result in the learning rate being in the 90% region. It becomes clear when examining the trend exhibited by the three ratios that as a particular shipbuilding operation becomes more and more automated, there is less and less of a learning curve.

Figure 1 shows learning curves from the 1970s and how they compare with learning curves from the 1990s. The plot shows that the 1990s learning curves are much flatter with slopes much closer to 100%. This corresponds with the fact that technology in the shipbuilding industry greatly improved over those two decades. Automated processes have become more prevalent in ship construction and as a result the slope of the learning curve has shifted closer and closer to 100%.

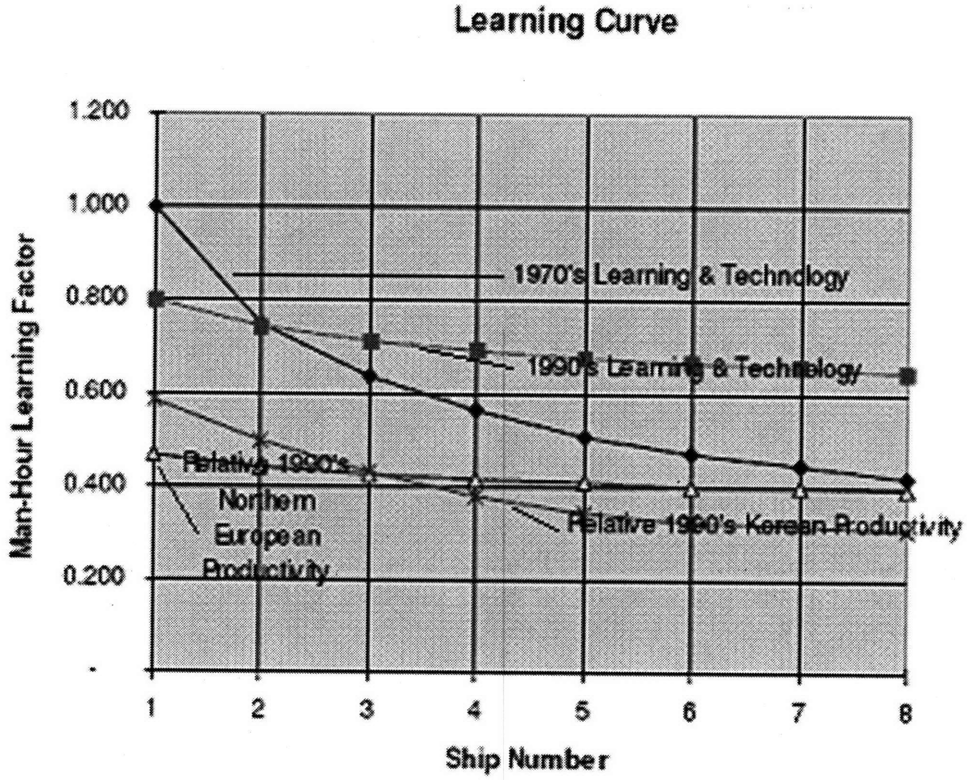
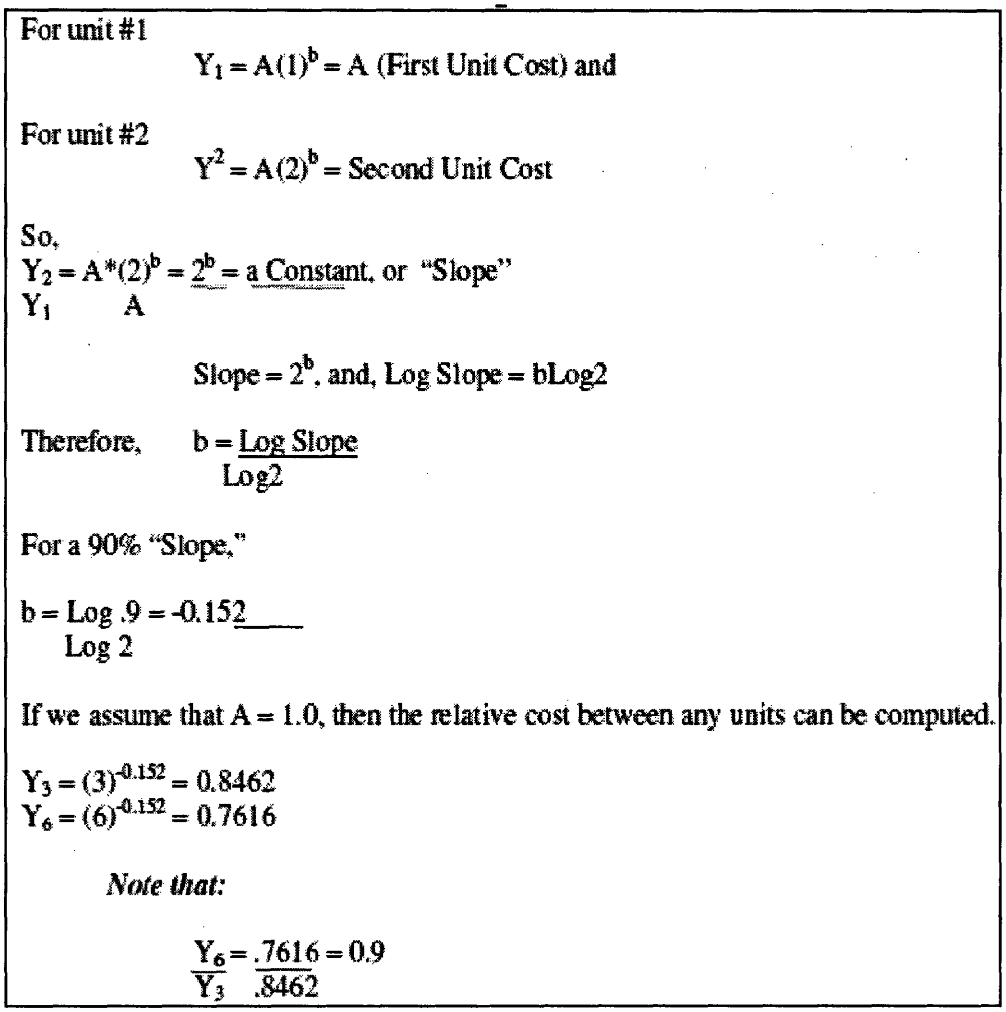


Figure 1: Relative Learning Curve Productivities Based Upon Applications of Advanced Shipbuilding Technologies (5)

In Figure 2, a series of equations is shown documenting the process in which a follow ship cost is developed from a lead ship cost with a given learning curve slope. It should be noted the slope is constant every time the number of products is doubled. Therefore given a 90% learning curve slope, the cost of the first follow ship constructed (ship #2) will be 90% of the cost of the lead ship (ship #1) while the cost of the sixth ship will be 90% of the cost of the third ship. The math proving this is also shown in Figure 2.



For unit #1

$$Y_1 = A(1)^b = A \text{ (First Unit Cost) and}$$

For unit #2

$$Y^2 = A(2)^b = \text{Second Unit Cost}$$

So,

$$\frac{Y_2}{Y_1} = \frac{A*(2)^b}{A} = 2^b = \text{a Constant, or "Slope"}$$

$$\text{Slope} = 2^b, \text{ and, Log Slope} = b\text{Log}2$$

Therefore, $b = \frac{\text{Log Slope}}{\text{Log}2}$

For a 90% "Slope,"

$$b = \frac{\text{Log }.9}{\text{Log }2} = -0.152$$

If we assume that A = 1.0, then the relative cost between any units can be computed.

$$Y_3 = (3)^{-0.152} = 0.8462$$
$$Y_6 = (6)^{-0.152} = 0.7616$$

Note that:

$$\frac{Y_6}{Y_3} = \frac{.7616}{.8462} = 0.9$$

Figure 2: Generation of Values for Cost Learning Curves (5)

Using the equations in Figure 2, a table has been generated that shows the data for two distinct learning curves (Table 3). The first represents a learning curve with a slope of 90%, and the second represents a learning curve slope of 95%. The table demonstrates how the impact of learning can affect the overall cost over a span of the construction of 20 ships. The results show the effects to be quite significant. A 5% difference in the slope of the two curves results in nearly a 20% difference in the cost of the 20th ship. Figure 3 shows a plot of the data provided in Table 3.

Ship No.	Percent Labor Hours Lead Ship	Percent Labor Hours Lead Ship
	95% slope	*90% Slope*
1	100.0	100.0
2	95.0	90.0
3	92.2	84.6
4	90.3	81.0
5	88.8	78.3
6	87.6	76.2
7	86.6	74.4
8	85.7	72.9
9	85.0	71.6
10	84.3	70.5
11	83.7	69.5
12	83.2	68.5
13	82.7	67.7
14	82.3	67.0
15	81.8	66.3
16	81.5	65.6
17	81.1	65.0
18	80.7	64.4
19	80.4	63.9
20	80.1	63.4

Table 3: Typical Learning Curve Factors (5)

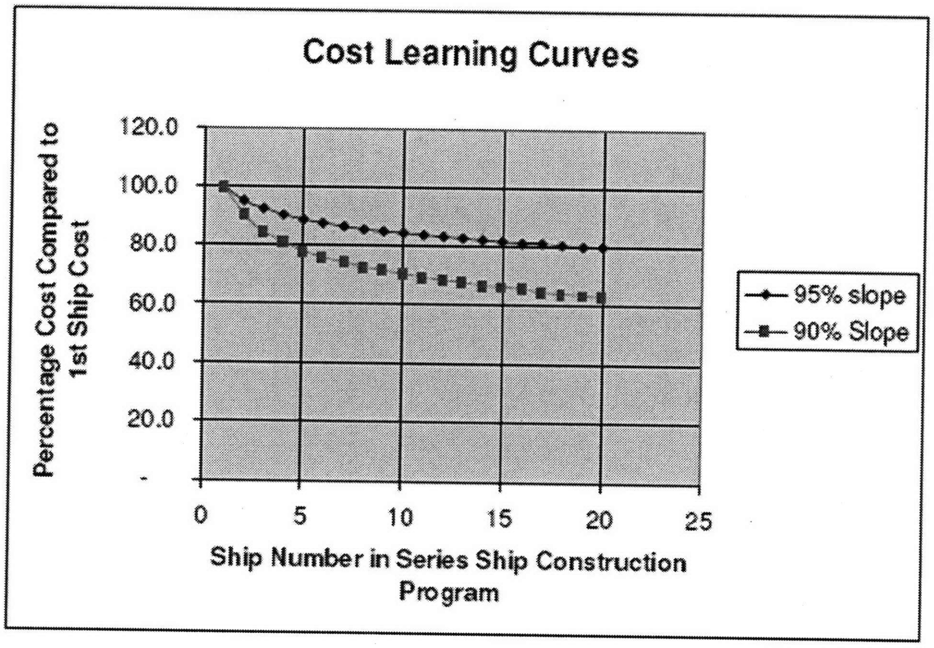


Figure 3: Graph of Typical Learning Curve Factors (5)

There are certain instances that will occur in the ship design process where using learning curve correction factors is not an appropriate action. These situations include times when ship construction is sporadic, during the construction of custom products where the types of functions performed are inconsistent with those of previous models, when work is highly automated and the production rate cannot be increased any further, when there are rules and regulations in place that limit the overall production rate, and when production quantities are small. (1)

Whether due to a low level of orders or labor issues, sporadic production can result in a notable decrease in overall production efficiency. Delays that cause production to be interrupted can also cause a step increase in the overall cost. Other instances where similar cost increases can occur include major upgrades to facilities and changes to production processes. Laborers require a certain amount of time in order to become accustomed to new facilities and production methods. In instances where this occurs, cost increases in the short run are generally unavoidable. Significant design changes and technological upgrades to a class of vessels can also result in a loss of learning because the production process will be inherently different from one version to the next. (1)

Production costs will typically decrease from ship to ship, but some shipyards will actually experience an increase in engineering costs for the second ship in a series. This is an indication that the prototype engineering used was likely less successful and that a renewed effort is needed to get the series program on a more efficient footing. All of this means that the CERs used by the Coast Guard and the Navy for ship cost estimating must be used with caution because there are a larger number of factors along the way that can result in significant variations between the predicted and the actual costs.

While the aforementioned learning curves indicate a gradual cost reduction per ship in a series, examining cost reductions for standard interim products and manufacturing processes across all types can realize the same experience. As shipyards introduce standard interim products as their primary means for designing and building ships, the effects of learning become a less important consideration. This is a good indication that the cost reductions are gained not by an actual learning experience, but more by a diminishing of expensive rework that could have been prevented and should not have occurred in the first place. Besides the benefit of learning curve effects upon labor costs, multiple ship contracts can also have a positive effect upon material costs. It has been estimated that the promise of a larger order backlog can elicit as much as a 15-20% cost reduction from vendors and suppliers. Busy shipyards can gain lower material costs simply because their suppliers can rely upon these shipyards with long-term business opportunities. (1)

1.4 Life Cycle Cost, Total Ownership Cost and Whole Ship Cost

In addition to Lead and Follow Ship Costs, the cost to maintain a ship over its life span must also be taken into consideration. Figure 4 shows the NATO Ship Life Cycle Cost Hierarchy. As seen in the diagram, the Whole Life Costs includes the Program Life Cycle Cost (PLCC), the Total Life Cycle Cost (TLCC), and the Total Ownership Cost (TOC).

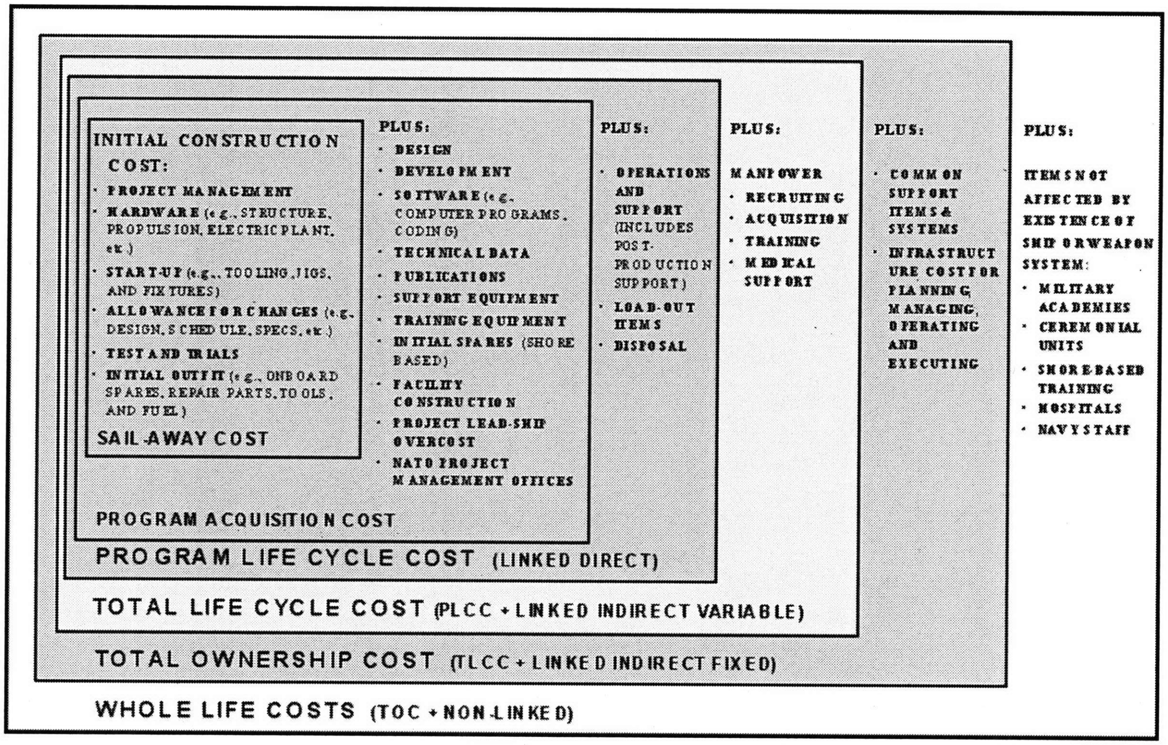


Figure 4: NATO Ship Life Cycle Cost Hierarchy (4)

Life Cycle Costs (LCC) include design and acquisition (production) costs as well as operations and support (O&S) costs throughout the life of the product. Life cycle costs have often been a major consideration for commercial shipowners who must look at the bottom line for profit and a return upon their investment. If the cost of design and construction, including the cost of money, cannot be recouped within a reasonable amount of time, the ship will not be built. Similarly, if the operating and maintenance costs exceed the operating revenues this will also cause the ship not to be built. (4)

Coast Guard ships do not have a bottom line commercial profit consideration. These ships are put into service only to satisfy a national security commitment to its citizens.

This does not mean they escape financial concerns during construction. As limited government funds address an ever-widening array of government responsibilities which has led to an increase in the Coast Guard's mission requirements, ship designs now must be developed with an increasing focus on getting "the biggest bang for the buck" (4). In short what this means is that mission effectiveness and capabilities must be maximized without increasing a ship's cost. Design and engineering trade-off studies can minimize costs without sacrificing these mission capabilities. Often these studies result in increased mission capabilities without an increase in cost.

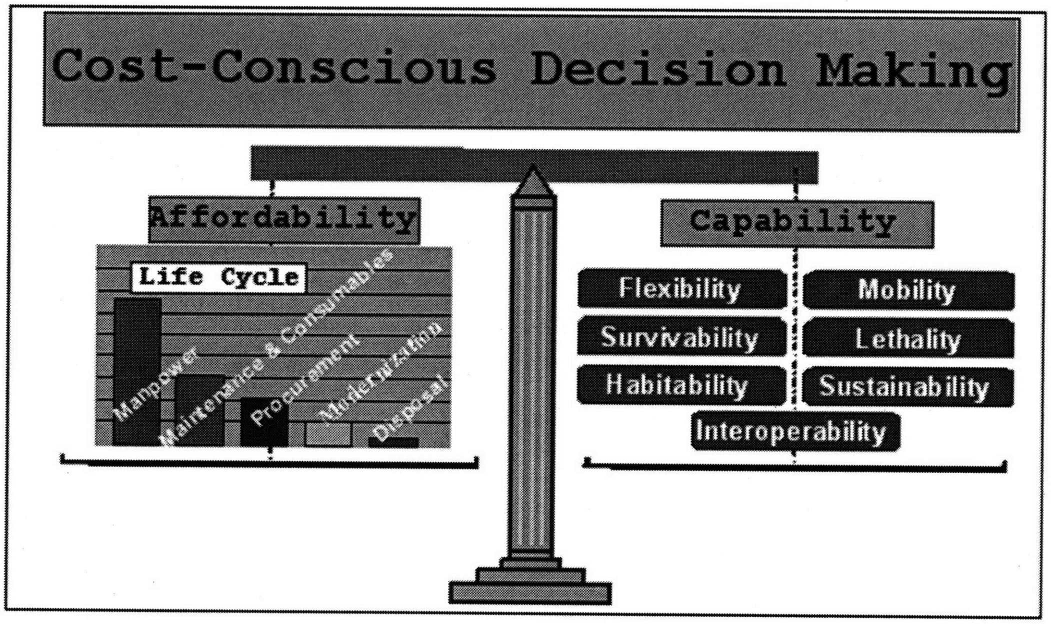


Figure 5: Trade-Off Study Between Affordability and Capability (4)

The life cycle of a ship is divided into essentially four main stages: The Conception Stage, the Acquisitions Stage, the In-Service Stage and the Disposal Stage. These stages are described on the next page.

Conception Stage: All activities necessary to develop and define a means for meeting a stated requirement. For ships and equipment, this normally includes research and development, design, contract specifications, identification of all support necessary for introduction of funding required and managerial structure for the acquisition.

Acquisitions Stage: All activities necessary to acquire the ship and provide support for the ship and equipment identified in the conception stage.

In-Service Stage: All activities necessary for operation, maintenance, support and modification of the ship or equipment throughout its operational life. The in-service stage is normally the longest stage.

Disposal Stage: All activities necessary to remove the ship or equipment and its supporting materials from service.

In order to determine the overall life cycle cost for a ship, costs must be estimated for each of the above stages.

When viewing the life cycle cost breakdown, only about 25% of the costs are directly related to the ship's acquisition. This means that the remaining 75% of the total cost comes from operation, support and disposal. These costs are made up of personnel, consumables, direct maintenance, sustaining investment, other direct costs, and indirect costs. Figure 6 shows the NATO cost categories for ships. For naval ships the largest of these costs is the cost of personnel which is roughly 37 percent of the total O&S cost. This is followed by the maintenance cost which accounts for 21% of the total O&S cost.

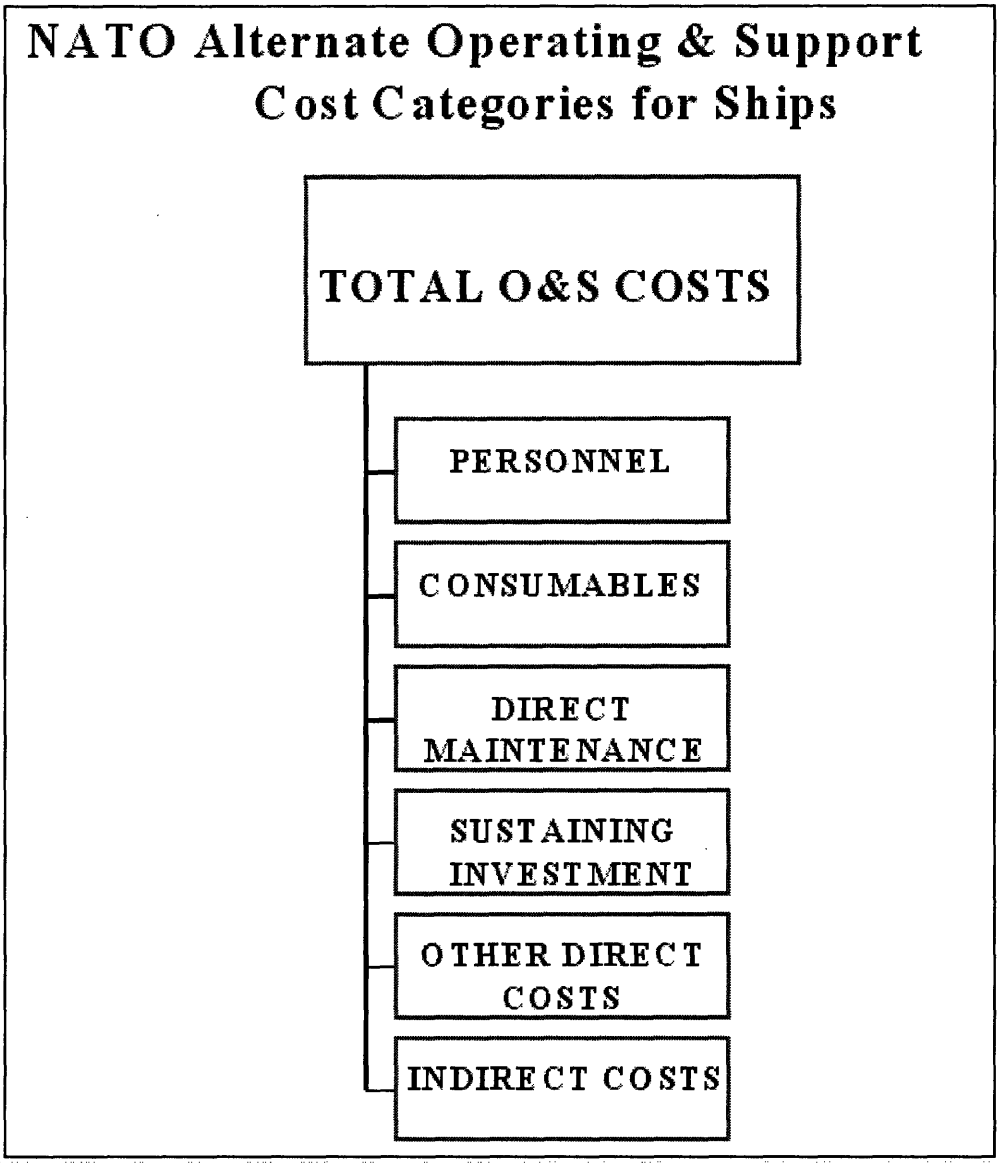


Figure 6: NATO Alternate Operating and Support Cost Categories for Ships (4)

Due to the fact that personnel costs are by far the largest contributor to operating expenses, this should be one of the first areas studied in an attempt to reduce overall costs.

The personnel category contains the cost of pay and allowances for personnel assigned to the ship. It includes the personnel required to meet combat readiness, training and administrative requirements, and covers base pay, allowances, and contributions by the government to federal social security and retirement funds. Costs are based on manning levels and skill categories rather than cost per hour. There are two basic approaches to reducing manpower requirements. The first is to increase the efficiency of the personnel onboard and the second is to aid the personnel by creating more automation so that the same tasks can be done with fewer people.

When working with new designs that propose to reduce crew requirements by amounts between 50 and 75 percent, the design strategy might be to incrementally upgrade each successive ship as new approaches and systems prove themselves. The design concept should also have a provision to retrofit previous editions, as these systems become workable. Research needs to be done in order to determine what can be done to first reduce manpower requirements with existing systems or with minor upgrades to these systems. Simple improvements in management practices, increased personnel training, and efficient system monitoring and reporting procedures can result in reduced manpower requirements. At more of an extreme, overall efficiency must be a prerequisite to the use of increased automation. Some interim systems modifications may be necessary before adopting a fully automated structure.

The Coast Guard has already started the process of moving towards ships with smaller crew sizes in an attempt to decrease life cycle costs. The Coast Guard Cutter Healy (WAGB 20), a 420' long icebreaking platform actively commissioned in 2000, has a crew complement of 85 including 19 officers and 66 enlisted. Its predecessors, the USCGC Polar Sea and USCGC Polar Star, have crews of 141 (15 officers and 126 enlisted). This is significant because the Polar Class icebreakers are also smaller than Healy measuring 399' in length. This is largely due to an increase in automation on board the Healy which has allowed the ship to conduct the same operations with fewer people.

Figure 7: USCGC Healy (6)

The recently constructed National Security Cutter (WMSL), a part of the Coast Guard's Deepwater Project, also takes advantage of upgrades in technology that will allow it to carry a smaller crew complement than its predecessor as well. The 378' Hamilton Class High Endurance Cutter, constructed during the 1960s, has a larger crew by nearly 20 people despite being 40 feet shorter than its replacement.

Increased automation can result in sizeable manpower reductions, but there are two important factors to consider. First, a smaller number of personnel on board usually means there is less crew backup capacity, both in terms of physical presence and more than likely in technical knowledge as well. The risk of this is that it may lead to reduced safety and operational ability for the ship. Any new design should consider the potential (and the related costs) to add personnel as a contingency measure and should develop a design layout that allows for additional living quarters and systems for additional users. Second, it must be considered that automation may have an overall negative effect on maintenance and modernization costs. The goal behind having a ship become more automated is to reduce the overall costs for the ship. If the savings in personnel cost lead to subsequent overages in the maintenance and acquisition budgets, then the process is not helping.

Some factors to consider when attempting to reduce the crew requirements of a ship include potentially higher acquisition costs for on board systems, a greater need for redundant or backup systems, higher training costs for the trainers, trainees and maintenance, higher repair costs, higher costs in salary, benefits, and incentives to help reduce turnover of highly skilled personnel, and recruitment costs for acquiring skilled personnel.

The second largest operation and support expense is maintenance. The maintenance category covers the cost of personnel, material, contractual services required to perform maintenance or modification of the ship, ships system, components and support equipment at government or industry repair facilities or on site by repair teams or at intermediate repair activities whether ashore or afloat. A key consideration is identifying the factors that drive these costs. In specifying materials and/or equipment, the first things to consider are the initial costs. This includes the cost of acquisition and installation, durability, suitability, as well as long-term maintenance costs. During the early development cycle, design decisions should balance production costs against ownership costs. Maintenance costs must be computed in several different formats depending upon the type of material and/or maintenance activity. Costs for other maintenance activities include dry-docking, cleaning, and temporary service hook-up, etc. These costs can be derived on the basis of ship length, displacement, or cubic number in conjunction with the number of maintenance cycles in service. Maintenance costs for items such as steel and piping must be computed by using a sum of repair CERs for tasks that will include sandblasting, painting, plate renewal, and pipe renewal. The CERs for items such as these can be detailed and specific, but they also can be derived on the basis of the ship's general characteristics such as light ship weight or some other general design parameter. (4)

The consumables category of the O&S cost contains the costs of energy required for peacetime operations, the costs of material consumed in the operation, maintenance and support of the ship, and the costs of expendable stores consumed in the training of the crew. It includes items such as the following: petroleum, oil, lubricants, additives, batteries, nuclear power, commercial and field electricity, stores materials, supplies, ammunition, sonobuoys, pyrotechnics, etc.

The sustaining investment category covers the replenishment of the inventory of spares and repair parts that are retained in stock, the costs of modifying ship platform or payload systems and support and training equipment used to achieve acceptable safety levels, overcome capability deficiencies and improve reliability. It also includes mid-life conversions and refit programs.

The "other direct costs" category covers other significant logistic or operating and support costs for items not specifically included in another O&S category. Included are the costs of equipment, services, information, helicopter O&S costs, trainers, simulators, and second destination transportation, etc.

Finally, the "indirect costs" category applies to costs that are required during the service life of the ship but are not directly related to a particular ship or subsystem. These costs include installation support, personnel, medical and dental personnel, personnel support (operations maintenance and permanent change of station), personnel acquisition and training (recruiting and basic and technical schools). (4)

Total Ownership Cost (TOC) is a holistic approach to understanding all of the costs that are affected by the existence or introduction of a naval program or project and is a key affordability assessment and decision-making tool. Although national experience, definitions, opinions and approaches can vary widely, the concept of TOC is considered by many nations to be an important method and the "way of the future" towards identifying all affected costs as a consequence of a program decision. TOC analysis helps with balancing near-term acquisition phase affordability constraints with the long-term life cycle cost objectives. The goal is to reduce the cost of ownership with the long-term life cycle cost objectives and thereby free up funding for modernization and recapitalization of weapon systems, e.g. ships. The name used to describe the sum of all costs attributed to a program is the phrase "Total Ownership Cost."

TOC consists of all elements that are a part of the life cycle cost plus the indirect, fixed and linked costs. The latter of these may include items such as common support equipment, common facilities, personnel required for unit command, administration, supervision, operations planning and control, fuel, and munitions handling. TOC represents all costs associated with the ownership of a system except non-linked fixed costs that are related to the running of the organization. TOC is used for budgeting purposes, determining the use of services between systems, for optimization purposes and for financial analysis. (4)

Whole Life Cost (WLC) consists of all elements that are part of the TOC plus indirect, fixed and non-linked costs. These latter may include items such as family housing, medical services, ceremonial units, basic training, headquarters and staff, academies, and recruiters. In WLC, all costs or expenses that are made by the organization are attributed to the systems or products they produce. As WLC represents the total budget provision including such elements as headquarters cost, it allows the visibility of the complete allocation of funds. WLC is used for a strategic view and high level studies.

Figure 8 shows a model for NATO's Ship Life cycle Costing broken down into four parts: Program Phases, Cost Models, Cost/Work Breakdown Structure and Hierarchy.

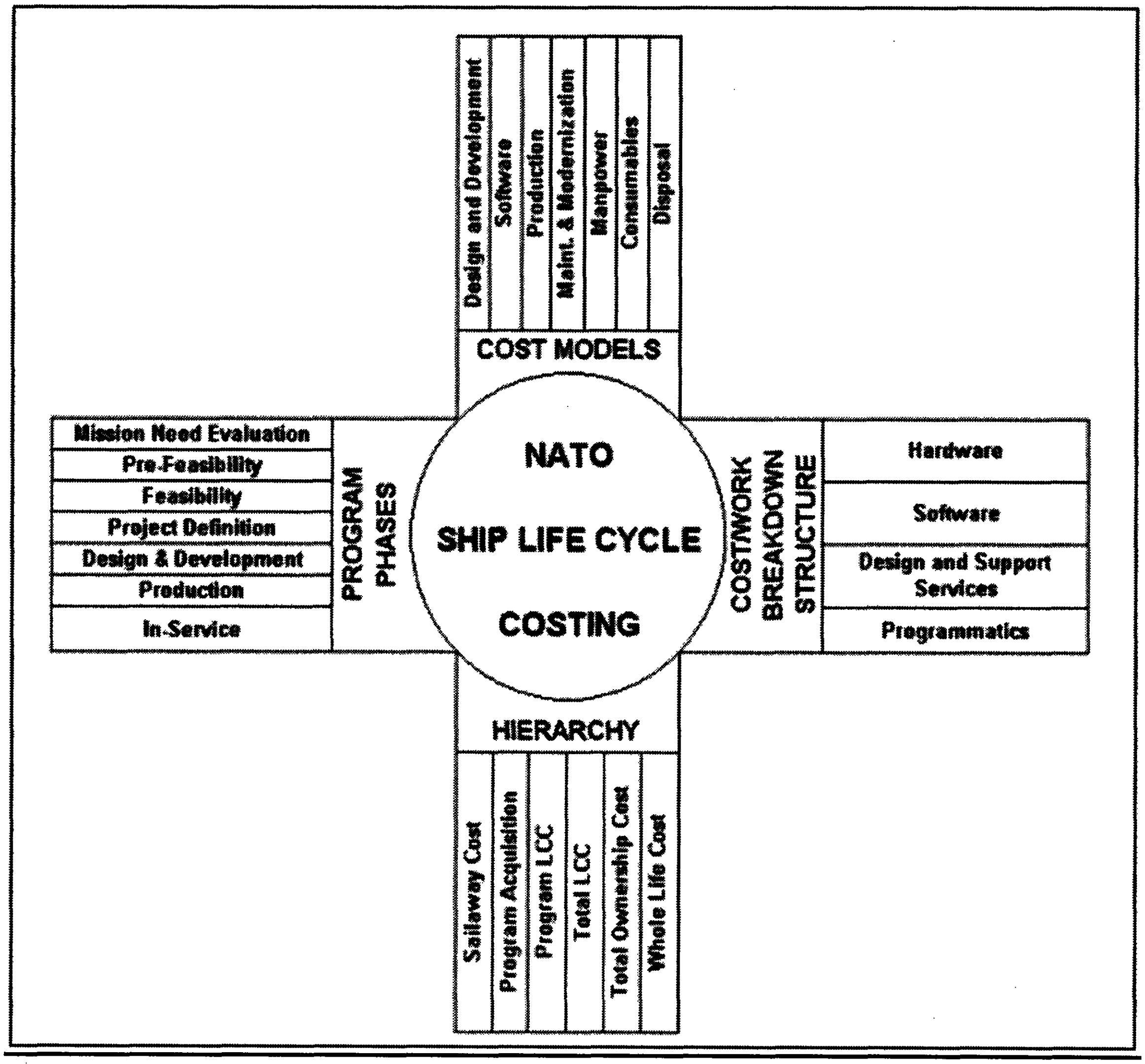


Figure 8: NATO Ship Costing Approach (4)

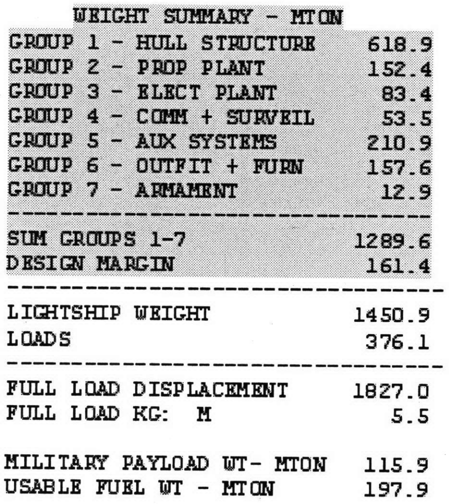
CHAPTER 2: THE MIT COST MODELS

At present, there are two different cost models for MIT students to use when developing preliminary cost estimates for a particular ship design: the BMTS Cost Model, and the MIT Math Model. Each of these models has its own advantages and disadvantages. As a result, it was determined to be beneficial to combine the two individual models into one working model to provide continuity in cost estimation for the 2N program, and to develop a model with fewer flaws than the two parent programs. Additionally, data on the 270' Famous Class Coast Guard Cutter (shown in Figure 9) was obtained to allow for the creation of CERs that would not be specific to Naval Combatants, thus expanding the capabilities of the program even further.

Figure 9: USCGC ESCANABA, Famous Class (6)

2.1 The BMTS Cost Model

To understand the process of combining the two models, it is beneficial to first take a look at each of them individually. The BMTS Cost Model is a weight based cost estimation model. To use it there are several required inputs. The most significant of these inputs are values for the one digit SWBS group weights measured in long tons. These values can easily be pulled off of ASSET's design summary report which is shown below in Figure 10. The fact that the information needed is so easily accessibly makes it an easy model for MIT students to use during the early design stages of ship design.



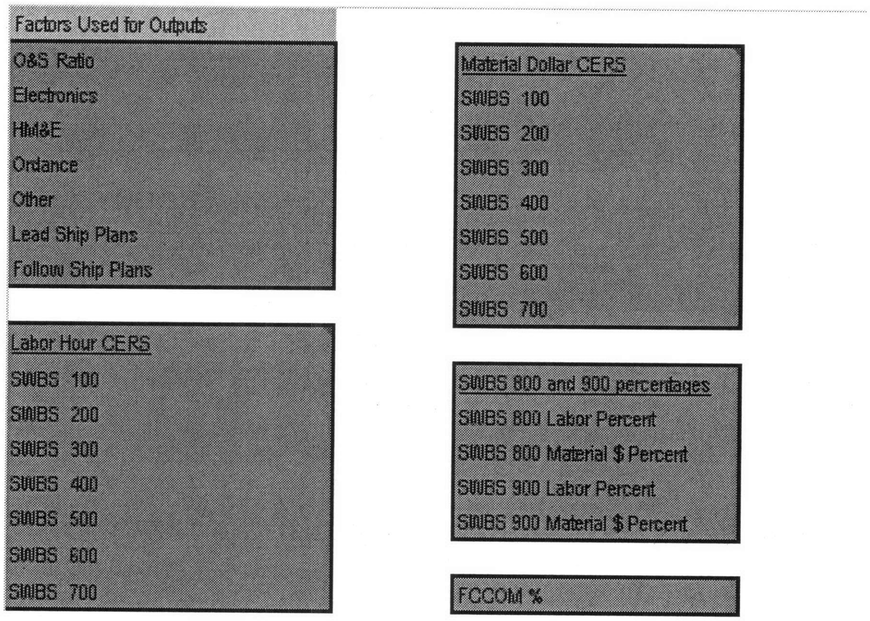
```
          WEIGHT SUMMARY - MTON
GROUP 1 - HULL STRUCTURE      618.9
GROUP 2 - PROP PLANT          152.4
GROUP 3 - ELECT PLANT          83.4
GROUP 4 - COMM + SURVEIL       53.5
GROUP 5 - AUX SYSTEMS         210.9
GROUP 6 - OUTFIT + FURN       157.6
GROUP 7 - ARMAMENT             12.9
-----------------------------------
SUM GROUPS 1-7               1289.6
DESIGN MARGIN                 161.4
------------------------------------
LIGHTSHIP WEIGHT             1450.9
LOADS                         376.1
------------------------------------
FULL LOAD DISPLACEMENT       1827.0
FULL LOAD KG:  M                5.5

MILITARY PAYLOAD WT- MTON     115.9
USABLE FUEL WT - MTON         197.9
```

Figure 10: Output from ASSET depicting breakdown of weights by SWBS groups

In addition to the SWBS group weights, the weight of the design margin is also required. This value must also be determined in terms of long tons and not as a percentage of the ship's weight. ASSET's design summary report also provides the user with the margin weight. There are six other primary inputs: The percentage of allowable change orders for both the lead ship and the follow ships, the percentage of profit to be generated by the shipyard from the project, the slope of the learning curve that the shipyard experiences between construction of subsequent ships, and the total number of ships being built.

These inputs are then applied to the cost estimating relationships that are provided in the model. These relationships are located on the FACTORS tab. The BMTS Cost Model has CERs for labor hours and for the cost of material, both as they pertain to weight. The CERs are broken down by the SWBS groups that the user is required to input numbers for. The CERs provided in this program only go as far as one digit SWBS groups making it a very general cost estimation program. It is possible to develop more detailed CERs to go into the two or even three digit SWBS numbers, but given the purpose of this program, it is not necessary to have a model with that level of detail. In addition to the list of CERs the FACTORS tab also includes another list of factors used to generate the outputs. The complete factors tab is shown below in Table 4.

The Lead Ship Cost and the Follow Ship Cost are generated on separate spreadsheets by the BMTS Cost Model. These spreadsheets take the inputs and CERs to deliver the resulting Lead Ship and Follow Ship Costs. The calculations used to determine the lead ship cost will be examined first. Each SWBS group receives cost contributions from 4 different areas: Direct Labor, Overhead, Material, and Material Overhead. The equations used to determine the associated costs are listed as Equations 2-5.



Factors Used for Outputs
O&S Ratio
Electronics
HM&E
Ordance
Other
Lead Ship Plans
Follow Ship Plans

Labor Hour CERS
SWBS 100
SWBS 200
SWBS 300
SWBS 400
SWBS 500
SWBS 600
SWBS 700

Material Dollar CERS
SWBS 100
SWBS 200
SWBS 300
SWBS 400
SWBS 500
SWBS 600
SWBS 700

SWBS 800 and 900 percentages
SWBS 800 Labor Percent
SWBS 800 Material $ Percent
SWBS 900 Labor Percent
SWBS 900 Material $ Percent

FCCOM %

Table 4: Factors Used For Outputs for BMTS Cost Model

Prior to implementing these cost equations, the program uses the Labor CERs to determine the overall amount of hours of shipyard labor spent on each SWBS group.

$$LaborHours = SWBSweight \cdot LaborCER \cdot NumberLeadShips^{\left(\frac{(LN(LearningCurve))}{(LN(2))}\right)}$$

Equation 1: Determining Labor Hours for an Individual SWBS group

The SWBSweight variable is the weight in long tons of a particular SWBS group while the LaborCER variable is the coinciding cost estimating relationship. NumberLeadShips is the amount of Lead Ships designated by the user (this number needs to be 1), and LearningCurve is the slope of the learning curve for the shipyard between subsequent projects. The resulting number of labor hours is then used to determine the overall cost of labor and the labor overhead.

$$LaborCost = LaborHours \cdot LaborRate$$

Equation 2: Labor Cost Equation for Lead Ship

The Labor Rate is predetermined on the FACTORS tab. The Rate for SWBS groups 100-700 and 900 all fall under the same rate while the SWBS 800 group has a unique rate of its own.

$$OverheadCost = LaborCost \cdot Overhead\%$$

Equation 3: Overhead Cost Equation for Lead Ship

The Overhead Percentage is listed on the FACTORS tab. Similar to the labor rate, SWBS groups 100-700 and 900 have the same overhead percentage while the SWBS 800 group has a separate rate.

$$MaterialCost = SWBSweight \cdot MaterialCER$$

Equation 4: Material Cost Equation for Lead Ship

The Material CER is a relationship relating the weight of a SWBS group to material cost. It is given in terms of dollars per long ton.

$$MatlOvhdCost = MaterialCost \cdot MatlOvhd\%$$

Equation 5: Material Overhead Cost Equation for Lead Ship

The Material Overhead Cost is calculated in a similar manner to the Overhead Cost. The Overhead Cost relates labor cost to overhead percentage while the Material Overhead Cost relates material cost to material overhead percentage.

The sum of these four costs is calculated for the SWBS 100-700 groups. The equations are slightly different for the SWBS 800 and 900 groups. Unlike the SWBS 100-700 groups, the SWBS 800 and 900 groups are not associated with a weight. Instead to get the labor hours, the labor percentages for these two groups (located on the FACTORS tab) are multiplied by the labor hours calculated for lightship weight (sum of the labor hours for the SWBS 100-700 groups plus the labor hours determined for the margin).

$$LaborHours_{800} and_{900} = SWBSLaborPercentage \cdot LightshipWeightLaborHours$$

Equation 6: SWBS 800 and 900 Labor Hours Calculation for Lead Ship

The calculation for Material Cost is also slightly different for SWBS groups 800 and 900 as once again percentages designated on the FACTORS tab are used in place of weight as in the case of the other SWBS groups. This percentage is then multiplied by the sum of the material cost for SWBS groups 100-700 and the material cost of the Margin.

$$MaterialCost_{800}and_{900} = SWBSMaterialPercentage \cdot LightshipMaterialCost$$

Equation 7: Material Cost for SWBS 800 and 900 for Lead Ship

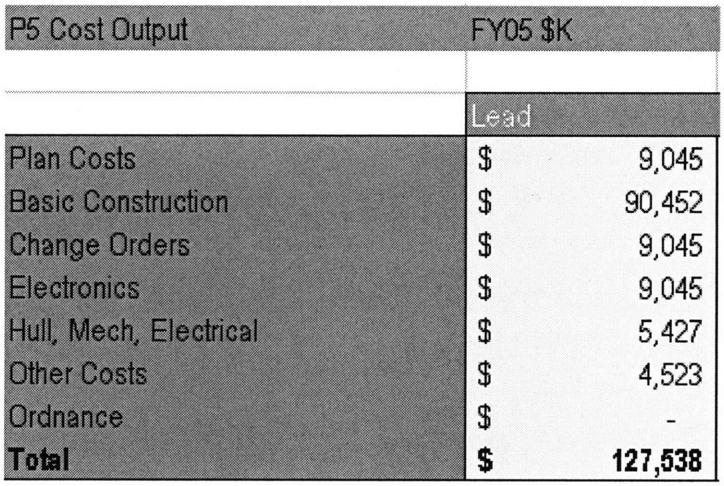
Labor Hours for the Margin are determined by taking the ratio of the Margin Weight to the SWBS 100-700 weight and then multiplying it by the Total Labor Hours used for the SWBS 100-700 groups.

$$MarginRatio = \frac{(MarginWeight)}{(SWBS_{100}to_{700}Weight)}$$

Equation 8: Margin Ratio as applied to Costs for Lead Ship

The overall cost for the SWBS groups 100-700 is then added to the overall cost of the margin to form the cost of the lightship weight. This value is subsequently added to the cost of SWBS groups 800 and 900 to produce the Target Cost. The Target Cost is then multiplied by the profit factor inputted by the user to determine the profit made by the shipyard for the project, and the Facilities Capital Cost of Money (FCCOM) percentage provided on the FACTORS tab is multiplied by the Total Direct Labor Cost. The sum of these three values equates to the Basic Contract Price for the Lead Ship.

The cost of the lead ship goes beyond just the basic contract price though. Other factors contribute as well and are listed on the OUTPUTS tab.



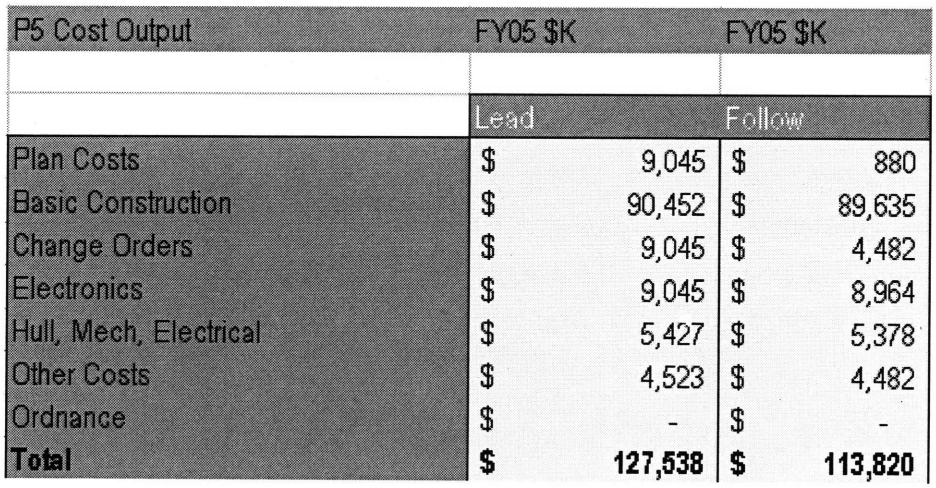
P5 Cost Output	FY05 $K	
	Lead	
Plan Costs	$	9,045
Basic Construction	$	90,452
Change Orders	$	9,045
Electronics	$	9,045
Hull, Mech, Electrical	$	5,427
Other Costs	$	4,523
Ordnance	$	-
Total	**$**	**127,538**

Table 5: Lead Ship Cost Contributors for the BMTS Cost Model

The factors used to generate these additional costs are either listed on the FACTORS tab, as in the case of Plan Costs, Electronics Costs, Hull, Mechanical and Electrical (HM&E) Costs, Other Costs and Ordnance Costs, and on the Inputs tab in the case of Change Orders Cost. The given factors (which are provided as percentages) are then multiplied by the Basic Construction Cost to generate the tabulated results. The output is given in thousands of dollars and is set to fiscal year 2005 so in order to get a present day estimate, an inflation factor must be applied to the end result.

The Follow Basic Construction tab contains all of the calculations for the follow ship cost. The equations for developing the cost of the subsequent ships are very similar to the lead ship equations with a few exceptions. Before discussing the equations in depth, several errors in the formulas for follow ship construction cost were discovered and they shall be addressed first.

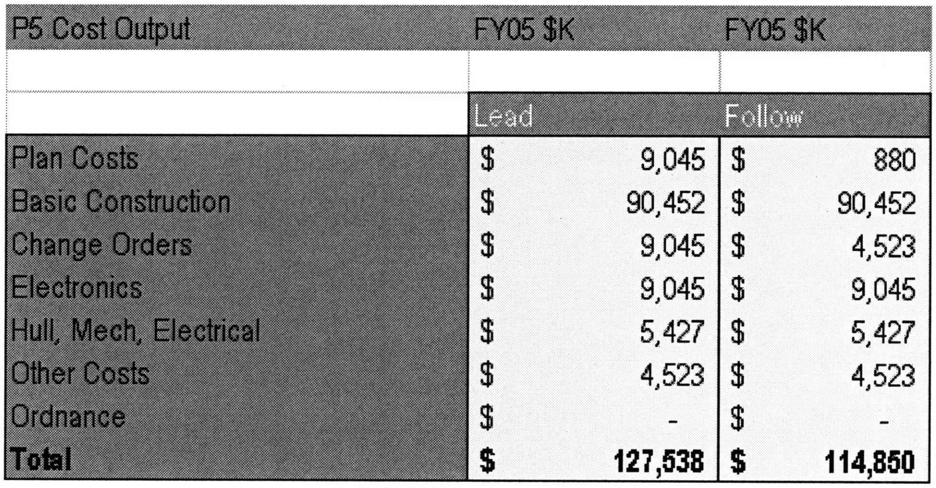
These errors were discovered when using test values of 1 lead ship and 1 follow ship so as to be able to examine the data and trends from one ship to the next. The first error occurs in the references of the Group 8 Engineering line. Initially the program references incorrect values for labor cost and overhead as it uses the values for the SWBS Groups 100-700 and 900 instead of those for the SWBS 800 group. With the incorrect references in place, it appears as though the learning curve is being applied to the follow ship cost seen below in Table 6.



P5 Cost Output	FY05 $K	FY05 $K
	Lead	Follow
Plan Costs	$ 9,045	$ 880
Basic Construction	$ 90,452	$ 89,635
Change Orders	$ 9,045	$ 4,482
Electronics	$ 9,045	$ 8,964
Hull, Mech, Electrical	$ 5,427	$ 5,378
Other Costs	$ 4,523	$ 4,482
Ordnance	$ -	$ -
Total	**$ 127,538**	**$ 113,820**

Table 6: Initial BMTS Cost Model Results with Incorrect SWBS 800 reference

Once the correction is made, it becomes clear that the learning curve is not being factored in to the Basic Construction Cost as the only costs that change are the plan costs and the change orders cost, and these only change because there are specific references that differ between the lead ship and following ships.



P5 Cost Output	FY05 $K	FY05 $K
	Lead	Follow
Plan Costs	$ 9,045	$ 880
Basic Construction	$ 90,452	$ 90,452
Change Orders	$ 9,045	$ 4,523
Electronics	$ 9,045	$ 9,045
Hull, Mech, Electrical	$ 5,427	$ 5,427
Other Costs	$ 4,523	$ 4,523
Ordnance	$ -	$ -
Total	**$ 127,538**	**$ 114,850**

Table 7: BMTS Cost Model Results with Faulty Learning Curve Equation

Upon a closer review of the equations used to determine follow ships costs, the reason that the learning curve does not factor in when the number of follow ships is set to 1 can be seen clearly in equation 9.

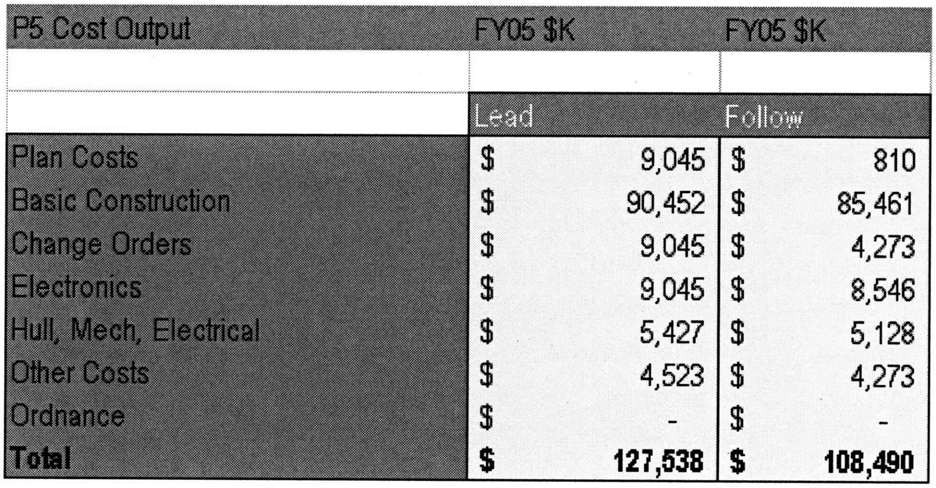
$$LaborHours = SWBSweight \cdot LaborCER \cdot NumberFollowShips^{\left(LN\frac{(LearningRate)}{(LN(2))}\right)}$$

Equation 9: Faulty Labor Hour Calculations for Follow Ship

The problem becomes apparent when the number of follow ships is equal to 1 because this eliminates the contributions of the exponent and thus negates the effects of the learning curve. To correct this error, the variable needs to account for the number of total ships produced and not just the number of follow ships. Adding the value of the number of lead ships produced to the equation prevents the program from not taking into account the learning curve for the first follow ship by the shipyard. Equation 10 below reflects this change and Table 8 shows the resulting costs with the corrections made.

$$LaborHours = SWBSweight \cdot LaborCER \cdot NumberTotalShips^{\left(LN\frac{(LearningRate)}{(LN(2))}\right)}$$

Equation 10: Corrected Learning Curve Equation for Follow Ship Cost Estimation

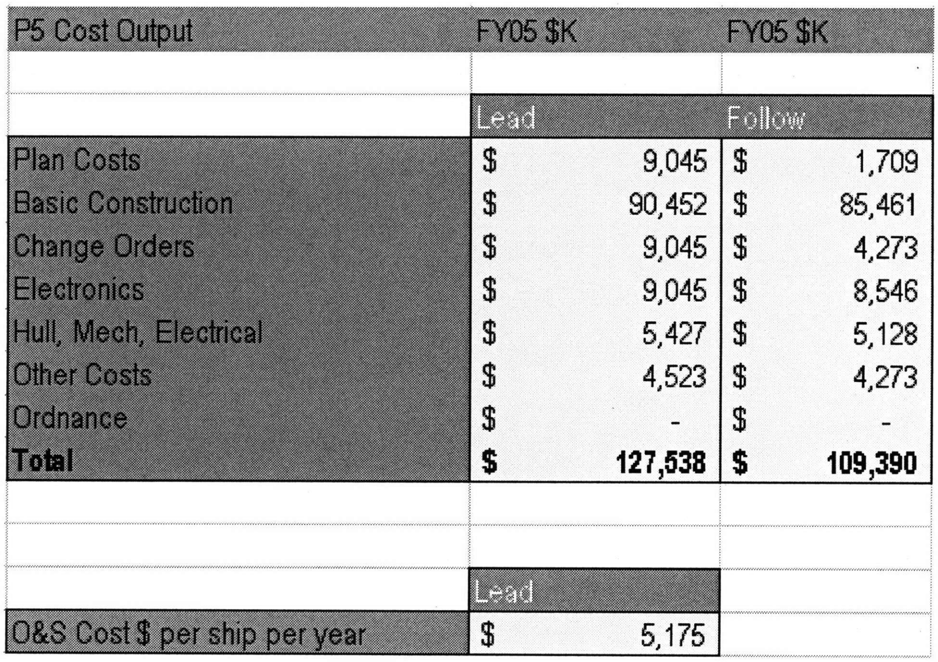


P5 Cost Output	FY05 $K	FY05 $K
	Lead	Follow
Plan Costs	$ 9,045	$ 810
Basic Construction	$ 90,452	$ 85,461
Change Orders	$ 9,045	$ 4,273
Electronics	$ 9,045	$ 8,546
Hull, Mech, Electrical	$ 5,427	$ 5,128
Other Costs	$ 4,523	$ 4,273
Ordnance	$ -	$ -
Total	**$ 127,538**	**$ 108,490**

Table 8: Cost Model Results with Corrected Learning Curve

There is one other error in the calculations for Follow Ship Cost and it occurs in the equation generating Plan Costs for the Follow Ship. The equation listed in the BMTS

Cost Model has unnecessary extra terms when it should be the same as the equation for Plan Costs for the Lead Ship, only with a different multiplier designated on the FACTORS tab. Once this is corrected, the final corrected costs are shown below in Table 9.



P5 Cost Output	FY05 $K	FY05 $K
	Lead	Follow
Plan Costs	$ 9,045	$ 1,709
Basic Construction	$ 90,452	$ 85,461
Change Orders	$ 9,045	$ 4,273
Electronics	$ 9,045	$ 8,546
Hull, Mech, Electrical	$ 5,427	$ 5,128
Other Costs	$ 4,523	$ 4,273
Ordnance	$ -	$ -
Total	**$ 127,538**	**$ 109,390**
	Lead	
O&S Cost $ per ship per year	$ 5,175	

Table 9: Final Outputs from Corrected BMTS Cost Model

The BMTS also provides the user with the operations and support cost per year for the ship. This is a very rough estimate as it calculates only the O&S cost, and does not take into account any specific factors that may affect. Therefore, whether or not the ship has 1000 people on board, or only 100 people on board, the difference is not reflected in this particular model. Instead it is merely calculated as a fixed percentage of the Basic Construction Cost of the lead ship.

While the model does not provide a very good approximation of the life cycle cost, it does offer a very good model for the lead ship and follow ship costs. The model is also very easy to use as all of the inputs are located in one place and additionally it is easy to adjust the CERs if a user did not want to use the data provided by the program itself.

2.2 The MIT Math Model

The MIT Math Model is set up a bit differently than the BMTS Cost Model. Like the BMTS Model, it is a weight based cost estimation model. The user is once again required to input the weights for the SWBS 100-700 groups, but this program additionally requests several other pieces of information. This includes Total Brake Horsepower, the weight of the SWBS 420 and 430 groups, the average deck height, the Ordnance Weight (including helicopter ordnance) and the weight and number of helicopters.

The MIT Math Model also requires the user to input crew complement. Three separate inputs are listed: officer, chief petty officer (CPO) and enlisted. The values of these three variables are then summed up to produce the total crew size.

The MIT Math model, like the BMTS Cost Model, does calculations for both the lead ship and the follow ship cost on separate spreadsheets. To compute the lead ship cost, the user is required to provide six more inputs. The inputs are Ship Service Life (in years), Year of Initial Operational Capability (Year), Total Ship Acquisition (number of ships), Ship Production Rate (How many ships are built per year), Base Year (year) and Average

Inflation Rate (%). The Average Inflation Rate is subsequently used to determine the Inflation Factor.

Below the inputs are a significant number of variables. These are listed in Table 10. The format for the MIT Math Model is much different as the cost breakdown does not factor in labor costs independently of material costs. There is simply one relationship for each SWBS group designated K_N. Costs are determined for 9 SWBS groups (100-900), and the summation of these costs generates the Total Lead Ship Construction Cost. Unlike the BMTS Cost Model where each of the SWBS groups operated uses identical formulas with the exception of the CERs specific to their group, the MIT Math Model uses different equations for each SWBS group. The K_N factors are listed in Table 11 and the equations (11-20) they are applied in are listed below them using the variables defined in Table 9.

Each of the equations listed generates a number in millions of dollars. Several variables occur in the equations that are not designated in Table 10. These are F1 (the inflation factor), WM24 (future growth weight margin) and WLS (margined lightship weight).

The sum of these costs, as stated earlier determines the Total Lead Ship Construction Cost. This cost is then added to the profit the shipyard makes on the ship. To determine the profit value, the profit factor is inputted by the user on the Lead Ship Cost tab. The profit factor is then multiplied by the Total Lead Ship Construction Cost to determine the profit. These numbers are then added together to determine the Lead Ship Price. The

Lead Ship Price is then added to the price of change orders to determine the Total Shipbuilder Portion of the cost. The price of change orders is calculated in a similar fashion as the profit. The Change Order Factor is inputted by the user and multiplied by the Lead Ship Price thus producing the cost of Change Orders.

VARIABLE NAME	VARIABLE DESCRIPTION
CL1D	SWBS 100 Cost
CL2D	SWBS 200 Cost
CL3D	SWBS 300 Cost
CL4D	SWBS 400 Cost
CL5D	SWBS 500 Cost
CL6D	SWBS 600 Cost
CL7D	SWBS 700 Cost
CL8D	SWBS 800 Cost
CL9D	SWBS 900 Cost
CLCC	Total Lead Ship Construction Cost
CLCORD	Change Orders
CLEND	Total End Cost
CLGOV	Total Government Cost
CLHMEG	HM&E GFE (Boats, IC)
CLM	Margin Cost
CLMPG	Ordnance and Electrical GFE (Military Payload GFE)
CLOTH	Other Support
CLOUT	Outfitting Cost
CLP	Profit
CLPMG	Program Manager's Growth
COF	Change Order Factor
CSB	Total Shipbuilder Portion
CSCER	Combat System GFE CER
FPROFIT	Profit Factor
HC	Helo Cost
HMEGFEF	HM&E GFE Factor
KN1	SWBS 100 Cost Factor
KN2	SWBS 200 Cost Factor
KN3	SWBS 300 Cost Factor
KN4	SWBS 400 Cost Factor
KN5	SWBS 500 Cost Factor
KN6	SWBS 600 Cost Factor
KN7	SWBS 700 Cost Factor
KN8	SWBS 800 Cost Factor
KN9	SWBS 900 Cost Factor
OCF	Outfitting Cost Factor
OSF	Other Support Factor
PL	Lead Ship Price
PMGF	Program Manager's Growth Factor
PSAC	PSA Cost
PSACF	Post Delivery Cost (PSA) Factor
TLSAC	Total Lead Ship Acquisition Cost
WMP	Weight of Costed Military Payload

Table 10: Variable List for Lead Ship Cost for MIT Math Model Cost Estimation

KN Table	
KN1	0.55
KN2	1.2
KN3	1
KN4	2
KN5	1.5
KN6	1
KN7	1.13
KN8	10
KN9	2

Table 11: KN Values as used by the MIT Math Model

$$CL_1 D = 0.3395 \cdot F_1 \cdot KN_1 \cdot (WT_1)^{0.772} \tag{11}$$

$$CL_2 D = 0.00186 \cdot F_1 \cdot KN_2 \cdot BrakeHorsePower^{(.808)} \tag{12}$$

$$CL_3 D = 0.07505 \cdot F_1 \cdot KN_3 \cdot (WT_3)^{0.91} \tag{13}$$

$$CL_4 D = .10857 \cdot F_1 \cdot KN_4 \cdot (WT_4)^{0.617} \tag{14}$$

$$CL_5 D = .09487 \cdot F_1 \cdot KN_5 \cdot (WT_5)^{.782} \tag{15}$$

$$CL_6 D = .09859 \cdot F_1 \cdot KN_6 \cdot (WT_6)^{.784} \tag{16}$$

$$CL_7 D = .00838 \cdot F_1 \cdot KN_7 \cdot (WT_7)^{.987} \tag{17}$$

$$CLM = \frac{(WM_{24})}{(WLS - WM_{24})} \cdot (CL_1 D + CL_2 D + CL_3 D + CL_4 D + CL_5 D + CL_6 D + CL_7 D)$$

(18)

$$CL_8 D = .034 \cdot KN_8 \cdot (CL_1 D + CL_2 D + CL_3 D + CL_4 D + CL_5 D + CL_6 D + CL_7 D + CLM)^{1.099}$$

(19)

$$CL_9 D = 0.135 \cdot KN_9 \cdot (CL_1 D + CL_2 D + CL_3 D + CL_4 D + CL_5 D + CL_6 D + CL_7 D + CLM)^{0.839}$$

(20)

Equations 11-20: MIT Math Model Basic Construction Cost Contributers

Once the Shipbuilder Portion of the Cost is calculated, the MIT Math Model moves on to calculate the Total Government Cost. To do this, a series of factors and CERs are provided in the spreadsheet: the Other Support Factor, the Program Manager's Growth Factor, the Combat System GFE CER, the HM&E Factor, and the Outfitting Cost Factor. The user is required to input the Program Manager's Growth Factor, but all of the other terms are given. This section of the spreadsheet also provides helicopter cost and weighted cost of military payload (in long tons). The Sum of the Other Support Cost, the Program Manager's Growth Cost, the Ordnance and Electrical GFE (Military Payload) Cost, the HM&E GFE (Boats, IC) Cost and the Outfitting Cost equals the Total Government Cost. Equations for these terms are listed below (For Variable Descriptions, See Table 10).

$$CLOTH = OSF \cdot PL \tag{21}$$

$$CLPMG = PMGF \cdot PL \tag{22}$$

$$CLMPG = F_1 \cdot (CSCER \cdot WMP + NHELO \cdot HC) \tag{23}$$

$$CLHMEG = HMEGFEF \cdot PL \tag{24}$$

$$CLOUT = OCF \cdot PL \tag{25}$$

Equations 21-25: Costs to Determine Total Government Cost for MIT Math Model

The Helicopter Terms in the determination of the Ordnance and Electrical GFE (Military Payload GFE) do not affect the lead ship cost. The variable NHELO is set in the program, but it carries explicit instructions: "Leave this set to 'zero'. Helicopter cost should not be included in lead ship cost." Therefore the helicopter does not impact this cost and this term is not required.

Once the Total Government Cost is computed, it is added to the Total Shipbuilder's Portion to determine the Total End Cost. The Final Step is for the user to input the Post Delivery Cost (PSA) Factor to generate the PSA Cost. This PSA Factor is multiplied by the Lead Ship Price to produce the PSA Cost. When the PSA Cost is added to the Total End Cost, it produces the Total Lead Ship Acquisition Cost. The next step is to calculate the follow ship cost. Similar to the lead ship cost tab, there are a substantial number of variables. Table 12 below shows the variables and their descriptions.

VARIABLE NAME	VARIABLE DESCRIPTION
CF800C	Integration/Engineering Cost
CF800E	Integration/Engineering Follow Ship Exponent
CF800F	Integration/Engineering Follow Ship Factor
CF900C	Ship Assembly and Support Cost
CFA	Total Follow Ship Acquisition Cost
CFBCC	Follow Ship Basic Construction Cost
CFCC	Total Follow Ship Construction Cost
CFEND	Total Follow Ship End Cost
CFM	Follw Ship Margin Cost
CFPSA	Follow Ship PSA Cost
CFPSAF	Follow Ship PSA Cost Factor
CFSB	Total Follow Ship Cost Shipbuilder Portion
CLPMG	Program Manager's Growth
COC	Change Order Cost
FCGOV	Total Follow Ship Government Cost
FCHMEG	Follow Ship HM&E GFE Cost
FCMPG	Follow Ship Ordnance and Electrical GFE Cost
FCOUT	Follow Ship Outfitting Cost
FHMEGFE	Follow Ship HM&E GFE Factor
FOCF	Follow Ship Outfitting Cost Factor
FPMG	Follow Ship Program Manager's Growth Cost
FPMGF	Follow Ship Program Manager's Growth Factor
FPROFIT	Profit
FSCOF	Follow Ship Change Order Factor
FSCSCER	Follow Ship Combat System GFE CER
FSOC	Follow Ship Other Cost
FSOCF	Follow Ship Other Cost Factor
LRF	Learning Rate Factor
LRF	Learning Rate
PF	Total Follow Ship Price

Table 12: Variable List for Follow Ship Cost Tab in MIT Math Model

Calculations for the follow ship cost are slightly different than the calculations for the lead ship cost. Unlike the lead ship cost, the follow ship cost is impacted by the Learning Rate Factor. The user is required to input the Learning Rate Factor which is used to calculate the Learning Rate. Equation 26 shows how the Learning Rate is generated from the Learning Factor.

$$LR = 2 \cdot LRF - 1$$

Equation 26: Derivation of Learning Rate from Learning Rate Factor

The Learning Rate is then applied to the SWBS group 100-700 Costs, the Margin Cost and the SWBS group 900 Cost to produce the Follow Ship Basic Construction Cost, the Follow Ship Margin Cost, and the Ship Assembly and Support Cost. For the SWBS 800 group, new factors are provided in the Follow Ship Cost tab: The Integration/Engineering Follow Ship Factor (CF800F), and the Integration/Engineering Follow Ship Exponent (CF800E). Equation 27 shows how these terms generate the Integration/Engineering Cost.

$$CF_{800}C = CF_{800}F \cdot (CFBCC \cdot CFM)^{(CF_{800}E)}$$

Equation 27: Integration/Engineering Cost for Follow Ship from MIT Math Model

This cost is then added to the three previously calculated costs on this tab thus generating the Total Follow Ship Construction Cost. The profit factor designated in the Lead Ship tab is then applied to the Total Follow Ship Construction Cost to determine the shipyard's earnings. When this value is then added to the Total Follow Ship Construction Cost it gives the user the Total Follow Ship Price. The next step is to take the Follow Ship Change Order Factor (designated by the user) and multiply it by the Total Follow Ship Price. The Change Order Cost is then added to the Total Follow Ship Price to produce the Total Follow Ship Cost Shipbuilder Portion.

As in the case of the Lead Ship Cost spreadsheet, the next step is to determine the government portion of the follow ship cost. The equations for this portion are the same as the ones for the lead ship cost, with just the factors changing. The Follow Ship Other Cost, the Follow Ship Program Manager's Growth Cost, the Follow Ship Ordnance and Electrical GFE Cost, the Follow Ship HM&E GFE Cost, and the Follow Ship Outfitting Cost are summed together to determine the Total Follow Ship Government Cost. This value summed with the shipbuilder's portion of the cost produces the Total Follow Ship End Cost. Finally, the Follow Ship PSA Cost Factor is multiplied by the Total Follow Ship Price to generate the Follow Ship PSA Cost. This summed with the Follow Ship PSA Cost Factor produces the Total Follow Ship Acquisition Cost.

While the lead and follow ship spreadsheets for the MIT Math Model are cluttered and not particularly user friendly, the model does have a very good spreadsheet for generating life cycle costs. Table 13 shows the variables used on this spreadsheet and their accompanying definitions. The Life Cycle Cost generated by the MIT Math Model takes into account costs from several areas: Research and Development, Investment, and Operations and Support. It also takes into account the Residual Value of the Ship over time. These four values are summed together to generate the total life cycle cost of the program, that is to say the cost of all of the ships constructed through the duration of their service life.

VARIABLE NAME	VARIABLE DESCRIPTION
ASCF	Average Ship Cost Factor
ASFCM	Average Ship Cost Factor for Maintenance
ASFCO	Average Ship Cost Factor for Operations
BSDDF	Basic Ship Construction Design and Development Factor
BSTEF	Basic Ship Construction Test and Evaluation Factor
CAVG	Average Ship Cost
CFE	CPO and Enlisted Cost Factor
CFO	Officer Cost Factor
CFUEL	Fuel Cost
CINV	Total Investment Cost
CISS	Cost of Spares and Repair Parts
CLIFE	Total Life Cycle Cost (Undiscounted)
CMSP	Cost of Major Support
CMTC	Total Maintenance Cost
CNRG	Total Fuel Cost
COAS	Total Operating and Support Cost
COPS	Cost of Operations
CPAY	Cost of Pay and Allowances
CPERS	Total Cost of Personnel
CRD	Total Ship Research and Development Cost
CREP	Replenishment Spares Cost
CSDD	Ship Design and Development Cost
CSPE	Cost of Ships
CSSE	Cost of Ship Support Equipment
CSTE	Ship Test and Evaluatoin Cost
CTAD	Cost of TAD
FCONV	Fuel Conversion
FRATE	Fuel Rate
H	Number of Operating Hours Per Year
MCF1	Maintenance Cost Factor 1
MCF2	Maintenance Cost Factor 2
MHCF	Maintenance Hours Cost Factor
MPGCF	Government Follow Ship Military Payload Cost Factor
MPSDDF	Government Military Payload Design and Devleopment Factor
MPSTEF	Government Military Payload Test and Evaluation Factor
MSF1	Major Support Factor 1
MSF2	Major Support Factor 2
MSOHF	Major Support Operating Hours Cost Factor
OCF1	Operations Cost Factor 1
OCF2	Operations Cost Factor 2
OHCF	Opreating Hours Cost Factor
RES	Residual Value
RVCF	Residual Value Cost Factor
SDDF	Ship Design and Development Factor
SEF	Support Equipment Factor
SRPF	Spares and Repair Parts Factor
STEF	Ship Test and Evaluation Factor
TADF	TAD Factor

Table 13: Variables and Definitions for MIT Math Model Life Cycle Cost Tab

The Total Ship Research and Development Cost is the sum of the Ship Design and Development Cost, and the Ship Test and Evaluation Cost. The equations for the two costs are listed below.

$$CSDD = (1 + SDFF)\cdot\left(BSDDF\cdot\left(\frac{(CFSB)}{(LR)}\right) + MPSDDF\cdot CLMPG\right) \tag{28}$$

$$CSTE = (1 + STEF)\cdot\left(BSTEF\cdot\left(\frac{(CFSB)}{(LR)}\right) + MPSTEF\cdot CLMPG\right) \tag{29}$$

Equations 28-29: Research and Development Cost Components

The bulk of the factors for these equations are provided in the Life Cycle Costs tab. The only variables are the Total Follow Ship Cost Shipbuilder Portion, the Ordnance and Electrical GFE (Military Payload GFE), and the Learning Rate. All of the other variables are fixed in the spreadsheet.

The Total Investment Cost is the sum of the Cost of the Ships, Cost of Ship Support Equipment, and the Cost of Spares and Repair Parts. The equations for these terms are listed below.

$$CSPE = \left(\frac{(CFA)}{(LR)}\right) \cdot NS^{\left(\frac{(LN(2 \cdot LRF))}{(LN(2))}\right)} \tag{30}$$

$$CSSE = SEF \cdot CSPE \tag{31}$$

$$CISS = SRPF \cdot CSPE \tag{32}$$

Equations 30-32: Total Investment Cost Components

The equation for Total Ship Cost presents a problem. If the Total Ship Acquisition is one, meaning one lead ship and no follow ships, then the cost of the ship should be the lead ship cost. This is not the result when these values are applied to this model. The Total Follow Ship Acquisition Cost divided by the Learning Rate does not equal the Total Lead Ship Acquisition Cost. To fix this, the equation for the Total Ship Cost must be modified. This fix will be addressed in the merger of the two models so that the Total Ship Cost equals the sum of the Total Lead Ship Acquisition Cost and the sum of all of the Total Follow Ship Acquisition Costs.

The remaining costs in the Investments column depend on factors given in the program. The Support Equipment Factor is used to determine the Cost of Ship Support Equipment while the Spares and Repair Parts Factor is used to calculate the Cost of Spares and Repair Parts. Each of these factors is multiplied by the Cost of Ships to determine their corresponding values and the sum of the three costs in this column provide the user with the Total Investment Cost.

The Operations and Support Cost has far more components than the costs previously discussed. Operations and Support is broken down into the Total Cost of Personnel, the Cost of Operations, the Total Maintenance Cost, the Total Fuel Cost, the Replenishment Spares Cost and the Cost of Major Support. These values are all summed together to provide the user with the Total Operating and Support Cost.

The Total Cost of Personnel is a combination of the Cost of Pay and Allowances for both officers and enlisted members and the Cost of Temporary Assigned Duty (TAD) personnel. As expected, over the lifespan of the ship, the cost of TAD personnel is fairly insignificant. To determine the cost of pay and allowances, the following equation is used:

$$CPAY = F_1 \cdot (CFO \cdot NO + (CFE \cdot (NCPO + NE))) \cdot NS \cdot LS$$

Equation 33: Cost of Pay and Allowances for Personnel

As shown in the equation the inputted numbers of officers and enlisted (enlisted members being a combination of chief petty officers and enlisted crewmembers) are multiplied by their corresponding factors provided in the spreadsheet. The total is then multiplied by the inflation factor calculated on the Lead Ship Cost tab. Finally these are multiplied by the total number of ships constructed during the acquisition and the ship service life.

The TAD cost is calculated in a slightly different manner. The equation below shows that there are not individual factors for officers and enlisted, just a blanket TAD factor that is multiplied by the crew size. Once the factor is applied, this number is again subject to being multiplied by the number of ships, the ship service life, and the inflation factor.

$$CTAD = F_1 \cdot (NO \cdot NCPO \cdot NE) \cdot NS \cdot LS \cdot TADF$$

Equation 34: Cost of TAD Personnel

The next factor is the Cost of Operations. The Cost of Operations requires the Number of Operating Hours per Year to be inputted by the user. There are five factors that affect the overall cost of operations: Operations Cost Factors one and two, the Operating Hours Cost Factor, The Average Ship Cost Factor for Operations, and the Government Follow Ship Military Payload Cost Factor. Equation 35 shows how these factors are applied to determine the Cost of Operations.

$$COPS = NS \cdot LS \cdot (F_1 \cdot .001 \cdot (OCF_1 + OCF_2 \cdot (NO + NCPO + NE) - H \cdot OHCF) + CAVG \cdot ASFCO + FCMPG \cdot MPGCF)$$

Equation 35: Cost of Operations

The Total Maintenance Cost is the next to be determined. There are four Cost Factors that determine the Total Maintenance Cost: Maintenance Cost Factors one and two, the Maintenance Hours Cost Factor, and the Average Ship Cost Factor for Maintenance. These factors are utilized in an equation similar to the one used to calculate the Cost of Operations which is shown below.

$$CMTC = NS \cdot LS \cdot (F_1 \cdot 0.001 \cdot (MCF_1 + MCF_2 \cdot (NO + NCPO + NE) - H \cdot MHCF) + CAVG \cdot ASFCM)$$

Equation 36: Cost of Maintenance

The next component of the Total Operating and Support Cost is the Total Fuel Cost. This requires two more user inputs in order to be calculated. The user must input the fuel cost in dollars per gallon, and the fuel consumption rate in long tons per hour. This leads to the equation for Total Fuel Cost.

$$CNRG = NS \cdot LS \cdot CFUEL \cdot \left(\frac{H}{(FCONV)}\right) \cdot \frac{(FRATE)}{1000}$$

Equation 37: Total Fuel Cost Equation

The Replenishment Spares Cost is determined using variables and factors already present in the program so no new factors are added. The Replenishment Spares Equation is listed below.

$$CREP = CISS \cdot \left(\frac{(LS - 4)}{4}\right)$$

Equation 38: Replenishment Spares Cost

The final component of the Total Operating and Support Cost is the Cost of Major Support. There are four factors that influence this cost: Major Support Factors one and two, the Major Support Operating Hours Cost Factor, and the Average Ship Cost Factor. These factors are applied in the equation below to give the Cost of Major Support.

$$CMSP = NS \cdot LS \cdot \left(MSF_1 + MSF_2 \cdot (NO + NCPO + NE) - \frac{H}{(MSOHF)} \right) \cdot \frac{(F_1)}{1000} + ASCF \cdot CAVG$$

Equation 39: Cost of Major Support

These components all add up together to form the Total Operating and Support Cost. There is one final value to be considered, and that is the Residual Value. This takes into account money that the ship is worth at the end of the life cycle, thus taking money away from the Total Program Life Cycle Cost. The Residual Value Cost Factor is inputted by the user and then applied to the following equation to determine the residual value.

$$RES = RVCF \cdot CSPE \cdot \left(1 - \left(\frac{2}{(LS)} \right) \right)^{(LS)}$$

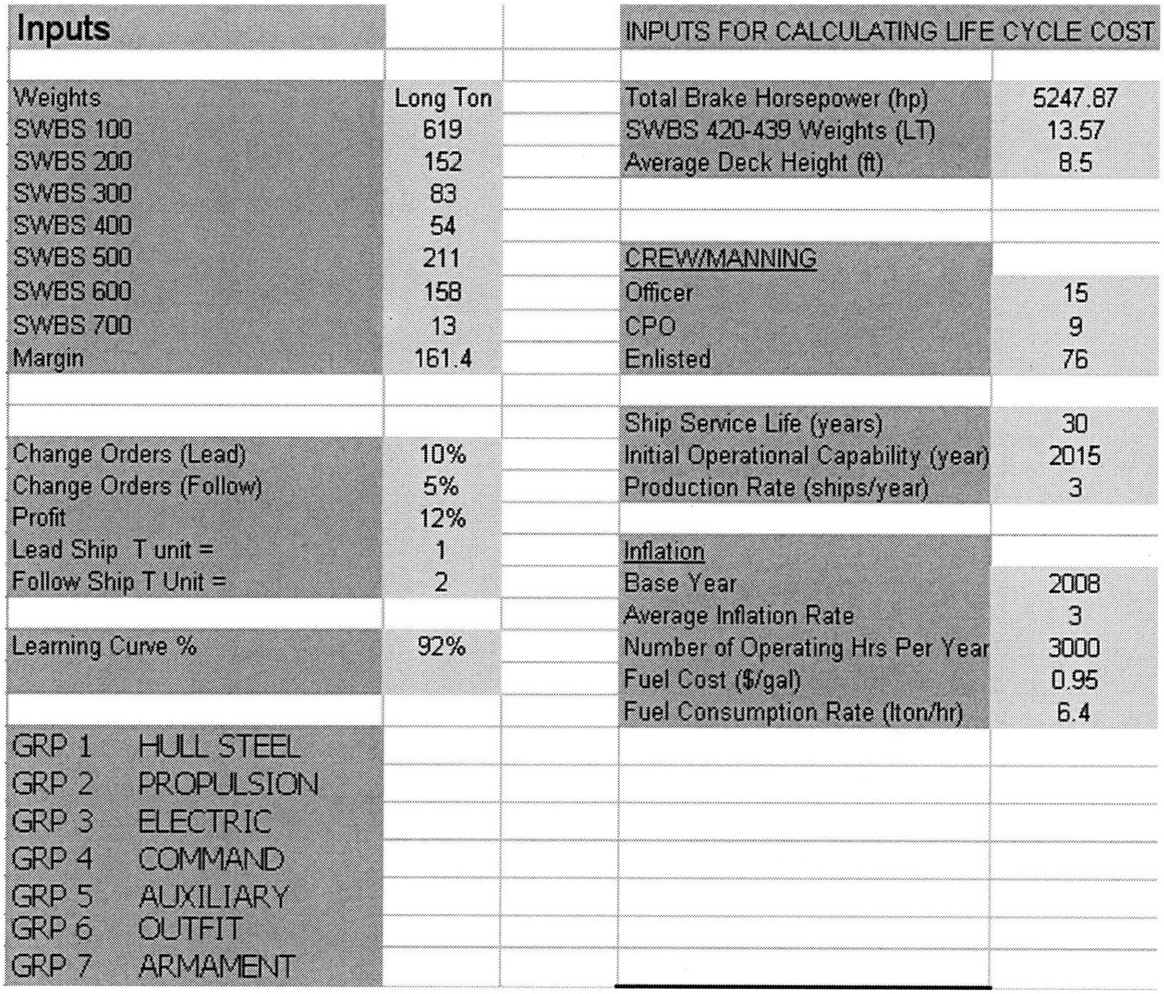
Equation 40: Residual Value Equation

This is the last component needed to calculate the Total Life Cycle Cost of the Program. This gives the total cost of the lead ship, all of the following ships over their entire lifespan.

2.3 Combining the Two Models

Having reviewed the components of each program it becomes clear that each program offers certain advantages. The BMTS Cost Model is far more user friendly. All of the inputs are located one tab as opposed to spread throughout the program. Additionally, all of the significant outputs are located in one place making it easy to find the results once the data has been put into the program. Ultimately, the organization as a whole is far superior to that of the MIT Math Model. Additionally, the BMTS Cost Model has a better model for Lead and Follow Ship Cost. It has separate CERs for both Labor Hours and Material Cost, and these CERs are easy to alter should the user so desire. The MIT Math Model, on the other hand, has a much stronger model for Life Cycle Cost. As opposed to the BMTS Model where the O&S cost per year is determined based solely on a percentage of the Basic Construction Cost, the MIT Math Model goes into great detail taking into account the cost of fuel, of personnel, of research and development and in short does a much better job of covering the many facets that make up the life cycle cost.

Because each of the models has different strengths and weaknesses, it is beneficial to merge the two models. The best way to do this is to use the template set forth by the BMTS Cost Model and maintain its spreadsheets for calculating the lead and follow ship costs. The Life Cycle Portion of the program will then be eliminated and replaced by the Life Cycle Portion of the MIT Math Model. Because the MIT Math Model requires inputs that are not required of the BMTS Cost Model, the inputs tab would be adjusted expanding the amount of variables the user is required to input. The new inputs page for the Combined Cost Model is shown below in Figure 11.



Inputs			INPUTS FOR CALCULATING LIFE CYCLE COST	
Weights	Long Ton		Total Brake Horsepower (hp)	5247.87
SWBS 100	619		SWBS 420-439 Weights (LT)	13.57
SWBS 200	152		Average Deck Height (ft)	8.5
SWBS 300	83			
SWBS 400	54			
SWBS 500	211		CREW/MANNING	
SWBS 600	158		Officer	15
SWBS 700	13		CPO	9
Margin	161.4		Enlisted	76
			Ship Service Life (years)	30
Change Orders (Lead)	10%		Initial Operational Capability (year)	2015
Change Orders (Follow)	5%		Production Rate (ships/year)	3
Profit	12%			
Lead Ship T unit =	1		Inflation	
Follow Ship T Unit =	2		Base Year	2008
			Average Inflation Rate	3
Learning Curve %	92%		Number of Operating Hrs Per Year	3000
			Fuel Cost ($/gal)	0.95
			Fuel Consumption Rate (lton/hr)	6.4
GRP 1 HULL STEEL				
GRP 2 PROPULSION				
GRP 3 ELECTRIC				
GRP 4 COMMAND				
GRP 5 AUXILIARY				
GRP 6 OUTFIT				
GRP 7 ARMAMENT				

Figure 11: Inputs for Combined Cost Model

With the addition of the inputs on the right hand side of the page, the user now is able to input all of the information that the program requires in order to generate life cycle cost in the Combined Cost Model. The next step in combining the models was adjusting the tabs that the Life Cycle Cost tab references when doing its calculations. To do this, values for the outputs from the BMTS Cost Model replaced values for the various lead and follow ship costs in the MIT Math Model. To test whether or not this was successful, the values for Total Lead Ship Cost and Total Follow Ship Cost on the Output tab needed to match the Total End Cost and Total Follow Ship End Cost generated. With this complete, the issue of the aforementioned inaccurate calculations for the Cost of Ships can be addressed.

The problem with the equation in the initial model was that it did not produce accurate results. If only one ship is built, then the value for the Cost of Ships should be equal to the Total Lead Ship Acquisition Cost. Subsequently, if two ships are built, the Cost of Ships should be equal to the Total Lead Ship Acquisition Cost plus the Total Follow Ship Acquisition Cost. Referring back to equation 30 shown below, it can be seen that this equation does not take into account the Total Lead Ship Acquisition Cost at all.

$$CSPE = \left(\frac{(CFA)}{(LR)}\right) \cdot NS^{\left(\frac{(LN(2 \cdot LRF))}{(LN(2))}\right)} \tag{30}$$

In place of the Total Lead Ship Acquisition Cost is the Total Follow Ship Acquisition Cost divided by the Learning Rate. This equation does not return the Total Lead Ship Acquisition Cost. The learning curve for the shipyard does not cause a constant reduction in the cost of the ship between lead ship and the follow ships. The reason for this is the learning curve only applies to portions of the cost that are directly affected by labor hours. The reduction in labor hours due to learning creates a reduction in some of the costs however it does not affect the material costs or the material overhead costs. The total change is therefore not a constant from ship to ship. As a result a new equation needed to be designed to take into account the fact that only a portion of the costs would experience the learning curve reduction, while others would remain fixed. Additionally this program would also have to accurately sum values of each follow ship. The following equation was developed after reviewing the relationships between lead ship cost and follow ship cost.

$$CSPE = 1.33[(CostFactor - 1)\cdot(VaryingA + VaryingB + VaryingProf) + (NS - 1)\cdot(Fixed + FixedProf)] + TLSAC$$

Equation 41: Cost of Ships Equation Developed for Combined Cost Model

Several new variables had to be created for the development of this equation. When it was realized that there were certain costs that varied and certain costs that were fixed, these values were split up into two separate categories referred to as fixed and varying. The varying costs would be affected by the learning curve, while the fixed costs would be constant for every ship of its class being built. The varying costs included the total cost of labor, the cost of labor overhead, as well as the percentage of profit and FCCOM generated as a result of the varying costs. As the FCCOM is directly related to labor cost, it does not affect the fixed costs. The fixed costs are the total material cost and overhead, and the percentage of the profit accrued as a result of the fixed portion of the total cost.

The next step was to determine how the learning curve affects the varying cost so that they could be summed together. Ultimately a table was generated with values for the Cost

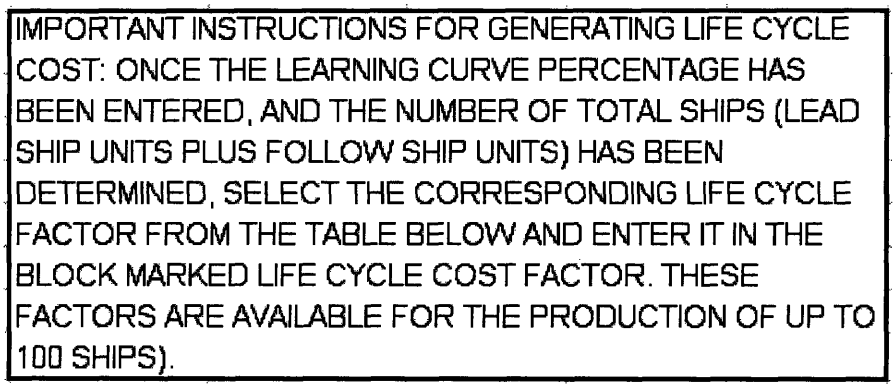
Factor, a value indicating how much the varying costs would change. The data is shown below in Table 14.

1	1.000	21	16.270	41	29.508	61	41.967	81	53.939
2	1.920	22	16.960	42	30.146	62	42.575	82	54.527
3	2.796	23	17.646	43	30.782	63	43.183	83	55.115
4	3.643	24	18.328	44	31.416	64	43.789	84	55.702
5	4.467	25	19.007	45	32.049	65	44.395	85	56.288
6	5.273	26	19.683	46	32.680	66	44.999	86	56.873
7	6.064	27	20.355	47	33.309	67	45.602	87	57.457
8	6.843	28	21.025	48	33.937	68	46.204	88	58.041
9	7.610	29	21.692	49	34.563	69	46.805	89	58.624
10	8.368	30	22.356	50	35.187	70	47.404	90	59.206
11	9.118	31	23.018	51	35.811	71	48.003	91	59.787
12	9.860	32	23.677	52	36.432	72	48.601	92	60.367
13	10.594	33	24.334	53	37.053	73	49.198	93	60.947
14	11.322	34	24.988	54	37.671	74	49.794	94	61.526
15	12.044	35	25.640	55	38.289	75	50.389	95	62.104
16	12.760	36	26.290	56	38.905	76	50.983	96	62.682
17	13.472	37	26.937	57	39.520	77	51.576	97	63.258
18	14.178	38	27.583	58	40.134	78	52.168	98	63.834
19	14.880	39	28.227	59	40.746	79	52.759	99	64.410
20	15.577	40	28.868	60	41.357	80	53.349	100	64.984

Table 14: Cost Factors for Life Cycle Cost- Determining the Cost of Ships

To use this table, the user must merely find the number of total ships being built (left hand column) and plug the corresponding CostFactor value into the block marked Life Cycle Cost Factor on the inputs tab. Without a learning curve the cost of building one ship is the cost of one lead ship, the cost of two ships is the cost of two lead ships and so on and so forth. However, when a learning curve is a applied this table shows that the costs will decrease as more units are built. While the lead ship will not see any sort of cost reduction, a 92% learning curve makes the cost of two ships is equal to the value of 1.92 lead ships. Three ships can then be made for the price of 2.796 and the reductions can be seen as it continues down the table. Values are provided for the production of up to 100 ships. It is important to note though that this only impacts the varying costs, hence why the cost factor is only applied to that portion of the overall cost.

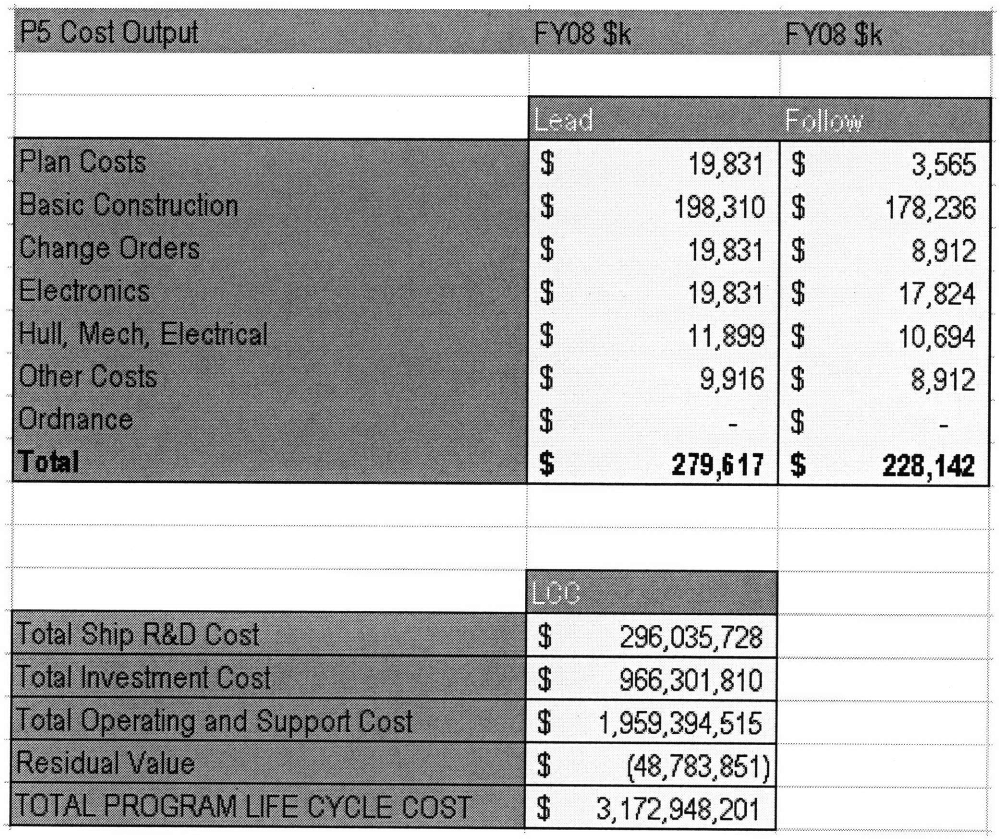
As all subsequent costs (HM&E, Electronics, Other, etc.) are related to the total cost of Basic Construction by means of a percentage, these percentages could be added up into one big multiplier to determine their impact on total cost. This factor does not change from follow ship to follow ship as these percentages are applied to the entire cost of basic construction, and not exclusively the varying or fixed portions. This explains the multiplier 1.33 at the front of the equation. Finally, a value of 1 is taken away from the cost factor and from the total number of ships so that when the number of ships is one (subsequently making the cost factor equal to 1), the entire term goes to zero making the Cost of Ships equal to just the Total Lead Ship Acquisition Cost. The following instructions have been added to the inputs page to inform the user on how to pick a value from the table.



IMPORTANT INSTRUCTIONS FOR GENERATING LIFE CYCLE COST: ONCE THE LEARNING CURVE PERCENTAGE HAS BEEN ENTERED, AND THE NUMBER OF TOTAL SHIPS (LEAD SHIP UNITS PLUS FOLLOW SHIP UNITS) HAS BEEN DETERMINED, SELECT THE CORRESPONDING LIFE CYCLE FACTOR FROM THE TABLE BELOW AND ENTER IT IN THE BLOCK MARKED LIFE CYCLE COST FACTOR. THESE FACTORS ARE AVAILABLE FOR THE PRODUCTION OF UP TO 100 SHIPS).

Figure 12: Disclaimer for How to Pick Life Cycle Cost Factors

With the program now functioning, the newly updated outputs tab shows the desired results from both programs producing accurate lead ship and follow ship costs, as well as a life cycle cost for the overall program.



P5 Cost Output	FY08 $k	FY08 $k
	Lead	Follow
Plan Costs	$ 19,831	$ 3,565
Basic Construction	$ 198,310	$ 178,236
Change Orders	$ 19,831	$ 8,912
Electronics	$ 19,831	$ 17,824
Hull, Mech, Electrical	$ 11,899	$ 10,694
Other Costs	$ 9,916	$ 8,912
Ordnance	$ -	$ -
Total	**$ 279,617**	**$ 228,142**

	LCC
Total Ship R&D Cost	$ 296,035,728
Total Investment Cost	$ 966,301,810
Total Operating and Support Cost	$ 1,959,394,515
Residual Value	$ (48,783,851)
TOTAL PROGRAM LIFE CYCLE COST	$ 3,172,948,201

Table 15: Depiction of Updated Outputs Tab in Combined Cost Model

2.4 Developing Coast Guard CERs

The final modifications to the program also include the development of Coast Guard specific CERs to replace the given CERs provided and linked to Naval Combatants. The new CERs were developed by examining the weights of various SWBS groups for the 270' Famous Class Cutter. Data was provided by the Coast Guard for each three digit

SWBS group for the first four Famous Class Cutters (USCGC Bear, USCGC Tampa, USCGC Harriet Lane and USCGC Northland). The data provided three key components needed for cost estimation: the weight of the SWBS group, the number of labor hours spent on the construction of that SWBS group, and the material cost for that SWBS group. A sample of how the data provided is shown below in Table 16. It should be noted that these are not the actual values, just a means of showing how the data was formatted.

SWBS	Weight (LT)	Labor (MH)				Material Cost per Hull
		Hull 1	Hull 2	Hull 3	Hull 4	
111	15.00	12,000	11,040	10,157	9,344	$ 25,000
114	20.00	4,000	3,680	3,386	3,115	$ 15,000
116	23.00	5,000	4,600	4,232	3,893	$ 10,000
120	26.00	4,000	3,680	3,386	3,115	$ 23,000
130	21.00	2,500	2,300	2,116	1,947	$ 50,000
150	50.00	1,600	1,472	1,354	1,246	$ 30,000
152	49.00	1,300	1,196	1,100	1,012	$ 12,000
123	20.00	1,500	1,380	1,270	1,168	$ 9,000
131	59.00	1,800	1,656	1,524	1,402	$ 40,000
136	43.00	2,100	1,932	1,777	1,635	$ 30,000
141	39.00	5,200	4,784	4,401	4,049	$ 25,000
151	50.00	2,300	2,116	1,947	1,791	$ 40,000
152	12.00	8,000	7,360	6,771	6,230	$ 23,000

Table 16: Sample Data provided in Coast Guard Format

With this data, it now became possible to develop cost estimating relationships in terms of labor hours per long ton, as well as material dollars per long ton. Because the newly combined cost model is set up to receive one digit SWBS inputs, the three digit values provided by the Coast Guard were combined into their respective one digit SWBS groups so the resulting CERs were based on the entire number of labor hours and the overall material cost per long ton of each of the main SWBS categories (100-700). A total of fourteen CERs were then generated using the information that was provided. These CERs would then replace the Naval Combatant CERs listed on the FACTORS tab of the program. It should be noted that the data provided could have been used to generate two or three digit SWBS group CERs if the user wanted a more specific cost estimate.

A quick comparison was made to ensure that the new cost estimating relationships seemed reasonable. At first glance the only CER that appeared to be incorrect was for the SWBS 400 (Command & Surveillance) group. While most of the CERs were within a factor of one or two of the Naval Combatant values, the value for the Coast Guard SWBS 400 group was on the order of a factor of ten larger than the same group for a Naval Combatant. Because there was no logical reason for Coast Guard systems to be significantly more expensive than the Navy systems, this led to throwing out this value and using the Naval Combatant CER for the Coast Guard model instead. This was determined to be an acceptable modification because as technology continues to progress, cost estimating relationships based on weight are becoming less and less accurate for the SWBS 400 group. The data provided for the Famous Class Cutter is from over 20 years ago so the discrepancy is likely due to the fact that technology has brought about drastic changes in the cost estimating relationships for computer-type technology.

Once the adjustments to the model were completed, it was tested using the ASSET data for a Coast Guard medium endurance cutter (WMEC). With this data inputted, a value of approximately $280 million dollars was determined to be the lead ship cost. This cost was compared against the funds allocated for the replacement WMEC, the Offshore Patrol Cutter (OPC). The Offshore Patrol Cutter is estimated to cost in the vicinity of

$300 million dollars. (9) It makes sense that the value would be slightly larger due to the fact that the OPC is estimated to be slightly bigger (320 feet versus 270 feet). However, as the prices are in the same vicinity it stands to reason that this model is accurate enough to be considered a valid cost estimation tool for the purposes in which it might be used at MIT.

2.5 Future Program Modifications

The Navy model has had its CERs updated to account for inflation through 2008, thus eliminating the need to factor in inflation between 2005 (when the model is set for) and present day. There are still some questions that could be addressed in future versions though. The inputs for crew and manning specify determining the number of chief petty officers in addition to the number of enlisted members. However, in all of the equations involving the crew impacts on cost, the chief petty officers have the same value as the enlisted. This hardly seems likely so research could be done to determine if there is a significant difference. Additionally, research could be done to determine the origins of the factors provided to see how they were in fact determined and whether or not they need to be modified. Finally, as improvements are made in generating cost estimating relationships based on more than solely weight based models, this too can be added to the program.

CHAPTER 3: APPLICATIONS AND LESSONS LEARNED

The United States Coast Guard has reached a pivotal point in its history. Many of its current assets are reaching, or have already gone beyond their expected service life. This presents a number of problems for the Coast Guard. A consequence of operating aged assets is the limitations resulting from the old, and in many cases obsolete, technology inherent in those assets. In addition to hindering operational performance, antiquated technology ultimately increases operating and maintenance costs. As a result of its aging fleet, the Coast Guard developed a 25-year program designed to recapitalize the service's aircraft, ships, logistics, and command and control systems called The Deepwater Project.

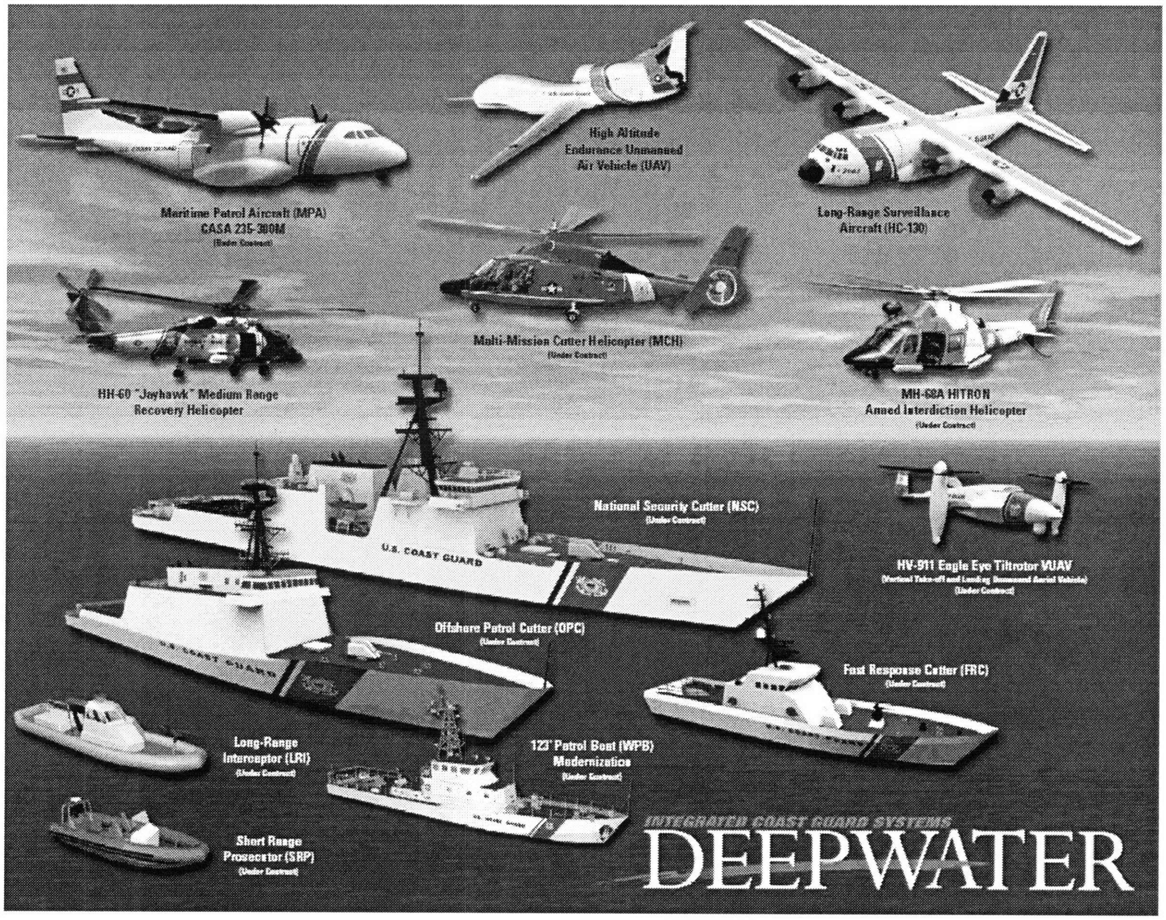


Figure 13: Coast Guard Deep Water Project Assets (6)

Three major classes of cutter are scheduled to be developed during this project, the Fast Response Cutter (FRC- a replacement for the Island Class Patrol Boat), the Offshore Patrol Cutter (OPC- a replacement for the Coast Guard's medium endurance cutters), and the National Security Cutter (NSC- a replacement for the Hamilton Class High Endurance Cutters). With shipbuilding a major priority for the Coast Guard right now, and with the Deepwater Project experiencing a number of unexpected problems, the ability to design ships at the cost estimated suddenly becomes very important to the Coast Guard.

One of the major contributing factors to increases in cost during the design process is the number of change orders that can come up during the construction process. Change orders can have a dramatic effect on the cost of a ship, rapidly inflating an acquisition cost. One of the temptations that leads to going over the allotted change orders in the budget is the desire to have the newest technology on board the ship. There is generally a good amount of time between when the designs are initially drawn up, and when the ship is finally built. The top-of-the-line technology included in the initial design might not be the best available by the time the ship goes to construction. The problem becomes that it is rarely as simple as replacing piece A with piece B. Parts come in different sizes, and depending on when the change comes along during the design process, this can cause significant rework leading not only to increases in cost, but to delays in production as well. Keeping change orders to a minimum is imperative in order to ensure a ship is delivered on time and on budget. The Coast Guard Great Lakes Ice Breaker (GLIB, see

Figure 14) project is a good example of a ship not undergoing significant change orders and therefore meeting its expected delivery date without any significant issues. (7)

Figure 14: Coast Guard Cutter Mackinaw (GLIB) (6)

The Deepwater Project has also shown that estimating cost on the basis of weight alone does not always deliver results. The FRC-A project was originally intended to be built with a composite hull. While the lighter composite hull materials would be cheaper than the steel typically used, the amount of money that it would cost in terms of assembly and maintenance would ultimately cause the price to skyrocket. (7) Similar results have been found with aluminum. While aluminum is much lighter and therefore cheaper to obtain, it requires much a more skilled labor force work with it. Thus once again it leads to higher costs overall.

Another weight related issue was already touched on briefly is the fact that it is no longer practical to estimate costs for SWBS 400 group or the SWBS 700 group based on their weights. Improvements in technology have allowed for equipment such as computers and guidance systems and weapons to be made lighter and smaller, but this does not equate to them being any cheaper. In many cases, the lighter, smaller equipment in these groups will cost even more than the big, heavy equipment. Because of this, various groups are working on developing a new means of conducting cost estimates based on density or complexity of a system. The more dense or complex a system is, the more it costs to construct. For the purpose of the student models used at MIT these methods aren't practical, but in the actual shipbuilding industry, they are being explored to see if they are in fact better approximations.

In addition to developing good cost estimates, and doing everything possible to meet the desired acquisition budget there are things that can be done to reduce the overall life cycle cost of the ship. As was stated earlier in the paper, a majority of the life cycle cost is tied up in O&S costs. Therefore the number of personnel allocated to a ship can become a significant cost issue. Wherever possible, measures should be made to have smaller crew sizes. That being said, it is not as simple as just cutting out half of the crew and replacing them with automated machinery. Tradeoff studies must be done in order to ascertain what the most efficient way to do business is. Cutting costs in one area and increasing costs in another does not help reduce the overall cost of the ship. Reducing the size of a crew causes a need for more highly skilled personnel with far more diversity in their training. The cost to train these personnel must also be factored into the equation to determine whether or not it is truly beneficial to go in that direction. It is imperative that when conducting tradeoff studies in areas such as these that all facets are considered so educated decisions can be made.

Another significant tradeoff study is in the propulsion plant. While a bigger engine may result in a great acquisition cost, it could save money in the long run because it operates more efficiently at the ship's transit speed. Close attention needs to be paid to fuel efficiency curves when picking out an engine to ensure that the engines selected can operate efficiently in the operating parameters specified for the ship. Again, it is imperative that a lot of effort goes into the trade-off study so that the mission effectiveness, acquisition cost and life cycle cost are all optimized. The new and improved MIT Cost Model can assist in these trade-off studies.

Factoring in maintenance is important as well. Little things like ensuring there is significant overhead space when designing a ship to allow for piping and cabling and auxiliary machinery can go a long way to reduce costs in the long run. Not only is it cheaper and easier to install equipment when there is more space, but upon a ship's completion, it is also much easier to do maintenance on equipment when there is easy access to it. This is principle behind the aforementioned density cost estimating relationships that are currently being studied. While this may increase costs in the short run because it causes the ship to be bigger and heavier, in the long run, a great deal of money can be saved on O&S costs. But once again, this is an area that needs to be carefully optimized.

All of these things can impact the cost of a ship significantly, so it cannot be overstated how important it is to look at all of these tradeoff studies early in the design process to allow for building the best ship possible for the amount of money available.

CONCLUSION

The Combined Cost Model developed in this thesis project is a significant upgrade to both of the models currently in use by MIT students. This new model has not only repaired several errors inherent in the original programs but it has taken the best aspects of each program and combined them to allow it to be able to determine both acquisition and life cycle costs. As shown in the paper, the life cycle cost cannot be ignored when developing a ship design. To merely select a ship design on the cost of its acquisition alone may cause a ship that is not the optimal design to be built ultimately costing a lot more money than needed to be spent. Having a program that produces accurate life cycle costs as well as acquisition costs should improve the quality of cost estimations in the 2N program.

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