Foundations of Value Based Gap Analysis: Commercial and Military Developments

Gary Langford
Graduate School of Engineering and Applied Sciences
Naval Postgraduate School
222 Bullard Hall
777 Dyer Road
Monterey, California 93943
United States of America
golangfo@nps.edu

Abstract. Gap Analysis is widely regarded as a useful tool to facilitate commercial and defense system acquisitions. This paper presents a rethinking of the theoretical foundations and systematics of Gap Analysis with practical extensions to illustrate its utility and limitations. The growing sophistication and complexity of new systems or system of systems have resulted in a dramatic increase in time and money to reach operational capability. Gap Analysis, properly defined and enacted, clarifies goals, appropriate investments and the end-use. This paper introduces the concept of thinking in terms of value and worth, termed Value Systems Thinking; and the concept of analyses and judgments for acquisition and product development – termed Value Systems Engineering.

Introduction

Relevance. The challenge of successfully acquiring and operating a new system is to ensure that the goal or mission will be accomplished within an acceptable level of economic loss during development and sustainment. To that end, there have been numerous attempts to develop and field systems that are intended to prevail in an environment of competition or in the event of conflict. Litanies of questions daunt the designers, developers, and users. For example, "How should these future systems should be defined? Who is responsible for defining these systems? What processes guide the system requirements? How are inefficiencies identified?" If we perceive a deficiency or a desire goal that is different from that which we are intending, then there could exist a basis for a gap in capability or desires, and therefore a need to close "the gap". One could view decisions as a means to fill these gaps.

Definition of Gap. What you desire versus what you have is, in essence, a Gap. The Gap is as much the relationship between what is perceived to be important and the derived difference between performance and expectations. The methodology and analysis of that difference can be thought of as the descriptive foundation for Gap Analysis. From a mission capability or product use perspective, a Gap may consist of deficiencies in operational or use concepts, current or projected operational or utility disadvantages, technologies, or misunderstood future needs. To be specific, a Gap must be founded on the starting and ending points as well as the difference between these points. Quantifying these measures involves evaluating a number of use situations or mission scenarios in concert with actions, or more generally stated, guidance from policy and goals.

Measures and Metrics. Guidance from policy and goals set the standards for defining Measures of Effectiveness (MOEs) has long formed the set of standards from which to determine how well a capability satisfies a requirement (Sproles, 2002). MOEs are distinguishable from Measures of Performance (MOPs) in that MOEs offer the external view, while MOPs are more consistent with the internal view. External views capture the system's beginning and ending points, including the MOE of alternative decisions that may result in filling the gap. Internal views involve quantifiable measures of how well one fills the gap, i.e., through MOPs. Therefore one must formulate both MOEs and MOPs to fully define a Gap. However, Chairman of the Joint Chiefs of Staff Instruction CJCSI 3170.01D Joint Capabilities Integration and Development System (12 March 2004) focuses on MOEs while there is no mention of MOPs. There is an implied admixture of MOEs and MOPs defined as MOEs, but the essential qualities of performance based metrics are missing for carrying out activities and actions, for measuring functions, and from which to determine economic and numeric losses due to achieving various levels of performance. Of particular importance in the proposed formulation of Gap Analysis are the measures of functions from the perspective of these losses incurred due to achieving the desired level of performance. This will be discussed further in the subsequent section on Quality.

Commercial. Many of the largest U.S. corporations use Gap Analysis to help answer five critical questions. What services are needed to satisfy customers? What best practices and skills are required to provide those services? How does an offering of services compare with competitive offerings? What are the potential new opportunities? Where are we today and where do we want to be in a defined future period? While Gap Analysis is not significantly instilled in the commercial world, its use and popularity are growing slowly.

Commercial enterprises are not driven by instructions or standards, but rather by revenues and profit derived by dominating markets and avoiding interventions of disruptive technologies and discontinuous innovations (Langford, 2006). The goal of commercial Gap Analysis is to identify shortcomings in market lines, identify new market areas, and suggest positioning of enterprise image to lay claims and assert influence. The methodology of Gap Analysis helps structure information and knowledge to facilitate decision fitness and decision making.

Defense. Gap Analysis is deeply embedded and fully institutionalized as a cornerstone of the United States Department of Defense (DoD) acquisition strategy. The purpose of Gap Analysis within DoD is to report on the evaluation of the performance, operational effectiveness, operational suitability, and estimated costs of the alternative systems to meet a desired mission capability. In this context, Gap Analysis is used to assess advantages and disadvantages of different alternatives.

The goal of the DoD Gap Analysis is to compare current capability to a set of requirements. Where differences arise, gaps are identified and quantified, and mitigations are prioritized and planned. This paper addresses the theoretical foundations and systematics of Gap Analysis with extensions to illustrate its utility as a useful management tool for both defense and commercial acquisition purposes. Without a considered theoretical foundation from which to conduct Gap Analysis, an inadequate level of guidance regarding appropriate methodology and analytical methods may well result. The metrics of Gap Analysis are defined on the basis of system value (Langford, 2006) and assessed risks (Langford and Huynh, 2007).

Discussion

What a manager desires versus what a manager has is, in essence, a Management Gap, or more pertinently, a Value Gap. The Value Gap is as much the relationship between what is perceived to be *important* and the derived difference between performance and expectations. From a management perspective, a Value Gap may consist of deficiencies in organization, current or planned operations, processes, technology maturity and readiness, integration and standards, misunderstood requirements, work performance, or task performance. A Value Gap is determined by two factors. First, the starting and ending points of the work (i.e., its boundary conditions) delineate the situation(s) that characterizes the work and bound the Value Gap. The boundary conditions include the beginning scenario and the end goal, resource allocations, human capital needs and fulfillments, equipment, facilities, processes, and political/economic support. Further, the difference between the starting and ending points exemplifies the task sequence(s) or paths that encompass the work. Quantifying the boundaries and constraints involves evaluating a number of work situations and operations scenarios in concert with the planned actions. The goal of the Value Based Gap Analysis (VBGA) is to compare current actions to a set of requirements (business, schedule, budget, operational; performance; quality; and physical). Where differences arise, gaps can be identified and quantified, and mitigations prioritized and planned. This paper addresses the theoretical foundations and systematics of Value Based Gap Analysis with extensions to illustrate its utility as a useful management tool. It is based on Earned Value formulations (Langford and Franck, 2008) and the fundamentals of Gap Analysis. Without a considered theoretical foundation from which to conduct Value Based Gap Analysis, an inadequate level of guidance regarding appropriate methodology and analytical methods may well result. The metrics of Value Gap Analysis are defined on the basis of system value (Langford, 2006; Langford and Huynh, 2007) and the assessed consequences of the chosen management plans.

Theory. Beginning with the basic structures of Gaps, Value Based Gap Analysis builds on causal histories—the telelogic argument that gaps in value exist and can be ameliorated by goal-directed actions. We define Value Gaps in terms of the system's functional requirements, the performances for which the functions are to be measured, the losses (i.e., quality) incurred to achieve those performances, and the physical incarnations that embody the enactment(s) of functions. Further, all Value Gaps are characterized in terms of capability of human capital and applied resources. Changes or enactments of policy, organization, training, materiel, leadership and education, and facilities are considered candidates to close Value Gaps. These factors are usually formally evaluated before recommending the start of a new development effort. The result of such an evaluation is a process of managing work tasks by means of a work breakdown structure to allow assessment and identification of Value Gaps. Many such types of Value Gaps can (and should) be identified during the planning stages of a project. It is at this early juncture that Value Gaps can be dealt with most proficiently and economically.

While Value Gaps can be identified and sometimes corrected *before* the work begins, a certain measure of uncertainty remains due to inadequate framing of the problem, poor definition of requirements, poor exploration of ideas with stakeholders, for example. According to the March 2001 GAO (U.S. General Accounting Office Report to the Chairman and Ranking Member, Subcommittee on Readiness and Management Support, Committee on Armed Services, U.S. Senate) report on best practices in systems engineering (GAO-01-2888), when organizations match the expectations of the work to the resources, schedule delays and cost growths are significantly less than when expectations and resources are poorly matched at the onset of the project. The net result of dealing with Value Gaps is to proffer a better alignment of resources, performance, budget, and schedule. Planning and execution of work benefit this alignment.

Programs	Expectations and resources adequately matched before launch	Product development cost growth	Product development schedule delays
Caterpillar 797 mining truck	Yes	5 percent	0 percent
NASA FUSE	Yes	20 percent	0 percent
Radio Frequency Countermeasures system	No	197 percent	23 percent
Crusader artillery vehicle	No	55 percent	26 percent
Comanche helicopter	No	127 percent	119 percent
Brilliant Anti-armor Submunition	No	99 percent	46 percent
Bombardier BRJ-X[a]	Yes	On target	On target
Tactical Unmanned Aerial Vehicle[a]	Yes	On target	On target
Global Hawk Unmanned Vehicle[a]	Yes	On target	On target

Table 1: Matching of Expectations to Resources and Product Development Outcomes (Source: GAO-01-2888, 2001)

Gap Analysis is concerned with the difference between the present and the future, the reality and the expected, but not with the time or discrete time-steps between these disparities. While the management typically formulates its development plans and milestones in a temporal domain (e.g., a timeline of activities), the development activities should be construed and managed as a discrete set of events. These two views of progress are correlated, and the efforts of management are to assure perfect alignment of both temporal and causal events. The performance of developers is expected to reflect the constraints of the work environment, schedule, budget, and resources. Expenditures are expected to be planned in advance (e.g., for the hiring, promotion, and development of the project's human capital assets). Financial planners, technical leads, and managers are expected to estimate work precisely and accurately. Should those estimates prove inadequate, ways must be found to ameliorate the resulting problems so that work can proceed with appropriate efficiencies and effectiveness. In total, these systems of behavior are cooperative, but oftentimes weakly coupled, with the managers working with a few tools and strategies to influence behaviors. Therefore Value Gap Analysis must contend with the coupling of these stakeholder behaviors to provide a set of measures that better quantify the relationships as they applied to achieving the desired objectives and goals.

Additionally, it is one of the purposes of the Systems Engineering Process Models to reinforce the notion of when to move from one stage of product development to the next stage, as well as what tasks need to be completed within each stage. At each stage, management is engaged in adjusting behaviors that will change performance to be in line with budget and schedule expectations. These stages are marked by milestone reviews that include budget, schedule, and performance. Consequently, the notion of a temporal juxtaposition of activities is less relevant to the event-driven outcomes which characterize a future set of circumstances. In other words, Value Gap Analysis does not quantify when something will actually happen, only that when it happens it will have a value that is more or less than planned. This defining of a Value Gap lends itself naturally to a display of intentions that accurately reflect the constraints of event-based management.

In total, this redacting of Value Gap Analysis into events rather than timelines eliminates the actual propositional attributes of the undefined value structures, but retains the notional attributes.

Propositional attributes iterate the validity of management beliefs and attitudes (i.e., I know what I know, I know what I want). Notional attributes include intentions and wishes (i.e., the end result is not influenced by the proposer's illative skills) (Duzi, 2002). Temporal considerations (e.g., I know when I want it) can be added as an attribute of the Enterprise Framework after forming a situational awareness in event-space. There are alternative interpretations of Enterprise Frameworks, most notably for software applications (Hafedh, Fayad, Brugali, Hamu & Dori, 2002). But the general notion is valid that such theories can be used to surmise a means to enforce consistency in process, application, and interpretation of Value Gaps.

Value. The prime distinguishing characteristic of value analysis (or as sometimes referred to, Value Engineering) is the use of functional (or function) analysis (Miles, 1972, first published 1961) as a means to appreciate what performance *does* rather than what it *is*. Value Analysis (VA) is a management process used to optimize the use of human capital within the constraints of schedule and cost. Alternatively, VA provides a view of the performance that associates it with what is necessary to accomplish a work activity at the lowest cost. In essence, analyzing value that is earned is the means of analyzing productivity, selecting alternative management strategies, and otherwise manipulating the ratio of Performance to Cost. It is this ratio that determines the value of work done. And it is accumulation of Performance to Cost between milestones that is used to determine a real measure of earned value. Coupling value with loss that ensues from a given level of performance (e.g., hours and dollars spent for work done) forms the basis for Value Analysis. VA is typically concerned with productivity, the use of labor, materials within time constraints to achieve a certain level of performance. Lowered levels of performance are a loss.

We broaden this perspective of loss due to performance by replacing the temporal aspects of a project that define the time from one point to another point with rather the events that delineate the beginning and ending milestones between which value is analyzed. The result is an event-based analysis of value rather than a time-based analysis of value.

The term value has many colloquial definitions, including the term's use and misuse often disguised as promoting various popularized concepts. But in the main, all constructs of value are without merit and meaning unless there is a relationship to the defining functions, and therefore by reference, to system objective(s) or use(s). Though related, value is not synonymous with cost or investment. Value for given functionality is performance of a workforce divided by the investment to deliver or sustain that performance. Further, value is distinguishable from worth. Worth is a measure of value given risk (discussed in next section). There are different types of value (use, esteem, cost, exchange, scrap, and so forth). The authors distinguish between the types of Value. Value is as defined and described as performance divided by investment.

Value is attributed to the development of functionality, i.e. for the use one receives versus what one invested (Langford, 2006). This notion of value explicitly requires a manager-worker model to determine Value. The manager-worker model presupposes there is always a "source and a sink", an "input and an output", a pre-condition and a post-condition that is the determinant of Value. Therefore, value for functionality is the ratio of the defining characteristics of the product (i.e. Performances) divided by the investment to achieve that functionality and performance. Value is measured in absolute terms. For example, the worker shall develop a function with a specified performance. That function does 0.5 of what was paid for (as perceived from the point of view of the developer). Or perhaps, the performance was measured at 90% of the requirement. The investment expended to achieve that functionality and performance was as planned. Therefore, the value was less than desired (developer's perspective). The Value Function (Equation 1) relates the System Value to the System Use(s) or to the System function(s) and their related performances divided by the investment.

Equation 1. Value Function

$$V_F(t) = \frac{\sum_F P(t)}{I(t)}$$

Where *F(t)*is a function (or sum of functions) performed by the system over a period; *P(t)*is a performance measure of the function *F(t)*, or the sum of performance measures of a set of or the aggregation of all functions; *I(t)*is the total investment (lifecycle cost) that corresponds to the aggregation of all investment events, e.g., dollars or other equivalent convenience of at-risk assets; and the time, t, is measured either as the lifecycle time (i.e., relative to the onset of initial investment in the project), or replaced entirely by individual investment events or sequences of investments events. The units of *V(t)* is the ratio of *P(t)*, performance (e.g., units of work or energy) divided by Investment (quantified in terms of dollars or another meaningful measure of units that represent an investment).

Value Systems Thinking and Value Systems Engineering. The new field of Value Systems Engineering facilitates the identification and analyses of the value(s) and worth(s) of functions for products and services. Value Systems Engineering has been used to define the requirements for major commercial and DoD systems, determine the value and worthof requirements, quantify stakeholder analyses, and determine validation metrics for Systems Engineering projects. Value Systems Engineering has fundamental roots in Systems Engineering, Value Engineering, Risk identification, management, economics, social sciences, biological sciences, and physics. Value Systems Thinking incorporates the consequences of actions during all stages of development of a product, all stages of becoming decision fit and making decisions, all aspects of management, all aspects of thinking. The difference between Value Systems Thinking and other paradigms is the fundamental inclusion of loss due to work done. Value Systems Engineering incorporates loss into engineering analyses and judgments; activities and processes; decision making and management.

When applied to Gap Analysis, the metrics used for analyzing requirements are value and Risk. Value is captured as the cost of the system's Functions and their Performances. In a common-sense fashion, Value is a measure of appreciation of assets (or conversely, the transformation / conversion) of investment(s) into performance. The result of a product's performance is to distinguish it from other competitive or adversarial products. Performance may be objective or subjective; and likewise, value may be objective or subjective. Objective value relates the independence of assessments as viewed from various perspectives—a consensus opinion of truth. Subjective value relates what is expected (the sum of all corporal and abstract happenings from which you benefit and expect from a situation if you participate in a certain fashion). Value is improved by minimizing cost (or its equivalency in time or numbers) to develop a product. By equivalency, we mean that value can be quantified in terms of the number of items exchanged for something, or the amount of time that one trades for in-kind work. Alternatively, value can be thought of as the use of a product (or service) that users expect for the investment(s) they are willing to make. Use can be further described in terms of the product's functions and the performance of the function. Additionally, value is a key consideration of lifecycle costs and lifecycle time that expresses the transformation of enterprise assets into profitability. In this case, value is characterized through Equation 1 by the results of performance of a function or aggregation of functions for a given investment or aggregation of investments. Each function is an activity that the product does with certain performance attributes. There are typically several performance requirements for each function. However, there is never a function without at least one performance measure.

Boundary conditions are exemplified by the product's function. For example, "the ship shall function in the marine environment". The ship hull's interface with the seawater is a boundary condition. In this case, the function performed by the ship is 'to float'. Boundary conditions serve both to limit the product's interactions as well as to define the functions that the product will perform. Often, the boundary conditions are misinterpreted to mean the limits of the problem that are to be solved. Rather it is more meaningful to consider the boundary conditions as characteristic of the problem statement so that the functions of the solution are instanced and represented.

Worth. Worth extends the concept of value to encompass the notion of loss as the result of achieving a given level of performance. Value Systems Engineering includes discussions of value and worth. The worth of a function is related to both the value of the function as well as to the loss incurred by achieving the performance of the function. For example, I may value my car because I can travel at high rates of speed for a given investment. But it is not worth it to me since the petrol consumption rate is too high per distance travelled.

We define worth as the Value $V(t)$ for a function multiplied by the quantity 1 minus the loss due to achieving the system's performance. The loss incurred is represented by a loss function that depends on the performance achieved, the performance desired, the magnitude of the relationship between the upper and lower bounds placed on performance, and the affect(s) of exceeding those bounds. Quality and loss are related by the general formula, Quality + Minimum Loss/Quality = Loss. This is to say, for every system there is a minimum loss (or alternatively, a minimum quality) that is indicate of and inherent in the system. The minimum loss is the difference between the quantification of loss and quality. This notion suggests a fundamental concept: perpetual motion is impossible, because there is always a loss. The measurement units of loss $L(t)$ and Quality $Q(t)$ are the same as the units for Investment, $I(t)$. $Q(t)$ can be measured by a loss function.

Following the convention described by Taguchi in 1990, we refer to *Quality* as the consistency of performance (or the specification of tolerances that signify the level of performance acceptability). In reference to the amount of pain, or equivalently loss that results from a performance of a system function that exceeds the upper or lower limits of its range of performance specifications the order of the loss function equation depends on the magnitude of the impacts due to exceeding those specifications. During the earliest stage of fundamental research for example, the attempts to obtain various performances for a function being investigated most likely results in negligible losses. An objective of fundamental research may be to just demonstrate there is an effect by performing some function, rather than to delimit the range of performance that is acceptable (as might be the desire during the stage of development). As such, the specifications that are envisioned during fundamental research are significantly more lenient than those imposed during development of a product. And likewise once the product has been delivered, there may be severe impacts on an enterprise if an upgrade ignores or breaches the product specifications. The specifications "loosely" imposed during fundamental research may have much less impact than those mandated for an existing product. Accordingly, the order of magnitude of the loss function should track the aftermath of the limits of the product specifications.

Measures of performance indicate how well a function is performed by the system. The quality of the function is indicated by the real cost of performing the function. In essence, functions result in capabilities; performances differentiate competing products; and quality affects the lifecycle cost of the product. We describe all systems in terms of four requirement types. The master type is functional. For each functional requirement, there are three additional types of requirements — performance, quality, and physical. The quality requirement indicates the variation and impact of the variation of the performance requirement of a function. Both performance and quality requirements are specified and tracked in Gap Analysis. In general, a system function may have multiple measures of performance, while each performance may have multiple measures of quality. The summation in Equation (1) is thus over all values of performance and quality, for the lifecycle time, and incorporates all uncertainties due to loss. Equation (2) indicates the worth of system, as it references the *Value* Function.

Equation 2. Worth Function $$W_F(t) = V_F(t) * Q(t) = \frac{\sum_F P(t) * Q(t)}{I(t)}$$

Where *Q(t)*is quality (the tolerance assigned to the performance measures) and the time, t, is measured relative to the milestone from which one measures earned value. We refer to the delineation of a function in terms of its performance, quality, and physical incarnation as the triadic decomposition of the function. In other words, traditional functional decomposition is followed naturally by performance decomposition, by quality requirement's decomposition, and then by allocation of functions, performances, and qualities to physical entities. When the measurement units of *Q(t)* are converted into the units of *I(t)* (Equation 1), the units of W(t) are that of *P(t),* since *F(t)* is dimensionless. *Q(t)* can be thought of as a loss that is incurred. Triadic Reductionism forms the basis for a management tool to perform Gap Analysis, measure earned value, determine decision fitness, manage activities, and in general, define requirements. Triadic Reductionism is the foundation of Value Systems Engineering.

The value of a product is thus quantified according to Equation (1) and the worth of a product is quantified according to Equation (2). From the manufacturer's point-of-view, a "product's worth" is one that has met some investment criteria to achieve value for the desired set of functionality, performance, and quality requirements. There is also a worth for the manufacturer according to their performance. From the purchaser's (or consumer's or user's) point-of-view, the expression in Equation (2) aids in the analyses of alternative between the applicability of a purchased product (in terms of the item's functionality, performance, and quality) and the total cost and time invested to purchase and use the product.

Value and worth are calculated at the moment of the agreed exchange of product/services for a given amount or recompense. At the time of exchange, there is equality between the risks assumed by the buyer and seller and their Values and Worths. Worth reflects the uncertainties based on losses associated with the exchange of energy (generally speaking) between any two elements of a system. These exchanges (or interactions) are quantifiable and may have a net impact on the value and worth of the system. By analogy, such exchanges between two or more systems through their respective elements, or system(s) of systems interactions result in similar constructs and impacts.

In this paper we are interested in the interactions that are measurable and have consequences in the lifecycle of the product or service. We define Net Impact, as a consequence that exceeds a threshold that is determinable to be of interest.

Quality. Quality is frequently thought of as conformance to specifications. When goods are within specification they are considered high quality, contrasted with low quality goods that are determined to be outside the bounds of specification. Such notion of quality is often typified by the statement: the quality is remembered long after the price is forgotten. However, Taguchi proposes a view of quality that relates to cost and therefore a loss measurable in monetary terms. This loss accrues not only to the designer, developer, and manufacturer but also to the customer, user, and broadly to society as a whole. In aggregation these entities represent the 'seller' in a buy sell relationship. For the seller, their loss is accumulated, perhaps throughout the product lifecycle, from conception to include the last simulacras of support. Whereas Taguchi offers that seller's losses are incurred up to the time that the product is shipped, we take a broader perspective and extend the seller's losses beyond the shipping event to include support, maintenance, and service. According to Taguchi, after the product is put into use, it is society and the customer who bear the cost for low quality. However, we distinguish between the customer's and society's responsibilities in contrast to those attributable to the seller. Even while the seller's purview can be narrowed to the Taguchi limit by eliminating all interactions with the customer after the shipping event, our general perspective considers real costs as well as the costs of negative customer reaction. Sellers sometimes have difficulty in capturing and accounting for money and money-equivalencies spent by customers to deal with problems, dissatisfaction, and inconvenience associated with low quality. Our approach of developing and applying a quality loss function allows quantitative evaluation of losses caused by variations in behaviors and limits of performance specifications as they consociate with various functions of the product (Choi and Langford, 2008).

Since Taguchi's quality loss function is primarily focused on manufacturing, we have difficulty applying his quadratic loss function to decisions that must be made during other lifecycle stages of the product, including conceptualization, research, development, operation, maintenance, and disposal. We define a requirement to develop a quality loss function that is applicable for the lifecycle of a product. In contrast to Taguchi, who only considered manufacturers and customers when assigning the losses due to quality, we take into account the broader perspective of all stakeholders. Therefore, we perform a stakeholder analysis to broadly consider multiple perspectives as integral to developing another quality loss function.

Further, we must tackle head-on the definition of product function and associated performance(s). Taguchi uses a quality loss function to evaluate product performance relative to the performance specification. When applying Taguchi methods, performance evaluation becomes a most demanding task that challenges managers without providing the benefit of firm definitions and theoretical standing. The diversity of definitions of performance, the complexity of the measuring performance, and the scarcity of generally accepted performance measures compound these problems. It is the purpose of this paper, in conjunction with the graphics from the presentation, to firmly establish workable definitions and theory to assist managers in making appropriate and justifiable decisions.

In general, there are at least seven distinct, although not necessarily mutually exclusive, performance measures used in practice. These are effectiveness, efficiency, quality, productivity, quality of work life, profitability, and innovation. Thus, performance can be defined as a concept that takes on different meanings in different situations for different organizational systems. (Kumpe & Bolwijn, 1994) and (Kaplan & Norton, 1992, 1993, 1996) for example, used efficiency, quality, time, innovation, and contribution to profit as performance measures. Taguchi used quality as a performance measure for evaluating product performance. The authors define performance as the net work accomplished during a period *t*. The work accomplished is equal to the amount of work "completed" minus the amount of rework required to finish the amount of work that was thought to be completed.

The quality loss function developed by Taguchi, 1990, is used to describe quality in terms of smaller-the-better, larger-the-better, and nominal-the-best characteristics. A smaller-the-better output response results when it is desirable to minimize the performance, with the ideal target for performance being zero. Examples of smaller-the-better output responses are the wear on a component, the amount of engine audible noise, the amount of air pollution, and the amount of heat loss. The larger-the-better output response reflects cases when it is desirable to maximize the result, the ideal target being infinity. Examples of larger-the-better output responses are strength of materiel or fuel efficiency. The nominal-the-best characteristic results when there is a finite target point (or domain of cooperative agreement) to achieve, often associated through a negotiated outcome. In this case there are typically upper and lower specification limits on both sides of the performance target, representing the maximum or minimum acceptable bounds for the parties of the negotiation. Examples of nominal-the-best characteristics are the plating thickness of a component, the length of a part, and the output current of a resistor at a given input voltage.

A great many papers relate to the quality loss function largely from only one side of the quality characteristics (Chung et. al., 2005), (Kapur, 1996), and (Yahya, 2007). Moreover, it is difficult to find a quality loss function applicable to broad categories of quality characteristics. For the purposes of Value Based Gap Analysis we derive a quality loss function for broader applicability in managing quality characteristics, regardless of domain and characterization.

There is some common ground that reconciles traditional and Taguchi views of quality. Quality is viewed as a step function such as a good or bad product. This sentiment assumes that the product quality is uniformly good between the lower specification and the upper specification, and bad outside these limits. Even traditional decision makers and those using Taguchi's loss function will make the same judgments. If decision makers consider both the position of the average and the variance, and if the averages are equal and/or the variances are equal, then the traditional decision maker and one using Taguchi's loss function will make the same decision. Typically, the traditional decision maker calculates the percentage of defective units over time, when both the average and variance are different. Both the average performance and variation from a target value are measures of quality (Taguchi, et. al., 1989).

Taguchi believes the customer becomes increasingly dissatisfied as performance departs farther from the target value for performance of a function. His extensive work with manufacturers over the past 30-years suggests a quadratic curve best represents a customer's dissatisfaction with a product's performance. The first derivative of a Taylor Series expansion taken about the target value is a quadratic curve when the target value is set to zero. The curve's minimum (or nominal position) is centered on the target value, which (Taguchi, et. al., 1989) has shown to provide the best performance in the eyes of the customer. However, identifying the appropriate performance measures as well as selecting the best target value is challenging. Designers sometimes offer their best guess. The quadratic form was chosen by Taguchi because it was both simple, and as it turned out, useful. Further, after the Taylor expansion, higher powers in the series change the loss at the target value by a very small margin, and for practical purposes can be ignored within experimental error. Symmetric formulations of loss functions are assumed to be approximate and accurate to a first order. Asymmetric loss functions are useful in specific situations.

The loss function offers a way to quantify the benefits achieved by reducing variability around the target. It can help justify a decision to invest further to improve a process that is already capable of meeting specifications. According to Taguchi, the objective of minimizing the loss to a customer was to improve product quality by minimizing the effects of variations in its performance while striving to achieve the performance target value. The narrower the performance limits, the higher the quality. However achieving higher quality does not need to come at the expense of eliminating the causes of that variation. The intent is to design robustness into the product to mitigate variation so that value can be imparted to the customer without an associated loss (Yao, et.al., 1999).

Types of Quality Loss Functions. For each quality characteristic, nominal-the-best, smaller-the-better, and larger-the-better, there exists some function that uniquely defines the relationship between economic loss and the deviation of the quality characteristic from its target value. Taguchi has demonstrated through practice that the quadratic representation of the quality loss function to be an efficient and effective way to assess the loss due to deviation of a quality characteristic from its target value. For a product with a target value *m*, from a customers' perspective, $m \pm \Delta_0$ represents the deviation at which functional failure of the product or component occurs. When a product is manufactured with its quality characteristic at the extremes, $m + \Delta_0$ or $m - \Delta_0$, some measure to counter the loss must be undertaken by the customer. The loss function *L* (average loss) with characteristic of nominal-the-best (NTB) is described in Equation 3.

Equation 3. Nominal-the-best $$L = k(y-m)^2 \quad k = \frac{A_0}{\Delta_0^2}$$

Where, k is a proportionality constant and could be the cost of each unit (returned, modified, reworked) divided by the range limits of process variability divided by 2, y is the measure of performance (e.g., output) for a given function, m is the target value of y, and A_0 is the cost of the countermeasure. The loss function can also be determined for cases when the output response is a smaller-the-better (STB) response. Following the same procedure as for the case of nominal-the-best, the loss function is described in Equation 4, where the target value for performance is zero.

Equation 4. Smaller-the-better $$L = ky^2 \quad k = \frac{A_0}{y_0^2}$$

Where, A_0 is the consumer loss and y_0 is the consumer tolerance.

For a larger-the-better (LTB) output response where the target is infinity, the loss function can be written as shown in Equation 5.

Equation 5. Larger-the-better $$L = k\frac{1}{y^2} \quad k = A_0 y_0^2$$

Outline of the General Quality Loss Function. To achieve the desired level of quality and to adopt the target value for a product within each stage of a product's lifecycle, stakeholders pose the question – how much loss can or will I incur? To address this question, a general quality loss function must be developed. We introduce a shape parameter that governs the amount of losses as a function of the product's lifecycle and present a function which covers all three quality types from the perspective of a product's stakeholders. Through this effort we propose a general quality loss function covering all lifecycle phases. It can be shown (Choi and Langford, 2008) that given the following notation and assumptions, a general quality loss function (Equation 6) reduces

Equation 6. General Quality Loss Function $L_n(x) = -2C_s m^n + C_s x^n (1 + m^{2n} x^{(-2n)})$

to STB, LTB, and NTB forms shown in Equations 3, 4, and 5. Further, Choi and Langford, 2008 derive the relationship between proportionality constants constant C_s (under smaller-the-better), and for C_l (under larger-the-better) as shown in Equation 7. A more complete derivation is found in the 19th Annual International Symposium of INCOSE (Langford, 2009).

Equation 6. Proportionality Constants and Target Value $C_l / C_s = m^{2n}$

Notation.

C_b: Baseline cost with a constant value

C_s: If the type of quality characteristic is smaller-the-better, this means a proportionality constant of stakeholder's loss per response of quality. Additionally, if the type of quality characteristic is larger-the-better, it means a proportionality constant of developer's or manufacturer's loss per response of quality.

C_l: If the type of quality characteristic is larger-the-better, this means a proportionality constant of developer's or manufacturer's loss per response of quality. Additionally, if the type of quality characteristic is smaller-the-better, it means a proportionality constant of stakeholder's loss per response of quality.

n: Shape parameter for representing an acquisition phase of a weapon system ($n > 0$)

x: Response of quality

$L_n(x)$: Total quality loss per piece in case of shape parameter n and quality response x

L_n : Expected quality loss per piece in case of shape parameter n and quality response x

Assumptions.

A1: The total quality loss ($L_n(x)$) consists of the stakeholders' loss plus unknown losses.

A2: If the level of quality equals the target value of the quality (i.e., m), the total quality loss is to be zero (or the minimum loss that is inherent in the system).

A3: If the acquisition phase is to production and deployment, the value of shape parameter n is equal to 2.

A4: The minimum value of a shape parameter is close to zero and the value of the shape parameter in the concept refinement phase of the acquisition phases varies from 0 to 1.

A5: When the acquisition phases are the technology development or system development and demonstration phase, the range value of shape parameter varies from greater than one to less than two.

A6: After the production and deployment phase, the value of the shape parameter is greater than two.

A7: The probability distribution of the quality response remains the same regardless of the acquisition phases.

Gap Analysis relies on determining the beginning and end points as well as the path in between. The general loss function (Equation 5) illustrates the relationship between the lifecycle phase and the order of loss that is indicative of technology, process, and management. This paper describes how revising Gap Analysis to include losses improves decision making. Additionally, Gap Analysis structured with loss functions includes: return on investment (ROI), competitive analysis, loss-elasticity of demand, and risk. For example, ROI can be stated as Gain – Loss divided by Investment. When the loss exceeds gain, ROI is negative. This is a typical description of the power of a user to derive benefit from a product's functions. Formulations of each of these objectives result from a triadic decomposition within an enterprise framework. Figure 1 illustrates the relationships. Steps 1.0, 2.0, 3.0, 4.0, 5.0 and 11.0 are typical of the current Gap Analysis. We revise Gap Analysis through the addition of 6.0, 7.0, 8.0, 9.0, and 10.0. These additions serve as feedback to assist in controlling Gap Analysis through the process of at least one iteration loop.

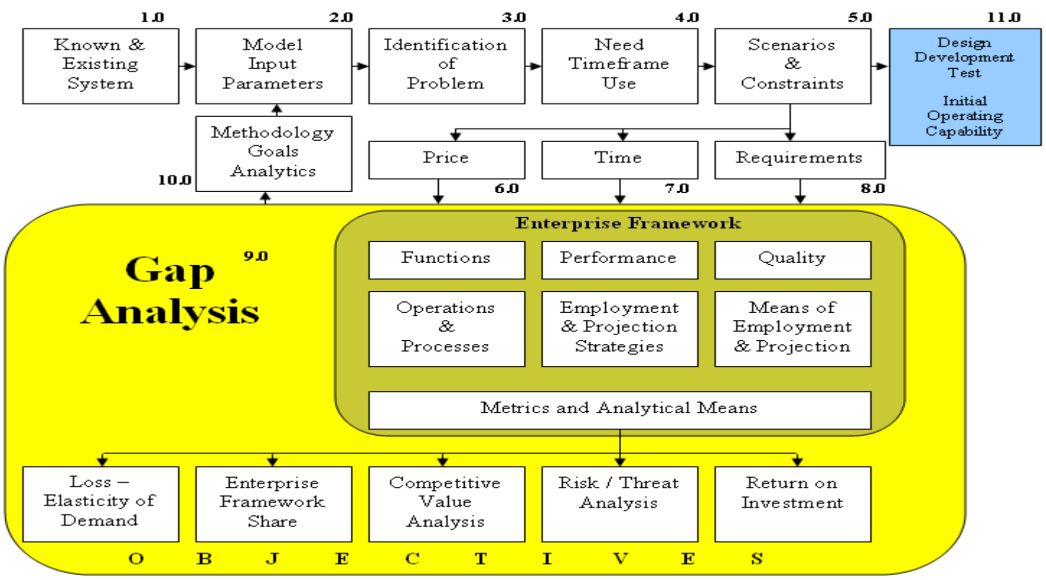

Figure 1. The Objectives of Gap Analysis

Conclusion

Gap Analysis is fundamental to the US DoD acquisition system and systematically adopted by large corporations. With the dismal results of time and cost overruns, ineffective use of constrained resources, and missed opportunities to make improvements without jeopardizing schedule and cost drive a critical evaluation of acquisition is warranted. Since the cost and the success of acquisition are in as much constrained by the initial conditions, it is prudent to develop and apply tools that can help improve both the evaluation and the processes of acquisition. Gap Analysis, one of the key early-phase drivers of the acquisition process, has significant room for improvement.

This paper discusses the Gap Analysis in the context of the ratio of triadic decomposition of requirements based on functions, performance, and quality to the investment in time and cost. Investors and stakeholders have expectations about the products they support. These expectations necessarily need to be complemented with a rigorous analysis of gaps. The notion has general adaptability and applicability to commercial and DoD acquisition. In the commercial sense, the Gap Analysis tools can be used to better position products in competitive market space. In the DoD sense, more effective use of constrained resources can be applied to military development activities.

The application of Gap Analysis to the general problem of satisfying requirements is challenged by more than simply improving methodology. Methodology that is encumbered with time-consuming steps and overburdened processes does not improve Gap Analysis. It is only through a streamlining of Gap Analysis that is efficacious, effective, and efficient that the forces and consequences of acquisition are better served. Thus, it is much more than determining merely what can be improved with Gap Analysis and more to the point, to determine how to improve the outcomes of Gap Analysis (which includes the time to complete the Gap Analysis process). To that end, the actions of Gap Analysis should not be obstructed by insistence on unnecessary procedures and folderol. Straightforward application of the formulations laid out in this report result in the application of sound value engineering and the systems engineering that have generally become widely accepted as standard practices.

Gap Analysis, as proposed and described, is used by Systems Engineers at the Naval Postgraduate School in support of grants and contracts from the US Department of Defense, as well as for degree-required Capstone projects and thesis work (Master's- and PhD-level). Research continues with loss functions, performance measures, measures of effectiveness, enterprise framework analysis, and theoretical foundations of Value Systems Thinking and Value Systems Engineering.

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Biography

Gary Langford is a lecturer in the Systems Engineering Department at the Naval Postgraduate School in Monterey, California. His research interests include the theory of systems engineering and its application to commercial and military competitiveness. Mr. Langford founded and ran five corporations – one NASDAQ listed. He was a NASA Ames Fellow. He received an A.B. in astronomy from UC Berkeley, and an M.S. in physics from Cal State Hayward. INCOSE Member