

# Weapon System Design Trade Offs

## Using Life Cycle Cost (LCC)

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F. Quentin Redman  
Raytheon Space and Airborne Systems  
2201 E. El Segundo Blvd,  
P.O. Box 902, EO/019/H130  
El Segundo, CA. 90245 USA

George L. Stratton  
Andrew Crepea  
Raytheon Missile Systems  
1151 E. Hermans Road  
P.O. Box 11337, M12/06  
Tucson, AZ. 85706 USA

This paper assumes the reader has some familiarity with Cost and An Independent Variable (CAIV), Design To Cost (DTC) and Life Cycle Cost (LCC).

### ABSTRACT

Cost Performance Trade-Off analysis is fundamental to the Systems Engineering process. A cost performance trade study, is a procedural search for a design solution that balances achieved systems performance, effectiveness and cost against the desired or required values for these features and the system. Life cycle cost (LCC) has become increasingly important as systems are designed with longer useful technological lives. Within this paper we will discuss the methodology and rationale behind the methodology for using life cycle cost estimates within these weapon system design trade-offs.

A cost performance trade study is an engineering philosophy where in all these aspects of the system (performance, effectiveness, cost and often schedule) are considered during systems requirements definition and subsequently system design. Implementing state-of-the-art methods and tools for planning, information, management, design, cost trade-off analysis, and modeling and simulation significantly improve the effectiveness of system design process. As a contractor, it is incumbent on us to become knowledgeable of the capabilities of the tools, to integrate them into our internal tool sets, and to improve service to our customers.

Deferred modernization due to limited budgets is causing many aging weapon systems lives to be extended, thus incurring greater support costs. This paper will present a short overview of the process of life cycle cost analysis (LCCA). It will address the basic concepts and applications, along with a review of methodologies and some aspects of engineering economics. LCC is defined as the sum total of the direct, indirect, recurring, non-recurring, and other related costs estimated to be incurred in the design, research and development (R&D), investment, operation, maintenance, and support of a system over its life cycle, i.e. its anticipated useful life span. It is normally organized into four phases: research, development, test, and evaluation (RDT&E); procurement (or acquisition), operations and support, and disposal.

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Economic Decisions are often made solely on initial investment or RDT&E and procurement cost. But this is only the proverbial tip of the iceberg – a portion of the total cost of ownership. More and more customers (especially government) are emphasizing and requiring an LCC perspective. To make intelligent acquisition decisions to meet a specific need, it is necessary to look beyond acquisition. In defense systems O&S costs can encompass up to 80% of the total LCC. LCC allows the evaluation of competing system proposals on the basis of total ownership cost and allows more effective budgeting of future funds such as O&S costs and disposal costs. A LCC perspective maximizes the benefit of applying strategies such as Cost as an Independent Variable (CAIV) and Design to Cost (DTC). Most Life Cycle Cost Analysis (LCCAs) require a mix of estimating methodologies. The methods may be applied individually or in combination. Analogy and parametric tend to be most useful in the early stages of product development. As program and system design stabilizes parametric estimating becomes more useful. A detailed design facilitates engineering estimate and projection of actuals.

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# Weapon System Design Trade Offs

## Using Life Cycle Cost (LCC)

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### 1.0 What is LCC?

**Definition.** MIL-HDBK-259 (Navy) provides the following comprehensive (if not long winded) expanded definition for LCC: “LCC is the sum total of the direct, indirect, recurring, non-recurring, and other related costs incurred, or estimated to be incurred in the design, research and development (R&D), investment, operation, maintenance, and support of a product over its life cycle, i.e. its anticipated useful life span. It is the total cost of the R&D, investment, O&S and, where applicable, disposal phases of the life cycle.”

More simply: LCC is the total cost to the customer for a program over its full life .It includes all costs directly and indirectly attributable to the program; i.e. any costs that would not occur if the system did not exist. Put simply, LCC is the Cradle to Grave cost.

Like most commonsense economic principles, the concept of LCC analysis (LCCA) has been applied for centuries. However, many of the methods and definitions we apply today were formalized in the mid-60s. An example is the computerized Highway Cost Model developed for the World Bank. LCC has long been emphasized at the Department of Defense as well as at other government agencies. It is particularly relevant to big dollar projects with long service life and multi-year investments.

Two terms in common usage that are often treated synonymously are Total Ownership Cost (TOC) and LCC. However, their definitions and usage are not necessarily synonymous. A United States Undersecretary of Defense (Acquisition and Technology) Memo dated November 13, 1998 defines them as follows:

“DoD TOC is the sum of all financial resources necessary to organize, equip, train, sustain and operate military forces sufficient to meet national goals in compliance with all laws, all policies applicable to DOD, all standards in effect for readiness, safety, and quality of life, and all other official measures of performance for DoD and its components. ....and all other costs of business operations of the DoD.”

*“Defense systems TOC is defined as Life Cycle Cost (LCC). LCC includes not only acquisition program direct costs, but also the indirect costs attributable to the acquisition program (I.e., costs that would not occur if the program did not exist). For Example: indirect costs would include the infrastructure that plans, manages, and executes a program over its full life and common support items and systems.”* (Black, 1999)

Therefore, at the United States DoD level TOC is at a higher level than LCC but at the service level the terms are interchangeable. The bottom line is that the cost analyst must assure he knows who is asking the question and that he has a clear understanding of their definition of LCC before conducting an analysis.

## 1.1 The Phases of the Life Cycle

Each LCC phase (Development, Acquisition, and Operations and Support) requires certain source data for accurate and credible estimates. This quality of this source data directly relates to the confidence able to be placed in the estimates regardless of which LCC phase is being considered.

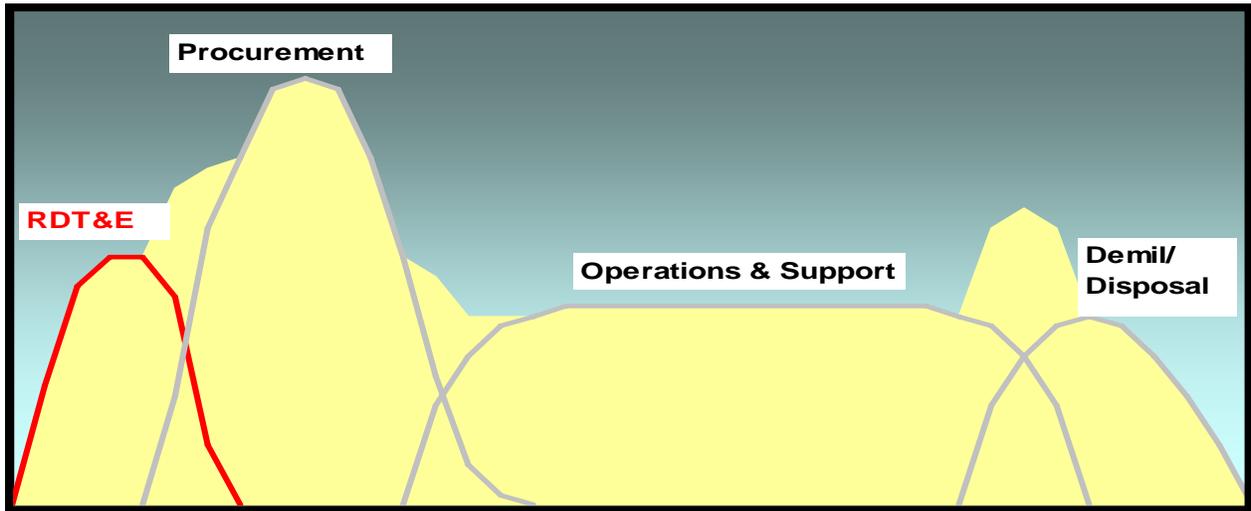


Figure 1 LCC Phases:  $LCC = RDT\&E \$ + Procurement \$ + O\&S \$ + Disposal \$$

**Research, Development, Test, and Evaluation (RDT&E).** RDT&E includes all contract and in-house costs required to bring a system from concept to production. It sometimes includes tooling and production start-up for Low Rate Initial Production (LRIP). Specific cost elements may include engineering design and development, fabrication, assembly and test of prototypes, system test and evaluation, as well as procedure and course development for operators and maintainers.

The Development phase costs for Architectures may be minimized by selecting existing subsystems, modifications of existing systems, NDI or COTS. The integration of subsystems including software will require effort and will be estimated. Should new technology for a subsystem require a full development process, a parametric approach will likely be adopted for this phase cost estimate.

**Procurement (Acquisition).** Procurement or acquisition costs include all contract and in-house costs, recurring and non-recurring, required to transform the developed system into a fully deployed and operational system. Sometimes this may be referred to as the Acquisition or Investment phase. Specific cost elements include prime hardware material and labor, support equipment, training, data, and initial spares as well as production start-up for full rate production.

Acquisition costs traditionally bear the most scrutiny because of the immediate budgetary implications. Quantities of recurring production costs drive the Acquisition phase total.

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However, the Acquisition cost estimating strategy will ensure that applicable costs such as the ILS elements of initial spares, training, and publications costs are also included. This inclusion again favors (in terms of Acquisition costs) the subsystems (or modifications) which are already in the fleet. Historical cost data forms the preferred basis for this phase estimate if available.

**Operations and Support (O&S).** O&S is comprised of all costs, including contract support, associated with the operation and maintenance of the system. Specific cost categories include personnel costs, SEPM, recurring training, maintenance, support equipment repair, inventory management, tech manual updates, replenishment spares, warranty and contractor support.

**Disposal.** Disposal includes all costs, in-house and contract, required to remove the system from inventory including demilitarization where appropriate. Disposal phase costs are sometimes included as a subset of O&S costs. Typical cost elements include disassembly, hazardous material disposal, material Processing, transportation, documentation, and regulatory Compliance. Some costs may be recouped through salvage value thus mitigating the cost of disposal.

## 1.2 Why Do We Use LCC?

Economic Decisions are often made solely on initial investment or procurement cost. Procurement cost is only the proverbial tip of the iceberg – a portion of the total cost of ownership. Operating and Support (O&S) costs are a growing percentage of LCC. For example O&S costs, depending on the system, may comprise between 12% and a whopping 83% of the LCC. Can we afford to ignore this? To make intelligent acquisition decisions to meet a specific need it is necessary to look beyond acquisition. Increasingly, customers (especially government) are emphasizing and requiring an LCC perspective.

<i>Missile ("Wooden Round")</i>		<i>Aircraft (F-16)</i>	
• RDTE	11%	• RDTE	2%
• Production/Acquisition	77%	• Production/Acquisition	20%
• O&S	12%	• O&S	78%
<i>Ship (Average)</i>		<i>Ground Vehicle (M-2 Bradley)</i>	
• RDTE	3%	• RDTE	2%
• Production/Acquisition	37%	• Production/Acquisition	14%
• O&S	60%	• O&S	84%

By the time requirements are set over 80% of LCC is committed by design decisions and by the time the design is final, approximately 90% of LCC is committed so early design efforts determine LCC. Clearly, the time to consider LCC is as early as possible in the program!

*"In actuality, our military hardware is now on a replacement cycle of about 54 years – this in a world where technology typically has a half-life from 2 to 10 years."* (Army RD&A Bulletin 1994)

## 1.3 LCC: How Do We Use It?

**Option Evaluation:** One of the most important applications of LCC is evaluation of competing system proposals on the basis of total ownership cost. This includes both comparing alternate technological solutions to a specific technological need and comparing the specific proposals of competing vendors. Given a set of requirements that the system must meet LCCA facilitates identifying the system that meets those requirements at the least cost. This represents the most efficient use of resources or the greatest value. LCCA should be conducted as early in the project development cycle as possible. The level of detail in the analysis should be consistent with the level of investment.

Basically, the process involves the following steps

- 1) Develop the concept of operations
- 2) Determine the development and acquisition strategy
3. Develop rehabilitation and maintenance strategies for the analysis period. (do not forget disposal as part of the strategy.)
- 2) Establish the timing (or expected life) of various equipments (and software) and their rehabilitation and maintenance strategies
- 3) Estimate the agency costs for construction, rehabilitation, and maintenance
- 4) Estimate user and non-user costs
- 5) Develop expenditure streams
- 6) Compute the present value
- 7) Analyze the results using either a deterministic or probabilistic approach
- 8) Reevaluate strategies and develop new ones as needed

**Improved Awareness:** LCC allows management and stakeholders a broader and more accurate assessment of cost drivers at any point in a project. Though a system may be well into production an LCC analysis may provide the first glimpse of the total cost of ownership. This in turn can facilitate the appropriate focus of resources to where they are needed and most efficient.

**Forecasting and Budgeting:** Forecasting involves the prediction of future expenditures in order to set budgets. Understanding LCC allows more effective budgeting of future funds such as O&S costs and disposal costs. This can be effective in preventing budgeting surprises and reducing cost risk.

**Cost Strategy Support:** With increasing frequency companies are implementing management disciplines such as Cost as an Independent variable (CAIV) and engineering design disciplines such as Design to cost (DTC). A LCC perspective is essential to maximizing the benefit of applying these strategies.

## 2.0 LCC – Phasing and Funding

The DODI 5000 Model of a program's Life Cycle is shown in figure 2. Note that development includes Concept Exploration, Component Advanced Development, Systems Integration and Systems Demo phases as apposed to the more simplistic model of LCC Development discussed in this paper.

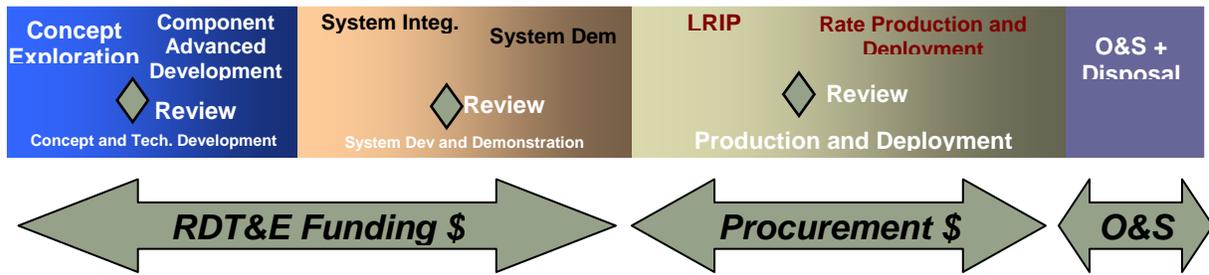


Figure 2. DODI 5000 LCC Model.

Each LCC phase (Development, Acquisition, and Operations and Support) must be estimated separately as each has a different funding line item with in the DOD budget systems. The top line DOD funds are called 051 Funds (DOD TOA) and include: Military Personnel, O&M, Procurement, RDT&E, Military Construction, Family Housing, R&M Funds, Defense Wide Contingency, Offsetting Receipts, Trust Funds, and Inter-fund Transactions. For our discussion of LCC we will only include the first 4 items.

- **Phase 1: RDT&E.** RDT&E consists of development costs incurred from the beginning of concept through the end of development. It may include Low Rate Initial Production (LRIP) if funded with RDT&E Dollars. Typical cost elements include:
  - Prime Mission equipment
  - Design/Development Engineering
  - Systems Eng/Program Management
  - Data Management
  - Special Tooling and Test Equipment
  - Peculiar support equipment
  - ILS
  - Training
  - Test and Evaluation
- **Phase 2: Procurement.** Procurement consists of production and deployment / fielding costs from LRIP through completion of FRP and fielding. Typical cost elements include:
  - Prime Mission equipment
  - Integration, Assembly, and Test
  - Special tooling and Test Equipment
  - Systems Eng/Program management
  - Lot Acceptance Testing
  - Peculiar Support Equipment
  - 1st Destination Transportation
  - Initial Spares
  - Warranty
  - Container
- **Phase 3: O&S.** Operating and Support costs include all costs of sustaining the system through the end of system operation. It includes all costs of operating and maintaining the system. Typical cost elements include:
  - Operator Training
  - Maintainer Training
  - O-level Maintenance
  - I-level Maintenance
  - Depot level maintenance
  - Support Equipment repair
  - Repair Transportation
  - Inventory management
  - Replenishment Spares
  - Mission Support
  - Software upgrades
  - Tech Manual Updates
  - Mission Programming

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- **Phase 4: Disposal.** Demil/Disposal costs include all costs associated with demilitarization and disposal of the system at the end of its useful life. These costs can be significant and should be considered early in the life cycle.
  - Typical cost elements include:
    - Disassembly
    - Hazardous Material Disposal
    - Material Processing
    - Transportation
    - Documentation
    - Regulatory Compliance
    - Some cost may be recouped through salvage value

### 3.0 Introduction to Cost Engineering Budgeting: Consideration of Colors of Money

“Colors” of money has nothing to do with the new currency issues. It is DoD/Industry slang for the US Government Budget (and DOD 051) budget/appropriations categories. Each service has its own nomenclature for the various “colors.” Below the 051 TOA various subdivision are created by each service. Some examples are as shown in figure 3.

Phase	Army	Air Force	Navy
Development	2040 / RDT&E	3600 / RDT&E	1318 / RDT&E
Procurement	2035 / Ammo / MIPA	3020 Missile Procurement	1507 / WPN
Operations & Support	2020 / OMA	3400 Operations and Maintenance	1804 / O&M

Figure 3 Examples from each Service’s LCC Budget Categories.

In evaluating alternative program decisions based upon LCC the decision maker must understand the priorities of the impact on budgetary considerations. Since the LCC includes multiple colors of money, funding priorities or lack of available funding in one or more funds must be considered.

### 3.1 DOD Appropriations by Title, Including Supplements

These LCC budget categories can vary over time but usually the percentages of the top line does not vary greatly year to year. The largest dollar amount is O&M with MILPERS (Personnel) second. Figure 4 provides that last 10 years, as of 2006, of budget history and a projection for the next 10 years. This projection is from the GEIA 2006 Vision Conference. Funding for many budget line items remains almost constant over the life of this projection while other, large acquisitions come and go. This chart is representative of what all services must prepare in order to plan for their anticipated acquisitions. The budget top line will probably not change much in constant dollars. Acquisition programs have a life cycle. There move from RDT&E funding to Procurement funding to O&M and Personnel funding.

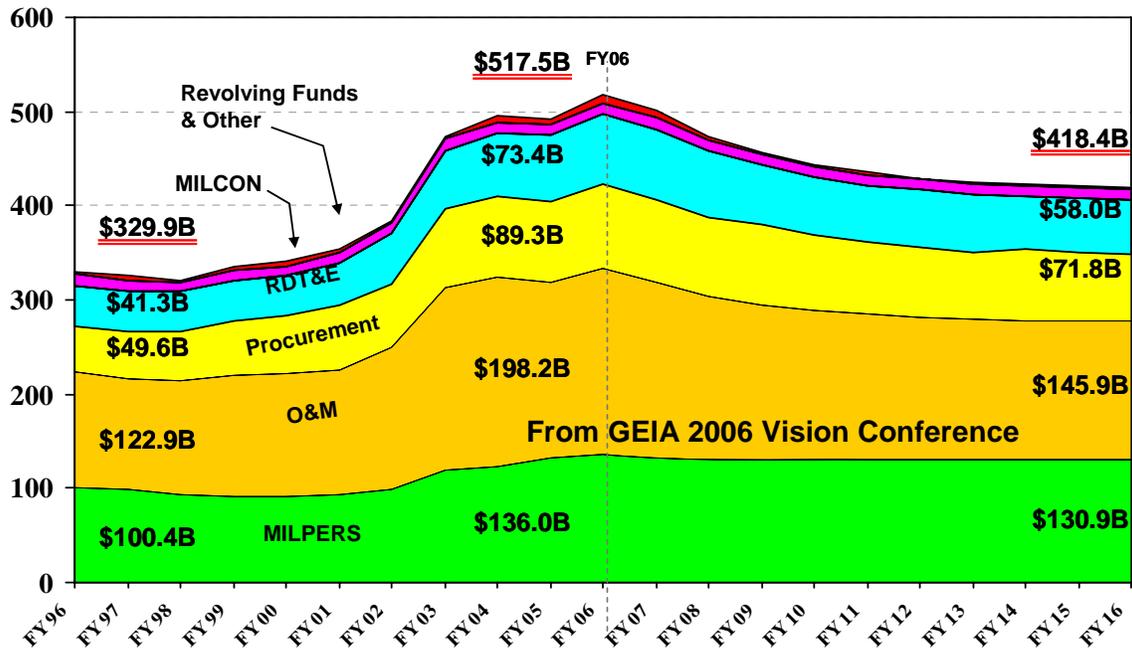
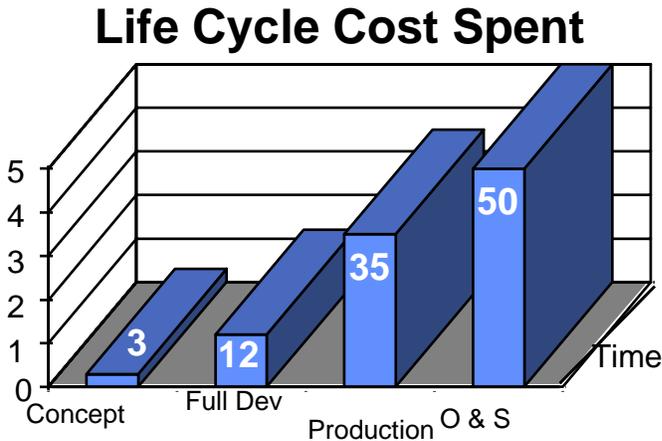


Figure 4 DOD Budget history and forecast.

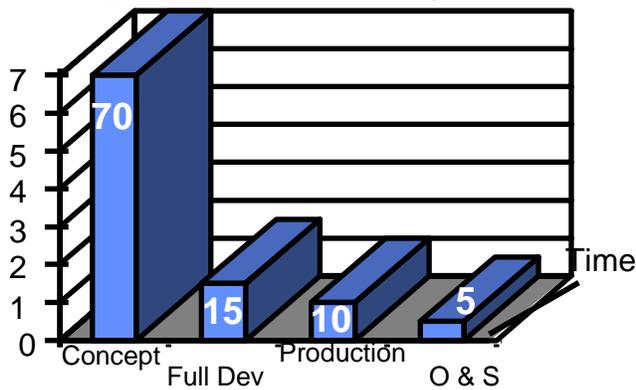
### 3.2 Trade Space Window Of Opportunity

The LCC of a program can be controlled/managed but it requires putting the effort to do so into the initial phases of the program. There are many ways to evaluate and manage a program cost estimate with its inherent uncertainty (risk). The ones used should be appropriate to the



program's size, complexity, and the stage in the acquisition cycle. As illustrated by Figure 5, once a program has a design as usually occurs with the Full Development (Systems Development and demonstration) phase, the ability to impact the programs LCC is minimal as the programs LCC is virtually completely set already. Therefore, early conceptual studies must address the programs LCC. As the system proceeds further into the acquisition process (i.e. Concept Development, PDRR, EMD, Production and Operation and Support), a more quantitative treatment of cost

## Impact On Life Cycle Cost



estimate uncertainty (risk) is possible. However, since the design has begun to be firmed up, the production environment is planned and the operational and support scenarios are in place, changes become expensive and often require program schedule slippage.

Figure 5 Trade Window of Opportunity

## 4.0 “HOW” Design to LCC IS UTILIZED

In order to create the most affordable design we must determine what our customers concerns are and fully understand those concerns. There are a number of methods to determine or create a listing of key concerns. These methods are:

- Explicit – Our customer states their cost goals or operating budgets
- Implicit – Our customer will imply things such as a desire to reduce operational staffing
- Next Phase – Our current contract contains a limited budget / funding
- Unit Production – We are given an average unit production cost (AUPC) goal
- Total Ownership Costs (TOC) – We may have reduced total ownership costs (RTOC)
- Life Cycle Costs (LCC) – We may be told that our customers desire is to have the new systems operational cost be some determined percent (normally 30%) less than the replaced system

We must also determine how the competition will impact system affordability. This competition may be from other potential new systems or from items currently within the customer’s inventory that may be switched to perform the mission our potential new system would be designed to full. Keep in mind that any existing systems may have modification costs or leave an other mission un filled if it is switched to perform out mission.

We next establish design affordability goals (including system cost goals and targets). These design goals are initially established at the top system or architecture level. Then they are allocated down to the subsystems. They also should include all phases. E.g. for each of the EMD, Procurement, and O&S phases.

We next must understand how our system performance requirements are impacted by or impact the system affordability requirements. The best way we can do this is to perform an economic analysis of the proposed solution with in the procurement and operational and support scenarios. We try to control the cost by establishing a cost as an independent variable, design to life cycle

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costs and or design to cost program. To make these programs successful, we must review the present estimates against goals often and react appropriately and expediently.

## ***4.1 Planning the Analysis***

The first step in any cost analysis is planning! You must determine the scope of the analysis, define your objective and achieve consensus on critical ground rules and assumptions.

In identifying the ground rules and assumptions we list any assumptions that will bound, constrain, or otherwise impact the analysis. These include the life cycle/ horizon, base year dollars, planned production units and schedule, and any performance constraints. We determine and document our assumed system life cycle (System service life: Useful life of the system depends on what the system is i.e. aircraft: 25 years, ship: 50 years, missile: 20 years, bridge: 100 years, etc.) and our planning horizon (period of time over which all costs are estimated). The planning horizon may or may not coincide with the actual system service life and may change over time. We should also estimate resources required to perform the analysis and our reporting schedule

One of the most important aspects of this planning phase is to develop the program work breakdown structure (WBS) and the cost element structure (CES). This WBS should include all elements of the system and will be essential to the further development of the analysis. The CES defines the cost element breakdown and assures that relevant and important cost categories are not inadvertently left out. It also assures that irrelevant cost categories are not included biasing the result.

The CES and WBS may be imposed as a requirement by the customer but there is no standard CES for all LCC application due to the tremendous variation in systems and programs. The level of detail will depend on the system itself as well as the purpose and scope of the analysis. As a minimum you should give consideration to the time phasing, philosophy of support, and significant cost generating components.

Estimating LCC requires breaking down the system into its cost elements and time phasing them. There is no standard CES for all LCC applications due to the tremendous variation in systems and programs (aircraft, missiles, electronics, ships, infrastructure, etc) The CES may be imposed as a requirement. The level of CES detail will depend on the system as well as the purpose of the analysis. Consider: Estimation methodology, Significant cost generating components, and Support philosophy.

Another important step in this phase is to begin a detailed documentation effort. This will allow the analysis to be validated and prevent false starts and later disagreements about intent or method.

## ***4.2 Select / Develop the Model***

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Cost models of various forms are the primary method of LCC estimating. These models may be commercial models or “homegrown”. They may be automated to varying degrees or manual. Whatever model is chosen, the analyst needs to assure that it is a useful and appropriate tool that is not simply a set of forced constraints. The model needs to support the intent and scope of the analysis rather than distorting the analysis to fit the model. Some general guidelines for a good LCC model are that the model:

- Should be responsive to changes in design and operational scenarios.
- It should clearly incorporate all major cost drivers.
- Include clear documentation.
- User friendly and should not require special programming support.
- Allow for adjustment of inflation, discounting, and learning curve where appropriate.
- Be able to compare and contrast alternatives.
- Identify areas of uncertainty.
- Support sensitivity analysis.

In general there are two categories of cost models; commercial software packages and homegrown spreadsheet or database based models. Some examples of current commercially available packages are CASA, ACE-IT, PRICE, and SEER. The scope of this article does not allow the specific discussion of the merits and shortcomings of these specific models. However, some are designed to estimate costs parametrically and some are designed to rollup costs in a specific accounting structure. Be careful of the purpose of the model before deciding on one.

Creating your own model using a spreadsheet package such as Excel may be the best path. Although all LCC models may have some common elements they may require unique characteristics. However, a model should be an analytical tool and not simply a place holder for data.

Although a spreadsheet based model may have many advantages in being specifically tailored for the unique parameters of a specific analysis they may require significant effort to validate for the customer. In any case validating the model with historical data increases credibility and may improve fidelity.

### **4.3 LCC vs. Sunk Cost**

Early in the study, the cost analyst must look at all potential costs of the alternatives being considered. However, a certain measure of relevance is that past costs or sunk costs are never appropriate to the study’s pending decision. Only future costs for each of the evolving alternatives need be considered. However, these sunk costs are oftentimes accrued but only to act as background (contextual) data, (or to act as analogies for projecting future costs). Such portrayals of the full baseline cost may be helpful to anchor your pending decision within a budgetary context but they are not a measure of lost opportunity and therefore are not pertinent to the analysis of cost-effectiveness. Thus, sunk costs are cost already spent. Committed costs are contracted for costs items or events not yet spent (Sunk) - Where in the cost to cancel equals or exceeds the cost to continue the effort. Therefore, early in the EMD phase, the LCC analysis (LCCa) still subject to design trades is:

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$LCCa = RDT\&E \$ (\text{Uncommitted SDD } \$) + \text{Procurement } \$ + O\&S \$$

where uncommitted SDD \$ =  $RDT\&E \$ - (\text{Sunk } \$ + \text{Committed RDT\&E } \$)$

It is important to note that design trades are only conducted for costs which you can influence!

Thus possible cost (\$) trade spaces are:

1. Minimizing: Total LCCa ( $LCC = RDT\&Ea + \text{Procurement} + O\&Sa$ )
2. Minimizing: RDT&Ea vs. PROCa vs. O&Sa (vs. Disposala)
3. Separate Individual Pots of Money. E.g. RDT&Ea vs. RDT&E Goal, PROCa vs. PROC Goal, and O&Sa vs. O&S Goal

Note: Disposala is assumed to be included within O&Sa

Remember that frequently there are technological answers, budgetary answers and political answers for a design trade and usually they are not the same! For this reason, care must be taken to document the ground rules and assumptions and the decision criteria for any trade to be performed.

Therefore, Early in the EMD phase, the LCCa still subject to design trades is:

$LCCa = RDT\&E \$ (\text{Uncommitted EMD } \$) + \text{Procurement } \$ + O\&S \$$

where Uncommitted EMD \$ =  $RDT\&E \$ - (\text{Sunk } \$ + \text{Committed RDT\&E } \$)$

#### **4.4 TRADE SPACE MATRIX – Cost Metric**

Selection of the cost metric for LCC trades can be issue and should be based upon the ground rule established for the decision criteria. LCC trades can place emphasis on any phase of the LCC such as the total LCC, the AUPC or just the Operation or Support Costs. Keep in mind that if one phase or element of the LCC is used as the decision criteria then the resulting systems design will tend to favor that criterion to the exclusion of other criteria.

One way of utilizing LCC estimates is to use it in conjunction with some measure of system effectiveness for a cost effectiveness trade-off. The parameters combined as a ratio give an indication of how well the system meets the needs of, or gives value to the customer. An appropriate measure of effectiveness (MOE) would be any quantifiable measure of a system parameter such as reliability, availability, dependability, capability, etc. It may represent a physical or operational characteristic of the system. Some examples include operational availability, system reliability, probability of kill (PK), speed, weight, etc. Whatever is chosen should be quantifiable and should be defined relative to a specific operational environment and scenario.

#### **4.5 TRADE SPACE – Decision Point**

Do not assume one solution is right but do the analysis for the options for the affordable and effective options. Weigh the systems cost vs. Utility (performance of effectiveness characteristics of interest) Our customers expect to get the “best valued” system possible for their available funds. One methodology to use to achieve this worthy goal is cost effectiveness

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analysis. Figure 6 illustrates this process. The red box on the right side of this figure, Selection and analysis, Performance vs. Effectiveness vs. Cost is the Trade Space Decision Point. This is the point at which we weight each system alternative against our decision criteria looking for the best solution.

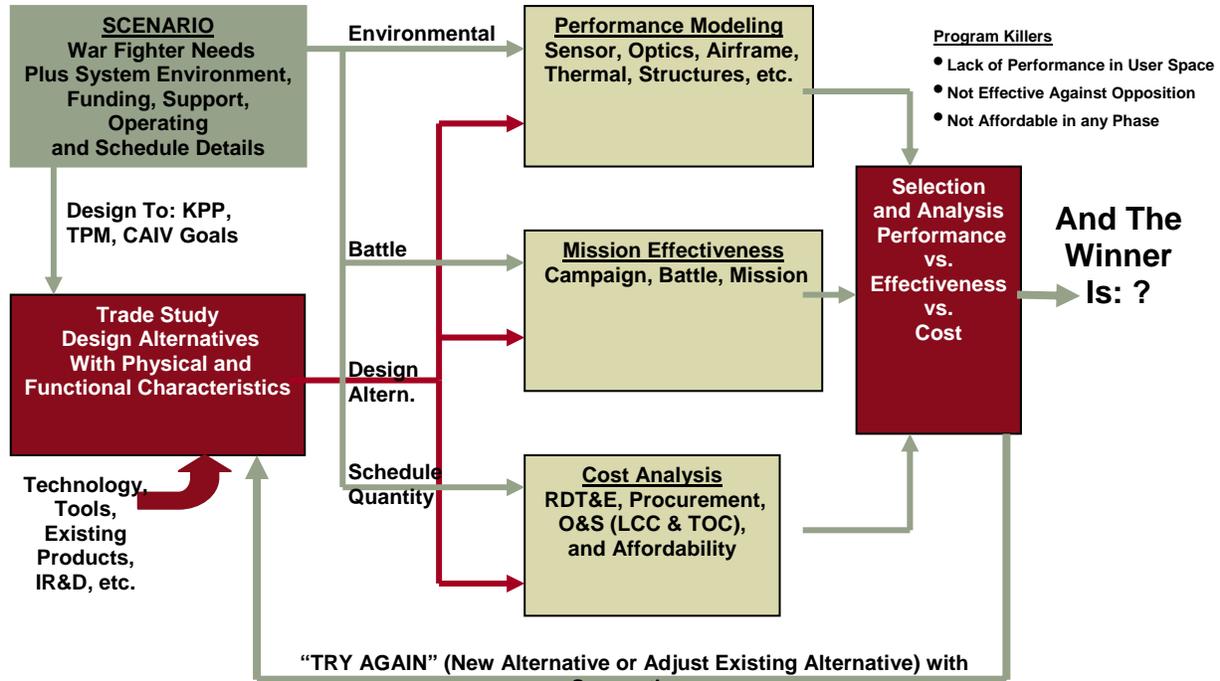


Figure 6 Selection of the “Best Value” Alternative Process.

Cost-effectiveness or cost-performance tradeoffs is a tradeoff of performance issues versus cost issues. This analysis must cover the complete “trade space” to the point where all the knees are identified. If a key performance threshold value can be achieved, or even nearly achieved, at a minimum cost, then that performance value and cost should be considered by the user and materiel developer for meeting the operational requirement. Similarly, if it is possible to reach an objective value through a marginal improvement in performance, but at a substantial increase in cost, then the user and materiel developer need to weigh the cost-benefit of such an increase in performance. The “best bang for the buck” is a region characterized by a substantial performance improvement at a reasonable increase in cost. Cost-performance tradeoff analyses need to be broad enough that all costs are considered when making early decisions on system design alternatives. Cost-performance tradeoffs are an essential part of the system design process. Cost is a design constraint just like any other performance parameter. Cost drivers identify areas that need special attention. The materiel developer, user, and contractor should work to reduce high cost drivers and maintain performance. Speed, weight, durability, interoperability are typical performance requirements that drive the system design. For cost-effectiveness studies, “cost” is basically defined as the economic valuation of the path taken versus the path not taken. More completely, the scope of our considered cost involves the alternative use of the resources that must be sacrificed in choosing a given alternative

### **4.5.1 Software and the Decision Point**

The decision as to perform a function in hardware or software can have monetary consequences to the various program phases. Hardware production cost can be reduced if functions are performed in software. However, the software development cost will greatly increase. Thus there is a possibility of trading off production funds vs. development funding as part of this tradeoff. Also, there is the fact that software does not wear out or deteriorate over time where as hardware does. Thus there may be a possibility of reduction some maintenance costs by performing functions in software. However, the operating environment, missions and operators will change as time passes thus modifications will be needed even to the software. Thus we actually have another trade off. E.g. will modifications to the system be easier and cheaper to the software or to the hardware?

As we perform our “best Value” or affordability or LCC analysis and especially when we get to the point where we are to select the “best Value” alternative, we need to be sure software estimates were included. An example of the software issues and where they fit in when we consider the design of a weapon systems are as shown in the following list from a recent missile trade study.

#### Example: Missile Alternative

- Physical and Functional Characteristics
  - Size, Weight, Speed, Range, Payload, etc.
  - Functions Performed (Search, Ballistic Load, etc.)
    - Hardware Resident
      - Seeker Head
      - Propulsion, Warhead, etc.
    - Software Resident
      - Target ID, Tracker, etc.
    - HW/SW Combined
      - Position in Space (IMU and GPS)
  - Software Issues
    - Functions Performed
      - Lines of code
      - Interfaces
    - Coding Group Capabilities
    - Environment
    - Schedule
    - Existing code (mod/reuse/etc)

### **4.5.2 Software Significant Alternatives: Consider the Software Life Cycle**

SW does not age! However, as hardware, processes, situations and people change, enhancements (and maintenance) are required. These can either be planned for as a continuous maintenance

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contract or in separate modification / upgrade contracts. Funding can be through O&S or RDT&E Funds. Typical SW LCC dollars the authors have experienced are:

- RDT&E – usually very large and for weapons 10 to 30 percent of development
- Procurement – approximately Zero,
- O&S – usually in the range of 50-75% of the SW LCC,
- Disposal - zero,
- average Development to Support = 47-53%)

New SW development typically have been observed to have the follow:

- Requirements (11%)
- Design (14%)
- Code (24%)
- Test (27%)
  - Function / Integ / Sim
  - SW in the Loop
  - HW in the Loop
  - Flight Tests (AD, SD)
  - Quality
- Documentation (10%)
- Installation (1%)
- Management (13%)

#### **4.6 LCC Sensitivity Analysis - Look for the Cost Driver(s)**

Sensitivity analysis is a systematic approach used to identify the cost impacts of realistic and possible changes to one or more of an estimate's major input parameters. The objective is to vary input parameters over a range of probable values and recalculate the estimate to determine how sensitive outcomes are to changes in the selected parameters. (From U. S. Air Force Cost Risk and Uncertainty Analysis Handbook, Air Force Cost Analysis Agency, April 2007)

Sensitivity analysis is useful for performing what-if analysis, determining how sensitive the point estimate is to changes in the cost drivers, and developing ranges of potential costs. A drawback of sensitivity analysis is that it looks only at the effects of changing one parameter at a time. In reality, many parameters could change at the same time. Therefore, in addition to a sensitivity analysis, an uncertainty analysis should be performed to capture the cumulative effect of additional risks. (From GAO Cost Guide, Chapter 14)

#### **4.7 Cost Risk and Uncertainty**

There are many ways to evaluate and manage the cost estimate uncertainty (risk) connected with a program; the ones used should be appropriate to the program's size, complexity, and the stage in the acquisition cycle. As the system proceeds further into the acquisition process (i.e. Concept Development, PDRR, EMD, Production and Operation and Support) a more quantitative treatment of cost estimate uncertainty (risk) should be possible. Each of the risk management

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activities contributes to assuring that designer addresses specified requirements. However, each adds cost to the resulting product for some degree of risk reduction. While recognizing the need for risk management in these areas, the acquisition strategy and the quality assurance provisions of the specification should be structured to minimize the added cost.

Cost risk and uncertainty refer to the fact that because a cost estimate is a forecast, there is always a chance that the actual cost will differ from the estimate due to:

- lack of knowledge about the future
- the error resulting from historical data inconsistencies, assumptions, cost estimating equations, and factors that were used to develop the estimate
- biases get into estimating program costs and developing program schedules.
  - biases may be cognitive—often based on estimators’ inexperience
  - or motivational where management intentionally reduces the estimate and/or shortens the schedule to make the project look good to stakeholders.

Recognizing the potential for error and deciding how best to quantify it is the purpose of risk and uncertainty analysis. From GAO Cost Guide, Chapter 14

Because there is always potential variability in inputs and assumptions applied in a LCC analysis, a single point estimate will never be correct. Some level of uncertainty, or risk, will always be present. Despite this studies have shown that in the defense industry a significant fraction of program managers do not accept risk assessment at all, not even “slightly”, and almost half think of risk assessments as intuitive judgments, without historical data or guided-survey.

When the inputs to a LCC model are fixed the model is called a deterministic model. In a deterministic approach a single set of “most likely” costs and other inputs are used to derive a point estimate. However, a point estimate cannot account for variability or the likelihood of achieving the given outcome. The estimate can be bounded by “best case” and “worst case” scenarios or iterated a finite number of times. This provides information to the decision maker that quantifies robustness of the outcome and highlights the degree to which the LCC is dependent on initial assumptions.

However, these discrete inputs are not equally likely. Most inputs are characterized by uncertainty that can be modeled as a probability distribution such as normal, triangular, uniform, etc. The outcome can then be described by a mean value and a measure of variance.

Most available Cost Risk Analysis data in the aerospace industry seems to use the triangular distribution. (“Black”) Reasons given for this preference specified the simplicity of applying the triangular distribution along with its conservative results.

In the triangular distribution the mean value is bounded by two endpoints; an assumed least value and greatest value. These are connected in a triangular distribution with straight lines running from the mean value to the two endpoints. The variation can then be calculated. In general, with symmetry, there is roughly a 75% chance that the true value lies within  $\pm .5$  base units of the mean where a base unit is the distance from the mean to the symmetrical endpoints. Thus, instead of a “most likely” point estimate we now have a mean value and a quantified measure of variation or risk.

A higher level of analysis is achieved using a stochastic model. In a stochastic model inputs

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are characterized by uncertainties that can be modeled as probability distributions. To model these distributions Monte Carlo simulation may be used to randomly generate values over and over in order to attain a central tendency. The Monte Carlo simulation repeatedly samples values from the descriptive probability distribution and uses these values to generate a mean value along with measures of variation and risk. Simulation can provide a more exact measure of the certainty of a given outcome than a deterministic approach.

The level of analysis pursued should effectively support the decision maker in the simplest manner. Although, more complex stochastic simulation efforts may provide better quantification of risk, complex models can sometimes cause confusion and require effort that may add little value. Start simple.

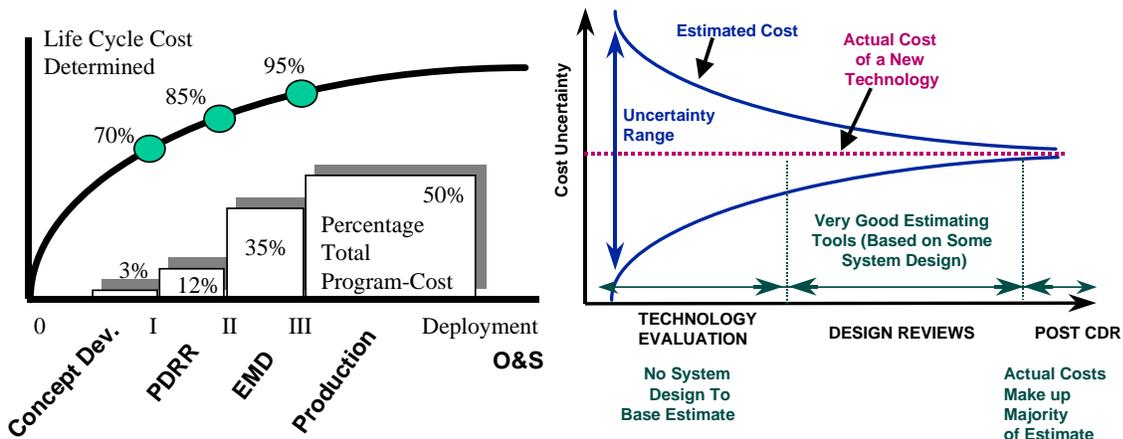


Figure 7 Cost Uncertainty Declines as Program Matures. Typical Cost History for Weapons and Platforms

#### 4.7.1 Risk and Uncertainty

Raytheon's best value will have an acceptable capability to manage the risk, i.e. Program Management. The Program Management assesses this capability and decides on how much flexibility can be provided how much risk is entailed. This should be done in the source selection process and used to structure the program management tasks in the resulting contract. The frequency of reviews and technical reports, work breakdown structure specification and method of cost reporting should also be tailored by the contract purpose, type and value.

As previously stated, integrated functional reviews are critical to influencing how Raytheon integrated the design effort. Separate government routine functional reviews should be minimized. Reviews should be scheduled for the government's concurrent engineering team as a body.

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System test and evaluation is conducted to ensure that systems meet the performance requirements of specification. The continuous assessment approach for system test and evaluation should provide feedback to Raytheon to improve system design and performance.

Raytheon is responsible for performing tests required by the specification and contract. The customer may witness these tests or verify the results by conducting an operational test or having them performed by an independent testing or inspection organization. It is appropriate that Raytheon develop the testing regime and conduct the testing program based on factory equipment and processes. Requiring specific inspection equipment and the amount of inspection will limit the efficiency of the manufacturing facility, add cost and limit competition. The test and evaluation process, for both Raytheon and government conducted tests, is continuous. Large amounts of data and analysis are accumulated to substantiate the system's performance. This large amount of evidence is the foundation of the evaluation process and should be kept in mind when establishing requirements for evaluations.

Simulation and continuous evaluation can be effective techniques for reducing developmental testing. Involving the customer developmental tester and evaluator as a member of the program's concurrent engineering team can improve communications and assist in tailoring requirements to minimize risk reduction costs.

Additionally, a very integral and important part of Raytheon and the Systems Engineering Affordability implementation is to control the manufacturing processes and verify conformance to the detail design and technical requirements of the technical data package. The quality assurance provisions in the technical data package serve to verify conformance of the parts and components of the system. Prior to acquisition reform the practice, throughout the government, has been to require test, examination and evaluation for each requirement, ranging from incidental dimensions to critical performance requirements, all at ambient and extreme environments. These all add significant cost to the product. Cost has seldom been a consideration in establishing the quality assurance provisions in specifications and on drawings. Once established, these provisions are difficult to change even though Raytheon has demonstrated an acceptable process capability. However, under acquisition reform/affordability the approach to quality assurance must be reassessed.

In today's marketplace, commercial quality techniques are at least equal, or surpass, the Military quality standards. In addition, these quality systems are much more efficient and cost effective than those quality requirements previously imposed in defense contracts.

Since the quality of every product is determined primarily by the product design, systems engineering and the manufacturing process, the past performance of Raytheon and the quality is evaluated during the source selection process.

Moving the acquisition system from a "risk adverse" to a more "risk management" orientation directly impacts source selection. Therefore, it is of utmost importance that Systems Engineering implement a disciplined Affordability Plan for a successful and profitable program. Shown below in figure 5 is a chart showing the typical program cost over the life of the a weapon (solid propellant missile) and also for a platform (modern attack aircraft). Note that the cost uncertainty is all in the early stages of the program, but this is also when the majority of the

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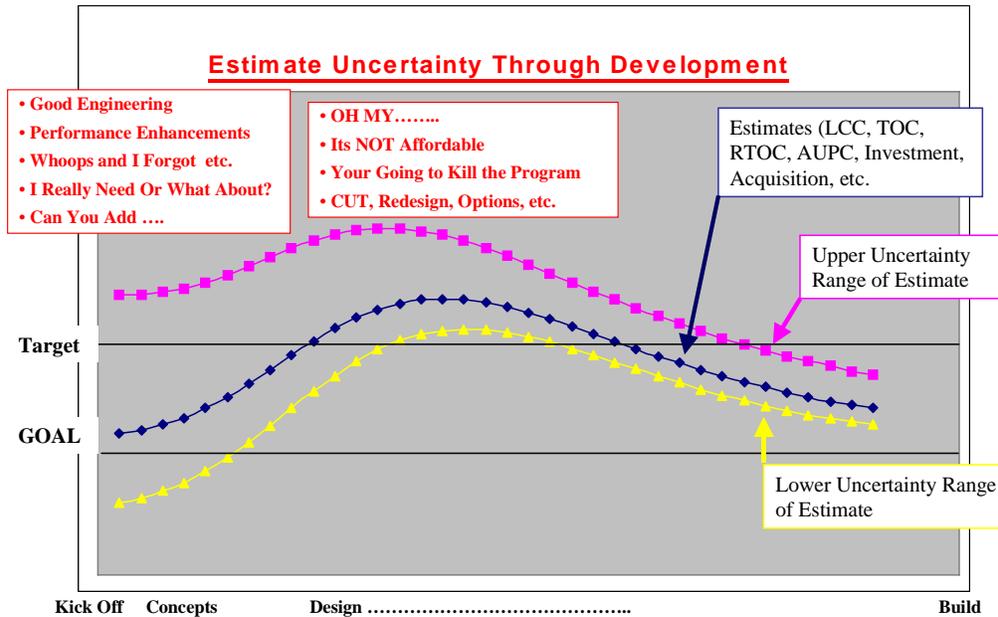
program costs are determined. As the program design firms up the acquisition cost are determined. The only chance left to effect these costs is in adjusting the schedule.

Another factor that must be accounted for and is often not understood is that the cost estimate for a program as well as any other cost metrics like unit production cost will often vary as the program matures. Figure 6 illustrates this effect for a hypothetical program. The major difference between this hypothetical program and a real program is that the line reflecting changes in your program estimates will not be this smooth and may have very different slopes.

The figure has two solid cost lines, the cost Target (sometimes called the cost threshold) and the cost Goal. The cost Target of threshold is the maximum the program can cost before it becomes unaffordable and subject to being canceled. Note, this chart could be a plot for any appropriate cost metric. Often this will be the average unit production cost, but may also be the average unit operating and support cost, or the TOC/RTOC of the program or any other appropriate metric. The Goal is the value for that measured cost metric for which you and/or your customer feel will be achieved by a design that's both affordable and effective. This is usually the "Best Value" design goal. The effectiveness is not shown on this chart and a brief discussion of its calculation will follow later with detailed discussions. You must also understand that the initial estimate may not be between the target and goal but may well be well above the target. In that case the important program factor is that the slope going to all succeeding estimates must be downward with a realistic program plan on how this will happen.

Establishing a cost estimate is a fairly complex effort. For some systems the baseline estimate may be a one year snap shot in time, the life cycle cost of the reduction initiative, or the systems remaining life cycle. Additionally most program environments are where the only constant is change, especially systems design and programmatic. In summary, typical cost estimates from concept through design, build and O&S are fluid and require constant and continual estimate updates with the changing current, accurate and complete program data.

**Understand Programs & Estimates Change**



**Typical Cost Estimating History Traced over Development of A Program**

Figure 8 Cost estimates for a program will change as the program matures. Note, the cost target is some times called the cost threshold and many of the often used phraseology heard on programs is on the chart in the appropriate locations.

Risk is defined as the chance of loss or injury. In a situation that includes favorable and unfavorable events, risk is the probability an unfavorable event occurs. Uncertainty is defined as the indefiniteness about the outcome of a situation. It is assessed in cost estimate models for the purpose of estimating the risk (probability) that a specific funding level will be exceeded.

For management to make good decisions, the program estimate must reflect the degree of uncertainty, so that a level of confidence can be given about the estimate. Having a range of costs around a point estimate is more useful to decision makers, because it conveys the level of confidence in achieving the most likely cost and also provides information regarding cost, schedule, and technical risks. Point estimates are more uncertain at the beginning of a program, because less is known about its detailed requirements and opportunity for change is greater. In addition, early in a program’s life cycle, only general statements can be made. As a program matures, general statements translate into clearer and more refined requirements that reduce the unknowns. However, more refined requirements often translate into additional costs, causing the distribution of potential costs to move further to the right. From GAO Cost Guide, Chapter 14

**4.7.2 The S Curve - (or cumulative probability curve)**

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Cost estimates should be based upon variables that are specified with realistic ranges for all inputs. Consider far future events as having potentially a greater risk – technology, or environment changes may not be known.

From Wikipedia, the free encyclopedia, The [Normal distribution](#), often called the "bell curve". When the random variable takes values in the set of [real numbers](#), the probability distribution is completely described by the [cumulative distribution function](#), whose value at each real  $x$  is the probability that the random variable is smaller than or equal to  $x$ .

The concept of the probability distribution and the [random variables](#) which they describe underlies the mathematical discipline of [probability theory](#), and the science of [statistics](#). There is spread or variability in almost any value that can be measured in a population (e.g. height of people, durability of a metal, etc.); almost all measurements are made with some [intrinsic error](#); in [physics](#) many processes are described probabilistically, from the [kinetic properties of gases](#) to the [quantum mechanical](#) description of [fundamental particles](#). For these and many other reasons, simple [numbers](#) are often inadequate for describing a quantity, while probability distributions are often more appropriate.

There are various probability distributions that show up in various different applications. One of the more important ones is the [normal distribution](#), which is also known as the Gaussian distribution or the bell curve and approximates many different naturally occurring distributions. The toss of a fair coin yields another familiar distribution, where the possible values are *heads* or *tails*, each with probability  $1/2$ .

Figure 9 illustrates an estimate for a weapons system at a 50% point probability. The estimate is made up of a number of subsystems each with has a cost estimate with its own normal distribution. One subsystem estimate is shown in green.

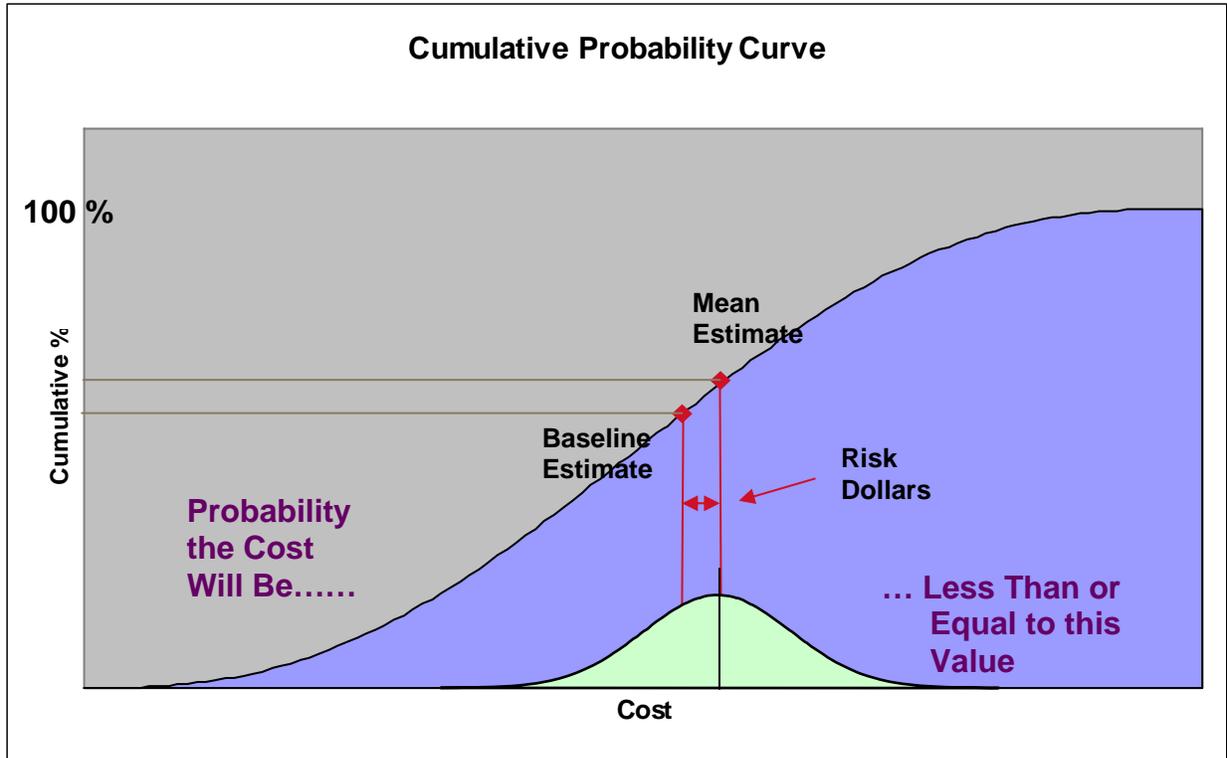


Figure 9 Cumulative Probability Curve

### 4.7.3 Estimates Must Contain Ranges

It's amazing the estimates we generate on tasks we really don't yet understand..... but each side wants cost/schedule/ earned value containment (Greg Shelton, RTN Ret.)

A point estimate represents one possible estimate based on a baseline set of program characteristics. The creditability of the estimate is based on a realistic and complete technical, schedule and programmatic baseline. However, even when the baseline is sound, many of the technical and schedule components may remain uncertain. The point estimate serves as the reference point on which the cost risk analysis is anchored. The definition of what is included and what is excluded from this anchor point should be clearly defined for each program cost estimate, especially any departures from baseline. This definition influences the magnitude of the point estimate and heavily influences how to define the uncertainty (distribution shape and bounds) of each element within the cost estimate. Ideally, the point estimate should be derived from the most likely WBS structure and most likely technical, schedule and programmatic inputs. This is consistent with the idea that the point estimate inputs should reflect the best assessment of what will actually happen. (From U. S. Air Force Cost Risk and Uncertainty Analysis Handbook, Air Force Cost Analysis Agency, April 2007)

Subjective uncertainty distribution bounds should be requested at and should be interpreted as capturing seventy percent of the total uncertainty. For symmetrical distributions this translates to the lower bound representing the fifteenth percentile and the upper bound represents the eighty-fifth percentile. For skewed distributions, the thirty percent of uncertainty should be apportioned to the upper and lower bound according to the ratio of the skewed distribution. For this purpose, skew is

Presented at the 2009 ISPA/SCEA Joint Annual Conference and Training Workshop - [www.iceaaonline.com](http://www.iceaaonline.com) defined as (mode-low)/(high-low), where the mode, high and low are the expert opinion. (From U. S. Air Force Cost Risk and Uncertainty Analysis Handbook, Air Force Cost Analysis Agency, April 2007)

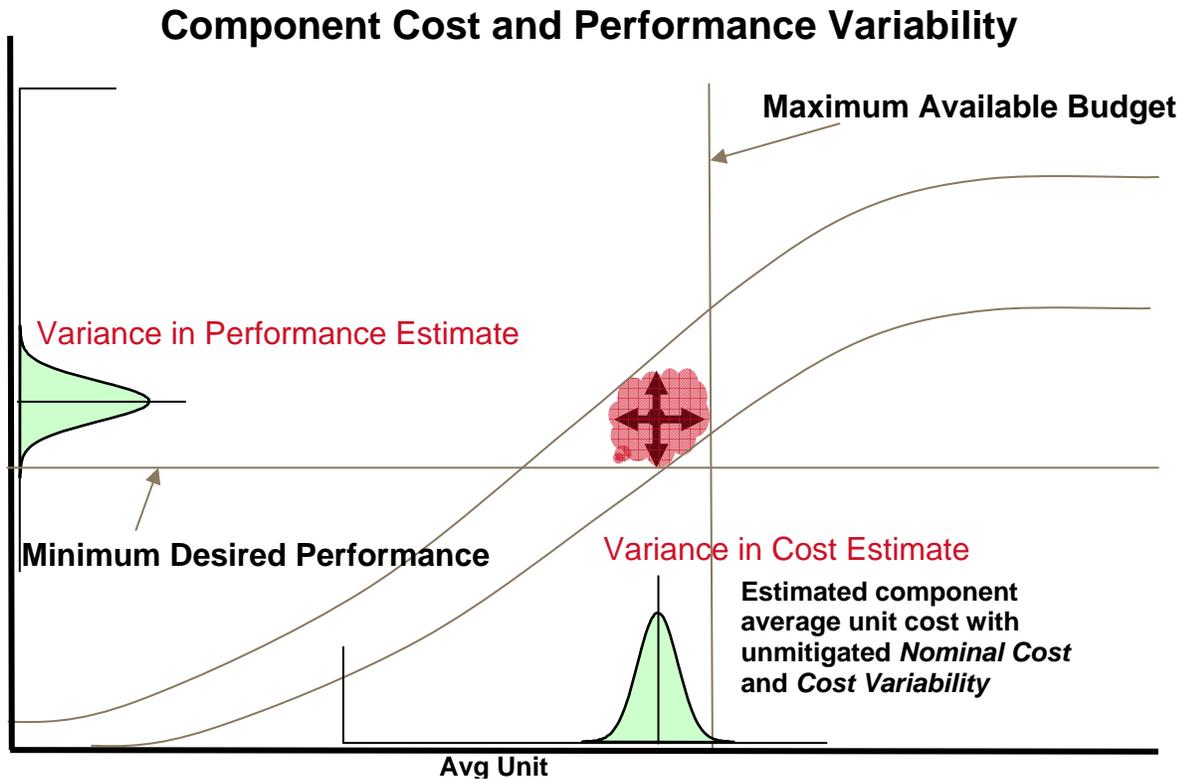


Figure 10 Component cost and performance estimates contain variability.

#### 4.7.4 Cost Risk and Uncertainty

DOD specifically directs that uncertainty be identified and quantified.

The Clinger-Cohen Act requires agencies to assess and manage the risks of major information systems, including the application of the risk adjusted return on investment criterion in deciding whether to undertake particular investments.

Estimate Uncertainty decreases as knowledge increases over time. e.g width of uncertainty range decreases. Growth in estimates occur due to increased knowledge and new requirements. Later reductions in growth are possible if cost management techniques are aggressively employed early on in the program life.

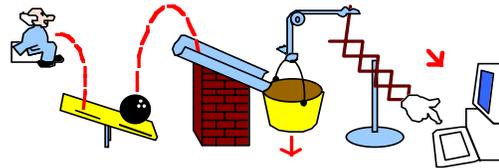
#### 5.0 Document and Review Results

Review you results! Do they make sense? If input values are not know precisely, have you bounded those elements within a range? Have you taken into account your customers conditions?

"You can start with erroneous assumptions, then use impeccable logic to arrive at the grand fallacy" Darrell Giesecking, Hughes Aircraft, circa 1995.

Document your effort. If no-one can understand the results or how they were arrived at then the analysis is ultimately a wasted effort. A well documented analysis is essential. The documentation should describe the problem, the system, and all ground rules and assumptions. In addition, it should present clearly the bottom-line result backed with an audit trail including data sources, computations, and risk and sensitivity analysis.

- If no one can figure out what you did, how you did it, and why you did it ----- It doesn't count!!
- Hard truth: The program may last longer than you
- Ground Rules and Assumptions
- Modeled System
- Overall LCC
- Cost Drivers
- Spikes
- Measure of Effectiveness
- Program Risks and Uncertainties



## 6.0 Summary

Life cycle cost (LCC) has become increasingly important as systems are designed with longer useful technological lives. LCC is a basic way of doing business and the business is engineering. LCC is the total cost to the customer for a program over its full life. Cost, including LCC is an engineering design parameter that needs to be considered from the beginning of the design effort. Total cost impact, not just initial near-term cost, must be considered. Economic Decisions are often made solely on initial investment or RDT&E and procurement cost. By ignoring O&S cost you may be missing as much as 83% of the life cycle cost. A well performing system solution that is too expensive and a cheap design that doesn't meet performance criteria are two sides of the same coin. More and more customers (especially government) are emphasizing and requiring an LCC perspective. Early design efforts determine LCC. Don't wait!!!!

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## Biographies

**F. Quentin Redman** is a Senior Department Manager and Engineer Fellow in the Systems Engineering laboratory of Raytheon Space and Airborne Systems in El Segundo California. He is responsible for Total Ownership Cost, Design and Life Cycle Cost, Risk Analysis, and Cost as an Independent Variable (CAIV) with 30 years of Economic experience. Quentin received his Bachelor of Science in Engineering Technology Electronics from California State University at Long Beach California in 1970 and his Masters of Science in Financial Economics from West Coast University Los Angeles in 1976. Quentin has been on the Board of Directors for the International Society Parametric Analyst and has also previously served as ISPA's Treasurer. Quentin has over 26 years with the company. Quentin has presented a number of papers at prior years Systems Engineering Symposia and at ISPA, SCEA, INCOSE, and NDIA conferences/symposia.

**Andrew Crepea** is a Principle Systems Engineer with Raytheon Missile Systems' Cost Engineering Center in Tucson, Arizona. He holds a Bachelor's degree in Bioengineering from the University of California, San Diego and a Master's of Science in Operations Research from the Naval Postgraduate School. Areas of responsibility include parametric cost estimating, Life Cycle Cost (LCC), Design-to-Cost (DTC), and Cost as an Independent Variable (CAIV). Prior to joining Raytheon he was an Operations Research Analyst with the Naval Air Systems Command in Patuxent River, Maryland. Andy served 24 years in active and reserve components of the United States Navy primarily in P-3C Orion maritime patrol aircraft. He also served as an aircraft carrier Tactical Action Officer, an Operations Test Director with the Operational Test and Evaluation Force and as an Aerospace Engineering Duty Officer.

**George L. Stratton** is an Engineer Fellow with Raytheon Missile Systems' Cost Engineering Center in Tucson, Arizona. He has over 28 years with Raytheon. He currently leads many challenging assignments. He holds degrees (AS, Dixie College & BS, Utah State) in Physics, an MBA (Pepperdine), and has completed partial work toward a Ph.D. (Claremont Graduate School) in management science. He is trained on Parametric models and was selected for and completed the Hughes line managers training course. He is a past vice president of the Southern California Chapter of ISPA (International Society of Parametric Analysts) and is now serving on ISPA's international Board of Directors.