Relating Cost to Performance:

The Performance-Based Cost Model

Michael Jeffers
Anna Irvine
Robert Jones
Robert Nehring
Jean-Ali Tavassoli
Kelly Meyers

Technomics
The Science of Informed Decision Making

NAVSEA
WARFARE CENTERS
Carderock

International Cost Estimating & Analysis Association

2014 Professional Development and Training Workshop

June 10-13, 2014

Distribution A: Approved for Public Release; Distribution Unlimited.

ABSTRACT

For decades, in order to produce a cost estimate, estimators have been heavily reliant on the technical characteristics of a system, such as weight for hardware elements or source lines of code for software elements, as specified by designers and engineers. Quite often, a question will arise about the cost of adding additional performance requirements to a system design, or in a design-to-cost scenario, the savings to be achieved by removing requirements. Traditionally, the engineers will then have to undertake a design cycle to determine how the shift in requirements will change the system. The resultant technical outputs are finally given to the cost estimators, who will run them through their cost model to arrive at the cost impact. However, what if a single model could estimate the cost from the performance of the system alone? A Performance Based Cost Model (PBCM) can do just that.

First introduced in 1996, a PBCM is an early-stage rough-order-of-magnitude (ROM) cost estimating tool that is focused on relating cost to performance factors. PBCMs are parametric cost models that are integrated with a parametric engineering model so that they estimate cost as a function of performance by simultaneously estimating major physical characteristics. They are derived from historical data and engineering principles, consistent with experience. PBCMs are quick, flexible, and easy to use and have proven to be a valuable supplement to standard, detailed concept design and costing methods.

This paper will explain essential PBCM concepts, including:

- A discussion of the interplay of capabilities, effectiveness, performance characteristics, and cost.
- How to identify the most meaningful cost drivers (i.e., performance characteristics, technology factors, and market conditions).
- How to identify the most meaningful output variables (i.e., those variables of prime interest to the PBCM user).
- How to create the mathematical structure that integrates cost drivers with cost and physical characteristics.
- How to obtain and normalize historical performance data, cost data, and technical data (physical characteristics).
- How to generate cost and physical characteristic equations.
- How to implement a PBCM.
- How to use a PBCM.

TABLE OF CONTENTS

INTRODUCTION

The need and desire for decision makers to effectively balance required capabilities with affordable resource requirements (costs) is longstanding. It has long been understood that decisions in the earliest phases of programs have the greatest influence on eventual program cost. However, it is also well understood in the cost community that early stage cost estimating is particularly difficult and uncertain. Standard cost estimating methods typically require descriptive and quantitative information about the system in question. In the earliest phases of programs this basic information is minimal, if it exists at all. Thus, standard methods are simply not applicable prior to some level of concept definition.

In practice, for most programs the first meaningful cost estimates are produced during an Analysis of Alternatives (AoA). Within an AoA, the cost estimates are developed relatively late since they are produced as one of the last steps in a serial process: Requirements and Concepts of Operations (CONOPS) → Alternative Concepts → Concept Designs → Cost Estimates → Cost vs. Capability Assessment. This process is usually intended to iterate, but, in practice, the number of iterations is limited by schedule, resource constraints, and the significant effort required, using standard methods, to produce and adequately vet both the concept designs and the cost estimates. Not infrequently, the result is a limited exploration of the capability-versus-cost trade space, and availability of a meaningful assessment of affordability only at the end of the AoA process. Such a result can leave decision makers with insufficient information for making an optimal concept decision or, worse, present a set of alternatives all of which are deemed to be unaffordable. The final stage of an AoA is too late in the process to discover that the specified requirements are unaffordable or that the trade space has not been adequately explored. The need remains to perform meaningful cost assessments earlier in the process and to cover a wider range of options. To address this need requires methods and tools that are more agile and less demanding, in terms of required level of concept definition, than the standard methods and tools. The authors believe that Performance Based Cost Models (PBCMs) satisfy this requirement.

Before proceeding further a description of what this paper means by "performance based cost model" is needed. Obviously, a PBCM is intended to relate cost to performance. Performance relates to observable measures of what the system can do, for example, things like speed, range, weapons capacity, etc. However, in order to relate cost to performance at a sufficient level of detail and accuracy, the PBCM also relates the principal physical characteristics of a concept (weights, materials, power, etc.) to performance characteristics and uses both physical and performance characteristics to drive cost. Therefore, simply stated, a PBCM is a parametric cost model in combination with a parametric engineering or technical model that simultaneously estimates (1) major physical characteristics and (2) cost for the concept as functions of major performance and other specified factors.

The remainder of this paper provides an overview of the PBCM concept. It briefly lays out a basic mathematical structure by which cost, system physical characteristics, and performance are related, and goes on to describe the relationships that could be derived and implemented in a model, explaining the details of its implementation in Microsoft Excel.

The concepts outlined in this paper can be applied to any type of system, for instance, any of the systems defined in the Department of Defense Standard: Work Breakdown Structures for Material Defense Items (MIL-STD-881C). For consistency, throughout the remainder of this paper, Sea Systems will be used as the basis for discussion.

CAPABILITIES, EFFECTIVENESS, PERFORMANCE CHARACTERISTICS, AND COST

Major defense programs initially come into being to provide the warfighters with "the capabilities required to successfully execute the missions assigned to them." The degree to which missions can be successfully executed is called "effectiveness." The requirements process is the starting point for any major program; normally, it emphasizes required capabilities, but also explicitly states an objective to meet the stated needs at an affordable cost. Thus, from the very beginning there is a tension – capability and effectiveness vs. affordable cost – that requires a balanced resolution in order to achieve, eventually, a satisfactory outcome. In general, cost analysts do not directly estimate the cost of capabilities or effectiveness; rather, they normally estimate the cost of systems based on their physical attributes and other factors. Therefore, it is a challenge to develop clear relationships between cost and capabilities-effectiveness to support well-informed decisions about the appropriate balance.

A necessary step in developing cost methods and models that address this problem is to lay out the overall structure of the relationship and driving factors. Figure 1 illustrates the top-level relationships.

- *Operational effectiveness*, consisting of capabilities that support desired results, drives the system performance factors that enable the capabilities. These relationships are the primary focus of the Joint Capabilities Integration and Development System (JCIDS) requirements process.
- *System performance* – the observable things that the system can do – drive the physical makeup of the system – the components, sizes, materials, technology, etc. required to produce the specified performance. These relationships are the focus of systems engineering and design.
- *System physical characteristics* and associated technology drive system cost. These relationships brings the analysis into a more familiar territory for cost analysis.
- *Programmatic and economic factors* – quantities, schedule, labor rates, inflation, etc. – also drive system cost. These relationships are the focus of the industrial analysis sector of cost analysis, again familiar and important territory for cost analysts but frequently outside of the normal focus of requirements analysis and systems engineering.

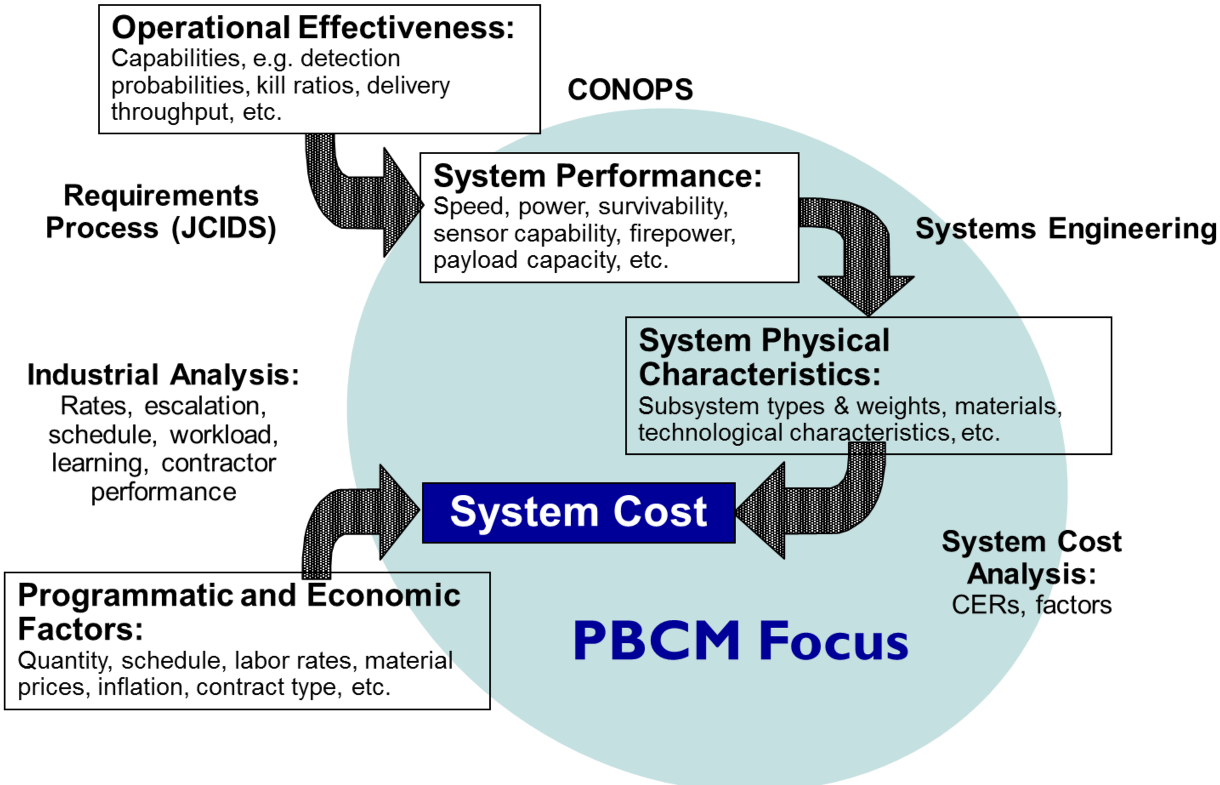

Figure 1: Effectiveness-Cost Relationships.

It is apparent that understanding the balance required to achieve effective capabilities at affordable cost is, at its simplest, a relatively complex undertaking involving four distinct disciplines: requirements-effectiveness analysis, systems engineering and design, system cost analysis, and economic/industrial analysis. Requirements and effectiveness analysis explore and quantify the relationships between effectiveness, required capabilities, and the performance attributes that support the capabilities. These analyses can be done, and often are done, “physics free,” that is, without reference to specific physical characteristics of systems. Thus, they do not have the existence of concept designs as a prerequisite for meaningful analysis.

Cost estimates, however, depend on some level of system definition. Even if cost could be related to effectiveness or performance through some form of direct parametric relationship, the “physics” of the relationship would be implicit and embedded in the process. A benefit of the PBCM approach is that it makes explicit the relationships between performance and physical characteristics as part of the process of relating performance to cost. Thus, the focus of a PBCM is a unified parametric approach to systems engineering…the relationship between performance and physical characteristics…and system cost analysis…the relationship between physical characteristics and cost. These cost relationships must be conditioned on reasonable, but explicitly stated assumptions on economic and industrial factors. Through this approach, performance can be used to establish the critical link between capabilities, effectiveness, and cost. The underlying hypothesis is that meaningful and sufficiently accurate quantitative relationships can be derived to support early stage tradeoffs for systems of interest.

MATHEMATICAL STRUCTURE OF PBCMS

In order to serve as a basis for a quantifiable model, the relationships described in Figure 1 above must be stated in mathematical form. At the most general level, the functional relationships between cost and effectiveness can be stated very simply:

Total cost (*TC*) of N units of a system with average unit cost C_u is

$$TC = N \cdot C_u$$

Nominal average unit cost of the system is a function of performance, physical characteristics (weights, etc.), technology, and economic and programmatic factors:

$$C_u = F(P, W, t, \varepsilon(N))$$

where

P is a vector of performance characteristics

W is a vector of system physical characteristics (e.g., weights)

t is a vector of technology characteristics

ε is a vector of economic and programmatic factors and may depend upon N

System effectiveness, represented by "measures of effectiveness," denoted MOE, is a function of system performance, numbers of systems, jointly operating systems if any, and the characteristics of the threat:

$$MOE = E(P,N,J,\Theta)$$

where

J is a vector of jointly operating systems

Θ is a vector of threat characteristics

In this simple mathematical structure it can clearly be seen that performance, P, is an argument in both cost and effectiveness functions and therefore is a critical link between the two. Similarly, number of systems, N, impacts effectiveness, unit cost through economic-programmatic factors (e.g., learning curve), and total cost directly.

Now, more closely consider the unit cost equation:

$$C_u = F(P, W, t, \varepsilon(N))$$

This form is too general to be useful as the underlying basis for a quantitative model. Additional structure, in the form of assumptions about appropriate functional forms, is needed.

Start by assuming that the economic and programmatic effects represented by ε are not intertwined in any important way with the other driving variables. This situation is called mathematical separability and it allows the relationship to be re-written, dropping the N as an explicit argument in ε for simplicity, as:

$$C_u = F(P, W, t, \varepsilon(N)) = h(\varepsilon) \cdot f(P, W, t)$$

Under this form, the impact of economic and programmatic factors, represented by the function $h(\varepsilon)$, can be analyzed separately and used to adjust a simpler cost function, $f(P, W, t)$, that focuses on costs driven by the engineering aspects of the system, performance, weights and other physical characteristics and technology. Consider this simpler function:

$$c_{nom} = f(P, W, t)$$

where the change to lower case c_{nom} denotes that this is not the same cost as in the previous equation. Lower case c_{nom} is best understood as the cost normalized to some static nominal economic and programmatic conditions, ε_0, consisting of, say, position on the learning curve, specific year of escalation and rates, specific acquisition strategy, manufacturing participation and industrial base conditions, etc. The function $h(\varepsilon)$ then should be understood as adjusting for economic and programmatic factors relative to the normalized conditions represented by ε_0.[1]

The expression above for normalized cost, c_{nom}, remains very general and abstract. Additional structure can be imposed by assuming that the function $f(P, W, t)$ is further separable as follows. Let

$$c_{nom} = f(P, W, t) = A(P, t, W) \cdot W(P, t)$$

This construct begins to assume the character of a typical cost model. Normalized cost is driven by a multiplicative cost factor (cost per pound, etc.), which is also driven by performance and technology, but potentially also by size in the case of scale effects. In addition, the normalized cost is driven by physical characteristics (weights and other), which are driven by performance factors and technology.

COST ESTIMATING EQUATIONS

One more step is required to get to a potentially quantifiable structure. Complex systems are made up of a number of subsystems; the underlying descriptive structure into which weights are sorted is a Work Breakdown Structure (WBS). One can think of *A*, and *W* in the expression above as vectors organized by WBS group. Using a Sea System as an example,

---

[1] This mathematical structure is described in more detail in (Jones, Jeffers, & Greenberg, Performance-Based Cost Models, 2001).

suppose that there are seven weight groups at the one-digit level of the WBS and the above expression above becomes:

$$c_{nom} = \sum_{i=1}^{7} c_i = \sum_{i=1}^{7} a_i\,(p_i, t_i, w_i) \cdot w_i(p_i, t_i, w_{j\neq i})$$

where

i is an index indicating WBS group where, for example,

i = *1,* Structure

2, Propulsion System

3, Electrical System

4, Command, Communications, and Surveillance

5, Auxiliary Systems

6, Outfit and Furnishings

7, Armament

a_i is the cost factor for WBS group i

w_i is the driving physical parameter (often weight) for WBS group i

p_i is the subset of performance factors that affect WBS group i

t_i t_i is the subset of technology factors that affect WBS group i

$w_{j\neq i}$ is a set of physical characteristics (weights, etc.) in other WBS groups ($j \neq i$) that impact the physical characteristics of WBS group i

Note that this simplified structure can easily be expanded to a greater level of detail or to separately address labor and material costs. It is also easily expandable to include additional relationships for, for instance, Integration/Engineering Services (WBS 8) and Assembly and Support Services (WBS 9), or to include the impact of additional items like margin and loads on physical characteristics of WBS 1 through 7 as appropriate.

The expression above is, in fact, nothing more than a mathematical statement of a typical cost model that is used for estimating procurement costs. The significance, in the present context, is that this paper has derived it from the more general statement of the relationships among effectiveness, performance, and cost.

One can also derive the manner in which performance and technology influence both physical characteristics and cost. Performance factors and technology factors both influence cost through their impact on cost factors directly and through their impact on physical characteristics that influence cost. Estimation or selection of the cost factors, $a_i(p_i, t_i, w_i)$, is within the normal purview of the cost analyst. Determination of the physical characteristics, $w_i(p_i, t_i, w_{j\neq i})$, is ordinarily the business of systems engineers and designers executing the engineering process of concept design. This is the process that has usually not yet been executed at the early stages. Even when individual concept designs have been developed early on, they are rarely sufficient in number to parametrically define the functional relationships of $w_i(p_i, t_i, w_{j\neq i})$ in adequate breadth to fully characterize the trade space of interest. Since it is clear that the engineering relationships are as critical as cost factor relationships to a realistic characterization of cost-performance trade space, the need for a viable early stage parametric approach to estimating physical characteristics is apparent. Therefore, the nature of a performance based cost model as a unified combination of a parametric cost model and a parametric engineering model follows naturally from the structure of the problem.

Recall from above the simplified expression for nominal unit cost:

$$c_{nom} = \sum_{i=1}^{7} c_i = \sum_{i=1}^{7} a_i\,(p_i, t_i, w_i) \cdot w_i(p_i, t_i, w_{j\neq i})$$

This expression contains within it the seeds of two models, a cost model and an engineering model, which can be written separately and separately structured for quantification. The cost model can be written more simply, hiding the functional aspects of w_i, as:

$$c_{nom} = \sum_{i=1}^{7} c_i = \sum_{i=1}^{7} a_i\,(p_i, t_i, w_i) \cdot w_i$$

In its simplest form, this is a seven equation model, with one relationship to be derived for each of the seven weight groups defined above. The parametric cost model would be quantified using regression or other techniques applied to data consisting of normalized return costs by WBS and weights and other relevant physical parameters, performance, and technology descriptors, supplemented where necessary by available concept designs and conventional cost estimates. The resulting cost model relationships, accompanied by the standard statistical metrics, are useful and would be applicable to any concept designs that were forthcoming. The statistical metrics provide a basis for evaluating the accuracy and applicability of the model and also constitute some of the required inputs to a risk analysis.

WEIGHT ESTIMATING EQUATIONS

When sufficient concept designs are not available, parametric engineering models can be used to estimate the main cost driving factors, e.g., weights and other physical characteristics. It is important to note that PBCMs are in no way a substitute for, or even an emulation of, the concept design process. It is a procedure for estimating, based on historical data, supplemented by available data from completed concept designs, the major cost driving characteristics that can be expected to result from the design. In that sense, it is not dissimilar to the cost model in terms of how it is derived. The model could consist of weight estimating relationships, speed-power estimating relationships, capacity estimating relationships, and, potentially, geometry and volume estimating relationships. These relationships are not intended to characterize all important aspects of the design but are focused, at a rough order of magnitude (ROM) level, on those that are major cost drivers. The extent to which this parametric engineering model can work depends upon the constancy of the laws of physics as applied to the system, the consistency of a disciplined system design process, and a sensitivity to structuring the relationships in the model in a manner generally consistent with engineering principles and the top level design imperatives. A major portion of the engineering model is derived from the weight relationships from the larger cost relationship above.

$$W_{A1} = \sum_{i=1}^{7} w_i = \sum_{i=1}^{7} w_i(p_i, t_i, w_{j \neq i})$$

where

W_{A1} is empty weight of the system

w_i is the weight for WBS group $i, i = 1,7$

p_i is the subset of performance factors that affect WBS group i

t_i is the subset of technology factors that affect WBS group i

$w_{j \neq i}$ is a set of physical characteristics (weights, etc.) in other WBS groups $(j \neq i)$ that impact the physical characteristics of WBS group i

The expression above includes seven weight relationships where the weight of each group depends on a system specific set of performance and technology factors, but also may depend on the weights (and possibly other associated characteristics) of other parts of the system. For example: for a given speed, the required power and the weight of the propulsion system depend on the overall size of the system; the structural weight is driven by the size of everything else in the system; and, for instance, paint and coatings contained within WBS 6, Outfit and Furnishings, depend on the size of the structure. Thus, the seven weight equations are not independent, but constitute an interdependent system of equations. This is the simple mathematical manifestation of the nature of systems and the system design process embodied in the notion of the "design spiral." In quantifying these relationships parametrically, it is particularly important to ensure that the structure of the individual functional relationships, and the independent variables included in each one, account for these important interrelationships as well as for the most applicable performance and technology variables.

In addition to the seven weight groups constituting empty weight, there may be additional weights, such as fuel, cargo, personnel and effects, etc., that contribute to the overall size of a system and may also play in the system interrelationships. A complete parametric engineering model for a system addresses these weights, too, typically using relatively simple factors.

OTHER ESTIMATING EQUATIONS

So far this discussion focuses on weight largely because many cost estimating processes and cost models are weight oriented. In the context of a parametric engineering model there are other critical relationships. The most critical are the propulsion system relationships relating speed, power, and propulsion system size. In the cost model, one may take the propulsion system weight as the literal driver or principal input to the propulsion cost relationship. But, it is obvious that the propulsion system weight is driven by the installed propulsion power which, in turn, is driven by a design speed requirement, or if specified on its own, determines the resulting design speed along with the size of the propulsion system and other aspects of the system. These relationships are governed to a large extent by the physics of aerodynamics or hydrodynamics which will need to be respected in the functional form of parametric relationships in this area. PBCMs must address all critical relationships.

Finally, geometry and volume are important, too. In fact, it is possible that a key requirement and constraint determining feasibility for a system is a properly balanced relationship between weight and volume. Indeed, if a correct balance is not achieved, the system might not function satisfactorily. PBCMs can be constructed to address geometry and volume.

PBCM BUILDING PROCESS

Building a PBCM consists of several activities: collecting/organizing data, defining systems, normalizing the data, and building relationships. Figure 2 graphically depicts the building process. Each will be discussed in depth below.

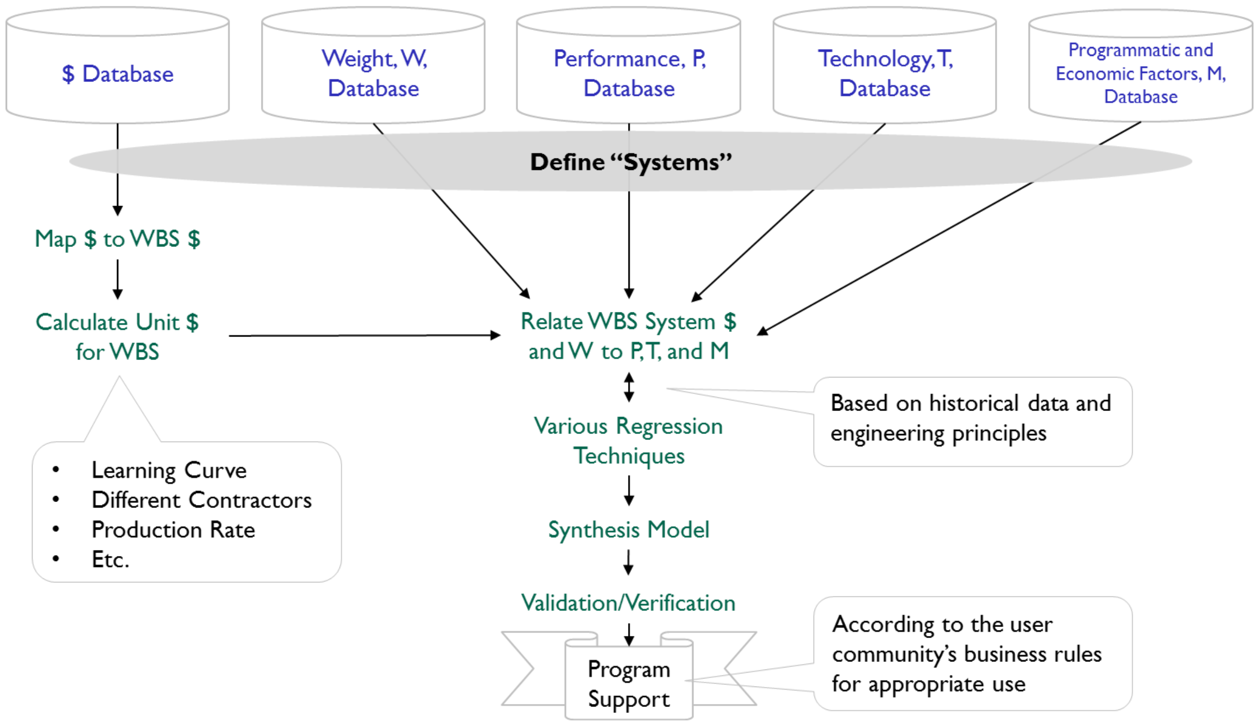

Figure 2: Typical PBCM Building Process

DATABASES

PBCMs consist of a set of quantitative relationships that relate the dependent-predicted variables to the independent-driver variables. Derivation of those relationships, obviously, depends on having data on all of the variables, both independent and dependent that participate in the model. Two separate classes of data can be used in the development of a PBCM. The first class is historical data on the technical characteristics and actually incurred costs for historical systems. This data is critical to the model development for two reasons. First, it should contain a fairly wide range of variation for many of the key variables, which is helpful in extracting relationships among them. Second, and perhaps even more important, the historical data embodies reality in that it reflects actual outcomes. Relationships derived from, and consistent with, this historical data inherit a degree of credibility from that reality. There are, however, limitations to historical data. It is what it is. That is, it may contain a limited range of variation for some variables, which may limit its usefulness in deriving some relationships of current interest. It is also dated and may require interpretation and adjustment to relate it appropriately to present technology, industrial base conditions, prices, etc.

A second class of data consists of the results of concept studies that bring together concept designs and associated cost estimates performed using valid and credible current engineering and cost analysis methods. The use of concept studies as data sources may expand the range of variation of key variables of interest for parametric analysis, and they can assist in relating current conditions to historical data. Concept studies may, in some cases, be available "off the shelf" as for studies performed in support of an AoA. Alternatively, they could potentially be performed specifically for the purpose of generating data to supplement the historical data in specific areas.

It is best to rely on authoritative, primary sources, supplemented as necessary by other, sometimes informal, sources for the data. Required data include weight data, technical and performance data, physical characteristics data, labor hours / cost data, and material cost data. Figure 3 shows typical databases needed to support a PBCM.

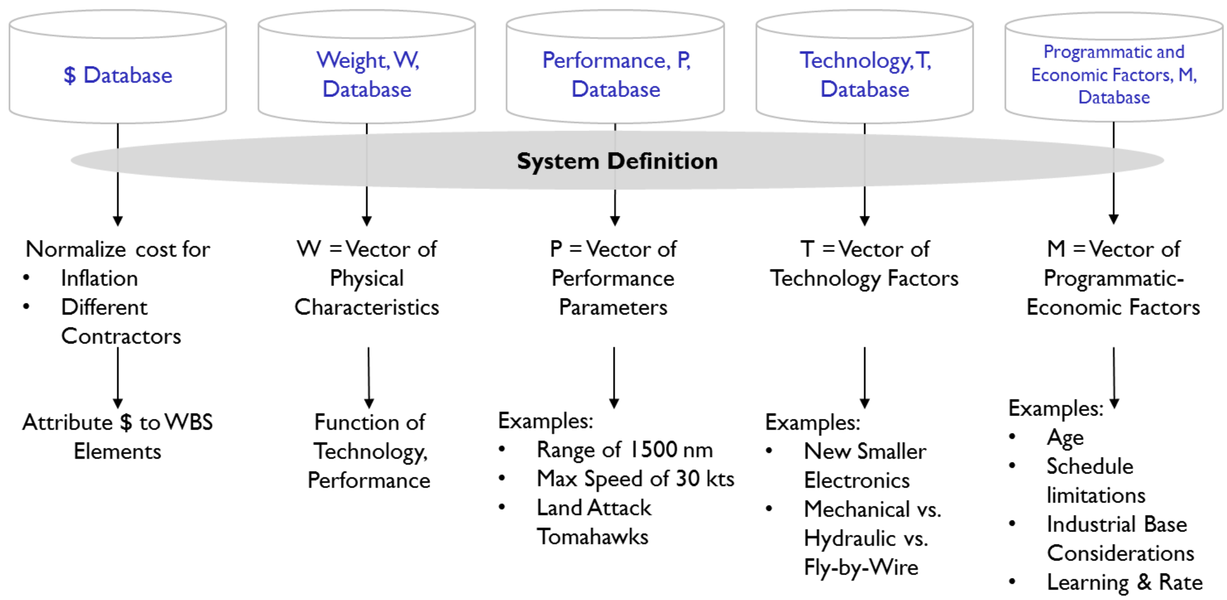

Figure 3: Typical PBCM Databases.

SYSTEM DEFINITIONS

Much of the data collected is pertinent to each individual unit produced. However, if each individual unit were to feed the regression analysis, the systems with many units produced would be weighted more heavily than those with less units produced. Therefore, groups of units need to be defined and aggregated into a single system that will serve as a data point in the regression analysis. In other words, units with similar characteristics need to be grouped together.

In order to group the units in a way that will produce a significant number of data points but not skew the analysis, many things should be taken in consideration:

1. **Similar Design and Performance**. Since a PBCM considers the performance and the technical characteristics of a system, it is vitally important that the units that comprise a system have a similar (if not identical) design. While slight variations are unavoidable, there should be no large performance disparities. For the purposes of a sea system, classes of ships make a good starting point. In many cases, one can even separate systems based on flights, if significant upgrades were performed.
2. **Consistent Weight**. Since weight is typically a driver of the technical characteristics, special attention should be paid to the weight of each WBS element to ensure that the weights are consistent across the units. If the units were made by different manufacturers, sometimes they may differ more at the lower WBS levels than expected, but this may be due to different accounting systems. However, the overall weight of the unit should be comparable to a unit produced by another manufacturer. For the purposes of a sea system, it is important to look at the seven (7) Ship WBS groups for each hull and ensure that they are similar.
3. **Comparable Technology**. The technology used in each unit should be very similar. Again, since performance is key, this is usually dependent on similar technology. However, for example, if speed is identical, but the units utilize different propulsion technology, they should not be aggregated. In addition, since technology changes over time, units built years apart should be carefully examined to ensure that the technology remained the same.
4. **Stable Production Runs**. Perhaps the easiest way to identify groupings is to look for stable production runs. Units built in sequence by the same manufacturer are often ideal candidates for systems. This is not a requirement, and units can be made by different manufacturers, but stable production runs make the cost data normalization significantly easier.

DATA NORMALIZATION

Since one data point is needed to represent each system, the data must often be normalized to develop the best representative point possible. This can be a difficult process, for there are many considerations, both technical (different manufacturers, different accounting systems, design modifications, etc.) and cost (learning, different manufacturers, different accounting systems, escalation, rates, productive industrial base, etc.).

In order to normalize the technical data, it is best to consult the technical community subject matter experts (SMEs). Alternatively, the normalization can be done through averages or other analysis of the data, but it is best to involve at least one person who has a sound technical understanding of the systems.

The cost data normalization is something that a cost analyst is much more adept at performing. For the typical system with a stable production run, one should first convert all the dollars to a constant year dollars. This should be done at the lowest level of the WBS, and if manhours are available, they would be preferable. In many cases, costs are only available at the top level, but the PBCM should operate at a lower level of the WBS. In this case, the costs must be mapped using bid data, analogous systems, or other methods. Once the costs are in the appropriate WBS, learning curve analysis should be performed on the data. The goal is to have one cost number for each WBS element, so any point on the learning curve can be selected, as long as there is consistency across all systems and your final model takes this into account. Figure 4 below illustrates an example of the normalization process and how the eighth (8th) unit on the learning curve was selected.

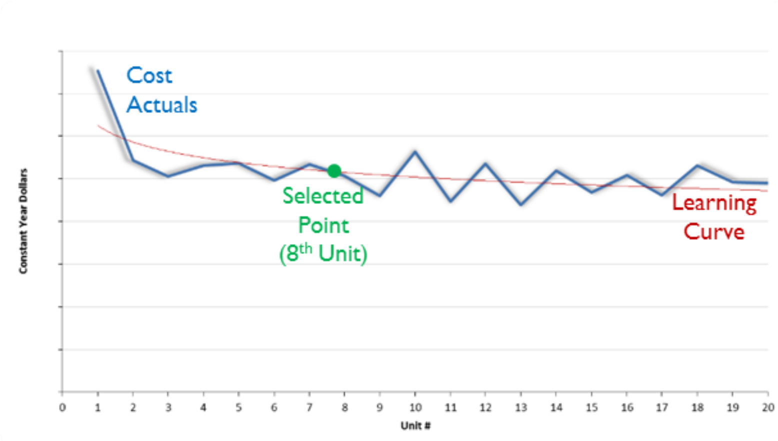

Figure 4: Cost Data Normalization.

ESTIMATING RELATIONSHIPS

PBCM estimating relationships will fall into four general categories:

- weight relationships,
- other technical relationships,
- cost estimating relationships including labor hour and material cost relationships, and
- economic-programmatic relationships (rates, cost-quantity relationships, etc.).

The weight and cost estimating relationships, as well as some of the other technical relationships, will fall into a natural organization by WBS. Each relationship will consist of a functional form relating a dependent variable to a specific set of independent variables. The functional form is quantified and becomes an estimating relationship through coefficients (parameters) that make specific the impact of each independent variable. Each relationship will include at least one, and usually more than one, parameter. The parameters are derived from data through regression analysis, or, in some cases, other data analysis or engineering analysis techniques.

Though much of the thoughts and basic equation concepts have already been discussed, the process for creating relationships involves first conceptualizing the relationships. This should be based on sound engineering principles (i.e., physics). Utilizing a Subject Matter Expert (SME) from the technical community can help discern these relationships and produce realistic equations. Relationships may produce good statistical results but violate physics, and they should, therefore, not be used. It is important to first understand how the system works and the interrelationships between the performance and the technical attributes before regressions are run. Often, plotting the data on scatter graphs can help with visualizing relationships, and the use of color coding can help separate cost drivers within the dataset. Once a concept is formed, various regression techniques should be used to estimate the parameters. The statistics should show if it is a good relationship, and other testing techniques can be utilized. Even once a good equation is determined, other equations, based on engineering principles, should be tested and compared. Often a good relationship is the result of many regression runs, analysis of the results, and SME input.

PBCM IMPLEMENTATION

Typically, one should implement a PBCM's technical, physical, and cost relationships in a self-contained Microsoft Excel workbook with the capability of multiple analysis sheets. The relationships are implemented in a single sheet within a single column in order to maximize usability, versatility, and efficiency, and to allow the user to view inputs and outputs from the same location. Any changes made to input parameters are shown immediately. This allows the user to quickly adjust designs as well as see the causal relationships working in the model. The column also exhibits a unique advantage in replication. The column may be copied to any number of columns, where a new set of inputs will produce another unique output. This allows the user to track changes to designs without losing the information from the previous design. This also allows a user to model a production process, learning curve, or design study in a single sheet in a matter of seconds. Figure 5 describes a typical PBCM structure.

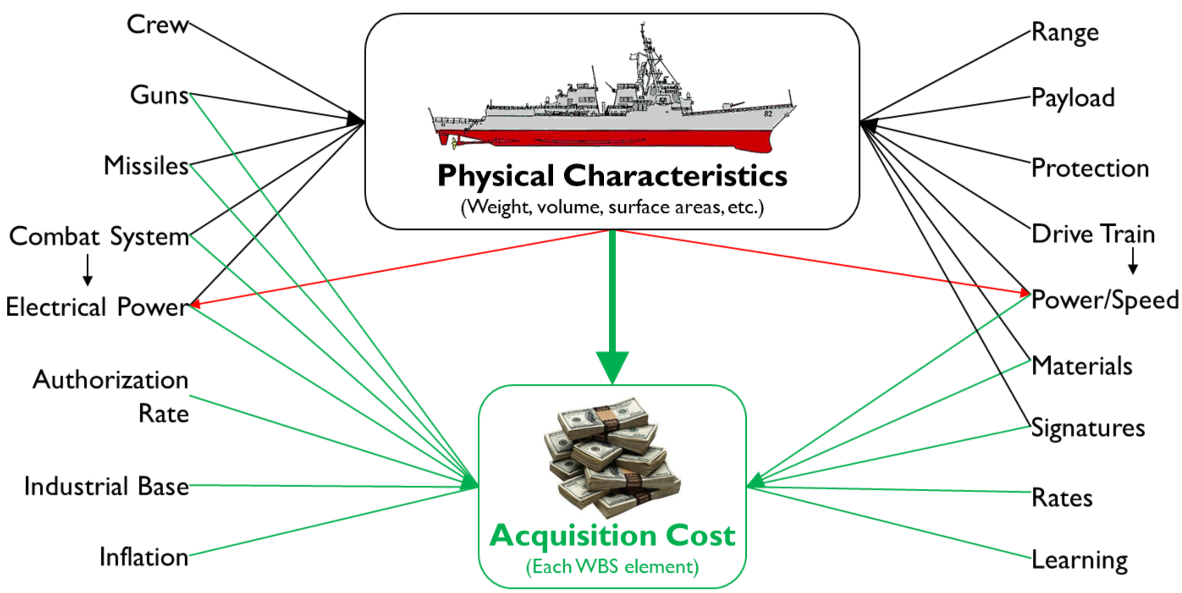

Figure 5: Typical PBCM Implementation with Inputs and Outputs.

The major strength of PBCMS is the efficiency with which they run. Properly designed, PBCMs use an iterative design spiral calculation process to allow an experienced user to create full studies within a matter of minutes. The starting design point can be calibrated using data from a historical system as a baseline, and the user can substitute known values for calculated values when they have better data. At the conclusion of a PBCM calculation, the model can log any study file with a summary page, to create a summary of all outputs from the model, including graphical outputs. It is also wise to implement a capability that allows one to change formulas and automatically update them throughout the model.

ITERATIVE "DESIGN SPIRAL" CALCULATION PROCESS

It was previously noted that the seven weight equations and additional relationships addressing speed-power, electrical loads, etc., are not independent but constitute an interdependent system of equations. Many of the relationships described above include, as arguments, the results of other equations. In a more elaborate model, area, volume, and other geometric variables could also be included within the system. In such a system, a single pass through the set of equations will not produce the intended consistent result because the arguments (dependent variables) of some equations change when others are evaluated. The system must be evaluated iteratively, in several passes, until acceptably stable (zero or negligible change from the last pass) evaluations of all equations in the system are achieved. This computational procedure mirrors parametrically the iterative nature of the system design process generally referred to as the "design spiral." In terms of implementation of such a system in Microsoft Excel, enabling the option to allow iterative or "circular" calculations is required for a PBCM to execute properly. Figure 6 shows a typical PBCM synthesis loop.

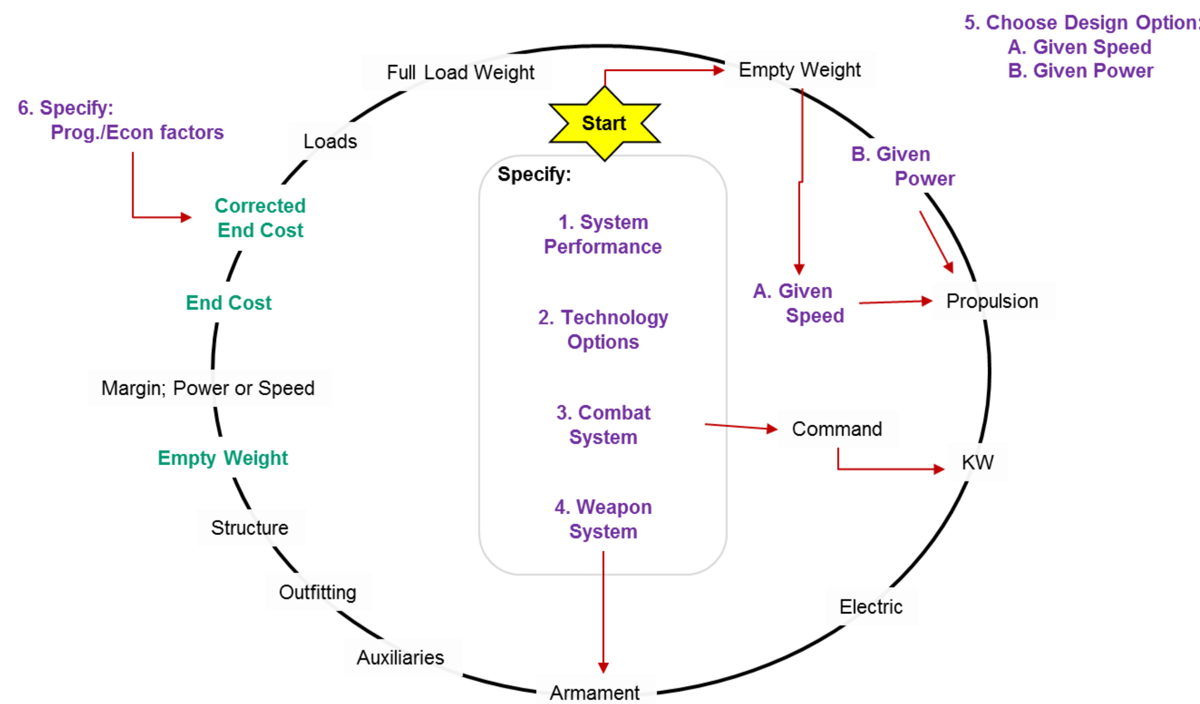

Figure 6: Typical PBCM Synthesis Loop.

SUBSTITUTION AND CALIBRATION PROCESSES

Other features can be incorporated in PBCMs. The first of these is a simple *substitution* process. This feature allows the user to specify any or all of the major technical outputs (weights, power, or speed) to override the results of the equations described above. Thus, if the user knows, or has a credible engineering estimate for, one or more of these inputs, then the model's associated technical equation(s) can be overridden. In the extreme case, where all of the technical values were substituted, say from a comprehensive design study, then the PBCM would function as a straight cost model operating on specified technical inputs.

The second feature, *calibration,* provides for the automated generation of "calibration factors" that can be used to cause any of the model's technical relationship to match a selected baseline – that is to be *calibrated* to – a specified value at a given, hopefully accurate, set of input parameters. This feature is useful for *calibrating* the model to exactly match a specified system, either real or a trusted design study, that is to serve as a baseline for a set of performance based excursions. The set of calibration factors derived from the baseline system can be used as inputs for the study excursions, thereby forcing the model, as applied to the excursions, to be consistent with the baseline.

Because of the iterative "design spiral" nature of the PBCM process, the set of calibration factors for all involved variables is interdependent. The calibration factors, like the technical output variables depend upon each other. They must be determined simultaneously using an iterative process in order to form a consistent set.

GRAPHICAL OUTPUTS

As with any good model, the outputs that it can produce are very important, for tables, charts, and graphs can be useful tools in illustrating your analysis and conveying your results. A PBCM is no exception to this, for many different chart types can be produced and used to display the model's outputs. Though many of these additional chart types exist, two ways of showing the data have proven to be especially useful in showing the power of a PBCM: the walkabout chart and the spider chart. In addition, these two chart-types help to achieve the objective of establishing the relationship between physical characteristics, system performance, and cost.

Consider first an example walkabout chart as illustrated below in Figure 7 for a notional study. This standard scatter plot shows weight, one of the primary physical characteristics, versus construction cost as a function of performance, technology, weight, and economic and industrial assumptions. Each data point represents a single run of the same PBCM, changing one input for each run. On the chart, each point is connected in the order in which the inputs were changed. In addition, both the X-axis and Y-axis are both dependent variables (i.e., outputs of the PBCM), but the data labels are the independent variables (i.e., inputs into the PBCM). The chart starts at the bottom left with a 'minimum capability of interest' system – a system that will carry a minimal crew and minimal cargo, without a weapon system or other battle-ready features. From this 'minimum capability of interest' data point, it adds capabilities one-by-one, generally increasing in both weight and cost with each new capability. It slowly works up to the current capability and then continues on to build up to the maximum capability of interest. Some capabilities are increased two different times as additional performance is added. This type of walkabout can help decision makers and systems engineers learn why the system costs so much, clearly seeing what capabilities are the key performance drivers of both weight and cost.

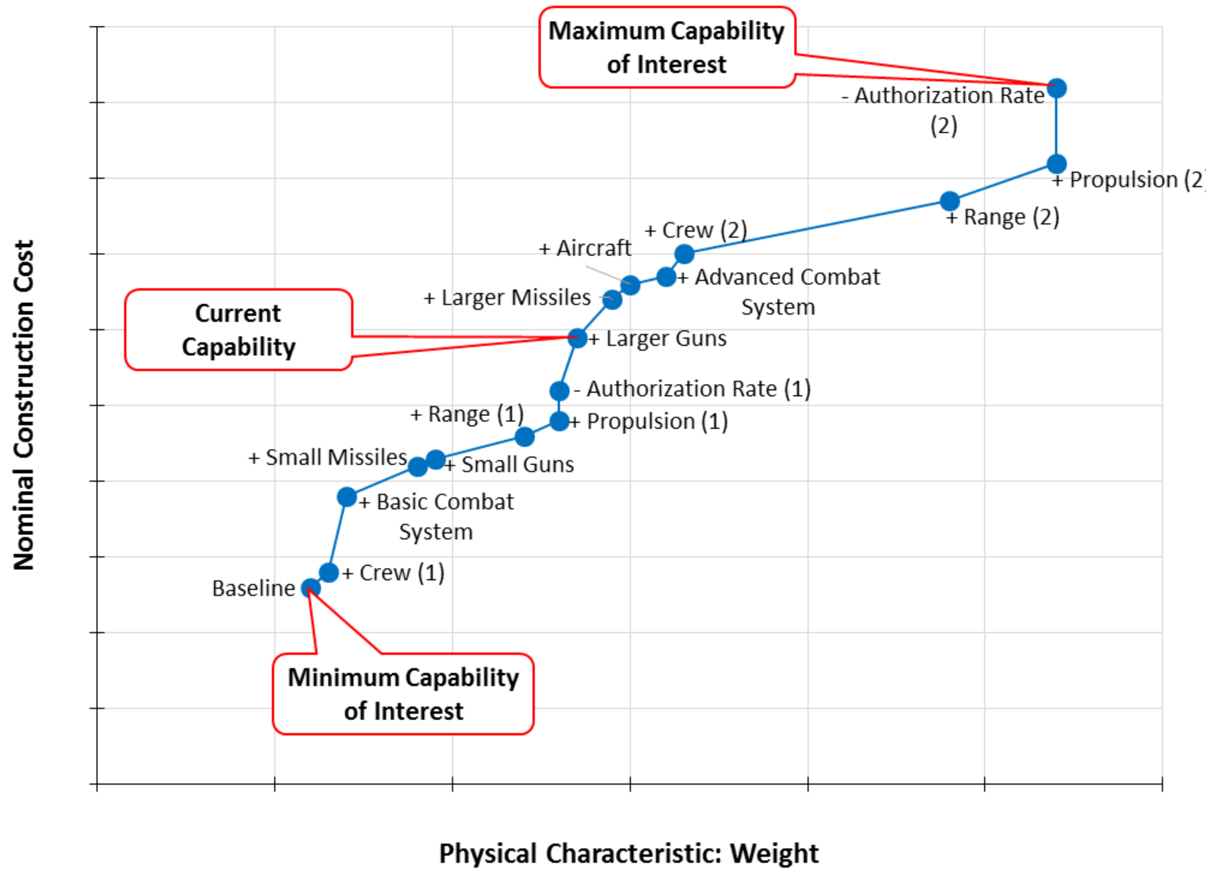

Figure 7: An example walkabout chart for a notional study.

Walkabout charts can often help refine the requirements and modify the designs to fit an affordability target, i.e., cost objective, without compromising key performance aspects. For instance, in Figure 8 below, an overlay of the cost constraint region is shown along with the cost objective and the cost cap, i.e., the maximum acceptable cost. The walkabout chart shows that all added "capabilities" up through "+ range (2)" are possible; additional "+ propulsion (2)," presumably needed to increase speed, is not possible. Lastly, the assumed low authorization rate (reduced quantity per buy) serves to exacerbate the cost problem. If PBCMs are constructed with each excursion (added capability) in a single column of an Excel worksheet, displays like this are very quick to generate.

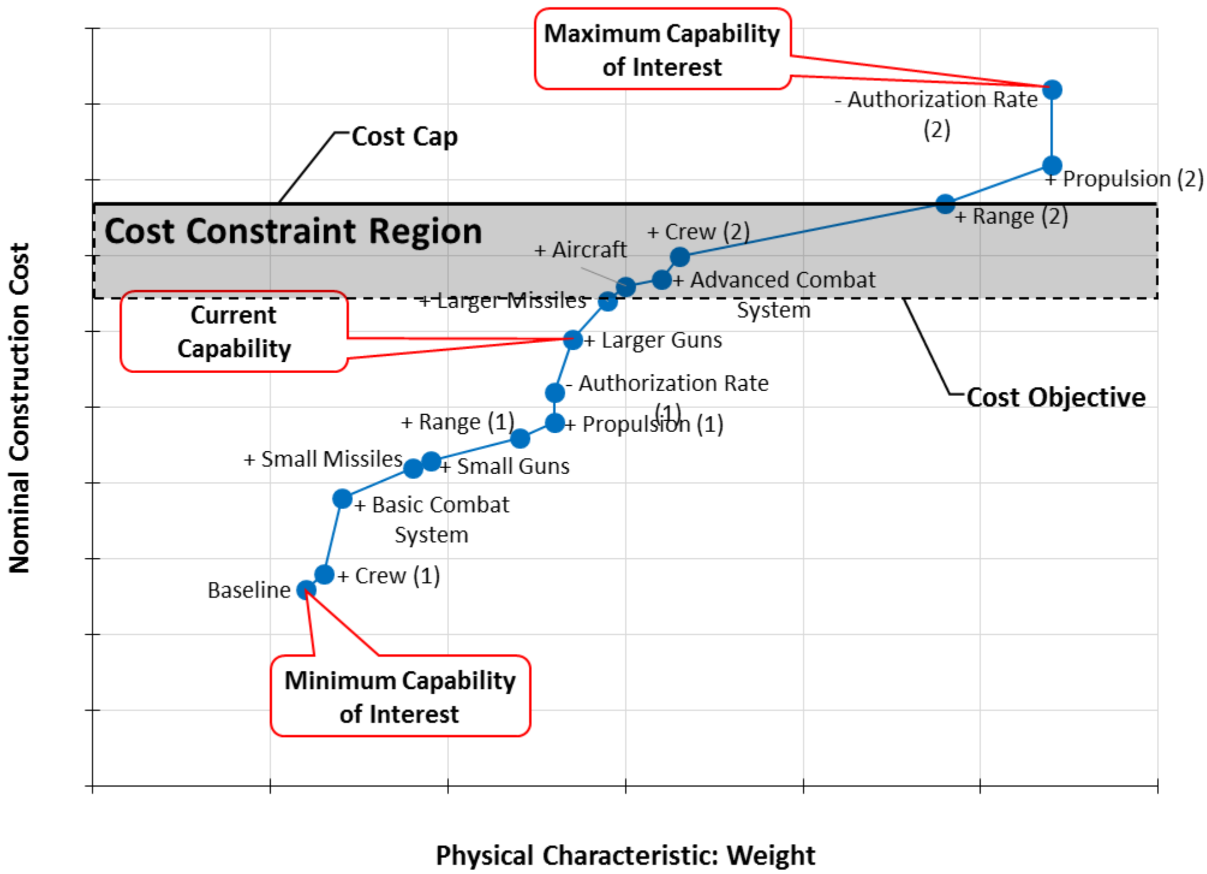

Figure 8: An example walkabout chart for a notional study with the cost constraint region shaded.

A spider chart is similar to a walkabout chart, except that it does not follow a single direction. Consider Figure 9 below as an example, showing the cost versus speed, one of the primary performance characteristics, for a notional study. The figure shows three different concepts and multiple performance excursions for each. Consider Concept #1 as an example and assume that this is one of the concepts presented in an AoA. The power was reduced from Concept #1 two different times, which, as expected, reduces the speed and cost, but the spider chart shows the magnitude of each reduction and the relationships that the performance excursions have to each other. As another excursion, the combat system was reduced, impacting mainly the cost. Lastly, the signatures were reduced, while keeping all other things constant (including power). This allowed the system to go faster at a lower cost, showing how much of a driver signatures are for this system. Note that when building these charts, the PBCM can be calibrated to detailed technical parameters that the system designers calculated. Following that, the calibration factors that were calculated can be used to run excursions.

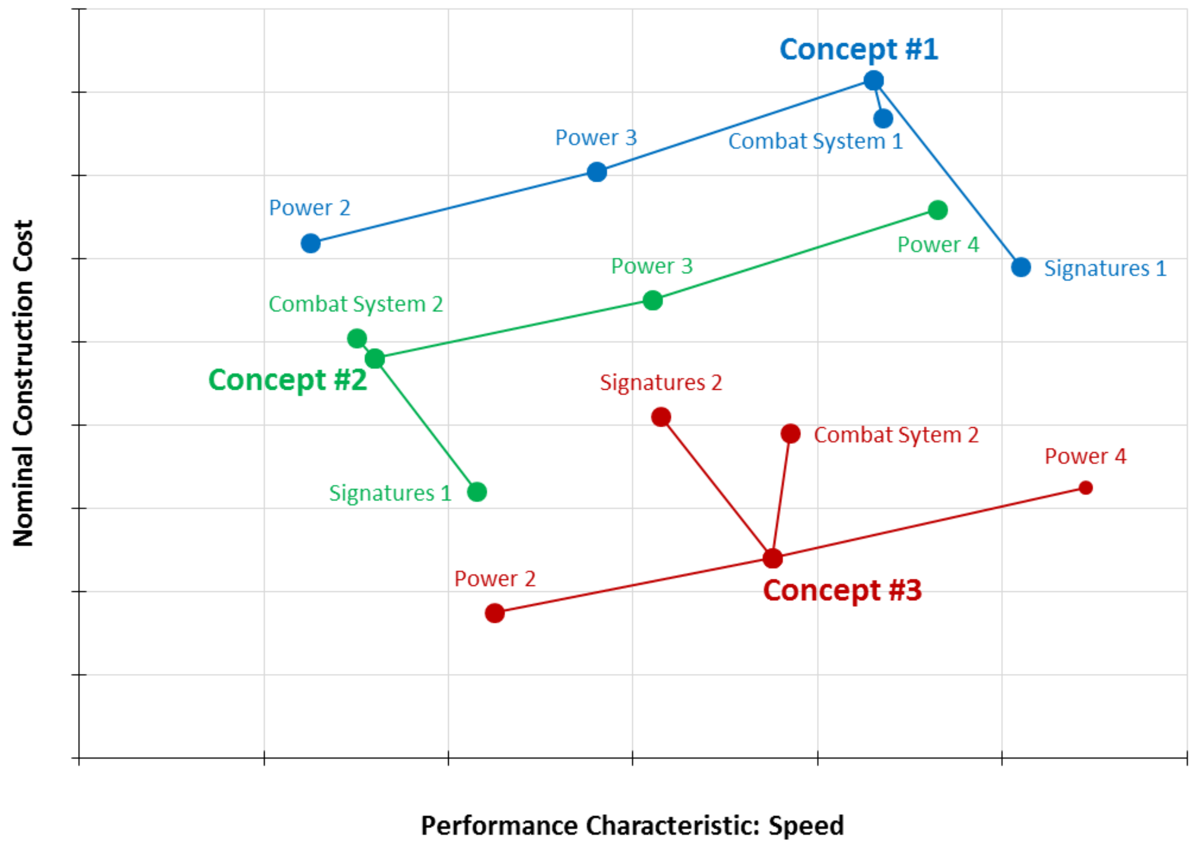

Figure 9: An example spider chart for a notional study.

The same spider chart also displays two other concepts, Concept #2 and Concept #3, along with excursions based on those concepts. Additional advantages of spider charts become apparent. First, consider in Figure 10 below, the overlaid cost constraint region along is displayed with its cost objective and cost cap. In this figure, see that (1) all Concept #1 options are infeasible except for the one with Signatures 1, (2) three of the four Concept #2 options are feasible, with the Power 4 option being the lone exception, and (3) all of the Concept #3 options fall within or below the cost constraint region. However, this analysis would not be complete without considering a performance characteristic: speed.

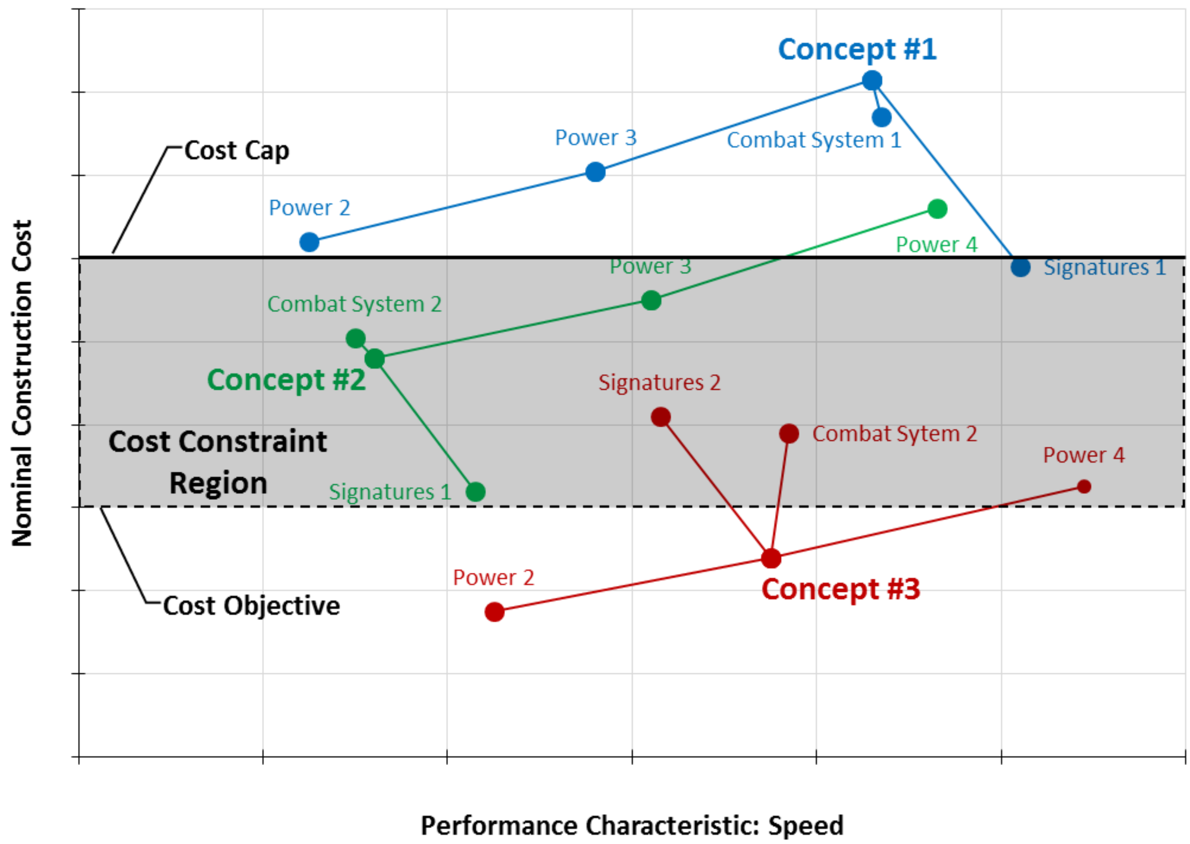

Figure 10: An example spider chart for a notional study with the cost constraint region shaded.

Considering speed, a performance characteristic, returns the discussion to a joint consideration of cost and performance, and lead to a second advantage of spider charts. In Figure 11 below, the speed constraint region is overlaid on the spider chart. In this case, the speed objective represents a speed below which operational effectiveness is compromised; higher speeds are acceptable, up to the point where cost becomes the decision-maker.

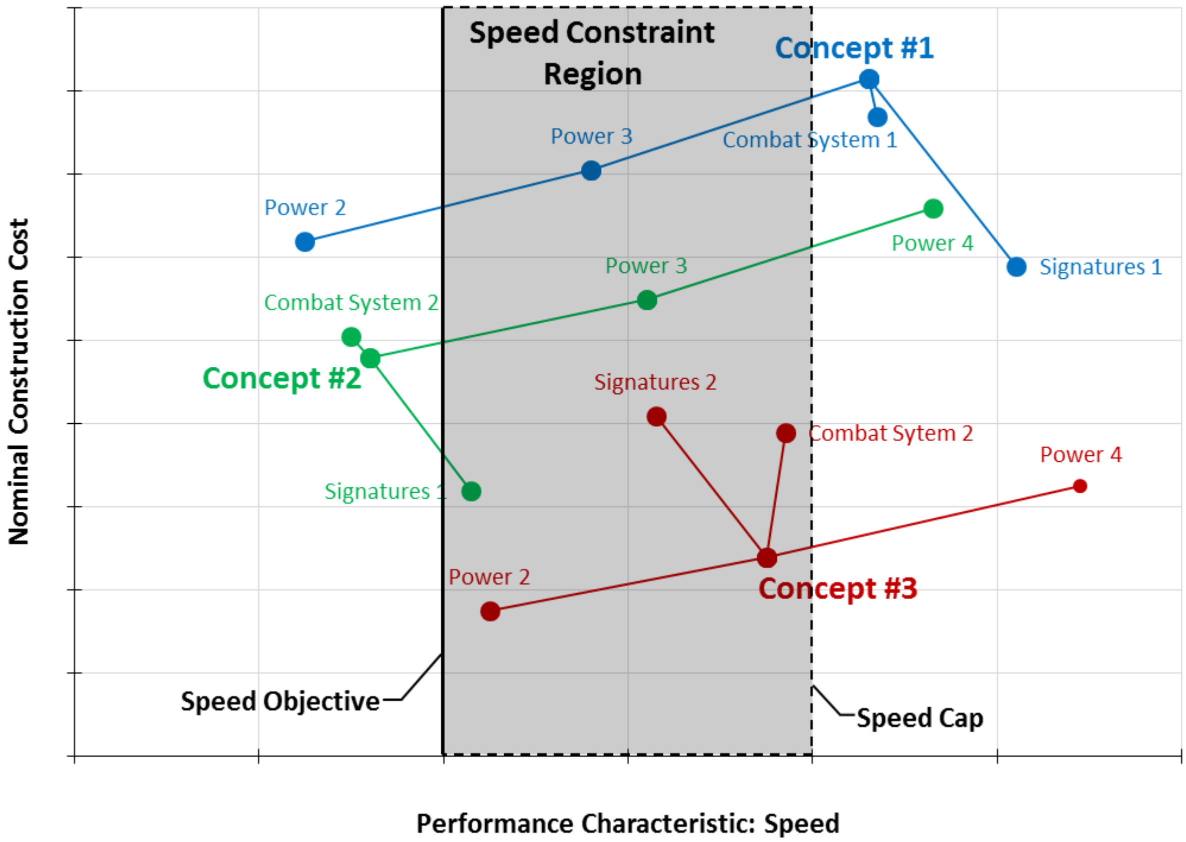

Figure 11: An example spider chart for a notional study with the speed constraint region shaded.

In Figure 12, both cost and performance characteristic objectives are considered, but the cost objective and speed cap have been removed. In addition, the question "How much speed is feasible?" is answered. Here see that (1) all Concept #1 options are infeasible except the one with Signatures 1 which includes the Concept #1 baseline power option, (2) only one of the four Concept #2 options is feasible, i.e., Power 3, and (3) all of the Concept #3 options fall within or below the cost constraint region and satisfy the speed objective. Since the combat system and signature options are also important performance characteristics, the process used to evaluate speed options vs. cost could also be used to evaluate combat system and signature options vs. cost.

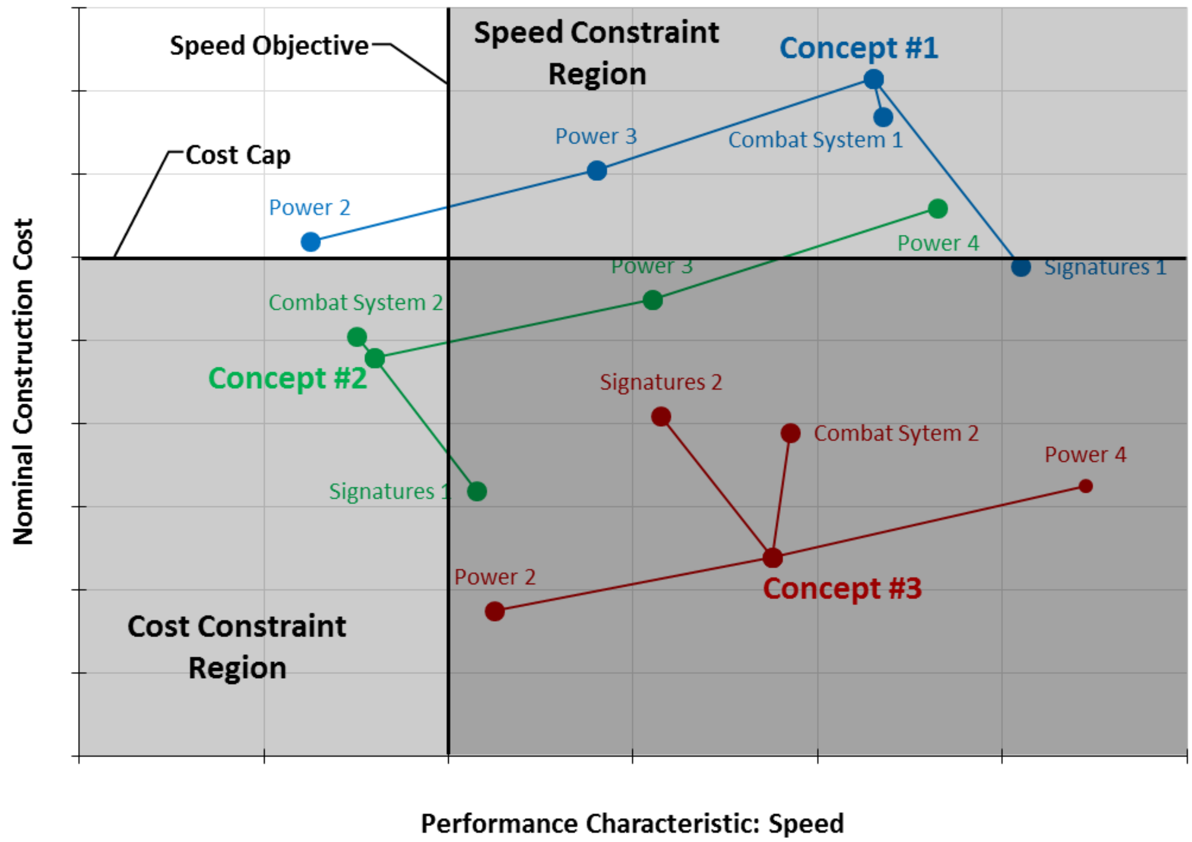

Figure 12: An example spider chart for a notional study with both the cost constraint and speed constraint regions shaded.

Spider charts allow decision makers and system designers to begin to understand the relationships between the concepts and how changes in performance can influence the cost, without coming up with a design for each performance excursion. This can save both time and money and ultimately allow decisions to be made based on engineering principles and historical data. As with the walkabout charts, a well-structured PBCM can quickly generate the data points necessary to construct these informative charts.

SUMMARY AND CONCLUSIONS

Performance Based Cost Models can be powerful and insightful tools for exploring cost vs. capability trade space in the earliest phases of acquisition programs and through the later phases as well. They have been used successfully in a number of sea systems programs. The performance-technical-cost relationships are unique to each program, and sound analysis does not always translate to strong statistical equations. In the cases where PBCM development was halted, for statistical or other reasons, the bringing together of the cost estimating and systems engineering disciplines has been beneficial to both communities.

A major challenge in building a useful PBCM is having it ready, validated, and available at the earliest stages of a new program. Developing and implementing a PBCM applicable to a particular product line, and adequately addressing the performance-capability issues of interest, can be a significant task requiring more resources and time than allotted to the study. Therefore, by the time a new program is established, it may already be too late to develop a new PBCM from scratch. To obviate this problem, a continuing research and development effort to construct and maintain PBCMs in various product areas would be beneficial. Then, ready or "almost ready" PBCMs could be available for new programs at the earliest stages requiring only limited update or customization to the detailed trades of interest.

Another challenge, is the common concern of estimate distribution. The PBCM can put technical insights into the hands of cost personnel, cost insights into the hands of technical personnel, and possibly cost and technical insights into the hands of program offices. Therefore, to keep all stakeholders happy with the collaboration it can be useful to establish business rules for appropriate use of the model and model results.

Despite the challenges, PBCMs are powerful tools that bring together the cost and technical communities and allow them to collaborate to produce a model that can quickly relate performance to cost. The authors intend to continue developing and improving PBCMs in our specific areas of sea systems and look forward to seeing future development of this type by others.

REFERENCES

1. MIL-STD-881C (2011). Department of Defense Standard Practice: Work Breakdown Structures for Defense Material items.

2. Jones, R. R., Jeffers, M. F., & Deegan, C. (1996). Submarine Performance Based Cost Models: Nuclear Attack Submarine Parametric Cost Model. *29th Annual DoD Cost Analysis Symposium*. Leesburg, VA.

3. Jones, R. R., Jeffers, M. F., & Greenberg, M. (2001). Performance-Based Cost Models. *Naval Surface Warfare Center Carderock Division Technical Journal* , 203-208.