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601 Pavonia Avenue, Jersey City, NJ 07306
Tel. (201) 798-4800 Fax. (201) 798-4975
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Product-Oriented Design And Construction Cost Model

Kristina Jasaitis Ennis, (V); Naval Surface Warfare Center, Carderock Division; **John J. Dougherty**, (V), Designers and Planners Inc.; **Thomas Lamb** (F), University of Michigan; **Charles R. Greenwell** (V), SPAR, Inc.; and **Richard Zimmermann**, (V), Designers and Planners, Inc.

ABSTRACT

Navy ship cost estimators traditionally estimate the cost of ships using system-based, weight-driven cost models. This approach has proven adequate in estimating the cost of ships with similar designs built using the same processes. However, this approach is not sensitive to changes in production processes, facilities, and advanced manufacturing techniques. In an effort to work more closely with industry to link ship design, manufacturing, schedule and costs, Naval Sea Systems Command sponsored the Product-Oriented Design and Construction (PODAC) Cost Model Project. This paper discusses the efforts and results of the PODAC project to date.

The aim of the cost model is to improve techniques for analyzing issues of ship cost reduction, advanced construction techniques, modular construction, new technology benefits, industry consortium and teaming arrangements. The model will enhance the Navy s and industry s ability to provide accurate, timely and meaningful cost feedback from cost analysts to ship designers and from production to design. By better relating to the actual construction process, such as interim products and stages of ship construction, the state of the art can be advanced by providing essential knowledge for effective decision making and program management. This should ensure cost effective choices and enhance the buying power of the Navy within its budget limitations. The PODAC cost model should be an invaluable tool to the shipbuilding industry as it works to improve its global competitiveness.

NOMENCLATURE

ATC Affordability Through Commonality
CER Cost Estimating Relationship
GBS Generic Build Strategy
G/PWBS Generic Product-Oriented Work Breakdown Structure
IPT Integrated Product Development Team
NSRP National Shipbuilding Research Program
PODAC Product-Oriented Design and Construction
PWBS Product Work Breakdown Structure
SWBS Ship Work Breakdown Structure
WBS Work Breakdown Structure
QFD Quality Functional Deployment

INTRODUCTION

The U.S. Navy has traditionally estimated the cost of ships using system-based, weight-driven cost models. This approach is not sensitive to changes in production processes and advanced manufacturing techniques. In an effort to link ship design, manufacturing processes, schedule and costs, Naval Sea Systems Command (NAVSEA) Mid-Term Sealift Ship Technology Development Program (MTSSTDP) and Affordability Through Commonality Program (ATC) sponsored the Product-Oriented Design and Construction (PODAC) Cost Model Project. The project is being closely coordinated by David Taylor Model Basin's Shipbuilding Technology Department with the MTSSTDP Generic Build Strategy task which includes the development of the Generic Product-Oriented Work Breakdown Structure (GPWBS) described in the concurrently published report, *Towards a Generic Product-Oriented Work Breakdown Structure.* See Reference [1].

A functioning prototype of the PODAC Cost Model was developed last year by a Navy/Industry Integrated Product Development Team (IPT). This team included the co-developers of the model, Designers and Planners Inc., the University of Michigan Transportation Research Institute (UMTRI), and SPAR Inc., as well as participants from the Navy's cost and design community, and two shipyards, NASSCO and Avondale. The team demonstrated the PODAC Cost Model prototype to a Steering Committee which includes members from NAVSEA's Program Management, Design, and Cost organizations, as well as members from the five major U.S. shipyards, Avondale, Bath Iron Works, Ingalls, NASSCO, and Newport News. Upon viewing the demonstration, all five shipyards expressed interest in working with the Navy to further test and enhance the model in the near future.

BACKGROUND

The Product-Oriented Design and Construction (PODAC) Cost Model Project is an effort to develop a cost model which is sensitive to the way that shipyards build ships today, as well as being sensitive to how they may be built in the future. The model must accommodate ever-improving production processes and major innovations in ship designs, equipment, and facilities. The vision and goals for the development of the PODAC cost model were set during a workshop in 1994 to determine the desired attributes of a new Navy cost model.

The goal of the PODAC Cost Model is to utilize a product-oriented work breakdown structure and group technology, as well as to accommodate alternative work breakdown structures. The new model will be a tool for smart business decisions in the areas of

- technology assessments,
- engineering trade-offs,
- design and construction processes, and
- ownership cost assessments.

Strengths and Weaknesses of Current Navy Cost Model

The development of the PODAC Cost Estimating Model was initiated by the Navy in order to tie together ship design, production processes and costs. Currently, the Navy estimates ship costs using traditional weight based cost estimating relationships and the Ship Work Breakdown Structure (SWBS) which is a functional breakdown of the ship by systems. Traditional weight based estimating relationships are broken out by labor, material and overhead. These are usually in the form of dollars per ton for material costs and man-hours per ton for direct labor. A percentage for overhead costs is applied to direct labor costs. These weight based cost estimating relationships do not reflect improvements that may occur in the production process. For example, if a new welding technique is used which takes 25% less man- hours per foot of weld, no change would be reflected in cost, because there is no change in the weight of the ship. Therefore, if a change in design or production process has no impact on weight, then the cost estimate will not change.

The SWBS structure is based on systems that are distributed throughout the ship. There are no geographical or zonal boundaries using SWBS. SWBS is linked to design features and functional characteristics of the ship, providing adequate information for estimating in the early design stage. However, a ship is actually constructed by zones, or geographically discrete products. Therefore, SWBS has no relation to the way a ship is built. These deficiencies in the cost estimating relationships and breakdown of the current system were aptly noted by Walt Christensen at the NSRP symposium in 1992,

> *Ship construction cost estimating relationships are derived from historical data reflecting past accounting methods and performance. Cost reductions resulting from newly adopted and developing shipbuilding technologies and production methods are not reflected in the existing historical based cost estimating techniques. Advanced shipbuilding technologies typically involve a modular, product oriented approach which cuts across elements of the existing SWBS. Thus, even the basic structure of the current approach to ship cost estimating is of questionable relevance for modeling the ship construction processes and cost estimates of the future.* See Reference [2].

There was very little dispute over the need for a better cost model. Rather than developing a model from scratch, however, the Navy wanted to identify the strengths and weakness of their current cost model and build from there. The strengths and weaknesses of the Navy's current model were discussed at the July 1994 PODAC Cost Model Workshop and are summarized below.

Strengths

- It is based on decades of historical data;
- It is defensible and reproducible;
- It is relatively simple (not overly burdensome with detail);
- It is tonnage based, requiring minimum design information to develop an estimate;
- It has been an accurate predictor of ship cost in the past; and
- It is adequate for budgeting and financial reporting.

Weaknesses

- It does not break down costs the way that ships are built;
- It is not useful in making design decisions;
- It does not relate to the design characteristics of a ship
- It can not address the impact of new technologies or processes; and
- It provides no feedback for engineering or production.

The general agreement of those attending the workshop was that the Navy's current shipbuilding cost model is of little use in providing information to make decisions regarding cost reduction in the design or production of ships. Therefore, the Navy needed to adopt new cost models which define the major design, production, and operational cost drivers as well as provide information necessary to make management decisions to reduce costs.

Steering Committee

In order to understand the concerns of the various Navy customers of this model, a Steering Committee chaired by the Cost Estimating and Analysis Division, NAVSEA 017, was formed in October 1994. This committee includes the SEA 03 sponsors as well as members from the Surface Ship Design and Engineering Group, NAVSEA 03D, the Ship Research, Development and Standards Group, NAVSEA 03R, NAVSEA 017, representatives from the SC21, Sealift, and LPD 17 Program Offices, the Cost and Economic Analysis Branch, NSWCCD 21, and the Shipbuilding Technology Office, NSWCCD 25.

The purpose of the Steering Committee is to provide to the IPT:

- Strategic leadership and oversight;
- Resources/Facilitization; and
- High level goals and objectives

The Navy Steering Committee also felt that for the model to be used successfully, it should have value to and be accepted by the shipbuilding industry. In that light, the Steering Committee just recently expanded its membership to include management from the five major U.S. shipyards.

Concept Exploration and Evaluation

The first year of the project involved concept exploration and evaluation. A search was performed to identify existing cost models which would meet the Navy's need for a new cost model. Three existing models were identified as being pertinent to the task at hand and three additional concepts were explored. The six producers of the models were:

1. System Programming, Analysis & Research (SPAR), Inc.
2. Jonathan Corporation,
3. Decision Dynamics, Inc.,
4. University of Michigan Transportation Research Institute (UMTRI),
5. John Dougherty as a subcontractor to Designers and Planners, Inc., and
6. DAI as a subcontractor to Designers and Planners, Inc.

A Navy Evaluation Team was set up to evaluate the models and make recommendations for continuing the effort of developing the PODAC Cost Model. The Navy Evaluation Team consisted of a chairman, facilitator, and nine representatives from the Navy cost, design, and program management communities. The criteria used for the Navy evaluation were developed by the NAVSEA PODAC Cost Model Steering Committee. This ensured that the results of the evaluation addressed the needs of the sponsors. The committee grouped the criteria in order of importance by assigning a high, medium, or low value to each. Listed below are the twenty-nine criteria and their stated importance.

<u>High Rank</u>

1. The model should be capable of performing relative cost estimates for comparative purposes and trade-off studies.
2. The model should be sensitive to Schedule.
3. The model should be able to measure the cost impacts of Alternative Configurations (ship/system/product).
4. The model should be capable of performing cost estimates at all stages of Design Maturity (Feasibility, Preliminary, and Contract).
5. The model should be sensitive to Work Environment (Stage).
6. The model should be sensitive to PWBS.
7. The model should be able to measure the cost impacts of Alternative Arrangements.
8. The model should be able to measure the cost impacts of design choices of materials/equipment.
9. The model should take into account rate effects, learning curves, and other quantity/volume related functions.
10. The model should be capable of converting from PWBS to SWBS and back.
11. The model should be able to measure the cost impacts of Alternative Manufacturing Processes.
12. The model should take into account acquisition strategy.
13. The model should be capable of performing budget quality cost estimates.

<u>Medium Rank</u>

14. The model should be integrated with CAD2.
15. The model should be sensitive to Sequence.
16. The model should be capable of performing rough-order-of magnitude cost estimates.
17. The model should be easy to use.
18. The model should estimate total Life Cycle Cost.
19. The model should be able to measure the cost impacts of varying standards and specifications.

<u>Low Rank</u>

20. The model should be able to measure the cost impacts of design choices affecting spatial density.
21. The model should be sensitive to overall industrial base.
22. The model should be sensitive to Facilities/Limitations and Constraints.
23. The schedule to complete development of the model is an important factor.
24. The model should be sensitive to the business base for specific yards.
25. The model should be evaluated on the development costs or cost to purchase a license agreement.
26. The model should be evaluated on the feasibility of acquiring sufficient cost and technical data to populate it and the cost to acquire the data.
27. The model should be sensitive to Laws and Regulations.
28. The model should be sensitive to Make/Buy choices.
29. The model should be capable of performing investment analysis.

PODAC Cost Model Concept Selection

The Navy's evaluation team found, after reviewing and ranking the six models and concepts, that none of the models met all the Navy's requirements. Thus developing a hybrid of the concepts was the best approach. The recommendations of the evaluation team were to:

Develop the PODAC Cost Model as a hybrid using features from the various concepts, which would include:

- an existing commercial model to minimize development time and provide a commercial user base to help support future improvements and maintenance of the model;
- the capability for early stage parametric costing with a top-down approach;
- an underlying cost database that supports a top-down approach;
- re-use modules for costing interim products; and
- a module to identify risk.

Establish an IPT to develop the PODAC Cost Model Specifications and the model itself. In addition to the chosen model developers, the team at a minimum should include a Navy design engineer, a Navy cost estimator, and representatives from each shipyard. This team should also develop the PODAC Cost Model System Specifications.

The conclusion of the evaluation team was that SPAR's model *ESTI-MATE*™ should be the starting point for the model, with John Dougherty of Designers & Planners, Inc. leading the development team and incorporating the concepts of the G/PWBS into the model.

PODAC Cost Model Development Plan Overview

Following the recommendations of the Navy evaluation team, an IPT was established to direct the effort of planning and developing a cost model which would have the capabilities discussed above. The team was selected to represent all of the diverse perspectives necessary for producing an effective and useful cost model for potential customers of the model, i.e., both Government and Industry personnel.

The IPT used Quality Functional Deployment to translate the Steering Committee's criteria into functional characteristics of a cost model. The team determined the model must have the following functions to address the Steering Committee criteria and meet the needs of the shipyards:

- Cost estimates must be organized in both system-based and production-based accounting schemes so that both early-stage system-based designs and later-stage production-based designs can be accommodated,
- Cost estimates for early-stage system based designs will be produced by drawing from an historical database containing Cost Estimating Relationships (CERs) which are empirically related to system-level parameters like steel weight or propulsion prime mover/power output,
- Cost estimates for later-stage production-based designs will be produced by drawing from an historical database containing CERs which are directly related to production-level parameters like weld length or pipe length,
- cost estimates will be accompanied by prediction uncertainty probability distributions based on comparison of historical estimates with actual costs expended,
- cost estimates will be capable of reflecting data transmitted directly to the cost model by ship designers using design synthesis models and computer-aided design tools.

In order to accomplish the above functions, the development of the model was then broken up into the following functional modules (see Figure 1):

- SPAR/ESTI-MATE Core Cost Model: baseline cost-estimating module to which enhancement modules were added,
- Design Tool Interface Module: provides a link between PODAC Cost Model and various computer-aided ship design tools,
- Return Cost Module: provides mechanism for electronically entering and storing return cost data,
- WBS Translation/Mapping Module: used to translate shipyard-unique cost data and historical Navy SWBS cost data into the Generic Product Work Breakdown Structure and back,
- Parametric Module: enables designers and estimators to develop reliable cost estimating relationships for ship design parameters available at the Concept, Preliminary, and Contract Design Stages.

THE PODAC COST MODEL

The PODAC Cost Model is designed to enable shipyards and the Navy for the first time to estimate cost by

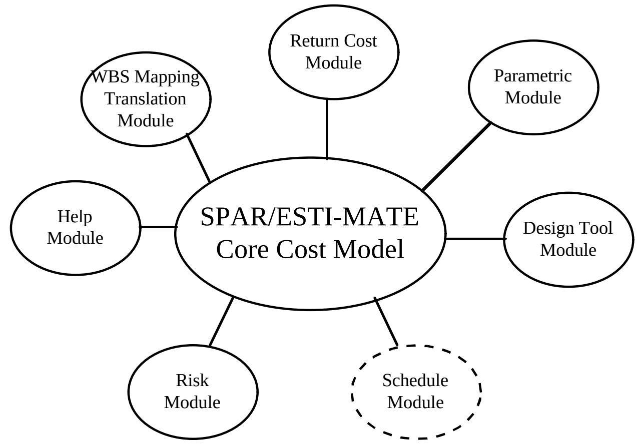


Figure 1. PODAC cost model development tasks.

analyzing the production-based return cost data collected in previous construction efforts. This data reflects the way ships are built using modern shipbuilding techniques and allows efficient analyses of man-hour expenditure rates that can lead to productivity improvements. These improvements can be achieved by upgrading facilities or changing inefficient processes.

Currently, new estimates are generated using a SWBS or SWBS-like system based accounting scheme because of the limited amount of design detail which is available to the estimators before a contract is actually awarded. However, once a contract has been signed, detailed design is performed and the production planners break up the construction of the ship using a production based work breakdown system to show what interim products will be produced where, when, and by what trades.

After work is performed, return costs are collected in the form of the yard's production-based system, not the system based structure for which the ship's cost estimate was developed. This creates an accounting disconnect between estimated and actual cost which has thus far prevented estimators from using production-based actual cost data to generate new ship estimates. The PODAC Cost Estimating Model knocks down the wall that isolates the estimating accounting scheme from the actual cost accounting, thus allowing the use of return cost data to generate new ship estimates. With the PODAC Cost Estimating Model new ship cost predictions can be made which reflect actual production-based data, thus improving the quality of the estimates and providing better information for reducing production costs earlier in the design stage.

The first two modules to be discussed, the Design Tool Interface Module and Return Cost Module are necessary for efficiently inputting the technical and return cost data needed in developing both detailed and empirical CERs for future ship or interim product estimates and design trade-off studies.

Design Tool Interface Module

The purpose of the Design Tool Interface Module is to provide a link between the PODAC Cost Estimating Model and various computer-aided ship design tools or product models. It is expected that these Product Models will soon hold all the cost and technical attributes associated with construction of a ship and its interim products.

The PODAC Cost Model is capable of importing technical data from design synthesis models such as the Navy's ASSET program, and from computer-aided design software like AutoCAD or Intergraph. In the future, this interface capability will allow ship designers to link directly with the PODAC CEM so they can quickly assess the cost impact of any design feature they may wish to consider.

Current capabilities that were demonstrated by the IPT were the importing of SWBS 3-digit weight estimates from the ASSET design synthesis model, as well as importing a Bill of Material directly from an AutoCAD drawing. The SWBS data can feed directly to the Parametric Module for formulating high level CERs. On the other hand, the Bill of Materials can be used for much more detailed estimating or trade-off studies. If a designer wanted to consider alternatives to a baseline configuration, the baseline drawing could be copied over, design changes made, the Bill of Material revised, and then the cost model would produce cost estimates for each of the alternatives, and feed the estimates back to the designer.

Return Cost Module

The purpose of the Return Cost Module is to provide a mechanism for electronically entering and storing return cost data in the form provided by individual shipyards as well as the capability to browse this data as entered or in the form of a Generic Product Work Breakdown Structure (G/PWBS).

The actual cost data collected at most shipyards is organized in a production-based accounting system, as shown in Tables I and II.

Table I shows a typical shipyard Work Order Record, the device used to plan the labor portion of a ship construction effort, and which establishes the data collection scheme for compiling actual labor costs.

Table II shows a typical shipyard Purchase Order, the device used to plan the material portion of a ship construction effort, and which establishes the data collection scheme for compiling actual material costs.

These two documents, the Work Order Record and the Purchase Order, collectively describe all the cost data collected for an actual cost report, so the PODAC CEM would ideally be able to accept all data elements in these two documents.

Collecting the data in the Work Orders and Purchase Orders for use in the PODAC Cost Estimating Model is straightforward. The Return Cost Module can be hooked to a shipyard's network to directly import Work Order Records and Purchase Orders. It would not be unusual for the number of Work Order Records and Purchase Orders for one ship to total more than twenty thousand. The time to input this data by hand would take hours. The PODAC Cost Model can be hooked up to a shipyard's network and import this data in a few minutes.

Because such data sometimes contains errors, there is additional work required to find and correct these errors in return cost files for existing ships. Working with thousands of data points at the Work Order and Purchase Order level is sometimes impractical. In order for this data to be more manageable and meaningful, the PODAC Cost Model uses the Translation/Mapping Module to aggregate the return cost at a more meaningful level.

WBS Mapping/Translation Module

The purpose of the WBS Mapping/Translation Module is to translate shipyard unique cost return and estimating data and historical Navy SWBS bid estimates and return cost data into one logical homogenous cost estimating database structure, the Generic Product Oriented Work Breakdown Structure as shown in Figure 2 [Reference 1], normalizing the data into a relevant format for further analysis. In addition to creating a homogenous database, the WBS Mapping/Translation Module also is used to overcome the obstacle of the organizational structure difference between estimated and actual costs.

The G/PWBS can help shipyards better identify their own cost drivers, and can provide them with a better basis to implement changes to their existing cost management systems if they see a benefit to do so. The G/PWBS is a well-organized, already-developed format that can work with their existing systems. The G/PWBS provides a way for a shipyard to better understand their own product-by-stage costs, especially if their existing cost management systems are not capable of providing good visibility.

<u>Shipyard PWBS-to-Generic PWBS Data Translation</u>

Because all shipyards use similar, but not identical, PWBS systems, it was necessary to develop a Generic PWBS capable of accommodating any shipyard's PWBS. The Translation/Mapping Module can map any yard's work breakdown structure to the three axes of the G/PWBS.

The first set of mappings is for the Product Structure axis. The PODAC Cost Estimating Model aggregates lower level return costs to zones (Figure 3), sub-zones (Figure 4), and blocks (Figure 5). The information to do this mapping is included on most shipyards' Work Order Records.

The translation of shipyard PWBS to G/PWBS provides the capability to import a ship set of work orders and populate the upper levels of the product structure as shown in Figure 6.

Work Order Records also provide the information necessary to map the shipyard's work type (Figure 7), stage of construction (Figure 8), and work center (Figure 9).

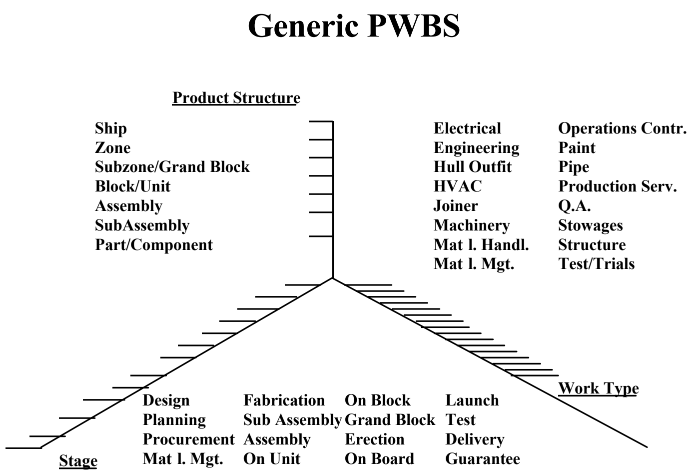


Figure 2. Generic Product-Oriented Work Breakdown Structure.

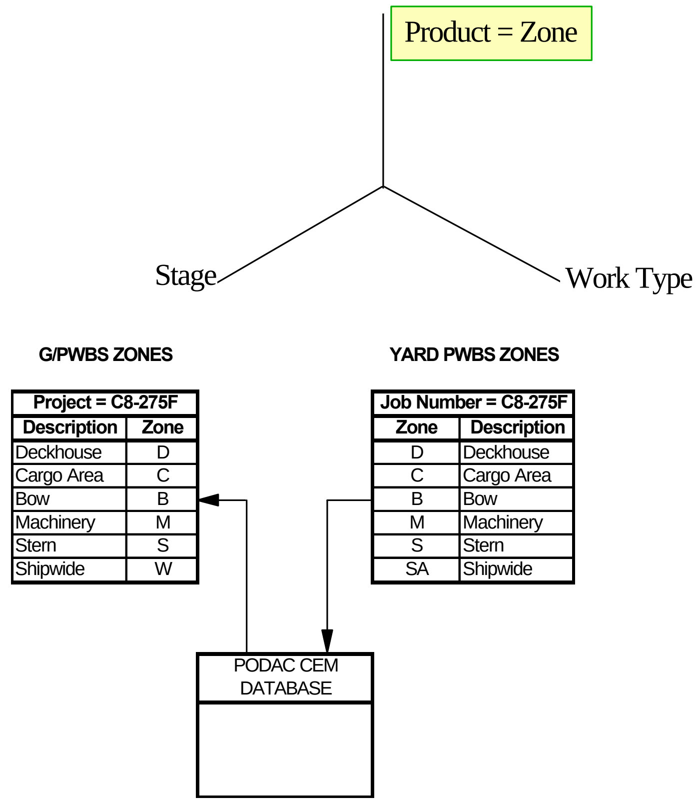


Figure 3. Mapping shipyard PWBS to G/PWBS, zone.

Ship	Cost Group	Wk Ord #	UoM	Qty	Zone	Unit	Est MH	Act MH	Pre MH	Tot MH	Work Cen	Plan Start	Act Start	Plan Comp	Act Comp
C150	xx F0 01	D6327	S	655	SW	0	24	25	0	25	907	7/8/91	7/12/91	9/31/91	10/2/91
C150	xx F0 02	D6144	S	950	SW	0	18	20	0	20	907	8/12/91	8/15/91	8/12/91	8/15/91
C150	xx F0 03	D6294	S	840	SW	0	20	17	0	17	907	7/18/91	7/12/91	7/18/91	7/12/91

Cost Groups	Description
xx 00 00	Engineering
xx F0 01	Manual burn/shear plates
xx F1 02	Machine burn/shear plates
xx F1 03	Roll and heat plates
xx F0 07	Blacksmith shop forming
xx F0 08	Pipe shop forming

Unit of Measure
T = ton
P = pound
L = linear foot
S = square foot
K = compartment

Zone
SW = shipwide
C = cargo
B = bow
M = machinery
S = stern

Unit
0 = not used
101 = ...
210 = ...
320 = ...

Man-hours
Estimated
Actual
Premium
Total

Work Centers
1 = Platen 1
2 = Platen 2
68 = Sheet Metal Shop
75 = Machine Shop
83 = Electrical Shop
907 = Plate Shop

Table I. Typical shipyard work order records.

Ship	Cost Group	Purch Ord #	UoM	Qty	Est $	Act $	Plan Arriv	Act Arriv
C150	xx F0 01	G4545	ea	20	7,000	9,500	7/8/91	7/12/91
C150	xx F0 02	H6898	T	950	12,500	10,800	8/12/91	8/15/91
C150	xx F0 03	M3095	S	840	25,700	24,600	7/18/91	7/12/91

Cost Groups	Description
xx 00 00	Engineering
xx F0 01	Manual burn/shear plates
xx F1 02	Machine burn/shear plates
xx F1 03	Roll and heat plates
xx F0 07	Blacksmith shop forming
xx F0 08	Pipe shop forming

Unit of Measure
T = ton
P = pound
L = linear foot
S = square foot
ea = each

Table II. Typical shipyard purchase order records.

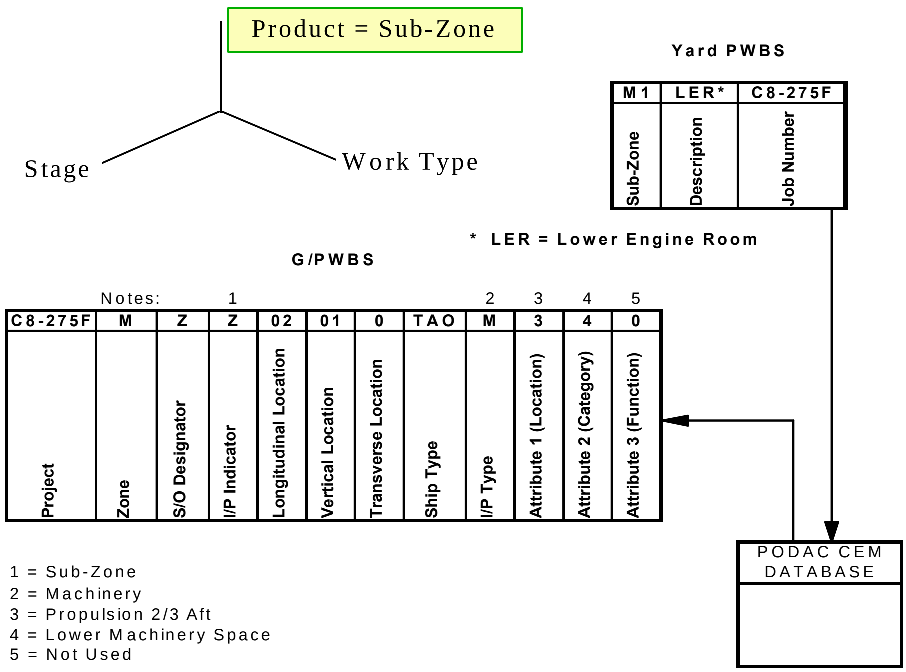


Figure 4. Mapping shipyard PWBS to G/PWBS, sub-zone.

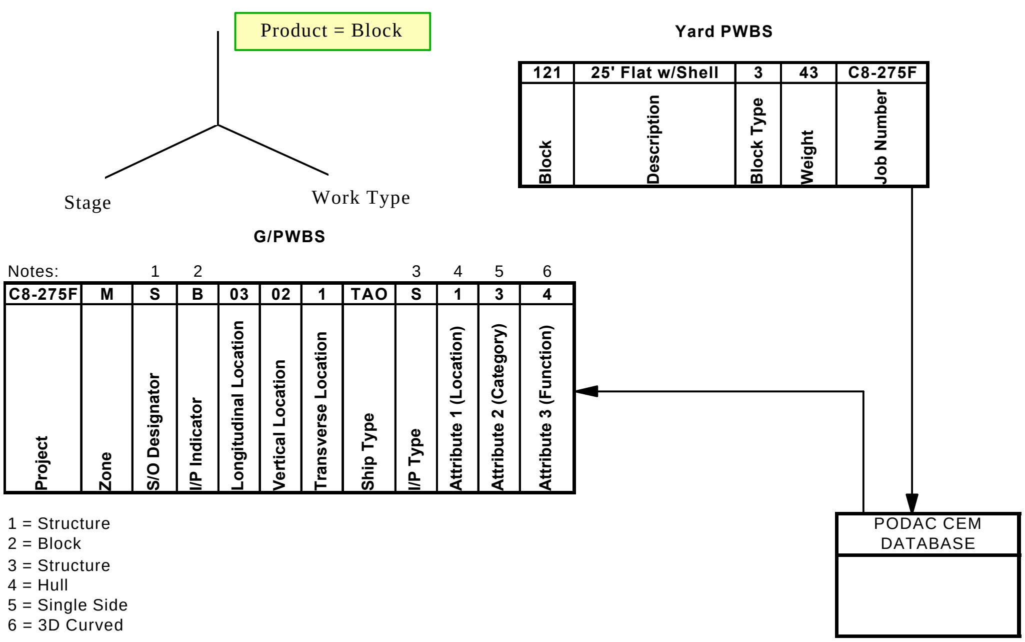


Figure 5. Mapping shipyard PWBS to G/PWBS, block.

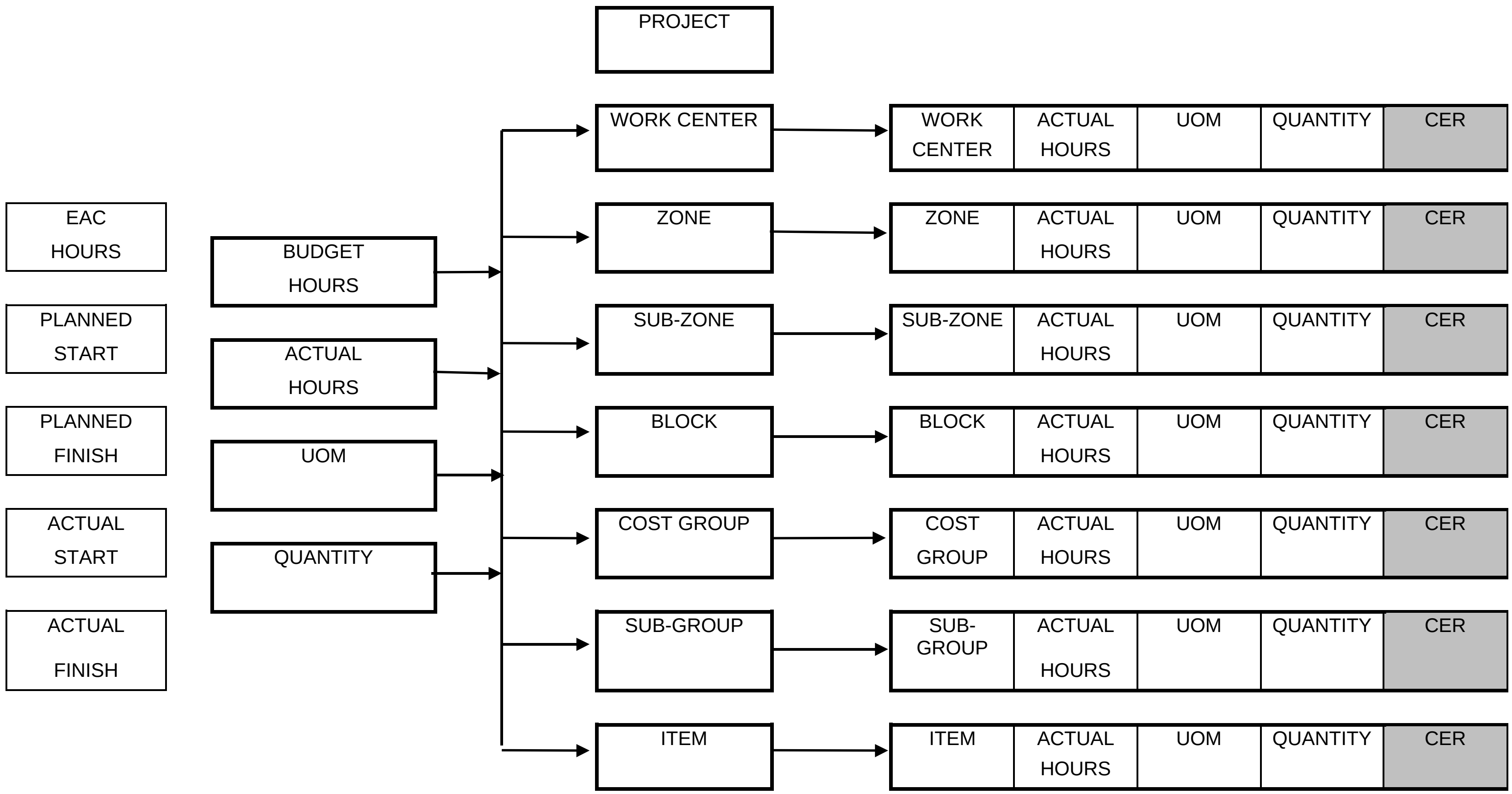
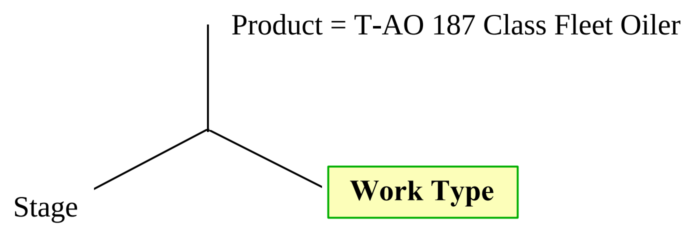
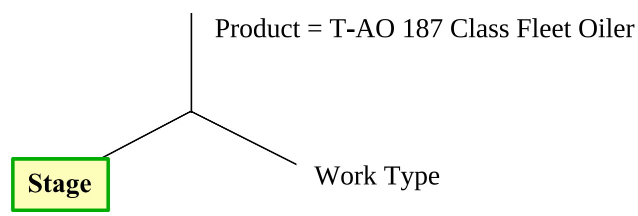


Figure 6. Populating upper levels of cost structure with an imported shipset of work orders.



G/PWBS Work Type	Shipyard Cost Code	Description
EG	xx	Engineering
HU	xx	Hull
SU	xx	Superstructure
JC	xx	Joiner
PI	xx	Piping
MC	xx	Machinery
EL	xx	Electrical
SM	xx	Sheetmetal
CY	xx	Carpentry
...	...	...
PD	xx	PDA & Delivery

Figure 7. Mapping work types.



G/PWBS Stage	Shipyard Stage	Description
FB	01	Fabrication
OU	02	Assembly (On-Block)
OO	03	On-Board
TT	07	Air & Hydro Tank/Compartment Test
AS/ER *	77	Rework
PU	98	Fixed Price Subcontractors
FB	F0	Pre-fabrication - Fit
SA	F1	Fabrication - Fit
AS	F2	Fabrication - Weld
ER	F3	Assembly - Fit / (On Unit)
AS/ER	F4	Assembly - Weld / (On Unit)
SA	W1	Erection - Fit / (On Board)
AS	W2	Erection - Weld / (On Board)
ER	W3	Miscellaneous - Fit
AS/ER	W4	Miscellaneous - Weld

* Pro-rated between Assembly and Erection

Figure 8. Mapping stages.

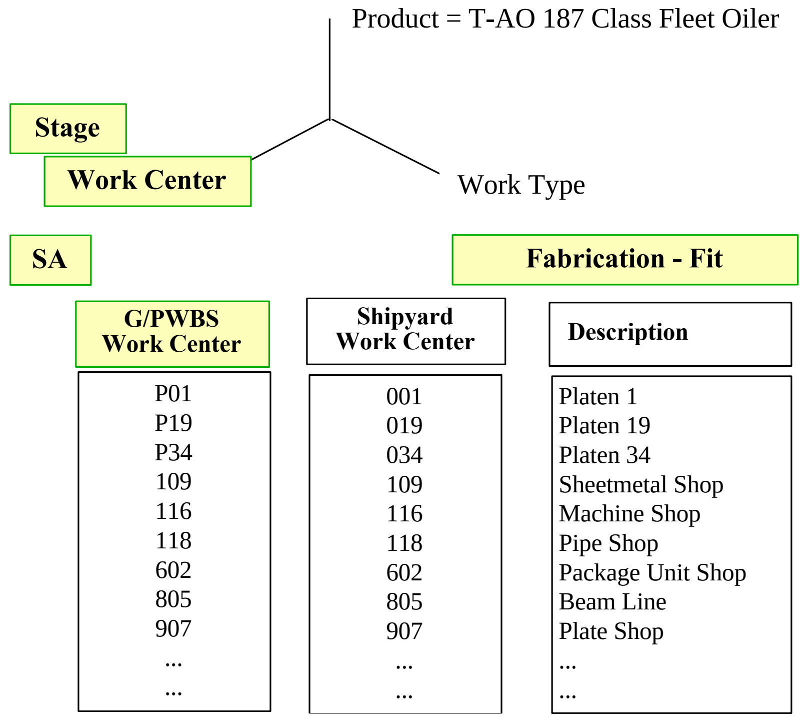


Figure 9. Mapping work centers.

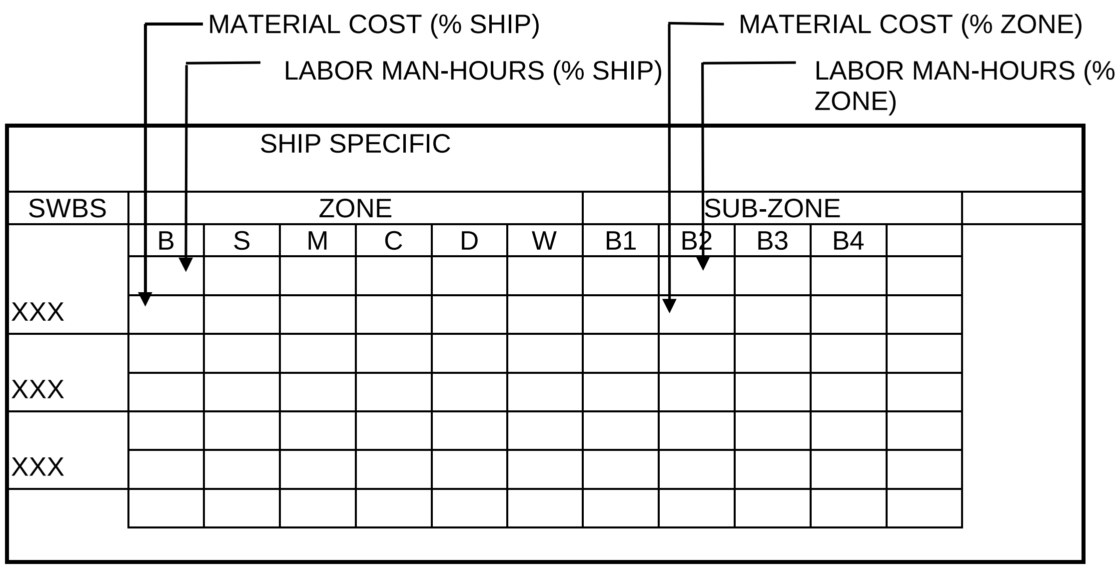


Figure 10. PWBS to SWBS translation template.

<u>G/PWBS to SWBS Data Translation</u>

The translation from the Shipyard PWBS to the Generic PWBS is straightforward and each element of one scheme maps directly to one element of the other. However, for translating from the Generic PWBS to a system-based accounting scheme like SWBS, a unique set of templates must be developed for each ship type under consideration. Extensive judgment is required to allocate numerous portions of a PWBS data set to a single SWBS account. Developing a set of templates could be termed a major operation. It involves a careful analysis of the drawings and weight report which define a particular ship design, and allocating portions of the ship's cost elements, as organized by PWBS, to their SWBS counterparts. Without the ability to translate data from one organizational scheme to the other, the utility of the PODAC Cost Estimating Model would be greatly reduced.

Figure 10 shows a typical translation template. These templates would be used to translate from PWBS to SWBS, but once they are defined, they can be used inversely for translating SWBS data to PWBS as well.

Parametric Module

The Parametric Module enables designers and estimators to develop reliable cost estimating relationships for ship design parameters available at the Concept, Preliminary, and Contract Design Stages. The Parametric Module provides the mechanism for entering the parameters available at the various design levels for specified ship types, and their associated costs.

The PODAC Cost Model uses two types of CERs:

- Empirical CERs, which relate cost to system-level parameters like structural weight and propulsion prime mover/power output, or cost relationships for higher level interim products such as blocks or zones.
- Direct CERs, which relate cost to production-based parameters like weld length and pipe length.

<u>Empirical CERs</u>

The purpose of Empirical CERs (ECERs) is to provide a parametric approach for estimating construction costs at the various stages of design. ECERs will permit new ship cost predictions long before detailed information becomes available for directly translating actual production parameters into cost. The Parametric Module is structured to use a statistical analysis that carefully considers factors like ship type, complexity, and basic ship characteristics such as displacement, speed, individual system weights, hullform, and associated ship costs, so new ship cost predictions can be correlated empirically to those parameters. The concept of the Parametric Module is to develop forms of equations by which the user could either tailor the equations or automatically update their coefficients with actual return costs that have been imported into the database.

The IPT received assistance from the statistical department at UMTRI to develop the SWBS-based Empirical CERs. These ECERs were developed using a limited database of both Navy and commercial vessels which included ships of all types from 36-ft workboats to 265,000 DWT tankers. It was found that for the same ship type, many of the proposed parameters are dependent on each other. For example, steel weight is dependent on length, beam, depth, draft, and speed. The dependencies of various ship characteristics or parameters were determined by limiting the required number of variables within the equations Next, the data points were plotted to find the best form of the equations. For each stage of construction (concept, preliminary, and contract) linear and non-linear regressions were performed to derive ECERs for a variety of parameter combinations and forms of equations. The equations with least error were selected as the recommended ECERs.

At the concept level, the price of the total ship is a function of displacement (DISPL), speed, and a complexity factor (CF): $\text{PRICE} = \text{CF} \times \text{A} \times \text{DISPL}^{b} \times \text{SPEED}^{c}$.

Values for the coefficient A and exponents b and c would be determined by applying this equation form in a regression analysis of a user's database of return costs.

Because the cost data available to the IPT was for various ship types, it was necessary to use a Complexity Factor to normalize the data and achieve better equations. The use of Complexity Factors is not unique to the PODAC Cost Model. Complexity Factors are used in other models such as the NASA Cost Estimating Model and Lockheed Martin's hardware cost model, PRICE H. The Complexity Factor the IPT used is derived from a Size Factor and Ship Type Factor; Size Factor is $32.47 \times \text{DISPL}^{-0.3792}$. The OECD coefficients for Compensated Gross Tons were used for both the ship type and the ship size factors. Table III lists ship type factors for ships ranging from crude oil tankers to Navy Combatants. There was no OECD data for Navy ships, so the available costs of these ships were fitted to a curve with the rest of the ships, and new factors were derived.

SHIP TYPE	TYPE FACTOR
Crude Oil Tanker	0.80
Product Tanker	1.13
Chemical Tanker	1.25
Double Hull Tanker	0.90
Bulk Carrier	0.86
Oil/Bulk/Ore Carrier	0.95
Containership	0.96
Roll-On/Roll-Off	0.83
Car Carrier	0.61
Ferry	1.25
Passenger Ship	3.00
Fishing Boat	2.20
Tug	0.80
Combatant - Cruiser (Nuclear)	9.00
Combatant - Destroyer	8.00
Combatant - Frigate	7.00
Amphibious - LHA/LHD	7.00
Amphibious - LSD/LPD	5.00
Auxiliary - Oiler	2.25
Auxiliary - Tender	4.50
Naval Research	1.25
Naval Tug, Oceangoing	1.00
Coast Guard Icebreaker	4.50
Coast Guard Buoytender	2.00

Table III. Ship type factors for the PODAC Cost Model Parametric Module.

SWBS	LABOR MAN-HOURS	MATERIAL DOLLARS
100	$CF \times 177 \times Weight_{100}^{0.862}$	$800 \times Weight_{100}$
200	$CF \times 365 \times Weight_{200}^{0.704}$	$15{,}000 + 20{,}000 \times Weight_{200}$
300	$682 \times Weight_{300}^{01.025}$	$25{,}000 \times Weight_{300}$
400	$1{,}605 \times Weight_{400}^{0.795}$	$40{,}000 \times Weight_{400}$
500	$CF \times 34.8 \times Weight_{500}^{1.24}$	$10{,}000 + 10{,}000 \times Weight_{500}$
600	$310 \times Weight_{600}^{0.949}$	$5{,}000 + 10{,}000 \times Weight_{600}$

Table IV. Typical preliminary design stage equations for the Parametric Module.

SHIP TYPE	PD-337
DISPLACEMENT	45,900 TONS
SPEED	20.2 KTS
SHIP TYPE FACTOR	0.83
COMPLEXITY FACTOR	0.4571
HULL WEIGHT	9,650 TONS
MACHINERY WEIGHT	1,400 TONS
ELECTRICAL WEIGHT	335 TONS
C & C WEIGHT	50 TONS
AUXILIARY WEIGHT	1,305 TONS
OUTFIT & FURN WEIGHT	1,960 TONS
LABOR RATE	$15/MH
LABOR OVERHEAD RATE	100%
MATERIAL OVERHEAD RATE	2%
PROFIT	10%

Table V. Sample preliminary design stage data input to the Parametric Module.

ITEM	WEIGHT	MAN-HOURS	MATERIAL $
HULL	9,650	220,114	$ 7,720,000
MACHINERY	1,400	27,364	28,015,000
ELECTRICAL	335	264,214	8,375,000
C & C WEIGHT	50	35,988	2,000,000
AUXILIARY	1,305	116,131	13,060,000
OUTFIT & FURN	1,960	412,774	19,605,000
LABOR TOTAL (man-hours)		1,076,584	
LABOR RATE		$15 / MH	
DIRECT COSTS		$16,148,760	$78,775,000
INDIRECT COSTS		$16,148,760	$ 1,575,500
PROFIT	$ 3,229,752	$ 8,035,050	
TOTAL PRICE		**$123,912,822**	

Table VI. Sample preliminary design cost estimate for a 45,900 ton RO/RO.

The same approach was used to derive SWBS-based ECERs for the preliminary and contract design stages. At these stages the information is likely to be available to estimate labor and material costs for all the SWBS groups. Table IV shows what the equations might look like at the one-digit SWBS level. These ECERs should not actually be used for estimates, but the different users of the PODAC Cost Model should use the forms of these ECERs along with their own cost data to develop their own solutions for these equations.

Using ECERs, the Navy or shipyards should be able to perform cost estimates in very little time with a minimum amount of data input. For example, at the concept stage, a customer might want to estimate the cost of a 45,900 ton RO/RO with a speed of 20.2 knots. A shipyard which has populated the PODAC Cost Model with their cost history could develop an estimate in a matter of minutes.

Many bids are prepared at the preliminary design stage, at which time more detailed information is available. To estimate the same RO/RO at the preliminary design stage, the information shown in Table V is typical input. Using this input and the sample equations shown earlier, an estimated price of $124 million is calculated, comprised of man-hour and material estimates as shown in Table VI.

The actual estimated cost for this ship depends on the ECERs developed using return cost from a user's specific database. In addition to using the PODAC Cost Model to tailor the ECERs, rather than using the OECD factors, a shipyard may wish to also develop their own complexity factors based on the various ship types produced in their yard.

<u>Product-Oriented ECERs</u>

The current version of the PODAC Cost Model includes only SWBS-based ECERs. However, the full capability of the PODAC Cost Model cannot be achieved without the development and use of ECERs for Interim Products. The IPT is currently working on developing such ECERs.

The Translation Module makes it possible to roll up return costs from the lowest level collected by a shipyard to determine the cost and cost drivers of higher level interim products, as shown in Figure 9. A shipyard can now use the PODAC Cost Model to develop their own ECERs for Interim Products. The IPT hopes to work with the shipyards this year to determine the forms of these process driven product-oriented equations.

<u>Direct CERs</u>

Direct CERs are production-based equations, in contrast to the product based equations of the Empirical CERs. A direct CER might be in the form of linear feet per hour for assembling and fitting, or square feet per hour for painting. Direct CERs are derived from one of three sources:

- from a single selected ship in the database (Calculated),
- from a set of selected ships in the database (Predictive), or
- manual input from the user (Manual).

Calculated CERs are derived directly from return costs from one ship in the database. Predictive CERs are developed using averaging or linear regression of Calculated CERs from a set of selected ships in the database to get a single equation. It is also possible to manually input CERs based on an individual user's assumptions, such as decreasing the Predictive CER by 20% due to an anticipated improvement in a shipyard's production process.

Risk Module

The purpose of the Risk Module is to provide an indication of the cost estimate uncertainty for a given ship design, a given shipyard, and a given construction schedule. The Risk Module is still evolving, but at the most fundamental level should include a cost prediction and a confidence level and probability distribution about the prediction. Currently the Risk Module uses an off-the-shelf statistical package to derive a shipyard's risk for meeting an estimate.

Traditionally, cost estimates have been point estimates which provide no information about probability of occurrence, or potential variance. Historical cost estimates and return cost data can be used to help assess the potential variance, or risk, of a new point estimate. Risk is usually defined as the square root of variance, or the standard deviation. With the PODAC Cost Model, a user can perform statistical analysis comparing historical cost estimates with actual cost returns to derive a probability distribution for a specific shipyard. This distribution can then be applied to a predicted cost to assess the uncertainty of the cost estimate.

The following example shows how the Risk Module works using an estimate for an interim product such as a block. Assuming that the model database has information on twelve similar type blocks, one would first compare the estimates and actual costs for these twelve blocks (VII).

If the PODAC Cost Model predicted a new point estimate of 2,030 man-hours for the block, then the Expected Actual Cost would be 2,010. This is derived using the following formulas:

$$\text{Expected Actual Cost} = (1 + \text{Mean}) \times \text{Estimate} \quad (1)$$

$$\text{Expected Actual Cost} = (1 - .01) \times 2{,}030 = 2{,}010 \quad (2)$$

There is a 50% probability that the Expected Actual Cost will be equal to or less than the derived value of 2,010 man-hours. Shipyard management may consider that it is too much of a risk to rely on this estimate and would prefer a higher degree of certainty around the estimate. The Risk Module employs an off-the-shelf statistical package, @Risk to derive the maximum estimates for different levels of risk. The data from Table VII can now be applied to derive a bell-shaped distribution profile.

Analysis of Historical Costs vs Estimates
(Labor Cost in Man-hours)

Block	Estimated Cost	Returned Cost	%Variance
1	2,975	2,903	-2.40%
2	2,888	2,808	-2.80%
3	2,755	2,763	0.30%
4	2,804	2,792	-0.40%
5	2,765	2,730	-1.30%
6	2,540	2,597	2.20%
7	2,523	2,586	2.50%
8	2,477	2,465	-0.50%
9	2,355	2,307	-2.00%
10	2,300	2,265	-1.50%
11	2,200	2,154	-2.10%
12	2,120	2,042	-3.70%
		Average Variance	-1.00%
		Standard Deviation	1.90%
		Maximum	2.50%
		Minimum	-3.70%

Table VII. Typical interim product block estimates versus actual costs

The program then performs Monte Carlo simulations to produce a range of certainty for the block estimate (Table VIII). The shipyard now has a better idea of which estimate they are comfortable going forward with based on the amount of risk they are willing to accept. Using a conservative range of 90% certainty, the estimate for the block would be 2,060 man-hours.

Schedule Module

Work will begin this year in developing this module to provide the Navy and shipbuilders with the ability to determine the lowest cost schedule. The Schedule Module will also aid in assessing the impact on cost of changes in construction schedule, sequence, and duration of shipbuilding activities. It is intended that the Schedule Module will be capable of importing schedule data from the shipyard's scheduling system. The Schedule Module itself may be a separate model such as a computer model with derived relationships or a simulation of the ship design and production process to develop relationships.

Analysis of New Estimate Based on Historic Performance to Estimate

New Block Estimate 2,030 man-hours

Percent Certainty	Cost Below
5.0	1,947
10.0	1,961
20.0	1,978
30.0	1,990
40.0	2,000
50.0	2,010
60.0	2,020
70.0	2,031
80.0	2,043
90.0	2,060
95.0	2,074
99.0	2,100
99.5	2,110

Table VIII. Range of Certainty for a Block Estimate

PODAC COST MODEL CAPABILITIES

A very powerful cost tool has been developed by integrating all the functions of the PODAC Cost Model. The PODAC Cost Model in its current state provides the following capabilities and benefits:

- Estimates ship cost based on how the ships are built;
- Estimates by product, process, and/or system;
- Electronically imports, aggregates, and stores return cost data;
- Automatically updates cost estimating relationships with this return cost data;
- Provides multiple views of costs by products or processes;
- Reduces the time and increases the accuracy of developing estimates for bids and production planning;
- Identifies cost drivers and their impacts so that designers can design ships which are easier and less costly to build; and
- Provides meaningful information for production process improvement.

FUTURE WORK

The PODAC Cost Model to date has focused on the design and production of ships. However, since the inception of this project, the Navy's emphasis has shifted from almost solely decreasing ship production costs to determining how to work with the shipyards to decrease overall Life Cycle Costs. The need has been identified for a model or set of models which can slice up the costs of a total ship program in many different ways to perform total life cycle trade-off analysis as well as provide multiple views (Figure 11) for other decisions.

The PODAC Cost Model IPT is researching existing efforts for developing Life Cycle Cost Models and hopes to integrate with these efforts.

In the near future, the PODAC IPT will be teaming with shipyards to evaluate and further refine the model. Empirical CER forms will be determined for interim products and the schedule and risk modules will be further developed. With the Navy and shipbuilding industry working together to make these improvements, the PODAC cost model will become an invaluable analysis tool in current and future acquisitions where shipbuilders will be involved in design development much earlier, and where more teaming among the shipbuilding and supporting industries may occur.

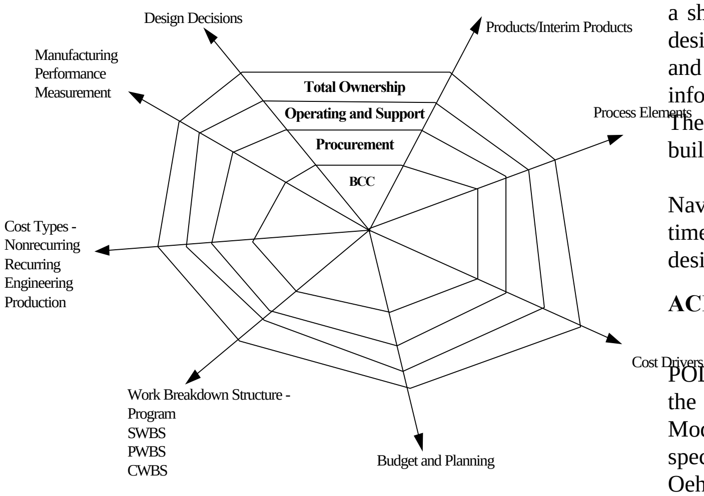


Figure 11. Multiple views of cost.

CONCLUSIONS

The PODAC Cost Model is much more than simply an estimating tool. The PODAC Cost Model stores and provides the information necessary for improving both the design and production of ships. Through use of the G/PWBS, the PODAC Cost model provides both a product view and a process view (Figure 12).

The product view provides information necessary for Navy and shipyard budgeting, planning, make-buy, and capital investment decisions. Knowing the cost of interim products helps the shipyards determine their most profitable product mix and teaming arrangements with other yards, vendors, and subcontractors. The product view is also applicable for bid preparation and evaluation, as well as for conducting ship performance trade-off studies.

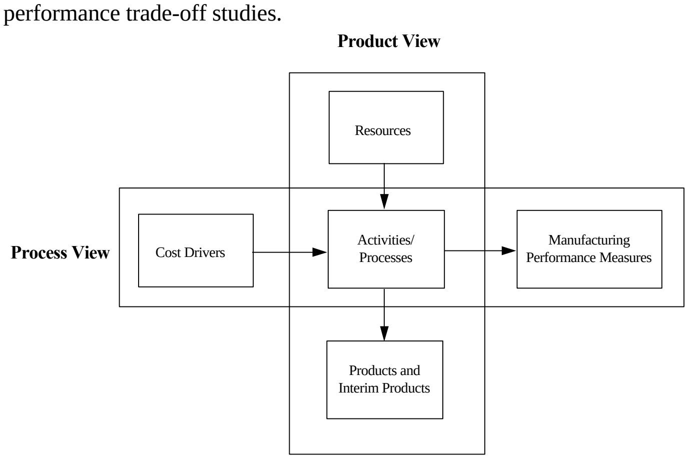


Figure 12. Product and process orientation of the PODAC Cost Model.

The process view is key for continuous improvement within both design and production. Understanding what the cost drivers are and how they affect the manufacturability and eventual cost of a ship or its products will help naval architects and designers to design more producible ships. The identification of cost drivers and performance measures provide the shipyards with the information necessary to perform process improvement studies. The ultimate application of the process view is to optimize the build strategy.

The product and process views together will enhance the Navy's and industy's ability to work together to provide accurate, timely, and meaningul cost feedback from cost analysts to ship designers and from production to design.

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