Relating Cost to Performance: The Performance-Based Cost Model

Briefing for 2014 ICEAA Professional Development & Training Workshop

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

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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 (SLOC) 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.

In this paper we 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.

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Agenda

- Introduction to PBCMs
- Building a PBCM
  - Databases
  - Data Normalization
  - Relationship Development
  - Implementation
- Using a PBCM
- Conclusions & Future Work

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Introduction to PBCMs

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Why are rapid analytical design/cost models needed?

- DOD 5000.02, Section 2366a - Increased requirement pre-MS A cost analysis
  - If, during Technology Development, the cost estimate upon which the MDA based the Milestone A certification increases by 25 percent or more, the PM shall notify the MDA
- Dr. Carter Memo – Memorandum for Acquisition Professionals, Nov 2010
  - "Required establishment of an affordability target which should be treated like a KPP at Phase A"
  - "…show results of capability excursions around expected design performance points"
  - "…provide cost tradeoff curves…to show how the program has established a cost effective design point"
- GAO report Jan 2012 – "Additional Analysis and Oversight Required to Support the Navy's Future Surface Combatant Plans"
  - The study…"Does not include a thorough trade-off analysis that would compare the relative costs and benefits of different solutions under consideration or provide robust insight into all cost alternatives"

A bulk of lifecycle costs are locked in by MSA even though sensitivities are still unknown

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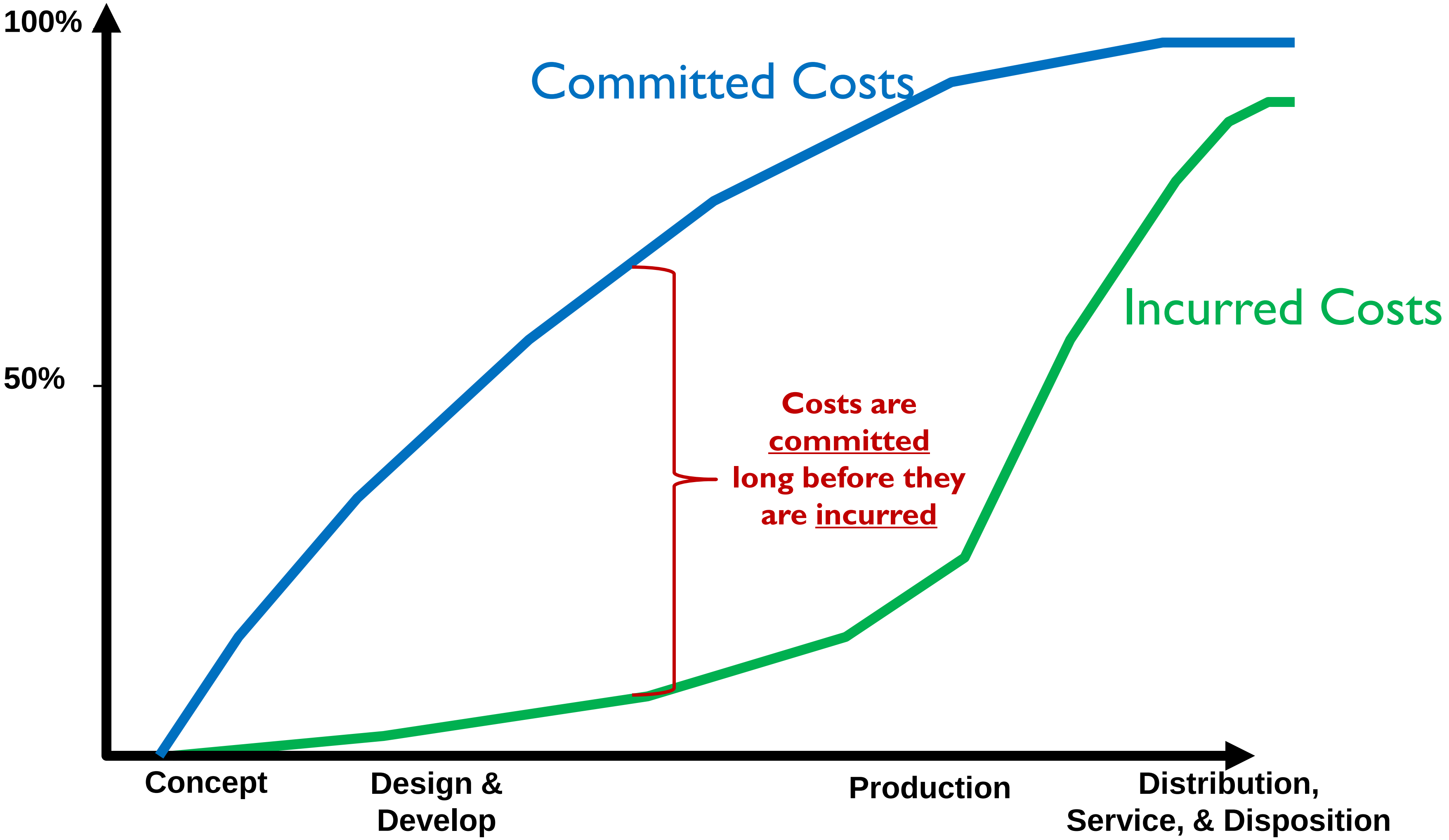
Early-Stage Cost Analysis



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What is Performance?

For your automobile:

- Speed (or horsepower)
- Range on a tank of gas
- Passenger Capacity
- Creature Comforts
- Trunk Volume
- Headlight Strength
- Communications Ability
  - Audio Features
  - GPS Unit

For a Navy ship:

- Speed (or horsepower)
- Range/Endurance
- Crew Size
- Habitability
- Payload Capacity
  - Guns (# and size)
  - Missiles (# and size)
- Electrical Capacity
- Combat System
  - Sensors, Comms, etc.
- Signatures

Measurable parameters that the system can achieve

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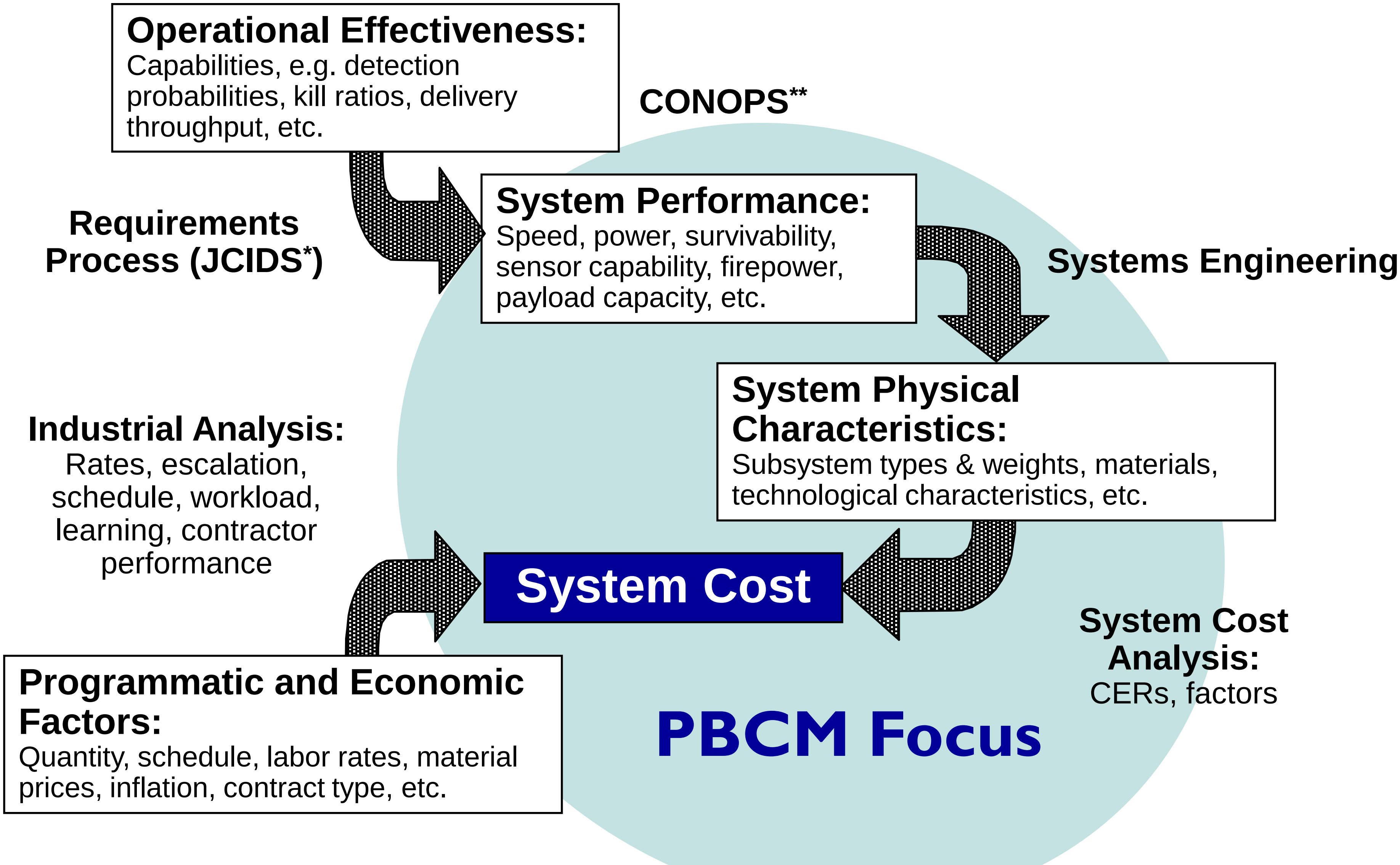
Effectiveness-Performance-Cost



* Joint Capabilities Integration and Development System
** Concept of Operations

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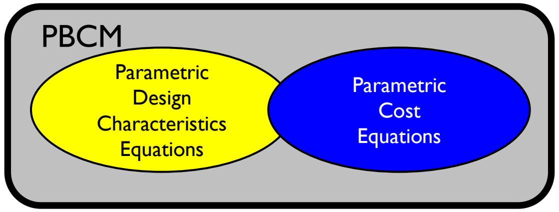
A Performance Based Cost Model is ……



- An *early stage* ROM costing tool
  - Focused on relating cost to *performance* factors
  - A *parametric cost model….*
  - …. integrated with a *parametric engineering model*
  - Estimates *cost* as a function of performance by *simultaneously* estimating major *physical characteristics*
- Derived from historical data and engineering principles
  - Consistent with experience, i.e. costs and characteristics of historical systems
  - Adaptable to current concepts by incorporating design data and adjustments based on engineering logic
- A flexible and rapid tool for exploring a broad trade space
  - Cost module can be used in conjunction with concept design data where available
  - A very good "gap filler" tool for excursions from concept design baselines
- A valuable *supplement* to standard concept design and costing methods

A systems engineering approach to early stage costing

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PBCM Applications

- A PBCM could be developed for *any* MIL-STD-881C system
  - Examples: Aircraft, Missiles, Sea, Space, Surface Vehicles, Space, Unmanned System etc.
- For consistency, all examples in this brief will use a Sea System

Sea Systems WBS[1]
Hull Structure
Propulsion Plant
Electric Plant
Command, Communications, & Surveillance
Auxiliary Systems
Outfit and Furnishings
Armament
Total Ship Integration/Engineering
Ship Assembly and Support Services

[1]Department of Defense Standard: Work Breakdown Structures (WBS) for Defense Material Items (MIL-STD-881C)
3 October 2011
Appendix E: p. 89-94

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Building a Practical PBCM

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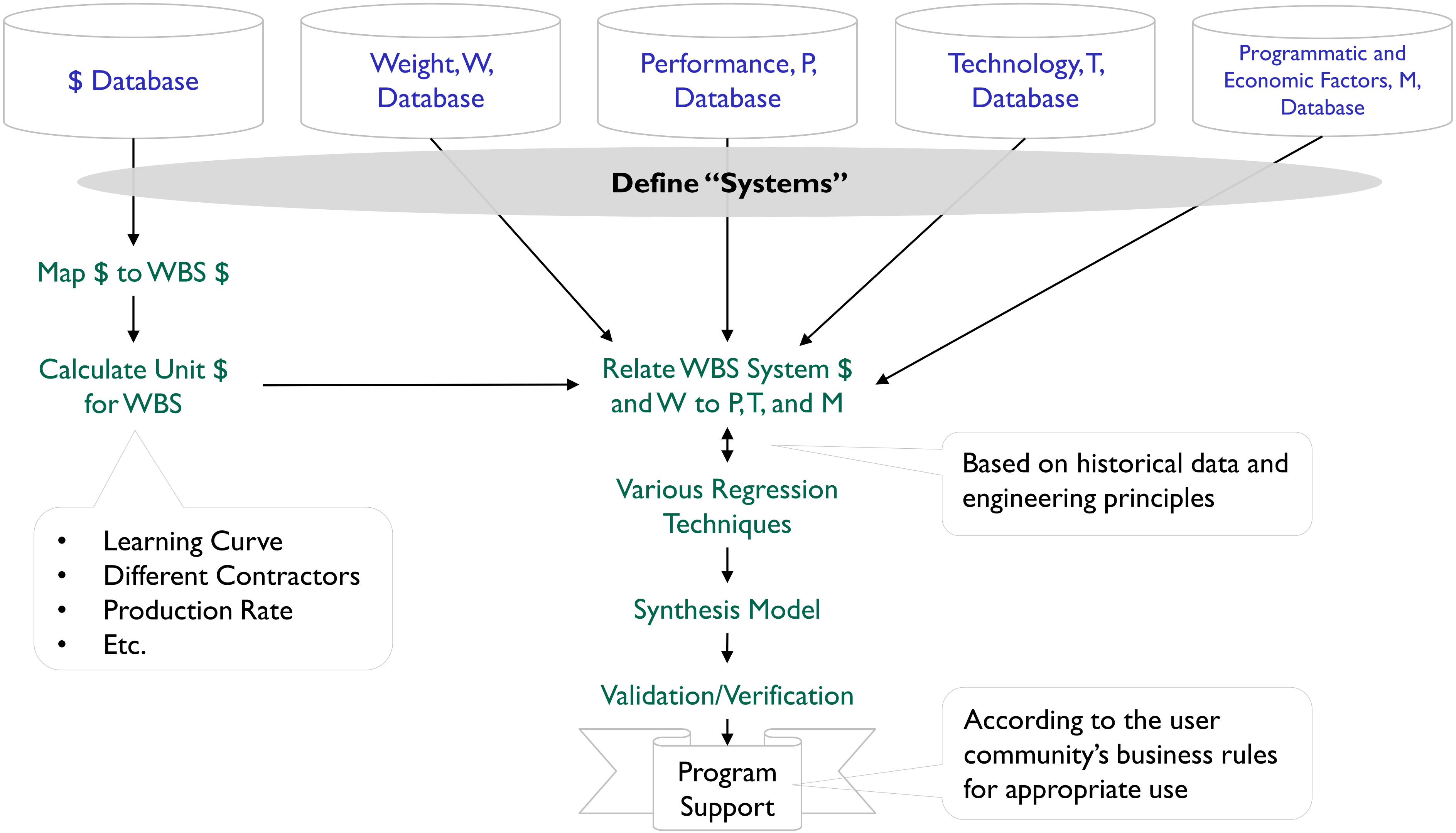
PBCM Building Process



A multi-step process requiring several different forms of data

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Databases

- Data to collect: Costs, Weights, Performance, Technology, and Programmatic & Economic Factors
  - Requires considerable time and many data sources
  - Should reflect a wide variety of data
    - Different programs, performance characteristics, sizes, missions, etc.
- Classes of Data:
  - Historical Data
    - Embodies reality – reflects actual outcomes
    - Contains a wide range of variation for many key variables
  - Concept Designs
    - May expand the range of variation of key variables
    - Reflect valid and credible current engineering and cost methods

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PBCM Databases

System Definition

$ Database

Normalize cost for
- Inflation
- Different Contractors

Attribute $ to WBS Elements

Weight, W, Database

W = Vector of Physical Characteristics

Function of Technology, Performance

Performance, P, Database

P = Vector of Performance Parameters

Examples:
- Range of 1500 nm
- Max Speed of 30 kts
- Land Attack Tomahawks

Technology, T, Database

T = Vector of Technology Factors

Examples:
- New Smaller Electronics
- Mechanical vs. Hydraulic vs. Fly-by-Wire

Programmatic and Economic Factors, M, Database

M = Vector of Programmatic-Economic Factors

Examples:
- Age
- Schedule limitations
- Industrial Base Considerations
- Learning & Rate

Hypothesize equation forms with an understanding of technical design

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System Definitions

Define "Systems"

- Data is collected for each unit produced
- Need to aggregate units into "Systems"
  - Each will become a data point in regression analysis
- System:
  - Similar design and performance
  - Consistent weight
  - Comparable technology
  - Stable production runs

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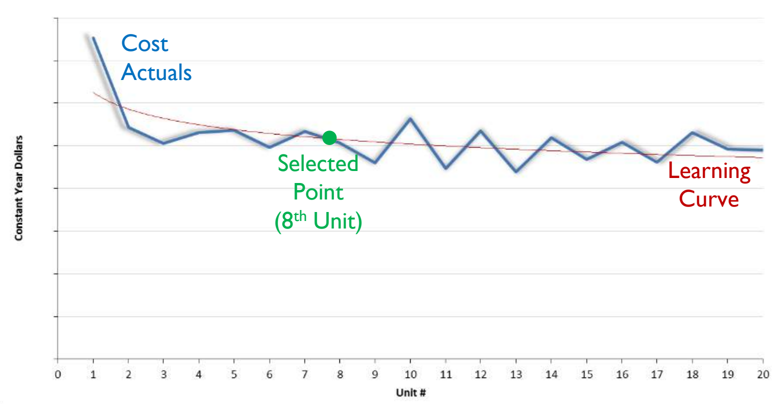
Data Normalization

- One representative cost data point is needed for each system
  - Technical Considerations: different engines, different manufacturers, different accounting, design modifications, etc.
  - Cost Considerations: Learning, different manufacturers, different data structures, escalation, rates, productivity, industrial base, etc.
- Technical Process: Discuss with Technical Subject Matter Experts
- Cost Process:
  1. Escalate all $ to a constant year Dollars
  2. Allocate all costs to the PBCM WBS
  3. Perform Learning Curve analysis for each WBS element
  4. Choose one consistent point on the resulting learning curves to use in the regression analysis



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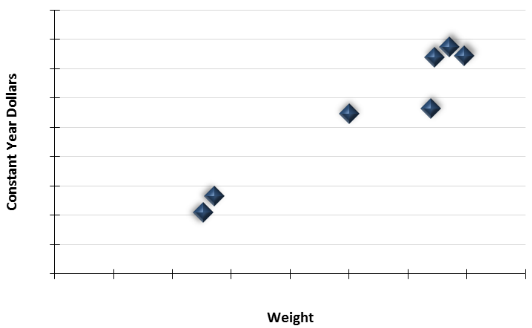
Relationships

- Relationships required for both technical characteristics and costs
  - Weight Relationships
  - Other Technical Relationships
  - Cost Estimating Relationships
  - Economics-Programmatic Relationships



- Process
  1. Conceptualize relationships
     - Based on engineering principles (physics-based)
     - Plot the data on scatter graphs
  2. Estimate parameters
     - Using various regression techniques
  3. Test parameters

Cost Modeling Structure

Unit Cost is given by:

Simple Model

Learning, rates, escalation, etc. — $/lb, $/HP, etc. — Weight (lb), power (HP), etc.

Unit Cost = (Programmatic and Economic Factors) × (Cost Parameter) × (Technical Characteristic)

Aggregate Model

$$\text{Unit Cost} = G(M) \times A(P, T, W) \times W(P, T)$$

Functions of derived from statistical & engineering analysis

- $G(M)$: Programmatic and Economic Factors
- $A(P, T, W)$: Weight, Technology, Performance
- $W(P, T)$: Technology, Performance

For a system with many systems, the equation becomes:

Detail Model

$$\text{Unit Cost} = G(M) \times \sum A_i(P_i, T_i, W_i) \times W_i(P_i, T_i, W_{j \neq i}(P, T))$$

Cost Realm — Technical Realm

System Numbers

i	Sea Systems WBS[1]
1	Hull Structure
2	Propulsion Plant
3	Electric Plant
4	Command, Communications, & Surveillance
5	Auxiliary Systems
6	Outfit and Furnishings
7	Armament
8	Total Ship Integration/Engineering
9	Ship Assembly and Support Services

- ***Performance factors impact both weight and CERs***
- ***Significant overlap of cost-technical community realms***
- ***Brings together economics-cost and physics***

[1] MIL-STD-881C
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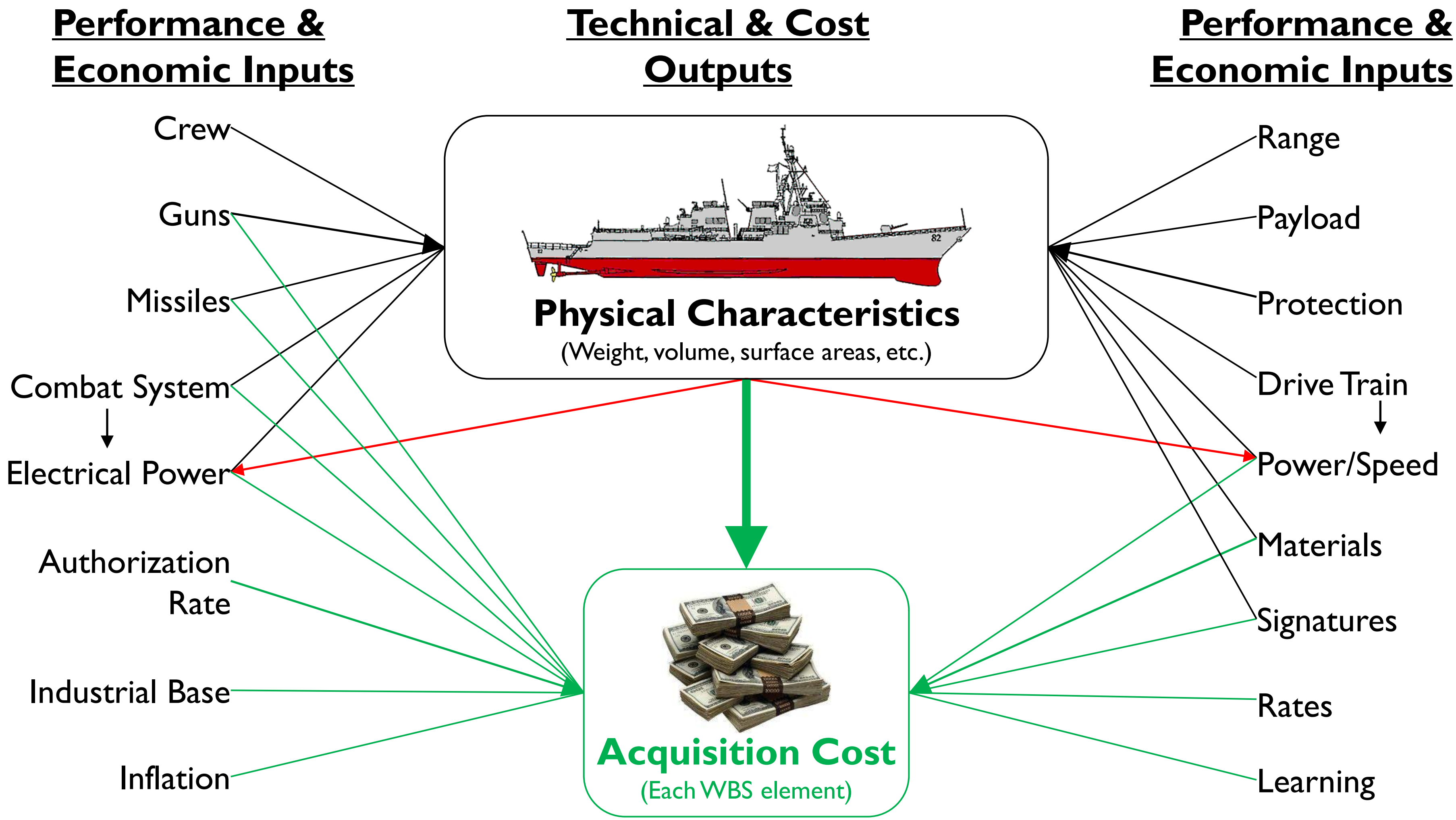
Appendix E: p. 89-94

Example Inputs and Outputs



Simultaneously estimates physical characteristics and cost

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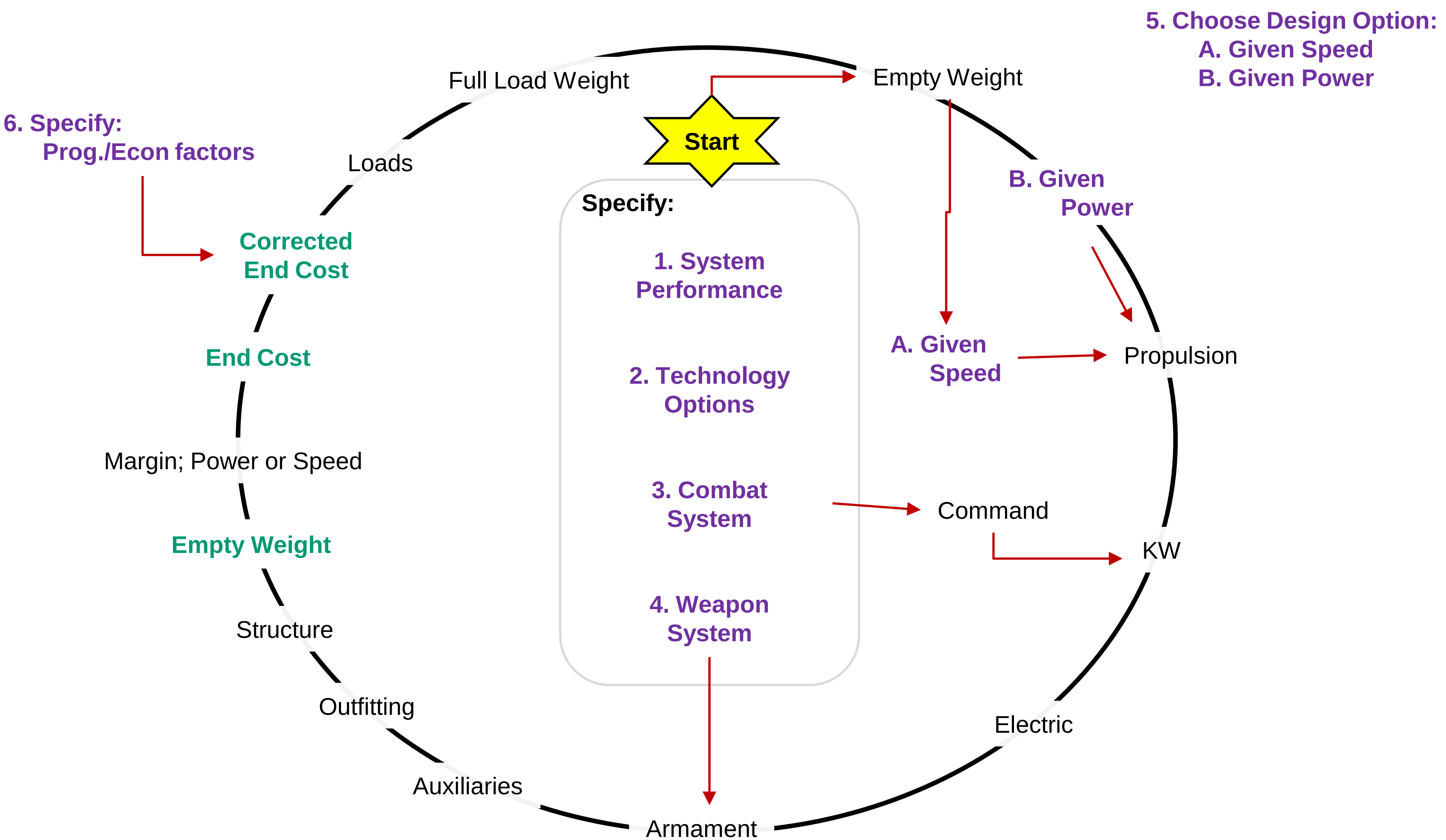
PBCM Operates as a "Synthesis Loop"



A PBCM includes a "parametric engineering" model that addresses system inter-relationships

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PBCM Implementation

- Implement PBCM as an Excel Workbook
- Plan for easy execution of various studies
  - Build model to execute completely in one column
  - A study (multiple related “runs”) can be built easily through copy and paste of columns
- Structure logically
  - Documentation and input section at top
  - Calculation Engine in middle
  - “Programmatic” adjustments below
  - Principle outputs collected at bottom
- Address calculation nuances
  - Total model is an inter-related system
    - Must allow “circular” calculations or won’t run
    - Need starting value (initial guess) for empty weight
- Adjust as needed to accommodate analysis needs
  - It does not take long to think of a problem the model is not set up for
- Post process outputs as necessary to provide insightful and meaningful display of results
- Create business rules to govern appropriate use of the model
  - Facilitates interaction between groups that are used to working separately and concerned about how the data will be used

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Using a PBCM

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Why would you want a PBCM?

- Increasing emphasis on pre-MS A cost analysis
  - Enable early understanding of cost implications of required capabilities
  - Avoid locking in unaffordable requirements at the very beginning of programs
  - Relevant concept designs & associated cost estimates are typically unavailable or, at best, very limited at this stage
- Expanded feasible trade space for AoAs and after
  - Supplements and fills gaps between formally developed concepts
  - Allows quick exploration of options and alternatives that arise after MS A in many programs ("Never Ending AoA")
- Independent check on more detailed methods
  - Provides traceability and historical context
  - Good platform for statistical risk analysis
- Facilitates the conversation among cost analysts, engineers, program managers, decision makers

Supplements and enhances more detailed Concept-Based Analysis

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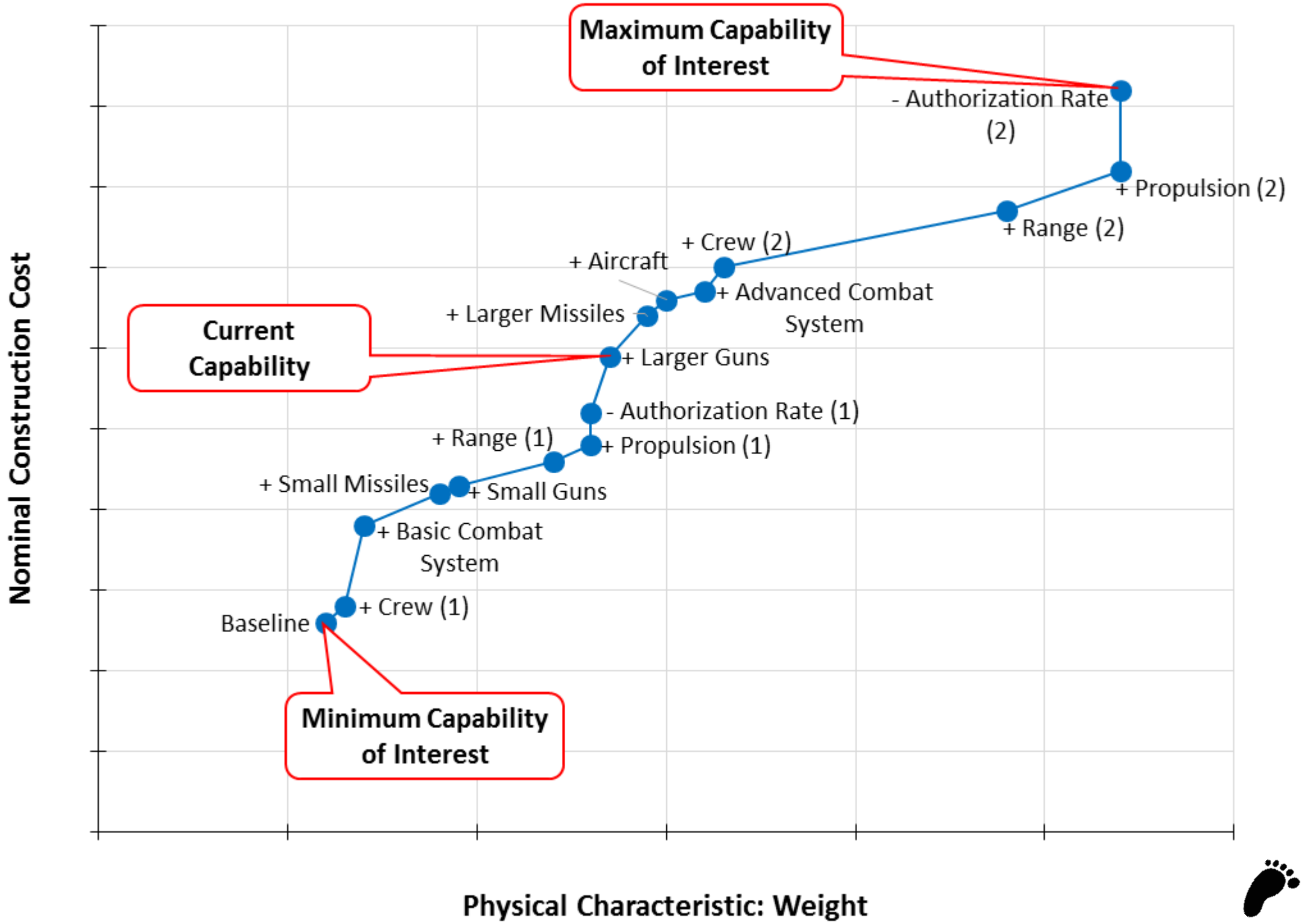
PBCM…What can it do?

Example PBCM Results – Walkabout Chart



Relative impacts of individual design/requirements can be clearly seen

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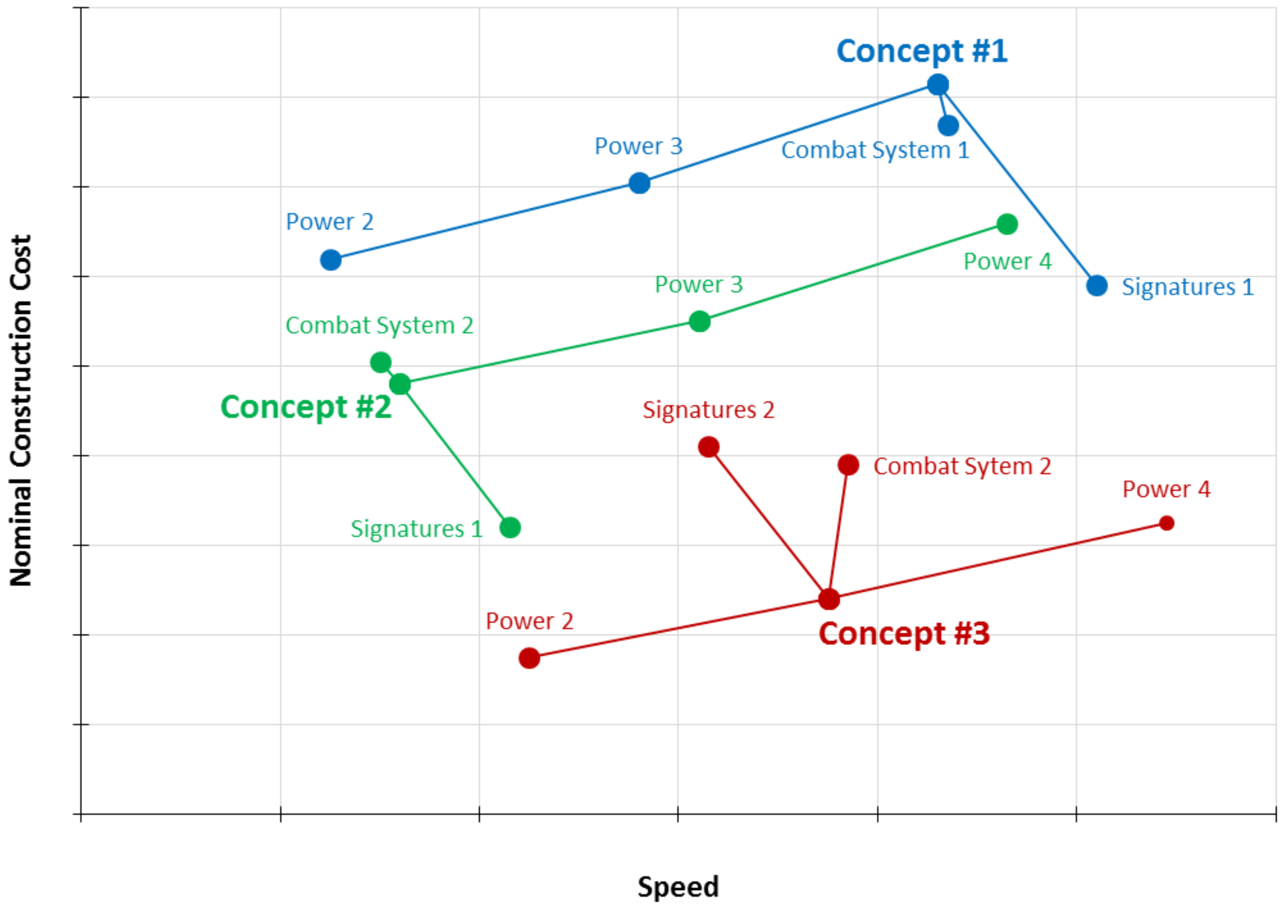
PBCM…What can it do?

Example PBCM Results – Spider Chart



What's a "dead spider"?

All it's legs go up, i.e., all the options increase cost

Illustrates impact of changing levels of multiple performance factors on individual concepts

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Conclusions
&
Future Work

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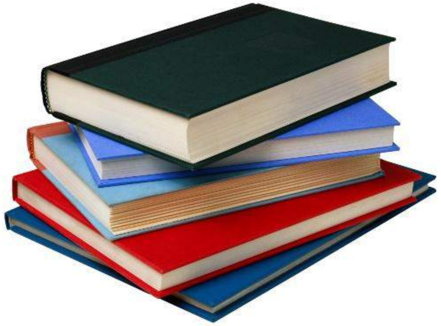
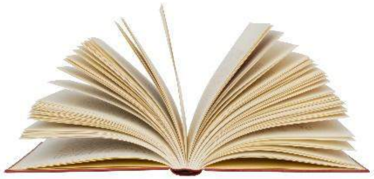
Further Benefits of a PBCM

- Cost and technical characteristics are directly related to performance requirements
- Equations are consistent with historical data and physics
- Enables sequential, orderly tradeoff studies
- Built on known error terms (for regression-derived relationships)
- Requires minimal input data to run excursions
- Fast
- Can validate via comparisons to historical database
- Can calibrate via use of other independent estimates



Future Work

- Establish PBCMs as a viable, consistent, and confident estimating tool for technical and cost communities
- Develop common understanding of how/when to apply PBCMs
  - Quick turn around/top level studies, pre MSA efforts, validate detailed models, sensitivity, populate risk data
- Integrate with technical communities
  - Create common baseline/interface between communities – increases and eases dialogue
  - Anchor to historically supported technical tools
  - Leverage vast technical databases and design efforts to further populate PBCMs – creates a feedback loop between communities
  - Use as a stepping stone to develop more robust integrated cost and design tools
- Use as a platform to bring operating and support cost visibility to early stage design



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Questions

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