Upgrading Complex Systems of Systems:

—A CAIV Methodology for Warfare Area Requirements Allocation

Georgia Institute of Technology

2nd Conference on the Economics of Test and Evaluation

3 November 1999

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Outline

- System of Systems Context
- System of Systems Cost/Performance Model Integration
- Naval Mine Countermeasures System of Systems
- Results:
  - Phase I: Closed Form Objective Function
  - Phase II: Simulation Objective Function
- Conclusions and Applications

System of Systems Context

Background

- Engineering of complex systems of systems has received increased recognition in recent years
- General Sheehan (Commander in Chief of Atlantic Forces), "Next Steps in Joint Force Integration," *Joint Force Quarterly*, January 1997:
  - ***"Victory will depend on the ability to master the 'system of systems' composed of multiservice hard- and soft-kill capabilities linked by advanced information technologies."***
- Admiral Owens (Vice Chairman of the Joint Chiefs of Staff), "The Emerging System of Systems," *U.S. Naval Institute Press*, May 1995:
  - ***"We have cultivated a planning programming and budgeting system that tends to handle programs as discrete entities…Yet, the interactions and synergisms of these systems constitute something new and very important. What is happening is driven in part by broad conceptual architectures---and in part by serendipity: It is the creation of a new system of systems."***
- Although system of systems engineering and operational challenges are well-stated, effective architecting approaches are still immature

USERS OUT IN FRONT OF SYSTEM ENGINEERING AND ACQUISITION PROCESSES

System of Systems Management Issues

- System of Systems Challenge:
  - Full system is actually an interoperating collection of systems
  - Each component system in different life-cycle stage
  - No opportunity to develop a completely new system of systems
  - Must build upon what there is to get something better
- What is the best allocation of top-level system of systems requirements?
  - New system(s)?
  - Additional legacy system(s)?
  - Advanced technology insertion into legacy system(s)?
- Constraints and boundary conditions:
  - Budgets/politics
  - Changing or emergent mission objectives
  - Technology potential, possible COTS mandate

Rarely get to start from scratch: Think "upgrades."

Usual System of Systems Upgrade Approach

- DoD Acquisition Process focuses on one system at a time
- Single System "Analysis of Alternatives"
- Typical methodologies
  - Hypothesize discrete set of reasonable alternatives/configurations
  - Utilize repeated modeling and simulation runs of an "engagement" or "campaign" with and without various competing notional system capabilities
  - May include multi-objective metric to balance performance, cost, and marginal utility to the larger system of systems
  - May assemble a panel of experts for qualitative assessments
  - Generally considers adding or replacing just one system at a time
- DoD decisionmakers seem to prefer <u>quantitative</u> "engineering analysis" over <u>qualitative</u> "decision support" methods such as the Analytic Hierarchy Process
  - Although ultimate decisions are subjective, desire objectively-derived alternatives
  - Since system of systems interactions and dependencies are difficult to quantify, may be overlooked

System of Systems Cost/Performance Model Integration

System of Systems CAIV Optimization Process

GOAL:

Develop and demonstrate a quantitative process to support complex systems requirements allocation as a function of cost.

From the system of systems performance perspective, where are the limited resources best applied?

Development Objectives

- Develop a quantitative process for complex system of systems cost-performance decision support
    - Enable a domain expert system architect or engineering team to generate "optimal" suites of requirements allocations as a function of total cost
    - "Optimal" with respect to specified top-level MOE and stated constraints
- Demonstrate the process on one real-world system of systems: Mine Countermeasures
    - Scope: practical, proof-of-principle
    - Phase I: Closed form equations that relate system design parameters to system of systems effectiveness
    - Phase II: Extend to utilize stochastic simulation

Decision Objectives and Boundary Conditions

- Two potential top-level objective approaches that incorporate cost:
  - Maximize system of systems performance subject to cost constraint
  - Minimize upgrade costs to meet performance thresholds
- Cost constraints
  - Flexibility: Willing to trade performance for cost savings
  - DoD Reform Initiative: Cost as Independent Variable (CAIV)
    - Requires modeling performance as function of cost: Performance Based Cost Model (PBCM)
- Performance constraints
  - Minimum thresholds for single system (or subsystem) Measures of Effectiveness (MOEs)
  - Minimum thresholds for secondary system of systems MOEs
  - Implicit technology limitations on design Measures of Performance (MOPs)
  - Sensitivity analysis of constraint thresholds yields insights relative to long-term technology investment strategy

CAIV Requirements Allocation Process

System Architecture Definition

Components/Functionality
Mission(s)
Scenarios

MOE/MOP Definition

Overarching MOE
Secondary MOE(s)
Component Systems MOPs

Specify Boundary Conditions

Component Cost Constraints
Technology Constraints
Force Structure Constraints
Secondary MOE Thresholds

Formulate Performance-Based Cost Models

Cost=h(MOP)

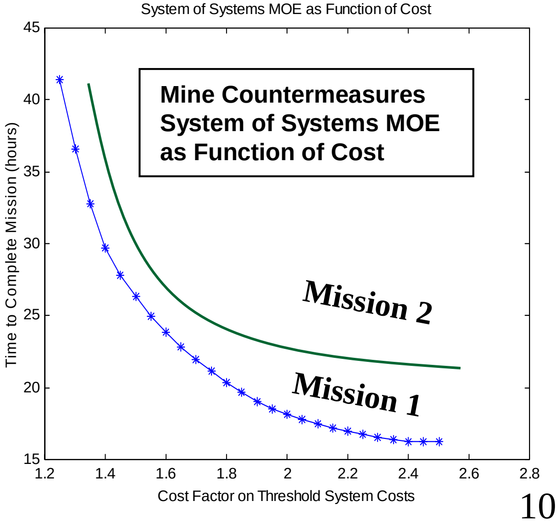
Develop/Adopt Systems Performance Models/Simulations

MOE=G(MOPs)

Optimization Processing [Deterministic or Simulation-Based]

Adjust Overall Cost Constraint

System of Systems
Parameters/Performance
as a Function of Cost
[MOE/MOP Estimates]



Integration of Cost and Performance Models

Challenges

- Defining the system of systems itself (boundaries)
- Defining Measures of Effectiveness (MOEs) for the system of systems
- Selection of Trade Space MOPs and allocation to system components
  - MOPs must map to top-level MOEs
  - MOPs must be cost-drivers when other system attributes are fixed
- Adaptation/adoption of appropriate performance model
  - Closed -form expressions are easiest to implement/optimize
  - Selection of appropriate simulation to represent inevitable random processes
- Performance Based Cost Models
  - Cost as function of performance over realistic MOP range
  - Information generally exists, but not synchronized with performance models
- Application of efficient and appropriate optimization algorithms
- Verification and Validation of process and models

Integration of Cost/Performance Models

System of Systems Optimization Examples

Mine Countermeasures

Min [*Time to Complete Area Clearance*]

Subject to: *Mine Clearance Percentage*>*q*
Total System of Systems Cost<C_k

DD21 Land Attack

Max [*No. of Destroyed Targets Ashore*]

Subject to:	Prob [*Raid Annihilation*]>*a%*	Engage Air Threats
	Prob [*First Strike*]>*b%*	Engage Submarine Threats
	Area Search Level>*c%*	Off-Board MIW
	Area Search Rate>*d%*	Off-Board MIW
	Mine Localization Accuracy>*e%*	Off-Board MIW
	Prob [*Mine Avoidance*]>*f%*	On-Board MIW
	Prob [*Successful Engagement*]>*g%*	Engage Surface Threats
	Total System of Systems Cost<C_k	

Cost as Independent Variable (CAIV) Approach

Notation for General Case

- n types of systems that comprise a system of systems, S $$S=\{S_1,\ldots,S_n\}$$
- m_i systems of type i, m total systems $$\mathbf{m}=\{m_1,\ldots,m_n\} \qquad m=\sum_{i=1}^{n} m_i$$
- r_i MOPs for each system type $$\mathbf{p}_i=\{p_{i,1},\ldots,p_{i,r_i}\} \qquad r=\sum_{i=1}^{n} r_i$$
- One overarching MOE for S $$E=\mathrm{G}(\mathbf{m},\mathbf{p}_1,\ldots,\mathbf{p}_n)$$
- Unit cost for S_i :
  - Nonlinear function of performance parameters $$c_i=\mathrm{h}_i(\mathbf{p}_i)$$
  - Total system of systems cost: $$C=\mathbf{m}\mathbf{c}^T \qquad \mathbf{c}=\{c_1,\ldots,c_n\}$$

$$\mathrm{Max}\,E=G(\mathbf{m},\mathbf{p}_1,\ldots,\mathbf{p}_n)$$

subject to:

$$\mathbf{m}^L \le \mathbf{m} \le \mathbf{m}^U$$

$$\mathbf{p}_i^L \le \mathbf{p}_i \le \mathbf{p}_i^U$$

$$\mathrm{q}(\mathbf{m},\mathbf{p}_1,\mathbf{p}_2,\ldots,\mathbf{p}_n) \ge \mathrm{q}_T$$

$$C(\mathbf{m},\mathbf{p}_1,\mathbf{p}_2,\ldots,\mathbf{p}_n) \le C_k^U$$

where :

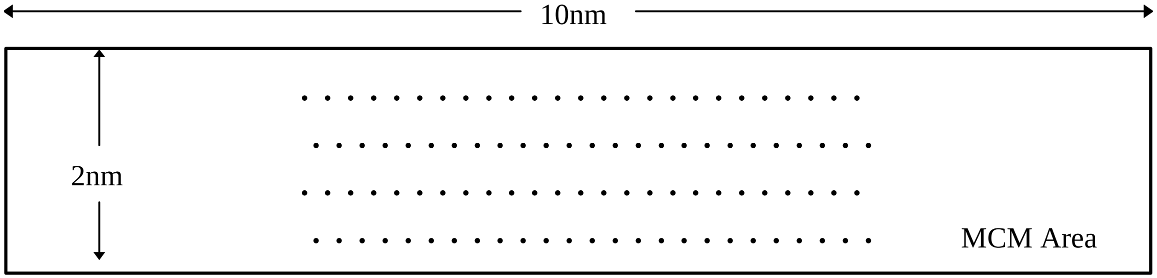
1. $\mathrm{C}_k^U = \mathrm{costfactor}_k \cdot \mathrm{C}^*$ is a sequence of cost upper bounds
2. C^* is cost to produce the threshold system of systems defined by $\{\mathrm{m}^L, \mathrm{p}_1^*, \ldots, \mathrm{p}_n^*\}$ -- minimum systems and threshold MOP values.

Naval Mine Countermeasures System of Systems

Naval Mine Countermeasures System of Systems

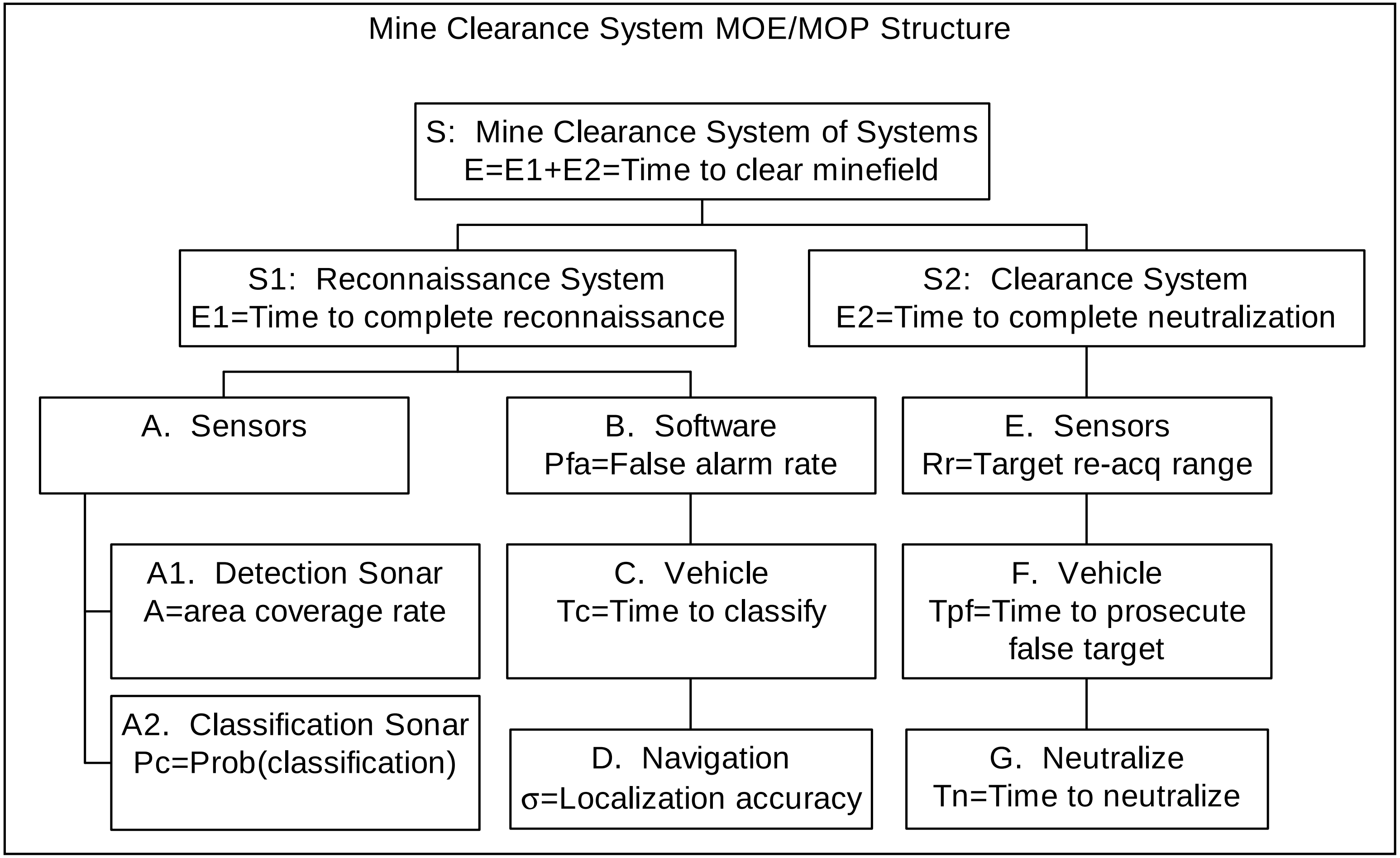
S: Simplified Mine Clearance System of Systems

- Two systems operating in sequence
  - S_1: Minefield Reconnaissance System
    - Survey entire suspected minefield area
    - Attempts to detect, classify, and localize all “mine-like objects”
  - S_2: Mine Neutralization System
    - Accept survey information and neutralize all mines
    - Attempts to re-acquire, identify, and place/detonate explosive charge
- Measures of Effectiveness
  - E: time required to complete minefield recon and neutralization ops
  - q: Quality threshold on the per-mine clearance probability necessary to achieve a specified minimum area clearance rate, α, with a certain degree of confidence, β



Performance Based Cost Models

- Associate MOPs with the subsystem to which they are major cost drivers
- Develop approximations of subsystem costs as a function of those primary subsystem MOPs



Mine Clearance System MOE/MOP Structure

S: Mine Clearance System of Systems
E=E1+E2=Time to clear minefield

S1: Reconnaissance System
E1=Time to complete reconnaissance

S2: Clearance System
E2=Time to complete neutralization

A. Sensors

A1. Detection Sonar
A=area coverage rate

A2. Classification Sonar
Pc=Prob(classification)

B. Software
Pfa=False alarm rate

C. Vehicle
Tc=Time to classify

D. Navigation
σ=Localization accuracy

E. Sensors
Rr=Target re-acq range

F. Vehicle
Tpf=Time to prosecute false target

G. Neutralize
Tn=Time to neutralize

PBCM Example: Area Coverage Rate, A

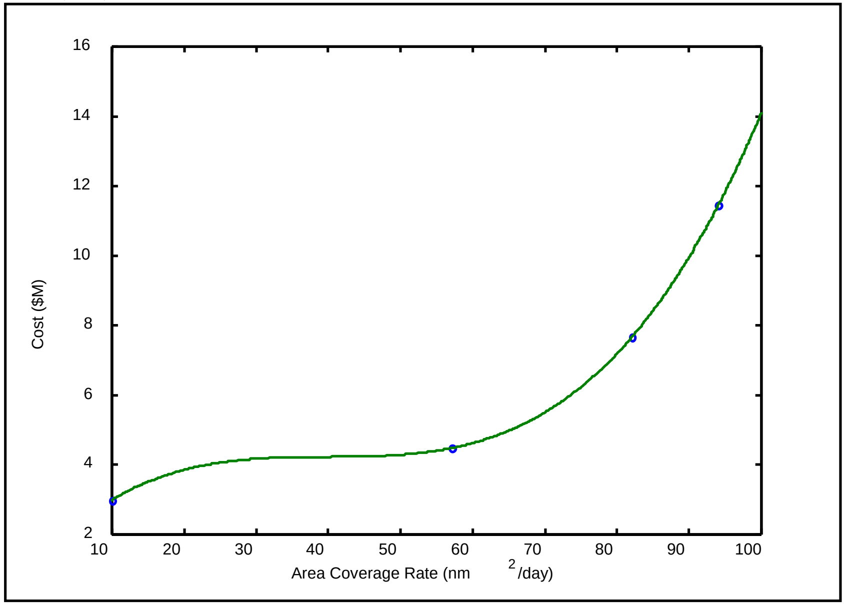
- Assumptions:*
  - Fixed $P_d = 0.90$, vehicle speed =7 knots
  - Some systems require several vehicle sorties
- Data points:

A (nm^2/day)	10	57	82	94
Cost ($M)	3	4.483	7.655	11.445

- PBCM:

$$p_{1,1}^{L} = 10,\ \ p_{1,1}^{U} = 100,\ \ p_{1,1}^{*} = 10$$

$$\mathrm{h}_{1,1}\left(p_{1,1}\right) = (4.5034\mathrm{e} - 005)\ p_{1,1}^{\ 3}\ -\ 0.0053861\, p_{1,1}^{\ 2}\ +\ 0.21593\ p_{1,1} + 1.3342$$



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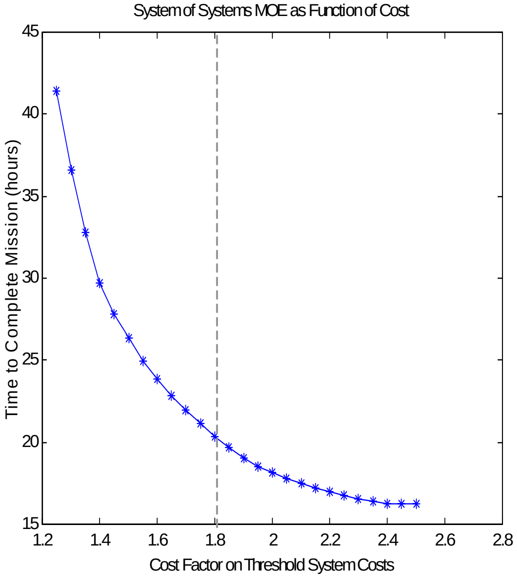
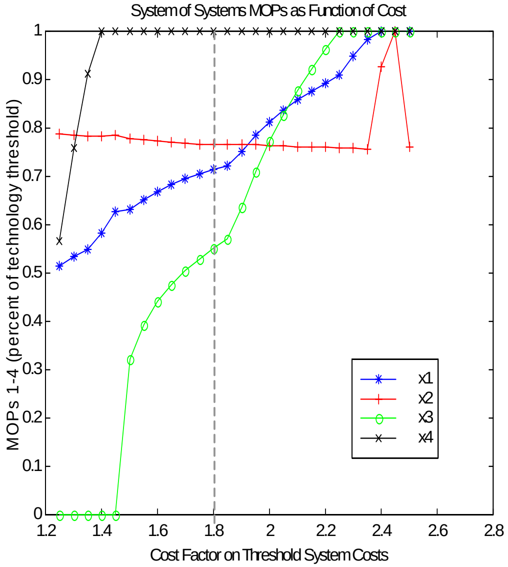
* Benedict. J. R., (1996). Final Report: Long-Term Mine Reconnaissance System (LMRS) Cost and Operational Effectiveness Analysis (COEA), Johns Hopkins University Applied Physics Laboratory Report NWA-96-009, September 1996.

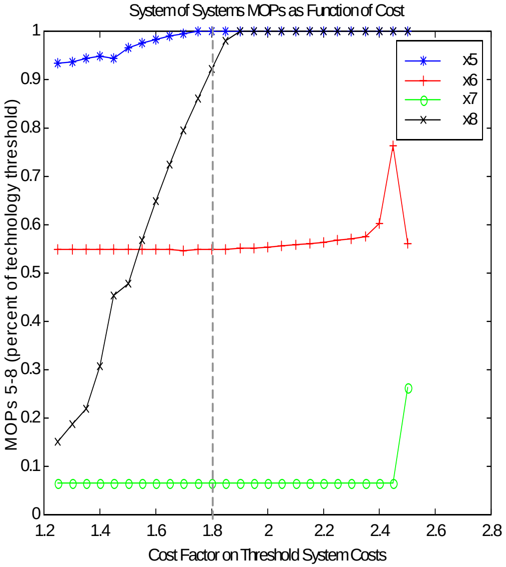
Numerical Results

- Phase I: Closed Form Objective Function
  - Non-Stochastic, “Deterministic” Analysis
  - Can Be Used with “Expected Value” Models
  - Used as Baseline for Phase II
- Phase II: Simulation as the Objective Function
  - Stochastic Models and Simulation
  - More Realistic Representation of System Behaviors and Interactions

Phase I: Closed Form Objective Function







- *E* improves steadily to asymptotic level as cost constraint is relaxed
- Must spend at least 1.25C* to meet clearance rate constraint of 84.6%
- Knee of the MOE curve at approximately 1.80C*: requirements allocation shown on MOP curves
- Component systems’ MOP requirements can be easily determined in a CAIV approach
  - Initial performance gained by improving x_4 (speed) and x_5 (location accuracy)
  - Additional performance gains are most effectively achieved by improving: x_1 (coverage rate), x_3 (FAR), and x_8 (neutral. Time)

Phase II: Simulation as the Objective Function

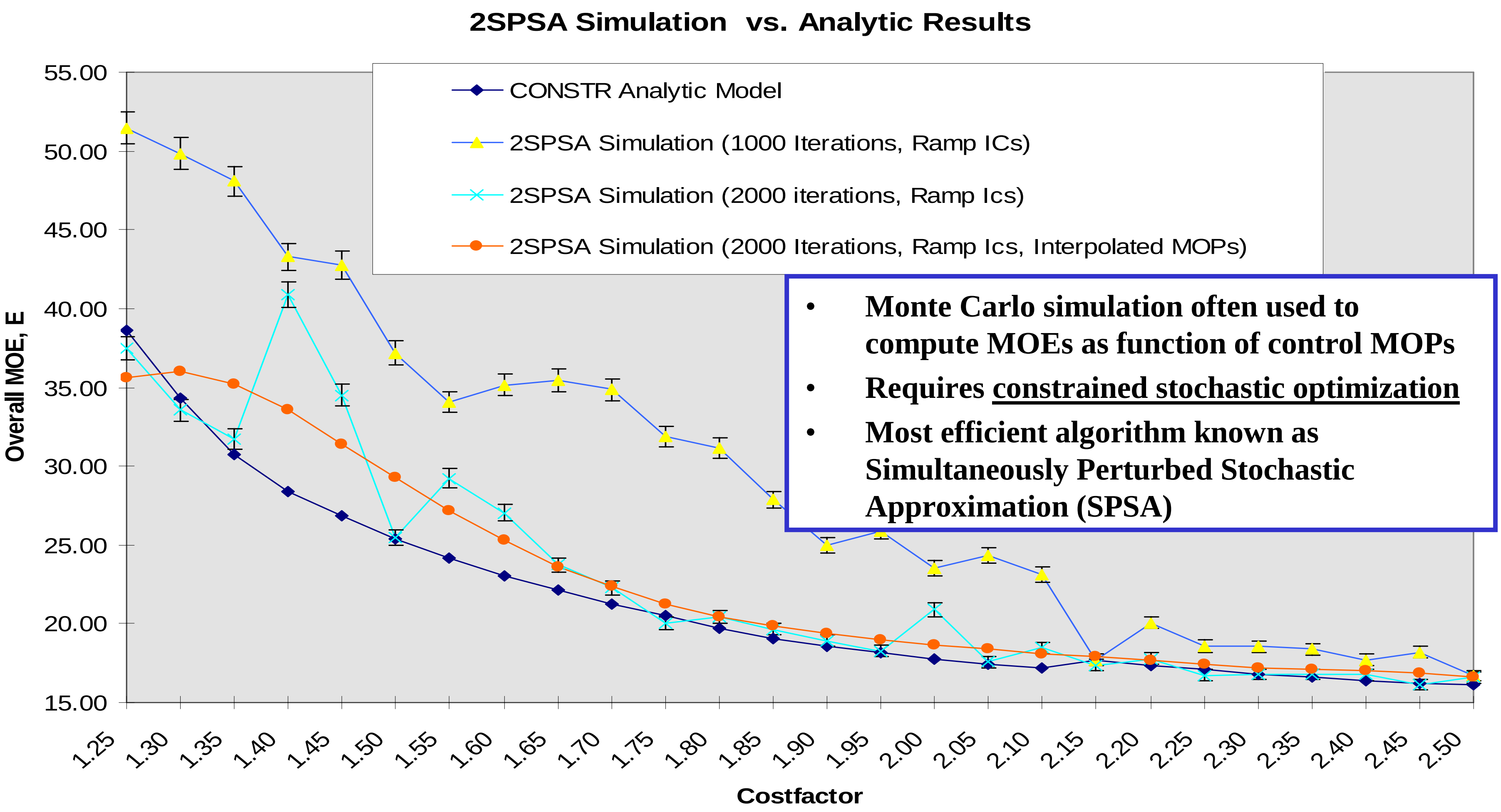
- Complex systems of systems analyses utilize simulation to calculate effectiveness measures
- Campaign or engagement simulations usually Monte Carlo
  - Objective function form:

$$E = G(\mathbf{m}, \mathbf{p_1}, \ldots, \mathbf{p_n}, \omega)$$

where ω represents simulation noise.

  - Extends the nonlinear programming problem to the domain of stochastic approximation
  - Also necessary when representing stochastic nature of cost estimates
- Most efficient stochastic optimization algorithm known as Simultaneously Perturbed Stochastic Approximation (SPSA)

Phase II: Practical Implementation and Final Results



- **Monte Carlo simulation often used to compute MOEs as function of control MOPs**
- **Requires constrained stochastic optimization**
- **Most efficient algorithm known as Simultaneously Perturbed Stochastic Approximation (SPSA)**

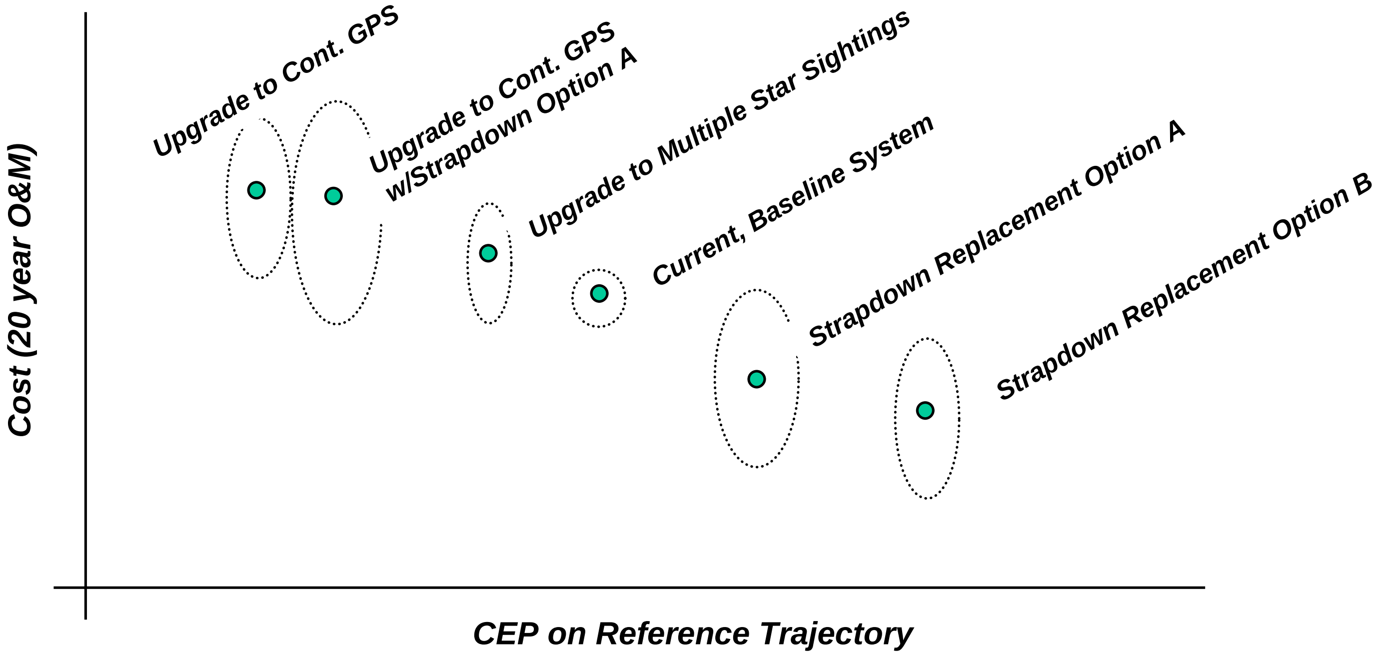
Sufficient Iterations and Interpolation of MOP Estimates Provides Excellent System of Systems Performance and Usable Parameter Estimates

PBCM Development Process (1)

PBCM Development: An Iterative Process in Collaboration With Industry:

- Identify cost driver MOPs for each sub-system
- Identify alternative approaches that affect cost/performance
- Estimate ROM performance and cost for each alternative, including uncertainties
- Refine estimates for each alternative
- Construct PBCM functional relationship across feasible MOP range

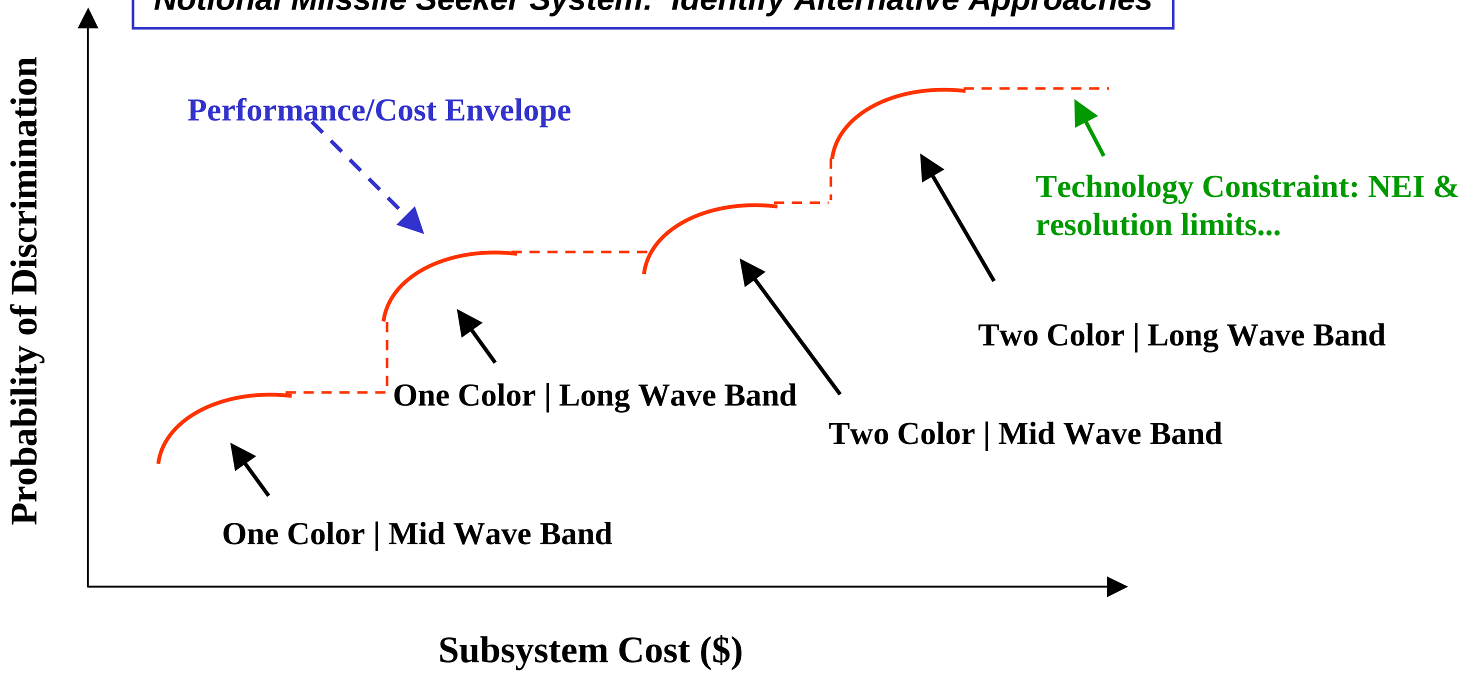
Notional MiissileGuidance System: Identify Alternative Approaches



PBCM Development Process (2)

- Realistic PBCMs not smooth curves:
  - Alternatives characterized by disparate technologies or approaches
  - Refinements create clusters of data points about each technology alternative
  - Result is either discrete or piecewise continuous

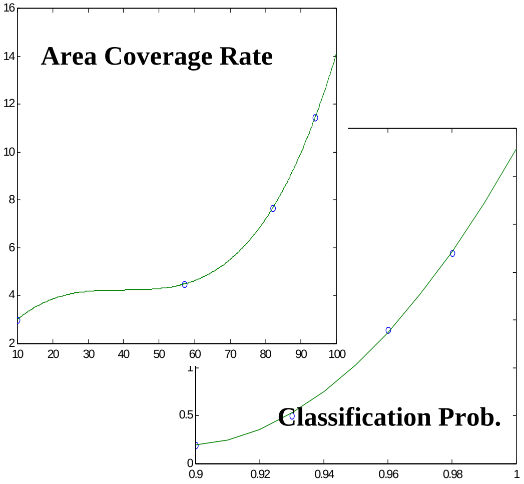
Notional Miissile Seeker System: Identify Alternative Approaches

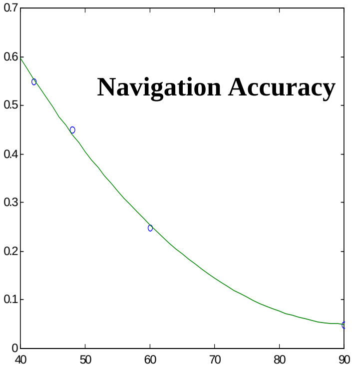


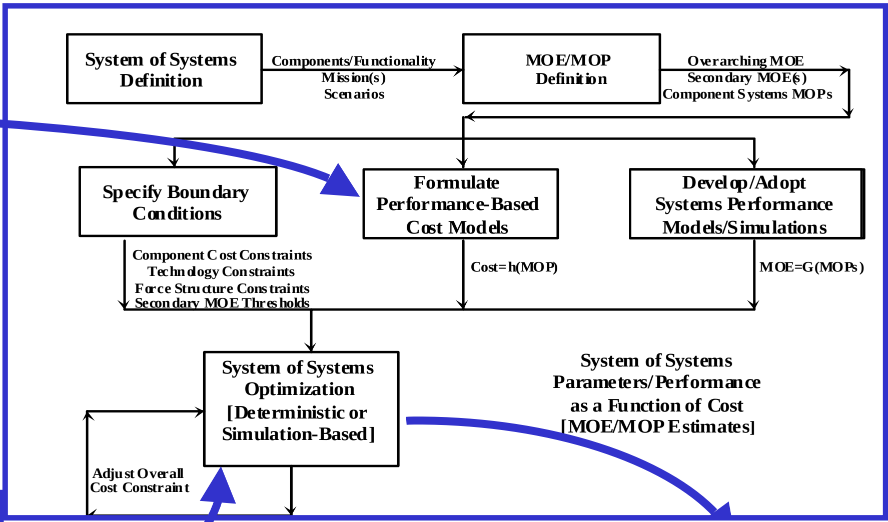
Integrated Cost-Performance Modeling

...for Requirements Allocation and Technology Investment Strategy Development

PERFORMANCE-BASED COST MODELS







System of Systems Definition

MOE/MOP Definition

Specify Boundary Conditions

Formulate Performance-Based Cost Models

Develop/Adopt Systems Performance Models/Simulations

System of Systems Optimization [Deterministic or Simulation-Based]

System of Systems Parameters/Performance as a Function of Cost [MOE/MOP Estimates]

Minimize: System of Systems Overarching MOE

Subject to:

Total Cost $< C^U$

$P_1^L < MOP_1 < P_1^U$

$P_2^L < MOP_2 < P_2^U$

$\vdots$

$P_n^L < MOP_n < P_n^U$

Technology Constraints

$m_1^L < \#\text{ Units Sys}_1 < m_1^U$

$m_2^L < \#\text{ Units Sys}_2 < m_2^U$

$\vdots$

$m_n^L < \#\text{ Units Sys}_n < m_n^U$

Inventory Constraints

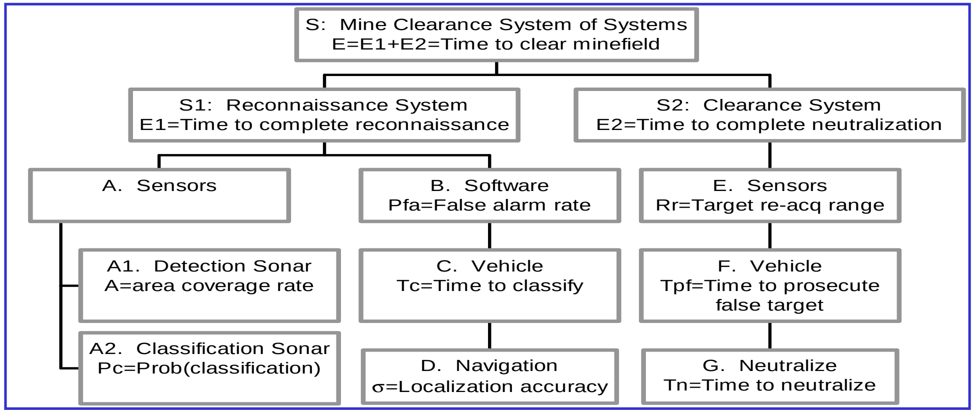
$MOE_1 < E_1^U$

$MOE_2 < E_2^U$

$\vdots$

$MOE_m < E_m^U$

Secondary MOE Constraints



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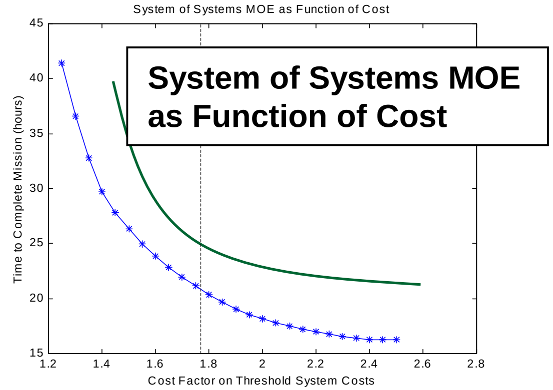
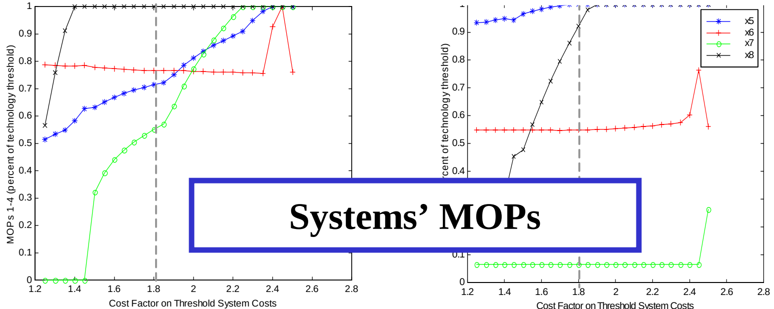


System of Systems MOE as Function of Cost



Systems' MOPs

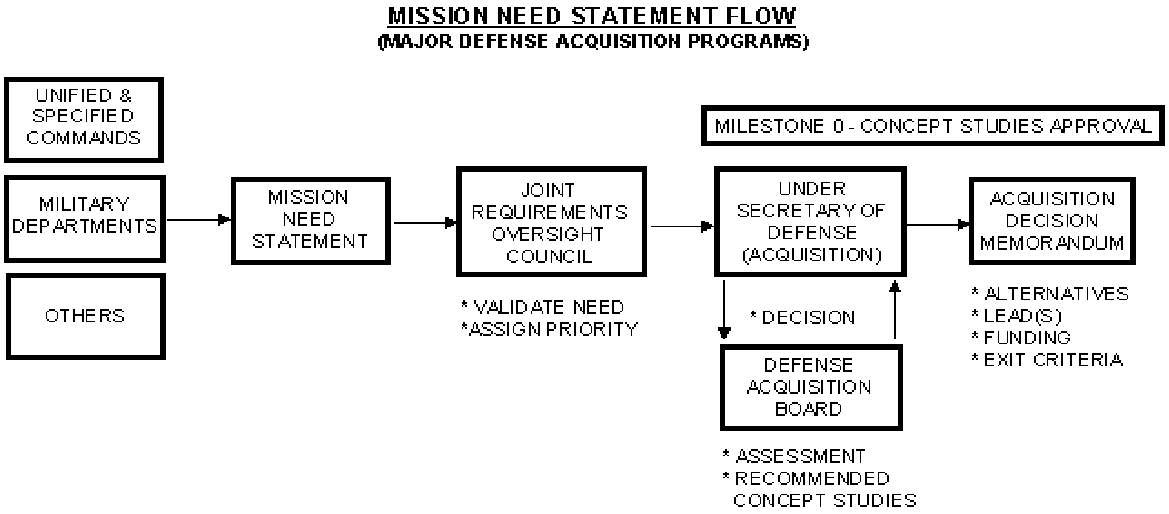
Conclusions and Applications

Conclusions

- Quantitative methodology for requirements allocation developed/demonstrated
- Alternative to treating each subsystem individually
- Cost-Performance Analysis Process Produces Optimal:
  - System effectiveness as function of cost (CAIV)
  - Corresponding subsystem MOP requirements allocations
  - Force structure or inputs to force level cost/performance analysis
- Sensitivity Analysis Produces:
  - Insights into threat, mission and system architecture assumptions
  - Insights necessary for effective technology investment strategy
- Enables continuing CAIV assessment of simultaneous technology insertion alternatives
- Successful application requires collaboration between:
  - Parametric cost modelers
  - Warfare area analysis and M&S experts
  - Industry

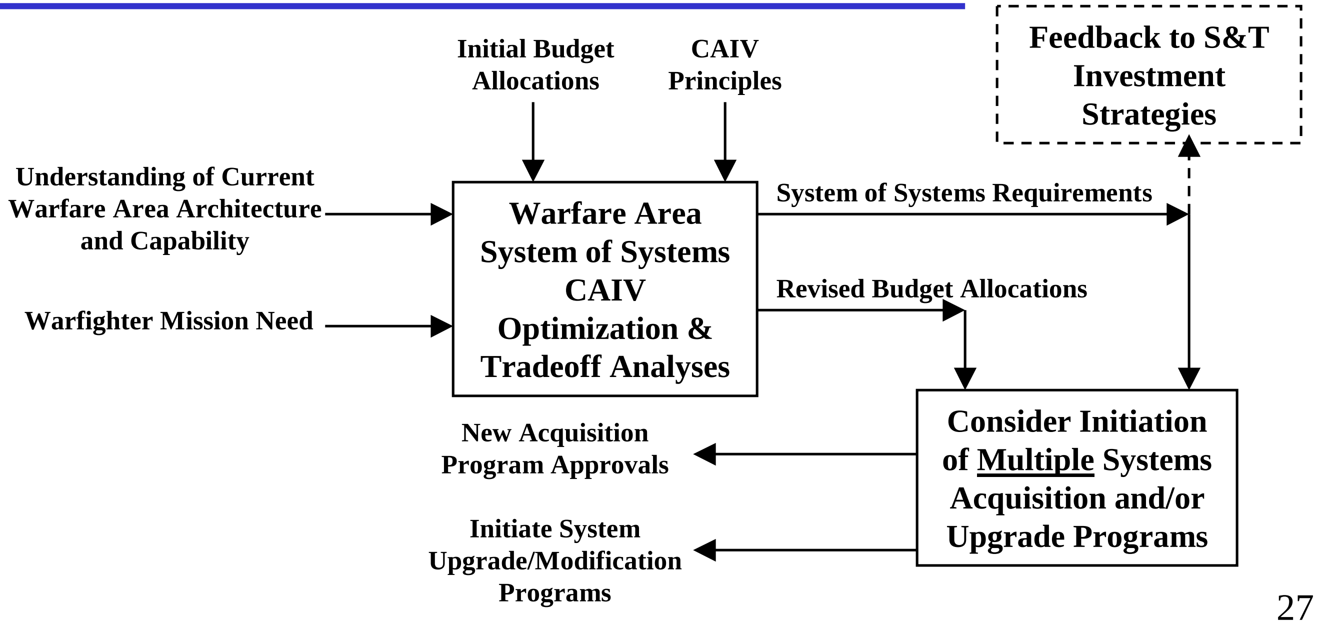
Paradigm Shift to *System of Systems* Acquisition

Requirements Process Focuses to Single Service and Single System Solutions



Warfare Area Architecting:

Adopt Warfighter's System of Systems Perspective During Concept Exploration Phase



The Way Ahead

- The system of systems process/methodology can be used for warfare area requirements allocation
  - Component systems' requirements development
  - Technology insertion strategy
  - Force sizing (fix MOPs and let force levels vary)
  - Analyses of Alternatives (COEAs)
  - Technology development strategy (relax MOP constraints and/or PBCMs)
- A practical method for applying cost as the independent variable (CAIV) at the warfare area level
  - Objective analysis provides cost-ordered set of system alternatives
  - Requires early integration of performance and cost modeling
- Management Challenge: Embrace the vision for implementing an acquisition paradigm shift to "systems of systems"
- Current applications:
  - MCM Future Systems Study for ONR
  - Navy Theater Wide Ballistic Missile Defense