

DEFINING THE “TRADE SPACE” FOR CAIV: A PILOT STUDY

Joseph. F. Krupa, Westinghouse Savannah River Co.
Paul J. Componation, The University of Alabama in Huntsville

Abstract

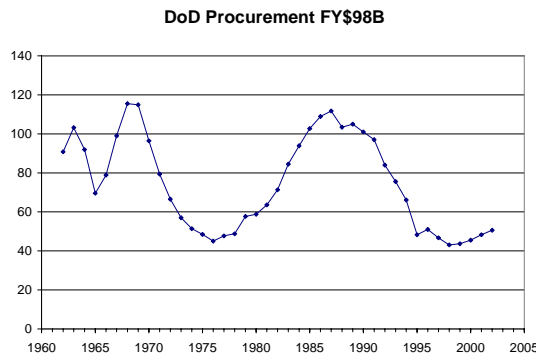
In 1995, Dr. Paul Kaminski, then Undersecretary for Defense for Acquisition and Technology, established CAIV — “Cost as an Independent Variable” — to emulate commercial use of Target Costing, which had allowed significant reductions in development time, and end item cost. In CAIV, Key Performance Parameters (KPPs) are limited to the critical few, thresholds and desired levels of performance are established, and performance is traded with cost in the “Trade Space”. However, a clear process has not emerged. This paper presents a pilot that proposes a foundation for a CAIV Trade Space methodology and proposes next steps for the continuation of this research effort.

Introduction

The functionality of systems continues to increase. Improvements in design, technology and integration have all contributed. The increases in functionality have also increased the complexity and cost to design and build these systems, and this has created significant problems for project managers, business managers and engineers. This has affected not only the private sector, but the public sector as well.

With the fall of the Soviet hegemony in the early 1990’s, pressures mounted for a “peace dividend” from the close of the Cold War. Public expectation was that defense expenditures would decrease significantly since the threat of global nuclear war was no longer a prime concern. The projected DoD systems acquisition budget in FY98 dollars is shown graphically below:

Exhibit 1. DoD Procurement Budget in FY98 \$B.



At the same time, however, the cost of defense systems was increasing dramatically. Meanwhile, U.S. commercial aviation firms were successfully implementing a Japanese systems development management method, Target Costing, to decrease the cycle time and cost of delivering complex commercial products. Boeing successfully implemented Target Costing to decrease the time from conception of the 777-200 from seven years to four years. They were not only able to hold to a tight schedule, but were able to meet all customer requirements and, more significantly, show a profit.

In Japan, the use of Target Costing and associated tools has become a high art. The process starts with assessing the customer perspective using tools like Quality Function Deployment. The product price, determined by subtracting desired profit from perceived customer value, is broken down into product subsystems. Zero and First look Value Engineering (VE) are used to push down subsystem costs to meet targets, while providing the desired quality and functionality. As the product goes to manufacturing, Kaizen Costing and Third look VE are used to address issues that drive subsystems costs up. The key is not minimizing costs, but having the most quality and functionality at a cost that the consumer feels is competitive. DoD procurements were not as successful. The B-2 bomber was projected to cost \$500 million, and ended up at \$2 billion per bomber. The C-17 was initially projected at \$100 million and currently costs \$360 million per unit. Both systems have deficiencies that require significant increases over projected maintenance per flight hour.

The defense community has seen many reform initiatives, including such things as “Design to Cost” (DTC). DTC attempted to set system costs, but there was no formal methodology to seek lower costs. In actuality, performance was the key driver, not cost. The drive to keep performance ahead of the Soviets caused many technologically immature concepts to be included in designs.

Dr. Paul Kaminski, then Undersecretary for Defense for Acquisition, Technology and Development, viewed this as an opportunity to change the way the DoD acquired high technology systems. In 1995, the concept of “Cost as an Independent Variable” or CAIV was born (Kaminski, 1995). CAIV is defined as managing cost as a constraint along with

performance and schedule to achieve a desired objective (DoD 5000.2R, (June, 2001)).

Key elements of CAIV include:

- Limiting the number of Key Performance Parameters (KPP).
- Developing early aggressive cost thresholds for systems.
- Trading off cost for schedule and performance.

Problem

Most discussions of CAIV concentrate on the “soft” side of implementation. This includes creation of Integrated Product Teams (IPTs) and contractor incentives. Steps for developing the “Trade Space”—the arena where decision-makers can make choices between system cost, schedule and performance—have not been formally developed.

CAIV has been proposed as an important part of a Systems Engineer’s toolkit (Brady, 2001). Systems Engineering Processes are considered mature if they are defined (written down), implemented in a consistent manner, and subject to continuous improvement (CMMi SE/SW, 2002). Although many articles and papers which discuss CAIV refer to the “Trade Space”, only one proposes any methodology for

developing it (Chollar and Peplinski, 1999), and the methodology proposed is incomplete (Exhibit 2).

Methodology

The general philosophy of CAIV has been explored, however, implementation methodologies for CAIV are not as well developed. This paper addresses the question, “Can an effective CAIV methodology for the formal definition of a “Trade Space” be created from existing Systems Engineering Tools and Techniques?” To answer this, a pilot study was conducted that provides a mathematically viable and consistent method of comparing cost to multiple performance variables in the “Trade Space”.

Most of the discussion of CAIV is in conference proceedings, DoD manuals, and DoD related internet web pages. Brady (2001) wrote an article on CAIV as an essential part of systems engineering for the *Systems Engineering*, the Journal of the International Council on Systems Engineering (INCOSE).

The papers reviewed consistently emphasized the goals and philosophy of CAIV implementation. Only in Chollar and Peplinski (1999) is a depiction of “Trade Space” actually developed. They used response surface methodology to model parametric estimates for two related components. This allowed them to represent cost as a third dimension against the two performance parameters.

Exhibit 2. CAIV Topics.

Source	Aggressive Cost Goals	Minimum KPPs	Thresholds & Minimums	IPTs	Incentives	Trades	Trade Methods
Azama, 1999	√			√	√	√	
CAIV WG, 1995	√			√	√	√	
Kaminski, 1996	√		√	√			
Kaye et al, 2000	√	√	√	√	√	√	
Kaminski, 1997	√	√		√	√	√	
Higgins, 1997	√	√	√			√	
Conrow, 1996	√	√				√	
Lewis, 1999	√	√				√	
Tyson, 1998	√	√	√	√	√	√	
Grasso, 2000	√			√	√		
Ruta, 2000	√			√	√	√	
Chollar and Peplinski, 1999				√		√	√
Brantley, 2002						√	
Luman, 1998	√	√	√			√	
Blev, 1997	√			√		√	
Brandy, 2001	√					√	
Coleman, 1999	√	√	√	√	√	√	
Hildebrandt, 1998					√	√	
Percentage	89%	44%	33%	67%	56%	83%	6%

It is unclear how more KPPs, i.e., more dimensions, would be treated to allow determination of

an “optimum” set. Luman (1998) discusses stochastic optimization, but provides no examples in the paper.

CAIV's was rooted in the success of US aerospace companies implementing Target Costing. Rocketdyne used Target Costing on the RS-68 to reduce production unit costs by 50%, non-recurring costs by 65% and time to market by 60%. Boeing used Target Costing (which they call Market Driven Target Cost) to reduce the costs of the Scandinavian Belly-Loader by 72% and the Boeing 757-300 by 43%.

This paper reports the results of our pilot study, where a proposed CAIV methodology was applied at the system requirements level. The methodology is comparable to the Market-driven costing phase of Target Cost implementation (Cooper, 1997). Since the purpose of a CAIV methodology is to develop a decision process, it is important that it be "transparent", i.e., it must provide a defined logic that can be examined, understood and reproduced (Goodwin and Wright, 1998). This follows the logic of the Capability Maturity Model (CMMi SE/SW, 2002).

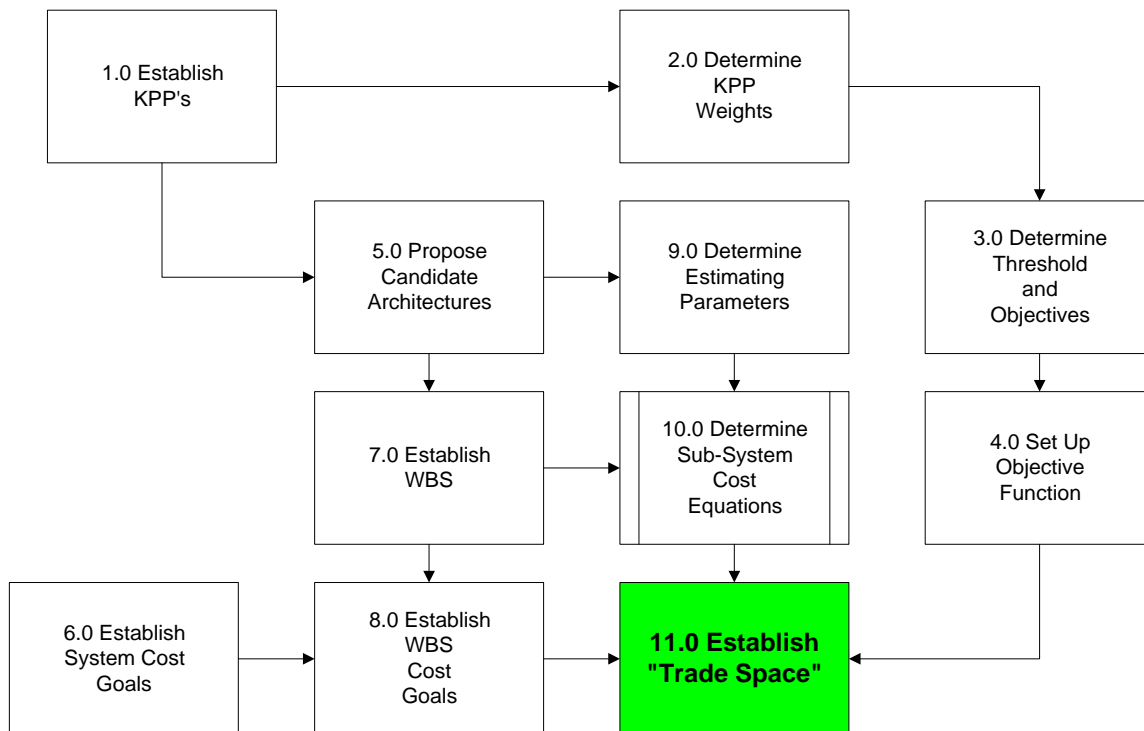
The CMMi SE/SW reflects the capability of organizations to manage complex systems using systems engineering processes. There are six levels of maturity (CMMi SE/SW, 2002):

- Capability Level 0: Incomplete
- Capability Level 1: Performed
- Capability Level 2: Managed
- Capability Level 3: Defined
- Capability Level 4: Quantitatively Managed
- Capability Level 5: Optimizing

Based on the lack of clear definition of a process that handles multiple objectives, CAIV is currently a Level 2 process. Development of a clear, repeatable methodology would allow maturation of up to level 4.

In the literature regarding the parallel decision-making process, decision-makers are protected from "band-width overload" by a clear reproducible process that focuses on the most important elements of the decision. For example, multi-attribute utility analysis, a recognized decision analysis methodology, has seen evolution from a complex formulation to simpler ones (SMART and SMARTER, Goodwin and Wright, 1998) that make the methodology more transparent. The proposed methodology for CAIV is presented in Exhibit 3 and discussed briefly below.

Exhibit 3. Proposed CAIV Methodology Architecture.



1.0 Establish KPPs. To start the analysis, the Key Performance Parameters are elicited from the user or users. Limiting the number of KPPs keeps the analysis focused on important system characteristics.

2.0 Determine KPP Weights. The relative importance of each of the KPP's are determined using Quality Function Deployment importance or any other appropriate method (Analytic Hierarchy Process, Rank Sum, Rank Reciprocal or Rank Order Centroid).

3.0 Determine Threshold and Objectives. For each KPP, the minimum acceptable (threshold) and desired (objective) levels of performance are determined. The minimum levels must be obtained unless it is determined that there is no solution without allowing a solution with less than the minimum performance in some parameter.

4.0 Set Up Objective Function. An objective function is formed to measure overall performance. It is the sum of the weights of each KPP times its utility. A system would have zero utility at the minimum and maximum utility (ten in the case of our pilot study) at the objective value. The simplest form of the utility curve would be linear between the threshold and the objective.

5.0 Propose Candidate Architectures. Here each KPP would be assigned to a system or subsystem.

6.0 Establish System Cost Goals. In this step the desired cost of the system is established by the customer.

7.0 Establish WBS. In this step the Work Breakdown Structure (WBS) is determined which shows the linkage between subsystems and the system.

8.0 Establish WBS Cost Goals. In this step, the system cost goals are associated with the WBS, to determine the cost available to support the WBS elements associated with KPPs.

9.0 Determine Estimating Parameters. Determine which parameters can be used in a Cost Estimating Relationship to establish the system costs.

10.0 Determine Sub-System Cost Equations. In this step, the sub-system CERs are chosen or developed for each of the KPPs.

11.0 Establish the Trade Space. Using the threshold and objective as performance constraints and the total

system cost for the sub-systems involved in the KPPs as the cost constraint, the "Trade Space" can be established using optimization techniques.

Pilot Study

A pilot system was created as a "Gedanken Experiment" to demonstrate the methodology. The pilot system is supposed to have three subsystems, each with two KPPs (Step 1). An importance matrix was created by the author for the KPPs (Step 2) using a Quality Function Deployment (QFD) format (Exhibit 4). In this format the customer is asked to rate the importance of performance parameters on a scale of importance as follows:

- L = low importance (value = 1)
- ML = Moderately low importance (value = 3)
- M = Moderate importance (value = 5)
- MH = Moderately High importance (value = 7)
- H = High importance (value = 9).

Exhibit 4. QFD Matrix and Weights.

Requirement	Importance	Numerical	Weight
X ₁	MH	7	0.2333
X ₂	ML	3	0.1000
X ₃	M	5	0.1667
X ₄	ML	3	0.1000
X ₅	MH	7	0.2333
X ₆	M	5	0.1667

When a more detailed view of the KPPs is needed, we can use Saaty's Analytic Hierarchy Process (1995). For the Pilot the QFD importance was converted to its numerical values and the resulting values were normalized.

The parametric cost equation (1) for each subsystem is of the form:

$$c_k = \prod_{j=2k-1}^{2k} a_j X_j^{b_j} \tag{1}$$

where:

- the c_k are the costs for each of the three (k) subsystems,
- the a_j and b_j are cost estimating parameters for each KPP,
- the X_j are the KPP parameters, and
- j is the index.

The total cost equation (2) for the system is then:

$$Cost = \sum_{k=1}^3 c_k \quad (2)$$

Parametric coefficients for the pilot study were selected by the author to define the cost model as a non-linear system, as shown in Exhibit 5.

Exhibit 5. Pilot Study Parametric Coefficients

X _j	X ₁	X ₂	X ₃	X ₄	X ₅	X ₆
a	3.6	4.4	5.1	2.1	1.6	4.6
b	0.6	0.5	0.75	0.4	0.8	0.6

A linear utility function equation (3) has the form:

$$u_i = 10 * \frac{(X_i - X_i^T)}{(X_i^O - X_i^T)} \quad (3)$$

where X_i^T is the threshold value for X_i , X_i^O is the objective value and u_i is the utility value. The threshold value is the minimum acceptable value for that KPP and the objective value is the desired (or maximum required) value. The utility values are chosen to vary from 0 to 10 for ease of evaluation. The KPP threshold and objective values are shown in Exhibit 6.

Exhibit 6. Threshold and Objective Values.

Parameter	X1	X2	X3	X4	X5	X6
Threshold	100	200	50	150	20	300
Objective	200	500	150	200	60	450

The system development cost was set at \$12,000. The objective function equations (4) are:

$$\begin{aligned} \max \quad & \sum_{i=1}^6 w_i u_i \\ \text{s.t.} \quad & \\ & \sum_{k=1}^3 c_k \leq \$12,000 \end{aligned} \quad (4)$$

where:

- the w_i are the weights for each KPP
- the u_i are the utilities for each KPP parameter based on equation (3), and

- the c_k are the costs for each subsystem from equation (1).

The optimization problem is then to maximize the weighted sum of the six KPP utilities such that the cost to implement the KPP performance does not exceed the desired \$12,000.

Results

The system was solved using GAMS 2.50E Windows NT/95/98 General Algebraic Modeling System. The GAMS setup for calculating the optimum is shown below in Exhibit 7.

Exhibit 7. GAMS Setup.

```

Sets
2   i   subsystems /1 * 3/
3   j   index /1 * 2/
4
5   Table a(i,j) first cost coefficient
6           1   2
7           1   3.6 4.4
8           2   5.1 2.1
9           3   1.6 4.6 ;
10
11
12  Table b(i,j) second cost coefficient (exponential)
13           1   2
14           1   0.6 0.5
15           2   0.75 0.4
16           3   0.8 0.6 ;
17
18
19  Table w(i,j) weights
20           1           2
21           1   0.2333333   0.1
22           2   0.1666667   0.1
23           3   0.2333333   0.1666667 ;
24
25
26  Table lb(i,j) lower threshold
27           1   2
28           1   100 200
29           2   50 150
30           3   20 300 ;
31
32
33  Table del(i,j) range
34           1           2
35           1   100 300
36           2   100 50
37           3   40 150 ;
38
39  Variables

```

```

40     x(i,j) KPPs
41     u(i,j) Utilities
42     z      Total value
43     subcost(i) cost of subsystem;
44
45     u.up(i,j) = 1;
46     u.lo(i,j) = 0;
47
48 Equations
49     value define objective function
50     kpp(i,j) define KPP
51     dsubcost(i) define subcost
52     cost define total cost;
53
54 value.. z=e= 10*(sum((i,j), w(i,j)*u(i,j)));
55 kpp(i,j).. x(i,j)=e= u(i,j)*del(i,j) + lb(i,j);
56 dsubcost(i).. subcost(i)=e= prod(j,
a(i,j)*x(i,j)**b(i,j));
57 cost.. sum(i, subcost(i))=l= 12000;
58
59 Model CAIV /all/;
60
61 solve CAIV using nlp maximizing z;
62 display x.l, x.m;

```

The local optimum was 6.3554. Parameters are shown below in Exhibit 8:

Exhibit 8. Optimum Parameters for Cost = \$12,000.

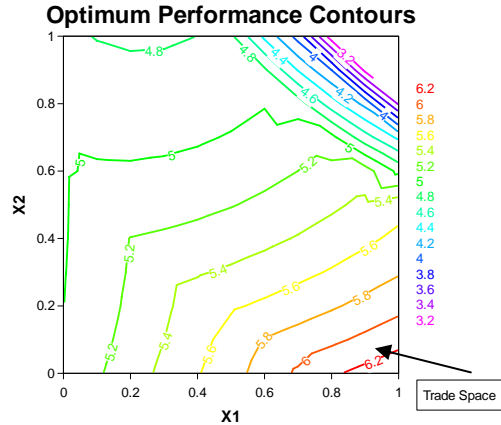
Parameter	X1	X2	X3	X4	X5	X6
Value	200	200	131.26	200	20	450

KPPs X_1 , X_4 and X_6 are at the objective value, while KPPs X_2 and X_5 are at their threshold values. KPP X_3 is at an intermediate value.

Knowing the local optimum is useful; it would also be useful to know how the optimum moves with changes in the other KPPs. Calculations of the optima for $X_1 = \{0, 0.1, 0.2, \dots, 0.9, 1\}$ and $X_2 = \{0, 0.1, 0.2, \dots, 0.9, 1\}$, allowing the remaining KPPs to float, were made using GAMS. Exhibit 9 shows the resulting contour plot.

In this case we do not have an optimal point, but rather an optimal region, or trade space. The optimum trade space occurs when X_1 is large, generally greater than 0.7, and when X_2 is small, generally less than 0.1. This contour plot shows that the system developers have a family of possible solutions rather than a single optimum point. As more KPPs are added to the solution it becomes difficult to visually depict the trade space.

Exhibit 9. Contour plot for Optima of X_1 and X_2 .



Conclusions and Next Steps

The pilot study did show the methodology is mathematically feasible. Given a set of KPPs, along with associated weights and performance ranges, the methodology was able to determine an optimal point and is able to provide a contour plot depicting the relationship between two given KPPs. To be of value to the system developer, the methodology must now be applied and verified using KPPs from fielded operational systems.

The next steps are to continue develop the methodology and then apply it to existing operational systems. The methodology can then be exercised to fully explore the trade space and determine optimal points in that space. Given that a fielded system is successful in meeting its required KPP values, we would expect the methodology to identify an optimal point that approaches the actual system performance values. If the fielded system is viewed as less than fully successful in meeting required KPP values, we would expect the methodology to identify an optimal point that varies from the actual system performance. Evaluating a range of systems would enable the methodology to be refined further.

The goal of this methodology is to provide the system designer with a tool that will fully explore the system trade space early in the design process. The tool should be able to identify if an optimal design point exists. Full development of the methodology would also allow for exploration of the trade space around the optimal design solution, allowing for exploration of alternative design solutions in conceptual design. Optimization at an earlier stage of design has the potential of yielding the highest performance for a given cost.

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About the Authors

Joseph. F. Krupa is a doctoral candidate at The University of Alabama in Huntsville. He is a Principal Technical Advisor in the Systems Engineering Department at Westinghouse Savannah River Company where he performs risk assessments, decision/alternative analyses, discrete-event system simulations, develops strategic plans, and leads a Focus Team on improving the Department's methods and delivery of systems engineering products.

Paul J. Componation is an Associate Professor of Industrial and Management Systems Engineering at The University of Alabama in Huntsville, and the Systems Engineering Resident Researcher at the Marshall Space Flight Center in Huntsville, Alabama. His research interests are in the areas of product and system development, engineering management and decision analysis.