Missile Defense Agency
Director for Operations

Cost Estimating and Analysis Handbook
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Prepared by
Cost Estimating and Analysis Directorate

J. GARY PENNETT
Director for Operations

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This is the initial draft version of the Missile Defense Agency (MDA) cost estimating handbook. It is the collective effort of several highly experienced cost analysts; Tom Hix, Dr. William Hughes, Robyn Kane, Dean Kimmel, Denise Dulee, and I all contributed chapters to the handbook. Dr. Hughes went above and beyond by contributing two chapters. As can be imagined, having six different individuals write separate chapters made the initial compilation seem disjointed. After the initial rough draft was completed, Robyn Kane undertook a significant effort to unify the language, point of view, and provide general editing. This draft also benefitted from suggestions and edits from Mr. Gary Pennett, MDA's Director for Operations, and Ms. Deborah Kelley, MDA's Comptroller and Chief Financial Officer. Once the rough draft was compiled, it was sent out to the Services and NASA for comments. Several individuals at NASA and the Services contributed comments. NASA was particularly helpful, and we received numerous constructive comments and suggestions from NASA's leading cost estimators, including Doug Comstock, Andy Prince, Barbara Stone-Towns, Leigh Rosenberg, Sherry Stukes, Charles Hunt, Kelly McCoy and Glenn Butts. We also received helpful comments and suggestions from the Air Force Cost Analysis Agency, the Naval Center for Cost Analysis, NAVAIR, and the National Reconnaissance Office.

Christian Smart, Ph.D.
Director, Cost Estimating and Analysis Directorate
Missile Defense Agency
April 27, 2012

PREFACE

The primary purpose of this guide is to standardize the Missile Defense Agency (MDA) Cost Estimating and Analysis Directorate (DOC) cost analysis requirements and procedures regarding the preparation, documentation, and presentation of Ballistic Missile Defense System (BMDS) cost estimates that are reviewed by the MDA DOC. This Handbook serves as a desk reference for MDA cost estimators and anyone who interfaces with MDA cost estimators or uses MDA cost estimates.

A secondary purpose of this guide is to identify and define a set of standard data requirements for MDA cost estimates. The MDA Cost Estimating and Analysis Handbook provides information and guidance to MDA cost analysts and other organizations that support preparation of and use MDA cost estimates. In short, it outlines how MDA creates cost estimates, MDA cost processes, and the MDA cost tools and products.

The Handbook is based upon the best practices as noted in handbooks from the Government Accountability Office (GAO), National Aeronautics and Space Administration (NASA), and Society of Cost Estimating and Analysis (SCEA) Cost Estimating Body of Knowledge (CEBoK); each tailored to the way business processes are conducted at MDA, which are unique due to its history.

MDA was established as an agency in 2002:

To develop and deploy a layered BMDS to defend the United States, its deployed forces, allies, and friends from ballistic missile attacks of all ranges and in all phases of flight.

The Missile Defense Agency's charter, as established in the National Missile Defense Act of 1999 (Public Law 106-38) states:

"It is the policy of the United States to deploy as soon as is technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic missile attack (whether accidental, unauthorized, or deliberate) with funding subject to the annual authorization of appropriations and the annual appropriation of funds for National Missile Defense."

As a result of this imperative to "deploy [missile defense] as soon as is technologically possible," MDA is exempt from DoD Series 5000 regulations and from the Joint Capability Interface Development System. Due to this exemption it is MDA's responsibility to establish and maintain appropriate credible cost estimating development and review processes.

In support of this mission the Missile Defense Agency develops cost estimates for a broad spectrum of requirements and customers. Internal cost estimates are prepared to support program offices, contracting, and resource baselines. External cost estimates are prepared to support acquisition decisions, external baselines, and source selections. Cost estimates also support business and alternatives analysis, and the Program Planning and Budget Execution (PPBE) process.

This handbook is organized around a cost estimating checklist described as part of the MDA Cost Estimating Process Overview in Chapter 1. The remaining chapters follow in order of the cost estimating check list score card:

- Documentation;
- Comprehensive, Credible and Accurate;
- Ground Rules and Assumptions;
- Data;
- Methodology;
- Sensitivity Analysis, and
- Cost Risk and Uncertainty.

A brief summary of the content of each chapter follows:

Chapter 1, The Cost Estimating Process Overview, discusses MDA's mission, the Cost Estimate and Analysis Directorate, and comprehensiveness of the estimating methodology and documentation developed for each cost estimate. Cost estimating leadership requires several items of information to be prepared (or updated) for review and those are discussed in more detail in this chapter. Chapter 1 also introduces and explains the estimate "score card" that is used by MDA to evaluate the quality of each estimate.

Chapter 2 discusses cost estimate Documentation, an important part of the cost estimating process. A cost analyst should document all steps used to develop the estimate so that a cost analyst unfamiliar with the program can recreate it quickly and produce the same result. The purpose of this documentation is to provide a detailed, written justification for the cost estimate so that it is repeatable and traceable for sufficiency reviews at all levels, internal and external to MDA. Without good solid documentation, cost estimates are merely numbers in a spreadsheet.

Chapter 3 explains the Comprehensiveness, Credibility and Accuracy of cost estimates. Comprehensiveness means that the estimate is complete. For example, a missile program estimate is complete when all parts of the missile are accounted for, and the related indirect costs such as system engineering and program management and the program office costs are incorporated. Further, the context of the estimate must be understood. In the case of a life-cycle estimate, then Research, Development, Test & Evaluation (RDT&E), production, and operations and sustainment costs including disposal are included.

Credibility is often mentioned but not described in words. If ten estimators are asked what makes an estimate credible, there will likely be ten different answers. The Government Accountability Office (GAO 2009) describes a twelve-step process that every good estimate must follow in order to be considered credible. This process starts with defining the scope of the estimate, continues through the collection and use of appropriate data, the development of a point estimate, sensitivity analysis; including risk, and then documenting the estimate and communicating it to management and obtaining approval for the estimate.

Accuracy, in the context provided by the Government Accountability Office (GAO 2009), does not mean that the initial cost estimate is similar to the final actual cost. The term accuracy for this handbook refers to the use of the most credible and comprehensive information available for the estimating process. In other words, the information that drives the estimate should be as accurate as possible. Accuracy also applies to program schedule, scope (weights, diameters, materials), and quantities.

Chapter 4 discusses Ground Rules and Assumptions. Ground rules and assumptions define the conditions upon which an estimate is based. Without understanding the ground rules and assumptions, it is impossible to accurately judge the quality of an estimate. Also without good ground rules and assumptions, cost estimating is largely a matter of "garbage in, garbage out."

Chapter 5 focuses on Data. Data are the foundation of every estimate. Cost estimators use past history to estimate future costs. As Shakespeare wrote in *The Tempest*, "What's past is prologue." Without appropriate data, it is impossible to project into the future with any fidelity. This chapter discusses types of data, the availability of data, and its normalization. In order to compare data from one program with another, raw data must be adjusted for inflation, production quantities, test quantities, and other factors. A comparison of data sources, such as historical data vice proposal data, is also discussed. Proposal data are suspect, and historical data is preferred in every case. Contract price data may be useful and is better than proposal data, but it is only considered reliable if the contract type is Fixed Price and the requirements are firm. However, there may be data in proposals, such as labor rates, that may be useful for developing sound cost estimates.

Chapter 6 explains four methodology types in detail: analogy, parametric, engineering build-ups, and projections from recent historical, actual costs. The type of methodology used changes as a program matures. Early in the life cycle in the concept stage, an Analogy may be most appropriate, since even the inputs needed for a parametric estimate are not available. During the development cycle, but still early in the process, parametric methods may be the best approach, since many of the parameters needed are available. Later, after project details mature, engineering build-ups can be useful, especially since these estimates help communicating the estimate with technical personnel and key decision makers. Once contracts are in place, and actual data has been collected, estimating with recent actuals may be the best way to estimate costs. This methodology is particularly applicable to operations and sustainment after the program reaches a steady-state.

Chapter 7 is an overview of Sensitivity Analysis. A good sensitivity analysis requires working with technical personnel to vary key parameters over valid ranges. It also involves determining the effect of changing ground rules and assumptions on costs. Using the MDA Targets and Countermeasures program as an example, the solid rocket boosters are often obtained from surplus boosters from other programs, and therefore considered free to MDA since they are furnished by another government agency. However, if these boosters are not available, then the target will cost significantly more. Also, changes in the solid rocket business base can have significant impact to the costs of solid rocket boosters used in missiles. An assumption that a new NASA launch vehicle will provide the bulk of solid rocket booster demand so that MDA will not have to pay for much of the fixed infrastructure cost will have an impact on missile costs. Sensitivity analysis is also important because it allows the estimator to find out those parameters to which cost is most sensitive. For example, if changing the software lines of code by 10% results in changing the software cost estimate by 50%, there may be issues with the underlying model, or the estimator may be extrapolating outside of the valid range of the inputs parameters for the cost estimating relationship (CER) used in the estimate.

Chapter 8 considers Cost Risk and Uncertainty in detail. MDA cost estimates incorporate cost risk and uncertainty. Inclusion of a sufficient amount of risk is necessary for a credible cost risk analysis. While some external factors, such as the potential for an earthquake to impact a test event at the Pacific Missile Range Facility may be excluded, many events, such as potential changes in model parameters, model uncertainty, and some external factors such as budget constraints and potential schedule slips, should be included. Incorporating cost risk and uncertainty involves assessing risk for the parameters in a model, as well as uncertainty about the estimate. Those programmatic factors determined to have a resource impact must be addressed. The risk process is discussed from assessing risk at the WBS level, to aggregating risk to the total level, through measuring and allocating this risk. The importance of correlation is stressed as well.

All references and appendices are included at the end of the handbook.

CHAPTER 1
MDA COST ESTIMATING PROCESS OVERVIEW

The Missile Defense Agency's mission was provided by the Department of Defense (DoD) Directive 5134.09, revised 17 September 2009. The portion of the directive that defines the MDA mission is listed in Table 1.1.

Missile Defense Agency (MDA) mission: MDA shall manage, direct, and execute the development of the BMDS in accordance with National Security Presidential Directive 23 (Reference (h)) and to achieve DoD priorities to: a. Defend the United States, deployed forces, allies, and friends from ballistic missile attacks of all ranges in all phases of flight. b. Develop and deploy, as directed, a layered BMDS. c. Enable the fielding of elements of the BMDS as soon as practicable. d. Provide capability in blocks, improving the effectiveness of fielded capability by inserting new technologies as they become available.

Table 1.1 MDA Mission

The MDA's missile Defense Agency's strategic goals are listed below in Table 1.2., MDA Strategic Goals.

The Missile Defense Agency is dedicated to the following goals: • The United States will continue to defend the homeland against the threat of limited ballistic missile attack. • The United States will defend against regional missile threats to U.S. forces, while protecting allies and partners and enabling them to defend themselves. • Before new capabilities are deployed, they must undergo testing that enables assessment under realistic operational conditions. • The commitment to new capabilities must be fiscally sustainable over the long term. • U.S. BMD capabilities must be flexible enough to adapt as threats change. • The United States will seek to lead expanded international efforts for missile defense.

Table 1.2. MDA Strategic Goals

In addition to the DoD Directed Strategic goals, the MDA Strategic Goals as outlined on the MDA public Website (http://www.mda.mil/careers/mission_goals.html) are:

1. Prove the power of missile defense through successful testing
2. Enable fielding of European Phased Adaptive Approach Phase 1
3. Provide a professionally rewarding work environment for a highly skilled and diverse workforce
4. Enhance leadership and management skills
5. Efficient use of taxpayers' investment in missile defense

6. Provide Department of Defense enterprise solutions to the Services and Combatant Commands (COCOM)s
7. Complete BMDS and element Phased Adaptive Approach Phase 3/4 Systems Engineering trades to maximize effectiveness and minimize cost
8. Implement National Security Strategy through international cooperation in missile defense
9. Capitalize on the creativity and innovation of the Nation's universities and small business community to enhance missile defense Science and Technology

MDA's organization is divided into functional and execution elements (and the Command Group Staff). The functional areas provide support to the program offices. These include the directorates for Test, Engineering, and Operations. See Figure 1.1 for a graphical depiction of MDA's top-level organization chart for 2011.

The execution elements are the program offices, such as Aegis Ballistic Missile Defense, Theater High Altitude Air Defense (THAAD) and Ground-Based Midcourse Defense (GMD).

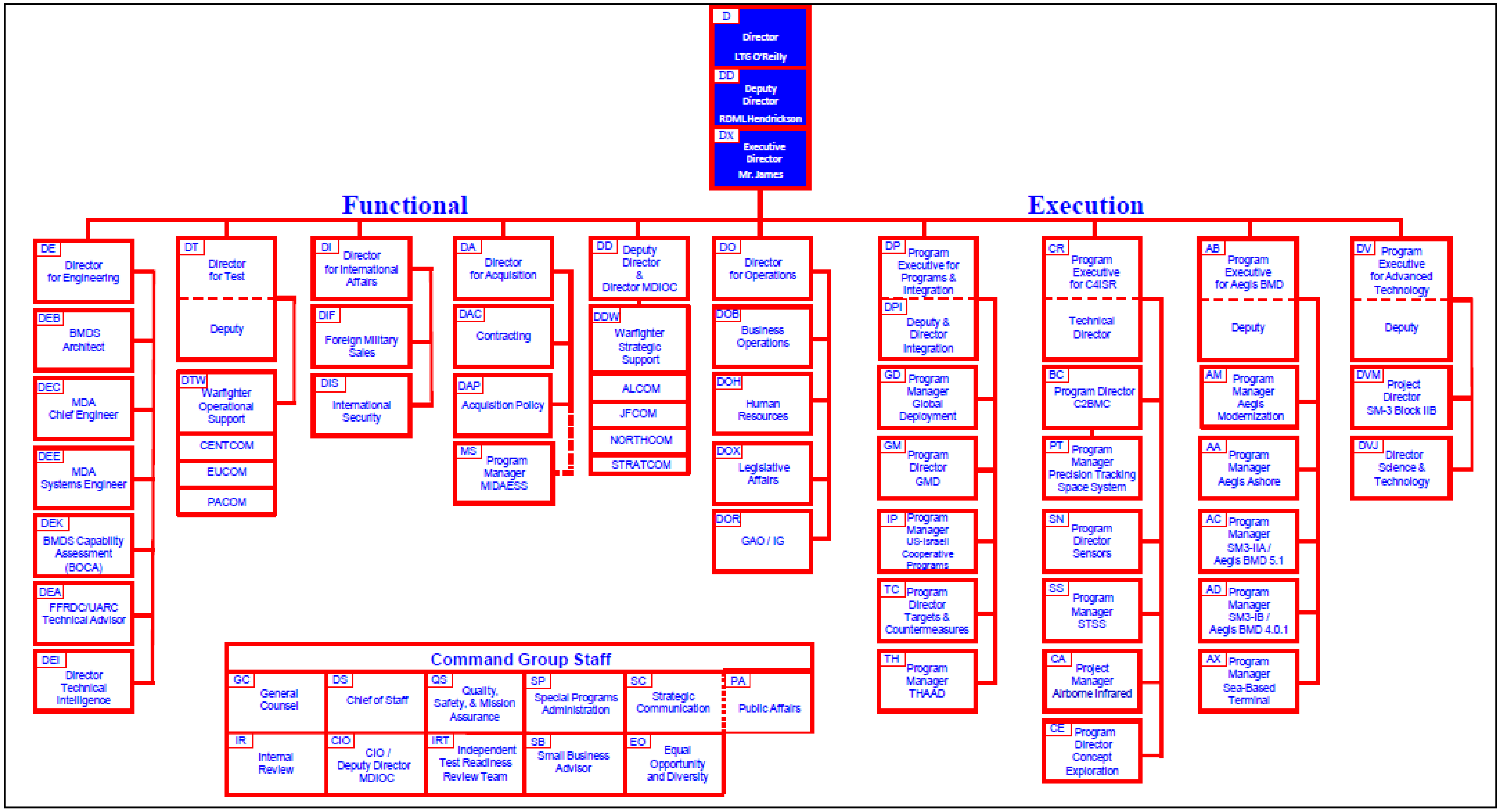

Figure 1.1. MDA Organization Chart (December 15, 2011)

As a functional office, the Director for Operations, or Operations Directorate, is responsible for several areas, including budget, cost, earned value, and resource planning. See Figure 1.2 for a graph of the organization chart for the MDA Operations Directorate (DO).

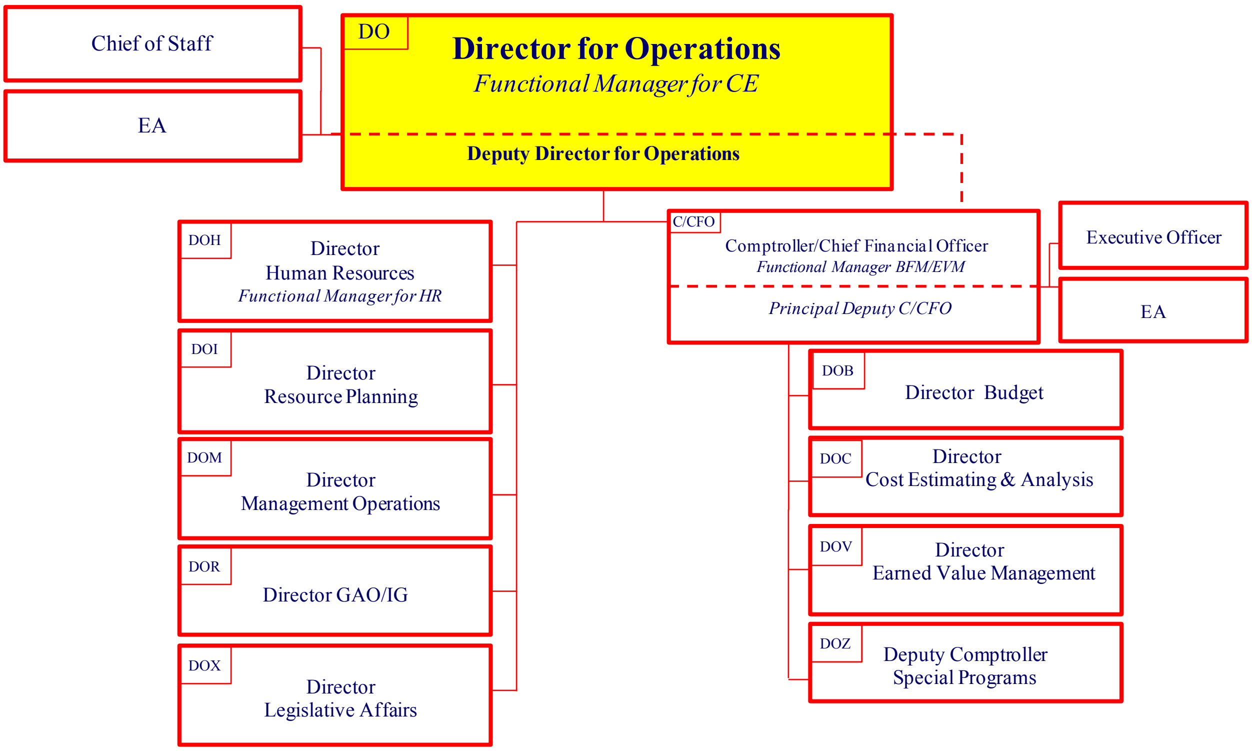

Figure 1.2. MDA DO Organization Chart (April 30, 2012)

Within DO, the Cost Estimating and Analysis Directorate (DOC) is responsible for providing a full range of cost estimating and analysis services for MDA program elements to support the MDA decision making process. DOC also supports analysis of alternatives for future architecture decisions and business case analyses of acquisition alternatives. DOC is responsible for BMDS-wide cost estimates for near term execution decisions.

DOC is also responsible for establishing and maintaining a Cost Estimating and Analysis Center of Excellence for MDA. DOC provides weekly internal training of cost estimating and technical topics to train and update the estimators in the cost directorate. This training includes one-hour seminars regarding cost risk, schedule risk, and product overviews of the BMDS hardware systems such as kill vehicles and radars.

DOC establishes common standards for the cost estimating and analysis function. This handbook contributes to these standards. It supplements the DOC documentation format and annual quality reviews that support the BMDS Accountability Report (BAR), and quarterly quality reviews that support the Baseline Execution Reviews (BERs).

DOC's core staff includes the Director, Technical Director, Division Chiefs, and Operations Division staff. The Director for Cost Estimating and Analysis (or DOC Director) is the agency's functional lead for cost estimating and provides oversight, policy, and guidance for the agency's cost estimates. The DOC Director develops policy and procedures, conducts quality reviews, handles the operation of the organization, and provides an objective perspective for cost estimating that is not influenced by any individual program office. The DOC Director also serves as an interface with external organizations.

As noted previously, MDA follows a matrix management framework. Cost estimating is the functional area, and the Cost Estimating and Analysis Directorate is the functional organization. The DOC Director collaborates with program executives to determine functional leads in program offices that report to program manager/directors, or project managers and provide direction and supervision to local staff. As the functional leader for cost estimating within a matrix management framework, the DOC Director is responsible for managing the functional workforce. The DOC Director performs workforce planning activities to ensure a high performing workforce, defines functional career competencies, determines skills gaps, hires cost estimators, and develops career paths. The DOC Director determines manpower requirements, provides for local functional management, and manages and assigns matrix workforce, to include functional leads supporting each Program Office or project.

The DOC Director directs common training for all cost estimators, and provides cost estimating oversight. He actively participates in the cost estimating community with involvement in the Society of Cost Estimating and Analysis, the International Society of Parametric Analysts, and the Space Systems Cost Analysis Group, among others.

The DOC Technical Director is responsible for providing guidance for technical questions and providing estimating support to analysts that need help with specific cost estimating needs. The Technical Director also serves as an alternate to the DOC Director. DOC Division Chiefs supervise the work for specific cost estimating teams and directly supervise Cost Leads. Division Chiefs ensure quality cost estimates are provided to the program offices by providing leadership, oversight, and hands-on guidance to the Cost Leads and Cost Analysts. The DOC Director, Technical Director, and Division Chiefs provide a sounding board for junior, less experienced analysts, as well as a feedback loop to ensure that the cost analysis process is correctly implemented in support of each program office. DOC's core staff provides an independent viewpoint not subject to the program offices.

The Cost Leads and Cost Analysts are matrixed to support specific program offices.

DOC conducts annual quality reviews of cost estimating and analysis products in support of the yearly BAR submitted to Congress. In addition, DOC conducts delta reviews on a quarterly basis to support the changes made during the BERs.

DOC coordinates activities with external cost estimating organizations in conjunction with DO and External Review (DOR). This includes interfacing with the Office of the Secretary of Defense's Cost Analysis and Program Evaluation (OSD CAPE) office, the GAO, and the Department of Defense's Inspector General. The CAPE is responsible, among its other duties, for developing independent cost estimates (ICEs) for MDA programs as well as for other Department of Defense agencies. Even though MDA is not subject to the Department of

Defense's series 5000 regulations, MDA annually requests ICEs for specific programs to help support production milestone decisions.

For example, the CAPE completed and delivered an ICE for the Aegis Ballistic Missile Defense program in 2008 and for THAAD production in 2010. At this writing DOC is working with the CAPE on an ICE for the Aegis Ballistic Missile Defense program and the Precision Tracking Space System project. DOC is also responsible for developing and maintaining joint cost estimates for Operations and Support with the lead Service responsible for MDA-designed operating systems. Examples of these include the Sea-Based X-band (SBX) and the AN/TPY-2 radars.

DOC coordinates with the Defense Cost and Research Center (DCARC) to ensure MDA contract data is included in their cost repository. The DCARC hosts a defense-wide collection of defense cost contract data used by defense estimating professionals.

DOC is also responsible for developing cost databases and research products useful for improving MDA cost estimates. DOC maintains an electronic cost research library and conducts regular meetings with DoD cost research leads in the service agencies to leverage cost research conducted by other organizations.

The DOC organization chart is displayed in Figure 1.3.

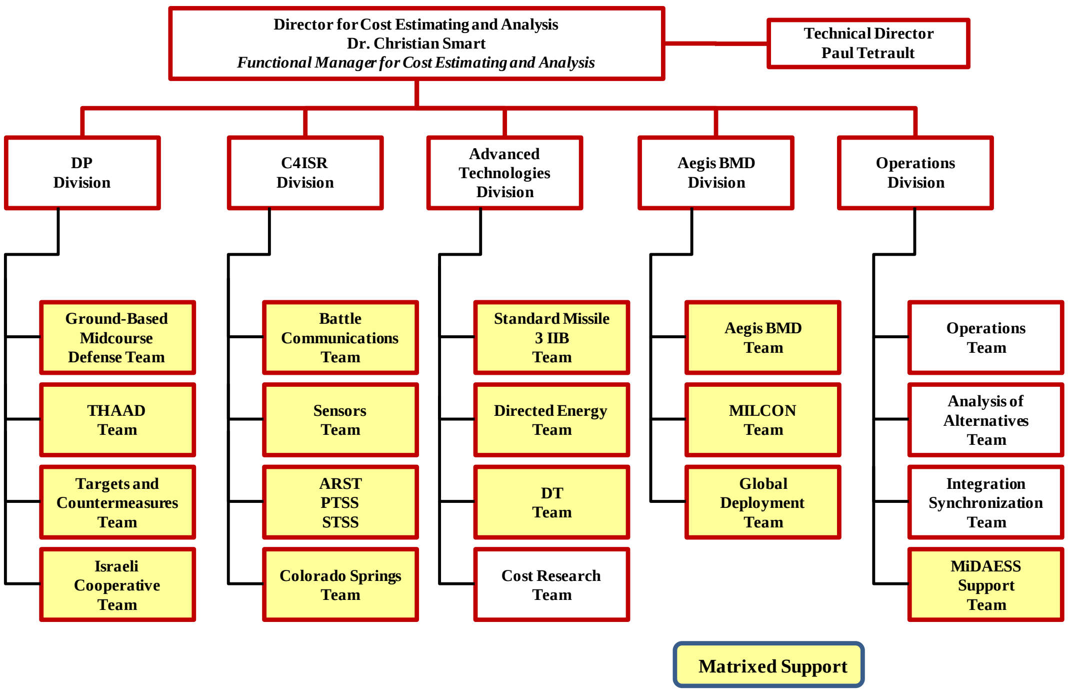

Figure 1.3. Organization Chart for the Cost Estimating and Analysis Directorate

The Resource Planning Directorate (DOI) is responsible for resource planning and for cost assessments. Since they are independent of DOC, DOI provides a program analysis and evaluation capability to the Director for Operations.

Cost estimators are an integral part of the annual budget planning and formulation process for all MDA program offices. Cost estimates are developed and updated to support annual budget formulation, to assess the impact of changes to the Integrated Master Test Plan (IMTP), to support new contract negotiations, to support competitive source selections, and for affordability drills. Cost estimators also work with budget analysts and program management to properly phase cost estimates so that the program office can stay within their cost controls.

Cost estimating and budget formulation is an iterative process. Cost estimates are continually updated to reflect changes to programs, such as adjustments to requirements and schedules. Figure 1.4 represents the steps in the program management business process within a program office and shows how the cost estimates play a part.

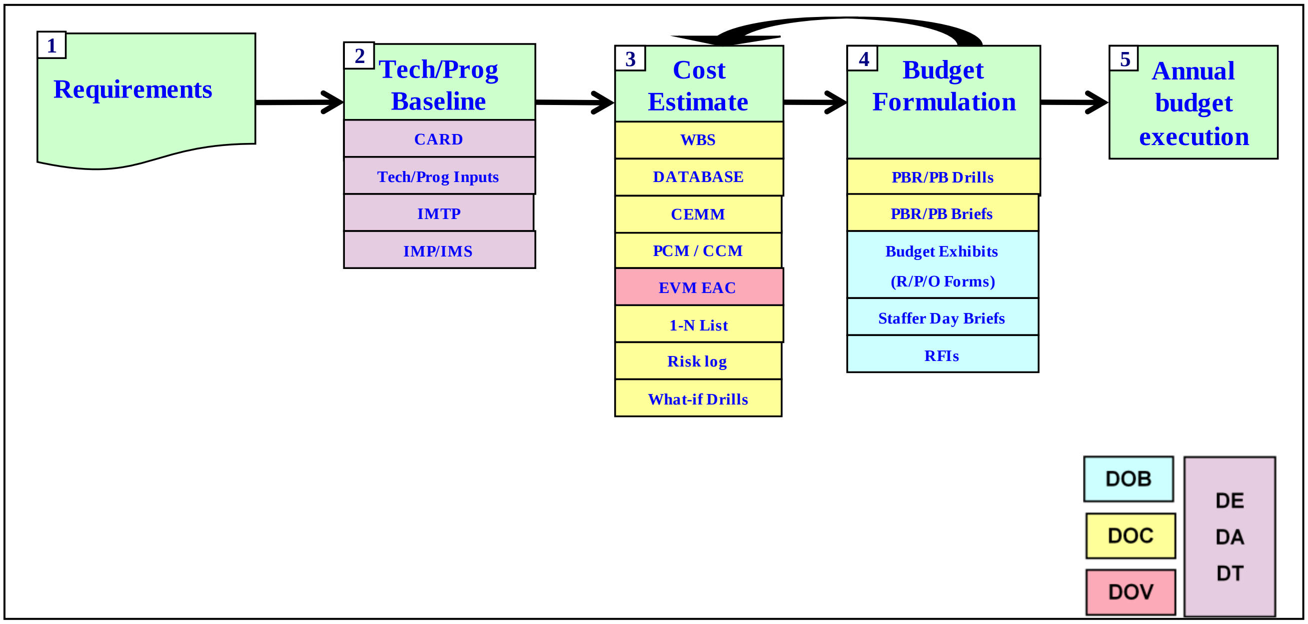

Figure 1.4. MDA Program Management Business Process

MDA program offices require life-cycle cost estimates for all programs, including those in the early stages of development. Cost estimators develop cost estimates for development, production, operations and support, military construction, and disposal costs, as applicable to the life cycle stage for the program.

All cost estimates follow the same process. The first step is to establish requirements used for the technical and programmatic baseline development. Documents supporting this baseline are the Cost Analysis Requirement Descriptions (CARDs), technical and programmatic inputs, the program's participation in the IMTP, and the Integrated Master Schedule (IMS). Inputs from the Acquisitions Directorate (DA), the Engineering Directorate (DE), and the Test Directorate (DT) are then used to develop the cost estimate.

Using the program requirements, the cost estimators develop the Work Breakdown Structure (WBS). Cost estimates are developed for each WBS line item using inputs from the IMS, the

IMTP, and other technical and programmatic inputs using program cost models. The cost estimate is then phased according to the program schedule.

After contract award, the cost estimators work together with the prime contractor(s) to establish a common cost methodology (CCM). The cost estimating team and the prime contractors do not utilize the same model; however there is significant interaction between the MDA cost estimating team and the prime contractor(s) to establish factors used as the basis for programmatic and technical inputs, such as learning and production rate factors.

Cost risk estimates are developed by incorporating uncertainty about cost model inputs as well as cost model uncertainty. (See Chapter 8 for more detail). Risks determined to have a potentially significant cost impact are also incorporated. For most BMDS program elements, risk is traded with affordability so that there is an equally likely chance of either a cost under-run or over-run. Cost affordability initiatives resulted in a fixed-price incentive fee (FPIF) contract for THAAD procurement that was negotiated below the should-cost estimate. MDA is undertaking numerous should-cost affordability initiatives in order to ensure the efficient use of taxpayers' investment in missile defense.

The cost estimate is documented in a summary level Cost Estimate Methodology Matrix (CEMM). The cost estimators also work with analysts from the Earned Value Directorate (DOV). The results of the completed cost estimate are used to formulate the program budget, which is listed by priority and hence termed a "1-N list." In addition to developing estimates used for annual budget requests, the cost estimators also respond to numerous what-if drills, which help program leadership compare alternative courses of action and make informed decisions about program adjustments.

Once estimates are complete, cost estimators work with budget personnel (DOB) to formulate budgets. Depending upon resources and program management priorities, planned acquisitions may need to be re-phased. For example, funding constraints may lead to program schedule extensions. In such cases, the cost estimate is re-phased to the program changes.

Cost estimators also work with budget personnel to refine the estimate, by participating in drills for program execution reviews (PERs) and program budget (PB) drills. Upon completion of the drills, the budget analysts develop budget exhibits, staffer day briefs, and respond to requests for information (RFIs). The Resource Planning Directorate (DOI) then works with DOB to execute the budget.

Budget execution is managed by several key reviews. The MDA Resource Baseline Handbook 21 Oct 2010 (version 9) provides guidance for the tables required for the resource baseline charts for the MDA Director's review of the Materiel Solution Analysis Phase (MSA), Technology Baseline Review (TBR), the Development Baseline Review (DBR) and most importantly, the resource input to the BMDS Accountability Report (BAR), which is updated and submitted to Congress on an annual basis.

The BAR presents baseline parameters to guide development of BMDS capabilities. It documents the strategic-level baseline and addresses variances from established schedule, technical, and resource or cost baselines experienced during program execution. The BAR may also present program Earned Value Management (EVM) data and Development Decision Memorandums (DDM) containing exit criteria to the current program acquisition phase. This report describes expected delivery of BMDS capabilities, and the resources associated with meeting development timelines, as well as future achievable BMDS cost, schedule, and performance goals based upon data from the BMDS Architecture, the Prioritized Capabilities List (PCL), and previous BARs. DOC supports the BAR by providing the cost estimates that populate the resource charts for the BAR. The resource chart is signed by the Program Executive, the Director for Acquisition, and the Director for Operations.

Cost estimates are reviewed by DOC leadership prior to submission of the BAR to Congress, and prior to quarterly BERs. The purpose for each BAR is to provide Congress the status of MDA's progress toward implementing the BMDS. Many Service programs submit progress reports to Congress, called Selected Acquisition Reports (SARs). MDA also submits a SAR annually, for the entire BMDS program. MDA also submits annual BARs for major BMDS subsystems (e.g., THAAD weapon system) to provide Congress with insight into the larger efforts within the BMDS. These BAR submissions are planned each year for the February time frame. A comprehensive program cost estimate review is required by MDA cost estimating leadership for each program for which a BAR submission is required.

See Figure 1.5 for an example of an MDA BAR resource chart.

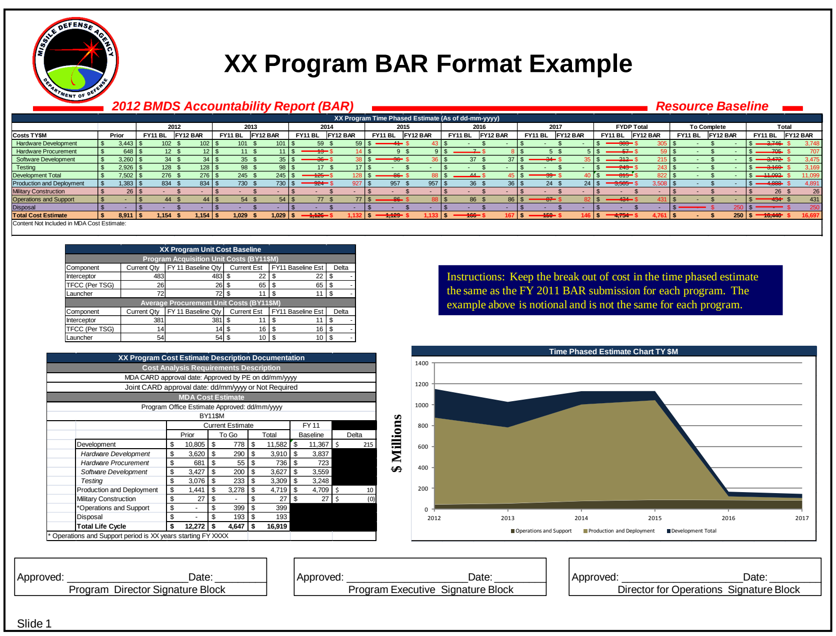

Figure 1.5. 2012 Draft Notional BAR Resource Chart

The execution status of the baselines (objectives and plans for MSA) is reported in the MDA Director-chaired BER. BERs are intended to provide executive-level review of program baseline execution and detailed discussion of medium- and high-risk execution issues. To maintain consistency and completeness of information, BERs require use of the DA-provided standard template available on the MDA Portal. BERs typically occur quarterly for each BMDS program and are intended to provide executive-level review of program baseline execution and a detailed discussion of medium-and high-risk execution issues. These quarterly updates review program baselines, objectives, plans, and the progress made over the last 90 days. Forecasts are provided addressing baseline execution, objectives, and important goals achievement planning for the next two years. Baseline issues and changes are resolved through the Integration Synchronization Group (ISG)/Program Change Board (PCB) process prior to the BER. (MDA Directive 5010.18) A pre-BER cost estimate review is required by MDA cost estimating Leadership prior to each BER. The scope of this cost estimate review focuses more closely on the changes to the cost estimate which have occurred since the last BER. See Figure 1.6 for an example of an MDA BER resource chart.

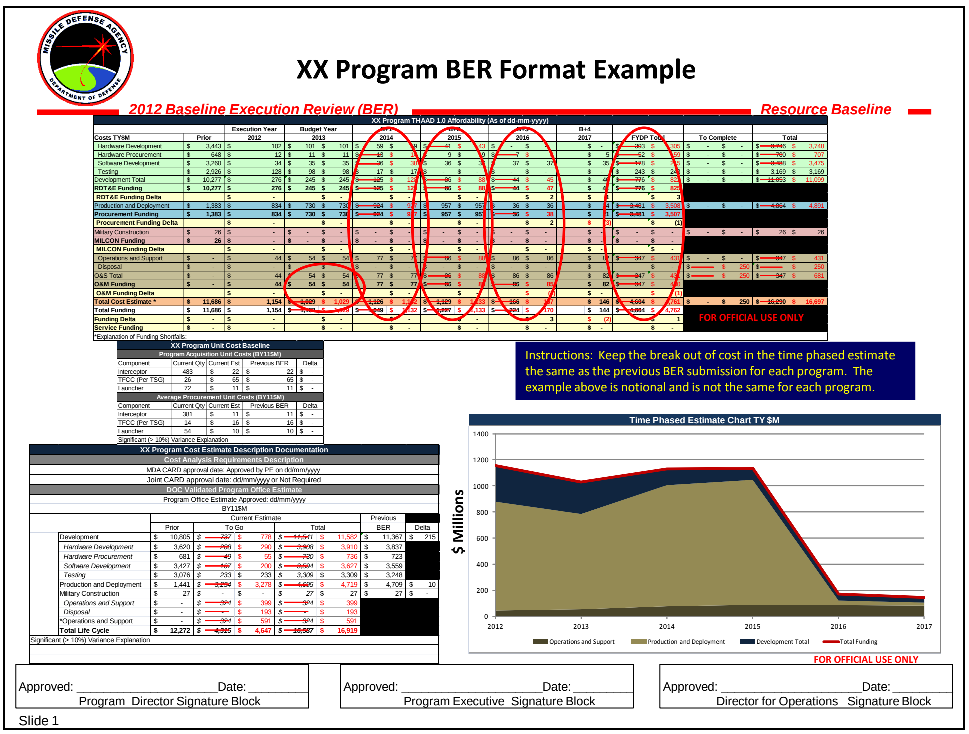

Figure 1.6. Current Notional Program BER Resource Chart

Full and comprehensive cost estimate reviews are also required annually for programs that have a joint cost estimate (i.e., with a Service or international partner). Additionally, full and comprehensive cost reviews are required when a program has a milestone review (i.e., to gain approval for entry into the next life cycle phase). Special cost reviews are sometimes required when a program is planned for other types of senior leadership reviews, such as for the Missile Defense Engineering Board (MDEB), or when a program is selected for an independent cost assessment by the Office of the Secretary of Defense: Cost Estimate and Program Evaluation (CAPE).

The purpose of each cost review is to assess the quality and comprehensiveness of the estimating methodology and documentation developed for each cost estimate. The pre-BER cost estimate review emphasizes changes to estimating methodologies and cost results which have occurred since the last BER. The cost estimate review for the Congressional pre-BAR submission or a pre-Milestone review is more thorough and comprehensive. Cost estimating leadership, to include the DOC Director, Technical Director, and Division Chief whose division is responsible for the cost estimate, utilizes an MDA/DOC scorecard to provide specific feedback for all cost estimate reviews. This scorecard, based on the scorecard developed by the Government Accountability Office (GAO), provides explicit grading of several areas of the cost estimate.

The comprehensiveness of the cost estimate is measured by the scorecard. A fully comprehensive estimate addresses all applicable life cycle phases and captures the complete technical and programmatic scope of the work to be performed. The WBS must capture all program requirements. The estimate must fully define the program and include documented, rational assumptions.

The completeness/soundness of documentation is also scored. Documentation must identify all data sources and justify all assumptions. It must show traceability to milestones and deliverables. Data must be sufficiently described so that its adequacy for use may be validated. The documentation must include an executive summary, introduction; and descriptions of estimating methods, with data broken out by WBS cost elements; a sensitivity analysis, risk and uncertainty analysis; and updates that reflect actual costs and changes. Contingency reserves must be discussed and the means by which they were derived, from the risk and uncertainty analysis; and the funding profile. Finally, the estimate and documentation must be accessible so that authorized personnel can find them and use them for other cost estimates, when required.

MDA Cost Estimate Score Card Format

The MDA Cost Estimate Score Card is used to gauge the quality of an estimate and its associated documentation. The resulting score for an estimate is not a grade; rather it represents the quality and maturity of an estimate. It also provides a guide for future estimates, pointing to areas where additional data or analysis may be required. Typically, an estimate conducted early in a program's life-cycle will have lower scores due to unavailable or incomplete data. Scores provided by DOC leadership reflect accuracy verifications for estimates/calculations used for each WBS; that they account for all costs, and that proper escalation factors were used appropriately. Scores also rate the degree to which questionable areas for estimating techniques were properly addressed and documented. The soundness of CERs and parametric cost models used for estimating is also scored.

Scores provided by DOC leadership also measure the degree to which ground rules and assumptions are properly handled. These scores measure the level of budget constraints definition, and any effect from delaying program content, if applicable. Also measured is the analysis performed with technical staff to determine risk distributions (and related assumptions) used in sensitivity and uncertainty analysis, and that these assumptions and results are documented.

The appropriateness of data used as the foundation of the estimate or estimating methods is scored. This includes accounting for the source of the data, their applicability to the estimate, the level of data analysis performed, and the proper documentation of the data/source.

Score cards capture the soundness of the data normalization process. This includes measuring the degree to which the data, including its limitations and risks, are understood. It also includes a review of how the data was segregated into nonrecurring and recurring costs, the level of validation of the data of use, the currency of the data, level of data analysis, and whether or not the data normalization process accounted for cost/size, mission/application, technological maturity and content. The means by which data was normalized to compensate for inflation is also assessed and scored.

Scores are provided for the appropriateness of methodologies, and for the consideration and proper use of cost estimating relationships (CERs). These scores provide feedback to the estimators whether or not appropriate estimating methodologies were used. More specifically, scores are provided to indicate the appropriateness of analogies, expert opinions, parametric methods, engineering buildups, and extrapolations from program actual costs. The score card allows leadership to assess the data normalization, statistical analyses, and the data set used to form the basis for the cost estimating relationships. For production activities, the scorecard is also used to assess the means in which learning was applied. It also provides an indication whether the summing of WBS levels was performed in an accurate manner; that nothing was left out, and there is no double-counting.

The sensitivity analysis process is measured by leadership scores. Scores indicate whether or not the analysis was performed, using the proper manner. The means by which the effects of changing key cost drivers assumptions and factors are determined, presented, and documented is scored according to several criteria. Scores also indicate whether the sensitivity analysis was thorough and complete.

Cost risk and uncertainty are measured by how well risk and uncertainty were quantified, and how well the effects on cost from changing key cost driver assumptions and factors were tested. Scores assess how well ranges of costs with associated certainty levels were computed and presented. The score card also measures how well the risk-adjusted estimate reflects the program's risks. The use of a cumulative density function (S-curve) and the means by which contingency reserves were developed and documented are assessed. Also assessed are the appropriateness of the means to determine program cost drivers and risks, and how they change due to variations in requirements, cost estimating errors, business/economic uncertainty, and technology, schedule, program, and software uncertainty. The proper use of probability theory and the means to develop a distribution of potential costs (i.e., Monte Carlo sampling or method of moments) are assessed and included on the score card. Additionally, the means to develop and present the risk-adjusted cost estimate, time phased and then adjusted for the effects of inflation, is also scored.

Score cards include a checkbox to indicate the score selected by each member of DOC Leadership assessing the program under consideration. Possible scores for each entry on a scorebook include "Met", "Substantially Met", "Partially Met", "Minimally Met", "Not Met", and "Not Applicable." A score of "Met" signifies that the estimate fully satisfies the criterion under consideration. A "Substantially Met" score indicates that a majority of the requirements necessary to satisfy the criterion are included in the estimate or documentation; some amount of work is required if the estimator is to raise the score to a "Met" value. A score of "Partially Met" means that it satisfied a reasonable portion of the requirements for satisfying the criterion, but that some work is needed to enhance the estimate and/or documentation. A "Minimally Met" score indicates that the criterion under consideration only satisfied a minor part of the criterion, and that much work is required to bring the score to a "Met". "Not Applicable" indicates that the criterion under consideration does not apply to the estimate being assessed.

Figure 1.7 shows the criteria used to develop the total score. Figures 1.8 through 1.15 explain specific criteria that are used in each of the key categories. The basis of the score card is the GAO Cost Estimating and Assessment Guide (GAO, 2009). The GAO score card was modified for use with MDA cost estimates. Some criteria were expanded using the experience of DOC leadership. Also the score card provides a quantitative score, as well as a qualitative assessment of an estimate. This quantitative comparison provides a simple way to compare the quality of estimates.

The score card is used to assess the quality of all program office cost estimates as part of the annual review process. A comprehensive assessment is conducted for all program office cost estimates. In 2011, DOC leadership conducted in-depth cost reviews for 25 program office cost estimates that considered all phases of a program's life-cycle. The score card results were used to provide feedback to the program office cost teams. Any areas for improvement were highlighted by the score card.

PROGRAM X COST REVIEW	Met (4)	Substantially Met (3-4)	Partially Met (2-3)	Minimally Met (1-2)	Not Met (0-1)	Not Applicable
Comprehensive						
Well-Documented						
Accuracy						
Ground Rules & Assumptions						
Data						
Sound Methodology						
Sensitivity Analysis						
Cost Risk						
Estimate Average Score =						

Figure 1.7. MDA DOC Scorecard Total Score

COMPREHENSIVE	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
.It is comprehensive, includes all possible costs, ensures that no costs were omitted or double-counted, and explains and documents key assumptions.					
<u>1</u> It completely defines the program, reflects the current schedule, and contains technically reasonable assumptions.					
<u>2</u> It captures the complete technical scope of the work to be performed, using a logical WBS that accounts for all performance criteria and requirements.					
<u>3</u> It is a complete LCCE, accounting for development (if any), procurement, O&S (as applicable), AND disposal					
Component Average Score =					

Figure 1.8. Comprehensiveness of Cost Estimate

WELL-DOCUMENTED	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
.The documentation describes the cost estimating process, data sources, and methods step by step so that a cost analyst unfamiliar with the program could understand what was done and replicate or update it. The documentation is sufficient for auditors to trace the estimate to its source information.					
<u>1</u> Supporting documentation identifies data sources, justifies all assumptions, and describes all estimating methods (including relationships) for all WBS elements.					
<u>2</u> Schedule milestones and deliverables can be traced and are consistent with the documentation.					
<u>3</u> Supporting data are adequate for easily updating the estimate to reflect actual costs or program changes and using them for future estimates.					
<u>4</u> The documentation describes the estimate with narrative and cost tables.					
<u>5</u> It contains an executive summary, introduction, and descriptions of methods, with data broken out by WBS cost elements, sensitivity analysis, risk and uncertainty analysis, management approval, and updates that reflect actual costs and changes.					
<u>6</u> Detail addresses best practices and the 12 steps of high-quality estimates.					
<u>7</u> The documentation is mathematically sensible and logical.					
<u>8</u> It discusses contingency reserves and how they were derived from risk and uncertainty analysis and the LCCE funding profile.					
.It includes access to an electronic copy, and both are stored so that authorized personnel can easily find and use them for other cost estimates.					
Component Average Score =					

Figure 1.9. Breadth and Scope of Estimate Documentation

ACCURATE	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
It.is accurate, not too conservative or too optimistic; is based on an assessment of most likely costs, adjusted properly for inflation; and contains few (if any) minor mistakes and contains no major errors.					
1 WBS estimates were checked to verify that calculations were accurate and accounted for all costs and that proper escalation factors were used to inflate costs so they were expressed consistently and accurately.					
2 Questions associated with estimating techniques were answered to determine the estimate's accuracy.					
3 CERs and parametric cost models were validated to ensure that they were good predictors of costs; the data used were current and applied to the program; the relationships between technical parameters were logical and statistically significant; and results were tested with independent data.					
				Component Average Score =	

Figure 1.10. Accuracy of Cost Estimate

GROUND RULES AND ASSUMPTIONS	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
.All ground rules and assumptions have been					
1 Developed by estimators with input from the technical community.					
2 Based on information in the technical baseline and WBS dictionary.					
3 Vetted and approved by upper management.					
4 Documented to include the rationale behind the assumptions and historical data to back up any claims.					
5 Accompanied by a level of risk of each assumption's failing and its effect on the estimate.					
.To mitigate risk,					
1 All GR&As have been placed in a singledocument so that risk and sensitivity analysis can be performed quickly and efficiently.					
2 All potential risks including cost, schedule, technical, and programmatic (e.g., risks associated with budget and funding, start up activities, staffing, and organizational issues) have been identified and traced to specific WBS elements.					
2.a A schedule risk analysis has been performed to determine the program schedule's realism.					
2.b A cost risk analysis, incorporating the results of the schedule risk analysis, has been performed to determine the program's cost estimate realism.					
Budget constraints, as well as the effect of delaying program content, have been defined.					
1 Peaks and valleys in time-phased budgets have been explained.					
2 Inflation index, source, and approval authority have been identified.					
3 Dependence on participating agencies, interdependencies with other BMDS programs, the availability of government furnished equipment, and the effects if these assumptions do not hold have been identified.					
4 Items excluded from the estimate have been documented and explained.					
5 Technology was mature before it was included; if its maturity was assumed, the estimate addresses the effect of the assumption's failure on cost and schedule.					
Cost estimators and auditors met with technical staff to determine risk distributions for all assumptions; the distributions were used in sensitivity and uncertainty analyses of the effects of invalid assumptions. Management has been briefed, and the results have been documented.					

Component Average Score =

Figure 1.11. Soundness and Comprehensiveness of Ground Rules and Assumptions

DATA	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
.As the foundation of an estimate, appropriate data were collected.					
1 They have been gathered from historical actuals, and include cost, schedule, programmatic and technical information.					
2 They apply to the program being estimated.					
3 They have been analyzed for cost drivers.					
4 They have been collected from primary sources, if possible, and secondary sources as the next best option (especially for cross-checking results).					
5 They have been adequately documented as to source, content, time, units, assessment of accuracy and reliability, and circumstances affecting the data.					
6 They have been continually collected, protected, and stored for future use.					
7 They were assembled as early as possible, so analysts can participate in site visits to understand the program and question data providers.					
.Before being used in a cost estimate, the data were normalized.					
1 They were fully reviewed to understand their limitations and risks.					
2 They were segregated into nonrecurring and recurring costs.					
3 They were validated, using historical data as a benchmark for reasonableness.					
4 They are current and were found applicable to the program being estimated.					
5 They were analyzed with a scatter plot to determine trends and outliers.					
6 They were analyzed with descriptive statistics.					
7 They were normalized to account for cost and sizing units, mission or application, technology maturity, and content so they are consistent for comparisons.					
8 They were normalized to constant base-year dollars to remove the effects of inflation, and the inflation index was documented and explained.					
Component Average Score =					

Figure 1.12. Quality of Data and the Data Normalization Process

METHODOLOGY	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)	Not applicable
The appropriate methodology is used to develop the estimate.						
1 Any analogies used were appropriate.						
a Applicable analogies were used.						
b The analogies used were adjusted in an appropriate manner - any complexity factors used were completely justified.						
2 Expert opinion was used appropriately - only as a last resort						
3 Parametric methods were used appropriately.						
a Appropriate data and statistical techniques were used to develop CERs.						
b Any pre-existing CERs used were applicable to the element(s) being estimated.						
4 Engineering build-ups were used appropriately. Valid, detailed data were available.						
5 Extrapolation from program actuals were incorporated in the estimate, if available.						
CERs were considered.						
1 Statistical techniques were used to develop CERs used in the estimate.						
a Data used to develop the CER were normalized.						
b CERs were statistically significant, with reported R2s, standard errors, F-test, t-tests for coefficients.						
2 Statistical techniques were used to develop CERs used in the estimate.						
a Data used were normalized. b CERs were statistically significant, with reported R^2s, standard errors, F-test, t-tests for coefficients.						
3 Before using a CER, the estimator:						
a Examined the data set to understand anomalies and outliers; b Checked the equation to ensure logical relationships (no wrong signs problems); c Ensured CER input were in valid ranges; d Checked modeling assumptions to make sure they are consistent with the program.						
If production activities were estimated:						
1 Learning was applied correctly; 2 Any production breaks were accounted for; 3 Production rate effects were incorporated.						
The estimate is developed at the WBS level and then aggregated by summing the WBS-level estimates.						
1 Results were cross-checked for accuracy, and to ensure that everything was included exactly once (nothing was left out, and there is no double-counting). 2 Independent estimates were developed when available.						

Component Average Score =

Figure 1.13. Appropriateness of Methodologies Utilized in Cost Estimate

SENSITIVITY ANALYSIS	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
.The cost estimate was accompanied by a sensitivity analysis that identified the effects of changing key cost driver assumption and factors.					
1 Well-documented sources supported the assumptions and factor ranges.					
2 The sensitivity analysis was part of a quantitative risk assessment and not based on arbitrary plus or minus percentages.					
3 Cost-sensitive assumptions and factors were further examined to see whether design changes should be implemented to mitigate risk.					
4 Sensitivity analysis was used to create a range of best and worst case costs.					
5 Assumptions and performance characteristics listed in the technical baseline description and GR&As were tested for sensitivity, especially those least understood or at risk of changing.					
6 Results were well documented and presented to management for decisions.					
.The following five steps were taken during the sensitivity analysis.					
1 Key cost drivers were identified.					
2 Cost elements representing the highest percentage of cost were determined and their parameters and assumptions were examined.					
3 The total cost was re-estimated by varying each parameter between its minimum and maximum range.					
4 Results were documented and the re-estimate was repeated for each parameter that was a key cost driver.					
5 Outcomes were evaluated for parameters most sensitive to change. .The sensitivity analysis provided a range of possible costs, a point estimate, and a method for performing what-if analysis.					
Component Average Score =					

Figure 1.14. Sensitivity Analyses Performed for Cost Estimate

COST RISK & UNCERTAINTY	Met (4)	Substantially Met (3)	Partially Met (2)	Minimally Met (1)	Not Met (0)
A.risk and uncertainty analysis quantified the imperfectly understood risks that are in the program and identified the effects of changing key cost driver assumptions and factors.					
1 Management was given a range of possible costs and the level of certainty in achieving the point estimate.					
2 A risk adjusted estimate that reflects the program's risks was determined.					
3 A cumulative probability density function, an S curve, mapped various cost estimates to a certain probability level and defensible contingency reserves were developed and including in the documentation.					
4 Periodic risk and uncertainty analysis was conducted to improve estimate uncertainty.					
Program cost drivers and associated risks were determined, including those related to changing requirements, cost estimating errors, business or economic uncertainty, and technology, schedule, program, and software uncertainty.					
1 All risks were documented for source, data quality and availability, and probability and consequence.					
2 Risks were collected from staff within and outside the program to counter optimism. Risks included reflect program risks (5x5 matrix risks are included)					
3 Uncertainty was determined by cost growth factor, expert opinion (adjusted to consider a wider range of risks), statistics, technology readiness levels, software engineering maturity models and risk evaluation methods, schedule risk analysis, risk cube (P-I matrix) method, or risk scoring.					
A probability distribution modeled each cost element's uncertainty based on data availability, reliability, and variability.					
1 A range of values and their respective probabilities were determined either based on statistics or expressed as 3-point estimates (best case, most likely, and worst case), and rationale for choosing which method was discussed.					
2 Documentation of the rationale for choosing the probability distributions were provided.					
3 Probability distributions used reflect the risk shape and the tails of the distribution reflect the best and worst case spread as well as any skewness. Distribution bounds were adjusted to account for stakeholder bias using organization default values when data specific to the program were not available.					
4 If the risk driver approach is used, the data collected, including probability of occurrence and impact, were applied to the risks themselves.					
5 Prediction interval statistical analysis was used for CER distribution bounds.					
The correlation between cost elements was incorporated.					
1 The correlation ensures that related cost elements move together during the simulation, resulting in reinforcement of the risks.					
2 Cost estimators examined the amount of correlation already existing in the model. If no correlation is present, a default of 20% was used,					
A Monte Carlo simulation or method of moments model was used to develop a distribution of total potential costs and an S curve showing alternative cost estimate probabilities was developed.					
1 High-priority risks were examined and identified for risk mitigation.					
2 Strength of correlated cost elements were examined and additional correlation added if necessary to account for risk.					
3 The S-curve was documented, along with associated total risk statistics, including mean, standard deviation, 5th, 95th, and deciles (10th, 20th, 30th, etc.)					
4 The probability associated with the point estimate was identified.					
5 Contingency reserves were recommended for achieving the desired confidence level.					
5.a Budgeting to at least the mean of the distribution or higher is necessary to guard against potential risk.					
5.b The cost risk and uncertainty results were vetted through a core group of experts to ensure that the proper steps were followed.					
5.c The estimate is continually updated with actual costs and any variances recorded to identify areas where estimating was difficult or sources of risks were not considered.					
The risk-adjusted cost estimate was allocated, phased, and converted to then year dollars for budgeting, and high-risk elements were identified to mitigate risks.					
A.risk management plan was implemented jointly with the contractor to identify and analyze risk, plan for risk mitigation, and continually track risk.					
1 A risk database watch list was developed, and a contractor's EVM system was used for root cause analysis of cost and schedule variances, monitoring worsening trends, and providing early risk warning.					
2 Event-driven reviews, technology demonstrations, modeling and simulation, and risk-mitigation prototyping were implemented.					
				Component Average Score =	

Figure 1.15. Risk and Uncertainty

For each score card, a single quality metric is assigned to each of the criteria. These have white spaces next to them on the score card, which means that scores are assigned at that level. The sub-factors in the gray scoring area contribute to the overall score, but are not scored separately. For example in Figure 1.9, there are three factors that contribute to comprehensiveness, but only overall comprehensiveness is assigned a rating of “met,” “substantially met,” “partially met,” “minimally met,” or “not met.”

To translate the qualitative metric to a quantitative one, a rating of “met” is assigned a score equal to 4; a rating of “substantially met” is assigned a score equal to 3; a rating of “partially met” is assigned a score equal to 2; a rating of “minimally met” is assigned a score equal to 1; and a rating of “not met” is assigned a score equal to 0.

Comprehensiveness is assigned one score so it is scored as a 0, 1, 2, 3, or 4. For those criteria that have two or more sub criteria that receive score, the overall criteria score is calculated as the simple average of the individual sub criteria. For example, suppose a category has two sub criteria that are scored. If these score as 3 and 4, then the overall score for data is (3+4)/2 = 3.5. The overall estimate score is then calculated as the average of the scores for the eight criteria, as shown in Figure 1.16.

PROGRAM X COST REVIEW	Met (4)	Substantially Met (3-4)	Partially Met (2-3)	Minimally Met (1-2)	Not Met (0-1)	Not Applicable
Comprehensive		3				
Well-Documented		3.5				
Accuracy			2			
Ground Rules & Assumptions		3.2				
Data			2.5			
Sound Methodology		3.3				
Sensitivity Analysis					0.5	
Cost Risk		3.2				
Estimate Average Score =						2.6

Figure 1.16. Example of Score Calculation for an Estimate

CHAPTER 2
DOCUMENTATION

The purpose of cost estimate documentation is to provide a detailed written justification for the cost estimate. No cost estimate is considered complete without documentation. The U.S. Government Accountability Office states that a well-documented cost estimate is a best practice for a high-quality estimate [GAO, 2009]. The resulting product should include sufficient information on logic, data, methodology, calculations, and risk and uncertainty to allow another cost estimator to pick up the documentation and accurately reproduce or revise the estimate.

With thorough documentation and written rationale, an estimate may be reviewed by cost estimating leadership without the constant need to interface with the estimate originator. A sound cost documentation package allows the estimate and documentation to be stored for years, and still be valuable to future estimators, even if the original estimator is no longer available to describe and present the logic and rational used. Documentation enables preparation to answer any future questions asked by oversight groups (e.g., GAO).

The best practice is to document each portion of the estimate, to include a description of the item being estimated, during the estimate's development. Explaining work while it is fresh on the estimator's mind, and while references are readily available has the added benefit of compelling the estimator to return to the detailed inner workings of the estimate and its place in the overall cost model. This reassessment of logic and calculations sometimes results in discovery of either an error which may then be resolved. Or by thinking about how to explain the estimate, the estimator finds a better method for the estimate.

There are eight different categories of information necessary for a well-documented MDA cost estimate. These include each of the following:

1. Ground rules and assumptions, utilized to develop the estimate and justify the methodologies
2. Methodologies, including the sources, data, and rationale utilized for each of the estimating methods selected for the cost estimate;
3. Risk and uncertainty analysis, including the methodologies and tools selected by the estimator, as well as underlying assumptions;
4. Sensitivity analysis, including rationale behind selection of input variables included for assessment;
5. Lessons learned, including details useful for revising the estimate or estimating a similar product;
6. Total cost estimate, documented in a final report which states a summary of the system estimated, ground rules and assumptions, cost estimating methodologies, risk analysis, and lessons learned;
7. MDA-specific documentation tailored to leadership reviews of the cost estimate; and
8. Storage and retrieval of any portions of the documentation, as well as the documentation package itself, which will support effective use of the documentation.

These categories of documentation requirements are similar to the GAO Documentation Checklist [2009], developed by the Government Accountability Office to ensure cost estimators develop comprehensive documentation packages. This checklist is provided in Table 2.1.

Best Practices Checklist: Documenting the Estimate	
The documentation describes the cost estimating process, data sources, and methods step by step so that a cost analyst unfamiliar with the program may understand what was done and replicate it.	
	- Supporting data are adequate for easily updating the estimate to reflect actual costs or program changes and using them for future estimates.
	- The documentation describes the estimate with narrative and cost tables.
	- It contains an executive summary, introduction, and descriptions of methods, with data broken out by WBS cost elements, sensitivity analysis, risk and uncertainty analysis, management approval, and updates that reflect actual costs and changes.
	- Detail addresses best practices and the 12 steps of high-quality estimates.
	- The documentation is mathematically sensible and logical.
	- It discusses contingency reserves and how they were derived from risk and uncertainty analysis and the LCCE funding profile.
It includes access to an electronic copy, and both are stored so that authorized personnel can easily find and use them for other cost estimates.	

Table 2.1. GAO Best Practices Checklist. Documenting the Estimate [GAO, pp. 196]

Documenting Ground Rules and Assumptions

MDA cost estimates are required for programs and systems with frequently limited information available about the program or system to be estimated. Thus, certain baseline conditions, constraints, and estimating assumptions must be established in order for a cost estimate to be developed. These constraints and assumptions are termed Ground Rules and Assumptions (GR&A).

A quality cost estimate includes detailed documentation which presents the specified rules (i.e., ground rules) used when developing a cost estimate. Ground rules are typically grouped together in documentation, as are assumptions, and then the ground rules and assumptions are documented either within the same, or subsequent, section(s) of the documentation package. Ground rules are reviewed up-front by anyone attempting to assess a cost estimate, because they form the underlying basis for the estimate – if a reviewer does not agree with the ground rules, the reviewer will not agree with the product cost estimate. Inflation indices and the year used for displaying Constant Year (CY) dollars are examples of ground rules. There are many potential sources from which ground rules may originate. These include a program's Cost Analysis Requirements Description (CARD), CARD-Minimum Technical Data Set (CARD-MTDS), and guidance provided by MDA leadership during BERs.

A CARD provides a time-phased description of the program's life cycle content describing development, production, fielding, operations and support, and demilitarization. The CARD is the basis for estimating life cycle costs for BMDS component programs. The CARD is signed by both the Program Manager (PM) and the cognizant Program Executive (PE). An approved CARD is required to "exit" the Technology Development Phase and "enter" the Product Development Phase.

A CARD-MTDS is a subset of the standard CARD (CARD-MTDS does not have production and operations and support content) used for bounding early development programs in the MSA Phase. An approved CARD-MTDS is a required document to "exit" the MSA Phase and "enter" the Technology Development Phase. (MDA 5010.18)

Complete documentation provides details necessary to link ground rules to important program and overarching MDA strategies, such as schedule milestones and deliverables.

Additionally, cost estimators are required to make a number of assumptions beyond the ground rules during the estimating process. The cost estimator is responsible for ensuring assumptions utilized have foundation, and are not arbitrarily determined. The source for each assumption, rationale and logic is well-documented. During any review of the cost estimate, the cost estimator carefully describes each assumption because invalid assumptions create invalid estimates. Poor assumptions can dramatically influence the estimate (in terms of magnitude or phasing of funding requirements), which can lead to ineffective management plans, strategies and decisions.

Documenting Cost Estimating Methodologies

There are four primary methods for developing cost estimates. These include using:

1. Analogy or analogies to comparable or relevant system(s) whose actual costs are known;
2. Parametric methods such as cost estimating relationships (CERs);
3. Industrial Engineering method where activities related to the estimate at hand are defined at a much lower level and then built up to the level where the estimate is required; and
4. Actual cost data derived specifically from the item being estimated.

Each of these types of estimating methods requires the development of documentation relevant to the type of method utilized. Most cost estimates are a combination of more than one method. A discussion of proper documentation expectations for each type of estimating method is included below:

1. When using the Analogy method, the source data from which the analogous item is defined is captured as documentation (i.e., cost, performance, schedule, technical. or other relevant characteristics). An analogous historical system may be similar, but differences will still exist. To account for these differences complexity factors are applied to the analogy. Any adjustments made to the analogous item to make it more similar to the item to be estimated, along with the specific rationale and logic associated with the need for the adjustments and their magnitude, is included with the documentation package.

2. When a CER is used, the form of the model should be presented and its source of development cited fully. This description includes the data set used to develop the CER, the source of the data, and relevant information about the data (e.g., base year dollar). It also includes an explanation of the explanatory variables considered for regression with cost, and rationale for why certain explanatory variables were chosen or omitted. If any of the data set is omitted from the regression analysis, rationale is required to explain the reason for the omission. The description includes resulting (relevant) model fit statistics and results of key hypothesis tests. Descriptive graphics are included that provide further evidence of the soundness of the model, such as a plot of cost versus the regression model, residual plots and an explanation of the robustness of the model. Documentation includes a discussion of the CER validation process, instructions for proper use of the CER, and cautions against potentially improper use, such as extrapolating beyond the range of the data utilized to develop the CER.

3. The Industrial Engineering approach involves breaking down the item to be estimated into the smallest parts or activities for which the item may be described and related costs derived. Occasionally this breakdown is performed by a Subject Matter Expert (SME), often with assistance of a breakdown of something similar to the item to be estimated. All Subject Matter Experts, the reason they qualify as Subject Matter Experts, and pertinent contact information is included in the documentation. All logic and rationale associated with the breakdown, as well as any uncertainties, contingencies (e.g., a line item labeled "miscellaneous") is described in the documentation, and the manner in which these small parts or activities are estimated included. The basis for any labor rates included in the estimating method is justified, as well as the means utilized to add burden (e.g., overhead, fee, etc.) to the rates. The number of hours and schedule used is documented.

4. Actual recent cost data may be the best method for estimating future costs with an ongoing contract that is level-of-effort, and steady-state, such as operations and support. For estimating purposes, the planned scope and extent of the effort for the future activity is similar to the actual costs used for the estimate. When actual cost data are utilized for estimating, the cost data source is clearly specified. The estimator also ensures supporting data are adequate. The contract number, contract type, contractor name, date of the report and etc. are included. When possible, the original data, along with any normalizing (or other) adjustments made to the data, is included with the documentation.

Regardless of the estimating approach, the source and origination date of the inflation rates/indices is included in the documentation. When a source of inflation indices is other than those published specifically by OSD, then rationale for using the non-MDA source is included in the documentation.

Documenting Risk and Uncertainty Analysis

A cost estimate will not be complete without a risk assessment and assignment of probabilistic costs over the range of potential costs. While an analyst may ignore risk in the estimating process that does not mean that risks fail to exist. As shown in Government Accountability Office reports on cost growth (GAO 1992, 2004, 2009), Department of Defense programs routinely have problems that lead to large budget overruns; such as underestimating technical readiness, overestimating heritage of historical systems, and experiencing external factors such as labor strikes and budget cuts and constraints. In order to document risk analysis, all assumptions and input variables are captured. These include:

(a) The tool and/or general means of applying risk analysis and the general assumptions associated with the tool is captured and documented. Examples include the use of such tools as Crystal Ball©, @Risk©, RI$K©, etc. These tools all utilize an electronic spreadsheet software (typically Microsoft Excel©) and built-in mathematical, statistical and macro functions. The method of random sampling selected (either Monte Carlo or Latin Hypercube sampling) is documented. Latin Hypercube sampling involves stratification of the cumulative distribution curve into equal intervals on the cumulative probability scale (i.e., 0 to 1). It draws exactly one sample for each stratum, and thus avoids non-representative clustering, especially when running the simulation for a relatively small number of iterations. This also ensures that a representative sample is taken for the entire distribution, to include the far end of the tail(s). Thus, Latin Hypercube sampling may be accurately performed utilizing less iteration. The Monte Carlo sampling technique is more commonly utilized because modern computers are capable of performing a sufficiently high number of iterations (i.e., samples) quickly. Regardless of the sampling method utilized, automated versions of these tools allow specification of a random number seed (used by the algorithm which generates the pseudo-random number). The random number seed utilized is noted within documentation since the results generated by the automated tool will vary according to the seed value selected. For this same reason, the number of iterations (samples) selected for the simulation is also documented.

(b) The means by which probability distribution parameters were determined is documented, whether around either costs or input variable values If the parameters are derived through statistical analysis, include the statistical analysis in the documentation. Information derived from other means, such as from Subject Matter Experts, historical data, etc., are documented in terms of the source of the data, and rationale as to why the source is valid (e.g., reason the Subject Matter Expert is an expert). Point of contact information is provided for any subject matter expert whose input is used in the estimating methodology. Ensure that the source(s) of correlation values between cost elements are incorporated in the documentation, as well as the rationale behind any assumed values. The random number seed utilized for generating the simulation is documented in order to be able to exactly reproduce the simulation.

(c) Programmatic risks and their incorporation into the cost risk and uncertainty analysis is documented. This is accomplished by the determination of program cost drivers and associated risks, which may include those related to changing requirements, and uncertainties associated with schedule, technologies, the economic and business environment, and others. These types of uncertainties are gleaned from both within the program under study, and outside the program. This helps ensure program personnel and leadership are not overly-optimistic with their assessments. Historical data for similar programs, expert opinions, technology readiness levels, and software maturity models are some of the sources for this type of information. In order to quantify uncertainties, probabilistic estimates over specific confidence intervals (e.g., 80%) are derived. The manner in which this is accomplished requires that a range of cost values be determined, along with the probabilities associated within this range. This is accomplished based on statistics (e.g., the mean and variance associated with a regression model), or through the use of 3-point estimates, where best case, most likely case, and worst case values are assigned to a cost element. Note that the terms "best case" and "worst case" can be difficult to interpret in terms of cumulative probability. The worst case does not mean that there is no possibility of a parameter value beyond that point, for example. Thus when the 3-point estimate method is used, an underlying assumption is that probabilities associated with these values – for example, the worst case value will be based on an assumed probability (e.g., 90%) that the actual cost will not exceed this worst case value. Whatever the source and means of establishing these uncertainties, specific information about each source and the rationale for its use as a source is well documented. Subject Matter Experts and expert opinions are a frequent source for such information. Specific information should be captured that describes why the subject matter expert is a credible source of the information. A more thorough examination of the process utilized by MDA to capture and quantify program risk and uncertainty is provided in Chapter 8: Cost Risk and Uncertainty.

(d) The results of cost risk and uncertainty analysis (e.g., S-curves, a useful graph from which the confidence levels can easily be read directly from the graph, cost values at specific confidence intervals of interest), is included in the documentation. Once the risk and uncertainty analyses are finished, the complete results of these analyses, including S-curves, cost values associated with specific confidence intervals of interest are described within the documentation.

Documenting Sensitivity Analysis

Sensitivity analysis is required to support a sound cost estimate. Sensitivity analysis determines the degree to which certain input variables affect the cost of a subsystem or the system-level cost. This is accomplished by testing pre-defined sets assumptions and other factors that may change. Each assumption or factor is assessed independently by revising the estimate to incorporate a single assumption (e.g., largest feasible booster diameter), while holding all other assumptions within the model constant. Such sensitivity analyses can determine program cost drivers, which may be defined as those cost elements and related assumptions which have the largest potential influence on overall program cost. Assessment of cost drivers provides program management and MDA leadership with information on how a cost element and related assumptions influence potential overall program cost, which supports them in determining where emphasis must be placed in order to constrain or reduce cost. All information, rationale, and results associated with these sensitivity analyses are documented. Potential best and worst case values, associated assumptions, and the means by which such information was derived (e.g., from Subject Matter Experts; historical information) is documented. Whenever a Subject Matter Expert was the source of the information, documentation must include the reason this person/group is deemed to be an expert, as well as sufficient point of contact information. Cost drivers, as well as results which depict their specific influence on overall program cost, are documented. Graphics such as pie charts and Pareto charts are often utilized to present this type of information, and any such graphics are described within the documentation.

Documenting Lessons Learned

Lessons learned may include any type of information for which the estimator believes may be beneficial to an estimator in the future who has the responsibility of updating the subject estimate, or who may be developing or updating an estimate containing similarities to the subject estimate. Since lessons learned are only remembered for a short time, or by a select group of people, documenting lessons learned enhances the longevity of the lessons, and increases the breadth of those who are given a chance to learn from them.

The primary criterion for inclusion of information as a lesson learned is whether or not the estimate/documentation developer believes that it would have been beneficial to have known in advance. An example of a lessons learned might the discovery that the planned analogy needs to be adjusted to remove the effects of a year-long labor strike at the contractor organization which occurred at the start of manufacturing the product. Since events such as labor strikes fall into the category of "should not be accommodated for in a cost estimate," the estimator would explain the labor strike and its effects on the analogy, and how these effects were factored out. The estimator might also want to include when the labor strike took place, as well as source documentation on the labor strike. In this case, documentation might show that the estimator contacted the Defense Cost and Resource Center (DCARC), obtained an account to enable a search through the SAR data base for the program of interest, downloaded annual reports to Congress for the analogous program, and the results of the assessment which were used to adjust the analogy.

MDA-Specific Documentation for Leadership Review

MDA cost estimating organization leadership requires specific documentation for the BAR and the BER.

- A formal program cost estimate review is required by MDA cost estimating leadership for each program for which a BAR submission is required.

- The composition of the cost estimating team is documented. Both government and contractor personnel are listed, as well as support received from cost estimating core personnel, as appropriate. The roles and responsibilities of each team member are described.

- A description of program content is required, such as an overview of the technical content and programmatics. Sample programmatics include the acquisition schedule, milestones, deliveries, procurements, test dates, and etc. Documentation links to schedule milestones and deliverables. The specific costs included, as well as excluded from the cost estimate are presented. All cost estimating changes from the previous BAR is presented for the pre-BAR cost estimate review, and all cost estimate changes made since the previous BER review must be presented for the pre-BER cost estimate.

- All ground rules and assumptions are presented. Ground rules include all technical and programmatic data provided to the cost estimator, while assumptions include all information the estimator must assume in order to prepare the cost estimate. A ground rule example might reference the Cost Analysis Requirements Description (including date and version number) utilized for the cost estimate. An assumption example might be that an otherwise unspecified (in ground rules) computer system is available commercially off-the-shelf.

- Power Point© slides are utilized in all cost reviews. There are prescribed content requirements and formats for these slides. Information presented include the point estimate value in base year (BY) and then year (TY) dollars, along with the confidence level associated with these values. It also provides a short description of the scope and content of the cost estimate, plus listing what is excluded from the estimate. The key assumptions for the estimate methodology are included. A brief description of the estimating approach (e.g., analogy) is provided, as well as the basis for the method. The source (e.g., report, along with type of report and date) of the data utilized in the methodology is briefly described. A simplistic view of the equation utilized by the methodology to calculate costs is presented. Key parameters (e.g., "learning curve/rate %") is identified if the equation is relatively long or complex. The methodology utilized to time phase (e.g., phased according to analogous program XYZ) is described. The means for establishing cost risks, to include the source of risk parameters and the methodology and/or tools used, are identified. Table 2.2 summarizes the requirements and format for a WBS-level documentation chart.

Point Estimate = $XXX.XX BY$M / $YYY.YY TY$M / ZZ% Confidence Level

Description:	Short description of content, scope, effort estimated
Assumptions:	Identify the key assumptions made for the cost element
Methodology:	Provide a short description of the approach to the estimate including basis for analogy, parametric, historical, engineering estimate, bottoms up, SME, Delphi, etc.
Source:	Identify the source of your data (report type, date of report, persons, etc.)
Calculation:	Show simplistic view of calculation where possible, identify key parameters for more complex calculations (example: learning/rate%, quantity, T1s, fee%, etc.)
Time Phasing:	Briefly describe the phasing methodology (e.g., "phasing from analogous program XYZ" or "used beta distribution and 60/40 rule of thumb for phasing development cost" or "phasing developed in conjunction with budgeted spend plans")
Risk:	Identify source of risk parameters and the methodology/tools used
	Mean = XX.XX BY10$M Standard Deviation = XX.XX BY10$M

Table 2.2. Example of WBS-level Documentation

For each cost review, a Cost Estimate Methodology Matrix (CEMM) is required. For each cost element (by name) in the estimate, the CEMM summarizes the base year (BY) dollar estimate and provides a brief description of the estimating methodology utilized for the cost element. Examples of entries for the methodology include "Engineering estimate based on actual and negotiated price," and "Analogy to SM-3 Block IA historical flight test support cost." Cost elements within the CEMM are indented according to WBS level, but there is no methodology input required for sum level WBS elements. The information contained within the CEMM for each cost element should track back to the WBS level documentation prepared for the cost element, and the BY dollar value shown for each cost element in the CEMM should match the BY dollar value shown on the WBS-level documentation for the cost element. Table 2.3 provides a summary of CEMM requirements.

WBS	Element Name	Total BY10$	Methodology
xyz	Widget	$1,000	Based on analogy to program ABC with 1.2 engineering scaler

Table 2.3. Cost Estimate Methodology Matrix

Cost estimate changes since the last BAR or BER cost review are documented using a Cost Estimate Trace Matrix (CETM). For each cost element changed requires a top level description of the WBS cost element, the BY cost value at the last review, the revised BY cost estimate, and the reason the change was necessary. The documentation used for the previous BAR/BER should be available during the cost review. Table 2.4 summarizes the requirements and format for a CETM.

WBS	Element Name	Total BY10$		Reason for Change
		July 2010 DOC Review	November 2010 DOC Review	
xyz	Widget	$800	$1,000	IMTP added 2 flight tests

Table 2.4. Cost Estimate Trace Matrix (CETM)

Cost reviews include an assessment of time phasing methodologies and inflation indices utilized, as well as a comparison of the time-phased Then Year (TY) dollars to the budget. TY costs are presented for each WBS element for all Program Objective Memorandum (POM) years. Additionally, prior (or sunk) costs, costs remaining beyond the POM year, and total program cost are presented. Table 2.5 presents the approved format for summarizing this information during a cost review.

TY$											
WBS	**Element Name**	**Prior**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**	**To Complete**	**Total**
xyz	Widget	$150	$100	$101	$102	$103	$104	$105	$106	$129	$1,000

Table 2.5 Time Phased Cost Estimate

Top Level Affordability Assessment (TY estimate vs. latest controls)

Cost reviews require a top-level affordability assessment, through comparison of the TY cost estimate against the latest program budget controls. The approved means for presenting this information is to provide a top-level time phased program cost estimate for the execution year and the Future Years Defense Program (FYDP) years, by top level categories of interest, with an associated program affordability (“sand”) chart. This sand chart visually describes program resource allocations, by top level category of interest, as well as the cost estimate for the total program with different colors (“sand”) for different categories of cost. The budget, by fiscal year, may then be easily compared against the cost estimate, to determine budget shortfalls or overages. Table 2.6 presents an example of a program resource allocation table, and Figure 2.1 presents the associated sand chart.

Resource Allocation Table (as of mm-dd-yyyy)								
		Execution Year	Budget Year	B +1	B +2	B +3	B +4	
Costs TY $M	**Prior**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**FYDP Total**
Hardware Analysis/Development		1	6	4	2			14
Software Analysis/Development		2	3	3	3			12
Demonstrations		0	2	4	6			11
Demonstration Item Fabrication		0	5	5	1			11
Integration		1	2	2	7			12
RDT&E Funding Total		4	19	18	19	0		60

Table 2.6. Example Program Resource Allocation Table

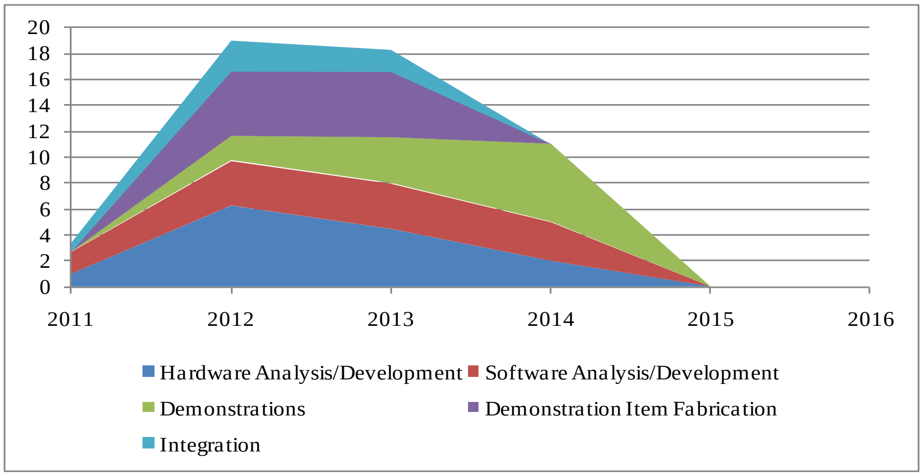

Figure 2.1. Example Resource Allocation Sand Chart

The total cost estimate, to include risk, is depicted graphically in the cost estimate documentation through the use of "S-Curves" which are named after the shape of the graph. S-curves, more formally known as cumulative distribution functions, plot the cumulative probability associated with all possible costs. It is common in cost analysis to refer to the cumulative probabilities as "confidence levels." For example the 80% cumulative probability is referred to as the "80% confidence level cost estimate." For the cost reviews, a probabilistic cost estimate and S-curve is required for each life cycle phase. The confidence levels on the Y-axis of a typical S-curve show the confidence level (in percentage) associated with cost estimates values associated with those specific confidence levels. Figure 2.2 presents an example of an S-curve.

Once the S-curve has been generated, the budget value is noted on the S-curve, and the level of confidence associated with the budget is described. A notional budget of $990 million is denoted on the chart. By drawing a straight line from the X-axis vertically up to the S-curve, and then following a straight line horizontally to the Y-axis, it is possible to determine that a budget value of $990 million represent a 50% level of confidence. This means there is about a 50% level of confidence that the actual costs will not exceed the budget value of $990 million.

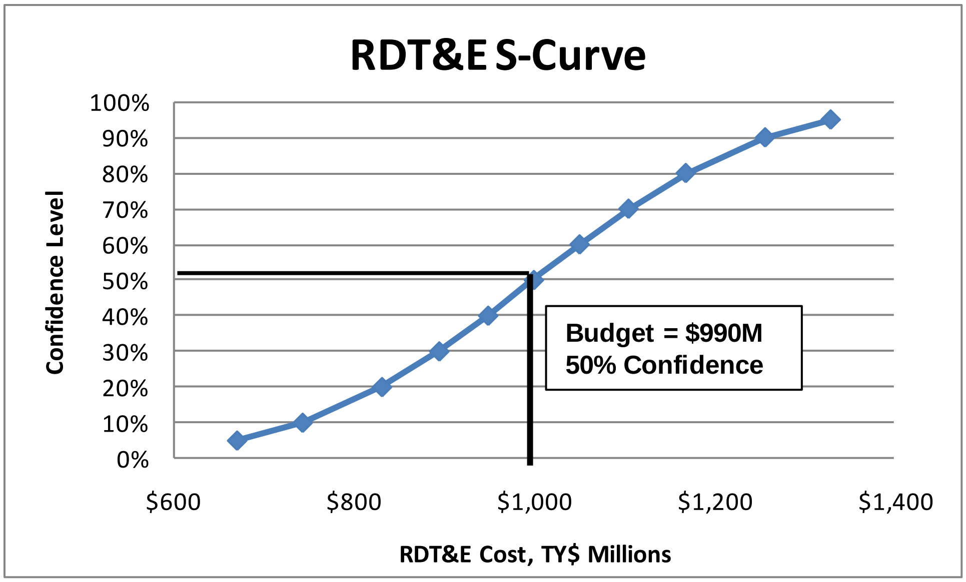

Figure 2.2. Notional Example of an S-Curve

Cost estimates do not always align to budget periods. Life-cycle cost estimates will typically extend well beyond the five-year Futures Years Defense Program (FYDP). In order to support the planning and budget process, the S-curves are also reported over the FYDP period, and these phased S-curves are then used for budget comparison.

Sensitivity analysis results must be provided during cost reviews. As mentioned previously, one of the primary reasons to perform sensitivity analyses is to determine cost drivers. The results of such cost driver analysis should be documented and presented in the cost review. More detailed information is presented in the Sensitivity Analysis - Chapter 7.

Cost Estimate Report

Each major cost estimate includes a cost estimate report that documents the complete cost estimate. The report provides a comprehensive description of the estimating process and documentation required for each step of the estimating process, organized by table of contents, page numbers, and subheadings. The use of tables and graphics to present information and enhance understanding is included. Further, the report provides a logical sequence of information which begins with the basics so that someone new to the estimate may understand the purpose and scope prior to delving into estimate details. The Government Accountability Office [2009, pp. 193] developed an outline which describes the sections that are included in cost estimate documentation. These sections, along with a summary of GAO's recommendation for the information to include in each section, are presented below:

1. Cover page and table of contents: Includes names of estimators, program name, date, and a listing of document's contents and supporting appendices
2. Executive summary: Clearly and concisely summarizes cost results, but with enough information about cost drivers and high risk areas that management can make informed decisions

3. Introduction: Provides a program overview, the purpose of the estimate, scope of the estimate, and lists ground rules and assumptions
4. System description: Describes the program background, major system components, performance parameters, support requirements and acquisition strategy
5. Program inputs: Details the program schedule and deliverables
6. Estimating method and data by WBS cost element: Incorporates the bulk of the documentation, and includes descriptions of cost elements, the methodology used to derive each, calculations of the estimate for each cost element, displays or references all data used to generate cost estimating methodologies, and any complexity or adjustment factors
7. Sensitivity analysis: Describes the effect of changing key cost drivers while everything else in the cost model is constant
8. Risk and uncertainty analysis: Discusses the sources of risk, and the effect of uncertainty associated with the point estimate as quantified by probability distributions and the resulting S-curves
9. Management approval: Includes briefings used to present the estimate to leadership for approval, documentation of management's approval, or recommendations for change
10. Updates reflecting actual costs and changes: Describes changes in programmatic or technical assumptions and related cost estimate results

Incorporating Detailed Documentation into a Cost Model

Most cost models are developed utilizing software tools. For example, the Automated Cost Estimating Integration Tool (ACEIT©) requires new or pre-established, built-in equations to estimate a certain portion of the cost estimate. The estimator enters input variables and values into ACEIT to enact the calculation operation. Similarly, Excel© spreadsheet models require equations added to electronic worksheets. Both of these tools allow copy-pasting of various other types of electronic files into a model, such that these attachments may also serve as documentation. Thus, cost reports containing actual cost data, pages from documented reports, printouts of statistical results, etc. may be easily added to a cost model to support cost estimate documentation. Whether entering documentation into the model itself, or providing the information as an attachment, information is provided to allow complete traceability to the source of the information of all pertinent assumptions and data.

Storing Documentation (and Cost Estimates)

Cost estimates and their documentation packages are of little use if they cannot be found when needed. Similarly, estimates and documentation that have undergone several revisions, resulting in multiple versions, require disciplined configuration control. Model documentation requires that configuration control of the assumptions, conditions, and changes to the model are recorded as they occur. All electronic cost estimates and documentation packages (if separate from the estimate) have electronic file names stating the purpose and date of the estimate. If the estimate or documentation package is revised, the file name notes the revision (why the revision was required, what was revised, etc.), the date of the original (i.e., baseline) estimate and the date of the revision. It is recommended to place such information on the pages of the estimate itself, so that a "misplaced" printout of an estimate does not get misinterpreted. The files are stored on MDA network drives allocated to the cost estimating organization division responsible for development of the estimate. Thus, files may be kept current and shared among those responsible for developing the estimate, and no files become unavailable because one team member is not available to access the file on a private network or computer folder. Finally, a meaningful storage folder naming convention is utilized so estimates and documentation packages (if separate from the estimate) are easily located, maintained, and remain under appropriate configuration control.

Summary

All high-quality, reliable cost estimates include thorough, detailed and robust documentation. The resulting documentation detail includes the logic and rationale so any cost estimator is able to recreate or revise the estimate. The recreated or revised estimate makes appropriate use of the ground rules, assumptions and estimating methodologies. Any estimating methodology requiring specific derivations requires traceability to the source of the data, the data itself, and the calculations. Estimates require documentation of ground rules and assumptions, estimating methodologies, risk analysis, sensitivity analyses, and lessons learned. A report is required for each significant cost estimate, and this report is sufficiently detailed to stand alone as an appropriate documentation package. MDA cost estimators are required to develop and maintain MDA-specific documentation and briefing materials for each cost estimate. Documentation is stored efficiently so it may be easily located and readily available to cost estimating team members.

CHAPTER 3
COMPREHENSIVE, CREDIBLE, AND ACCURATE COST ESTIMATES

Best practices must be followed if comprehensive, accurate, and credible cost estimates are to be developed. These best practices represent an overall process of established, repeatable methods that result in high-quality cost estimates that are both comprehensive and accurate and which can be easily and clearly traced, replicated, and updated. For use in this handbook, the term "accurate" does not refer to the accuracy of an estimate, since this is a contradiction in terms. To paraphrase the well-known statistician George Box, all estimates are inherently wrong, but some are useful. The term accuracy for this handbook refers to using the most credible and comprehensive information available for accuracy in the estimating process. This means the information that drives the estimate should be as current and complete as possible; not that the results of the estimate in and of itself are accurate. This includes program schedule, scope (weights, diameters, materials), and quantities.

The comprehensiveness, credibility, and accuracy of an estimate is addressed in each step of the estimating process; from defining the estimate's purpose; defining the program's characteristics; obtaining data for use in the estimate; conducting sensitivity analysis; and updating estimates to reflect actual costs. MDA adopted the GAO steps for use in its cost estimating process.

The Government Accountability Office's 1972 Version of the Basic Characteristics of Credible Cost Estimates (GAO 2009) provides the details needed for a credible cost estimate:

- Clear identification of task
  - Estimator must be provided with the system description, ground rules and assumptions, and technical and performance characteristics. Estimate's constraints and conditions must be clearly identified to ensure the preparation of a well-documented estimate.
- Broad participation in preparing estimates
  - All stakeholders should be involved in deciding mission need and requirements and in defining system parameters and other characteristics. Data should be independently verified for accuracy, completeness, and reliability.
- Availability of valid data
  - Numerous sources of suitable, relevant, and available data should be used. Relevant, historical data should be used from similar systems to project costs of new systems; these data should be directly related to the system's performance characteristics.
- Standardized structure for the estimate
  - A standard work breakdown structure, as detailed as possible, should be used, refining it as the cost estimate matures and the system becomes more defined. The work breakdown structure ensures that no portions of the estimate are omitted and makes it easier to make comparisons to similar systems and programs.
- Provision for program uncertainties
  - Uncertainties should be identified and allowance developed to cover the cost effect. Known costs should be included and unknown costs should be allowed for.
- Recognition of inflation

  - The estimator should ensure that economic changes, such as inflation, are properly and realistically reflected in the life-cycle cost estimate.
- Recognition of excluded costs
  - All costs associated with a system should be included; any excluded costs should be disclosed and given a rationale.
- Independent review of estimates
  - Conducting an independent review of an estimate is crucial to establishing confidence in the estimate; the independent reviewer should verify, modify, and correct an estimate to ensure realism, completeness, and consistency.
- Revision of estimates for significant program changes
  - Estimates should be updated to reflect changes in a system's design requirements. Large changes that affect costs can significantly influence program decisions.

These characteristics form the criteria used to judge the credibility of an estimate, and by extension, the credibility of the estimator. The characteristics and descriptions from the Government Accountability Office's 1972 definition of a credible estimate still hold true today.

This chapter discusses necessary steps to produce a comprehensive, credible, and accurate estimate. The next section discusses the 12 Steps of a high-quality cost estimating process in terms of these three key characteristics. These discussion points are covered in other chapters but each will be addressed in turn in the following section.

The Estimator's 12 Steps of a High-Quality Cost Estimating Process (GAO 2009)

1. Define Estimate's Purpose

Determining the estimate's purpose, required level of detail, and overall scope establishes the

- Life Cycle Cost Estimate (LCCE);
- Business Case Analyses (BCA);
- Rough-Order of Magnitude (ROM) estimate;
- Independent Cost Estimate ICE (performed by the OSD CAPE);
- Independent Government Estimate (IGE); and
- Estimate at Completion (EAC)

ground work for the rest of the estimating process. The recipient of the estimate and the timeline for completion are major factors for determining the type of estimate that can be accomplished while ensuring it is comprehensive, credible, and accurate.

The purpose defines the types of estimates produced.

For a more detailed description of each of these estimates, see the GAO Cost Estimating and Assessment Guide (GAO 2009 pages 34-36).

For an LCCE to be comprehensive, credible, and accurate, the estimate follows all phases of the acquisition process. This includes Engineering, Manufacturing and Development (EMD), production, operations and sustainment, and disposal. The technical, schedule, and cost estimating data captures all activities included within each phase using the most current data available. The estimate follows the 12 steps as referenced earlier in the GAO Cost Estimating and Assessment Guide (GAO 2009).

A BCA includes all reasonable alternatives. Current detailed technical, schedule, and cost data is included to be comprehensive, credible and accurate.

A ROM estimate is one that is based on limited information, and driven by a need for a quick estimate. It is termed “Rough Order of Magnitude” because it is recognized that such estimates include a great deal of uncertainty, with limited accuracy. ROMs are as credible as the time allowed to complete them and they should never be confused with a fully documented LCCE.

The OSD CAPE develops ICEs. These follow the same format and guide as listed for the LCCE to make them comprehensive, credible and accurate. See Step 2. “Develop Estimating Plan” for more details regarding OSD CAPE ICE’s.

Most IGEs are developed in support of a request for proposal (RFP). The IGE includes all of the activities listed in the scope of the RFP and are comprehensive enough to compare against incoming responses from industry. The same basic steps are followed as the LCCE in order to generate a credible and accurate IGE.

For an EAC to be credible, comprehensive, and accurate, the monthly Contractor Performance Reports (CPRs) need to be current and accurate.

2. Develop estimating plan

Once the purpose is established, the estimator must determine the cost estimating team and develop a master schedule. The cost estimating team consists of a balanced skill set and with estimating assignments based on the individual’s areas of strength. Formulating a task matrix covering all phases of the estimate, WBS elements, and the estimators assigned to each is highly recommended. This detailed tracking will ensure comprehensiveness and accuracy of the task. The master schedule should be comprehensive enough and contain sufficient detail so that the lead estimator can track and report the cost estimate’s progress. Updates of the schedule should be presented to leadership (GAO, 2009).

For the MDA, the Office of the Secretary of Defense’s Cost Analysis and Program Evaluation (OSD CAPE) office performs ICEs for its programs. The MDA Director submits an annual memorandum to the CAPE requesting ICEs for particular programs, in order to help support production decision milestones. The OSD CAPE selects the MDA programs for which they will conduct ICEs based on their resources. MDA/DOC and programs for which the ICE is being conducted engage with the CAPE and provide information and answers to questions about the program office estimates. At the completion of the ICE, the CAPE presents this information to the MDA/D or the MDA/DO. The OSD CAPE is the only entity within OSD that performs ICEs.

MDA leads the development of Joint Service Cost Positions with the Army and Navy on several programs, Since MDA is a research and development organization, most of its systems are fielded by one of the DoD Services, i.e., Army, Navy, or Air Force. To obtain Operations and Sustainment costs of those systems operated by one of the Services, MDA works with the applicable Service to conduct Joint Cost Estimates (JCEs). For example, the SBX is operated by the Navy, and a jointly developed cost estimate was developed and is updated on a regular basis.

3. Define Program Characteristics

The final accuracy of the cost estimate depends on how well the program is defined. The key to developing a credible estimate is having an adequate understanding of the acquisition program - the acquisition strategy, technical definition, characteristics, system design features, and technologies to be included in its design. This information is used to identify the technical and program parameters that drive the cost estimate. The amount of information gathered directly affects the overall quality and flexibility of the estimate. Less information means more assumptions must be made, therefore increasing the risk that the estimate will not be accurate. The objective of the technical baseline is to provide a common definition of the program - including a detailed technical, program, and schedule description of the system - from which all LCCEs will be derived. This includes both program and Independent Cost Estimates (ICEs).

At times the information in the technical baseline will facilitate the use of a particular estimating approach. However, the technical baseline should be flexible enough to accommodate a variety of estimating methodologies. It is critical that the technical baseline contain no cost data, so it can be used as the common baseline for ICEs. In addition to providing a comprehensive program description, the technical baseline is used to benchmark life-cycle costs and identify specific technical and programmatic risks. The technical baseline aids the estimator in focusing on areas or issues which might have a major cost effect. The program characteristics should include any technology implications and its relationship to other existing systems, including predecessor or similar legacy systems. Other information includes support (manpower, training, etc.), security needs and risk items, system quantities for development, test, and production, and deployment and maintenance plans. For a more complete listing of the typical technical baseline elements, see the GAO Cost Estimating and Assessment Guide (GAO 2009, pages 58-59). All of the elements of a baseline are required to ensure the estimate is comprehensive, credible, and accurate.

4. Determine Estimating Structure

The fourth step is to define a Work Breakdown Structure (WBS) and describe each element in a WBS dictionary. The MDA has several reference WBS structures to assist with defining a WBS. The BMDS follows the DoD Series 5000 regulations, but MDA programs within MDA do not. This means that MDA does not currently adhere to MIL STD 881C. There are several unique characteristics about MDA programs that are not fully addressed by MIL STD 881 C, such as kill vehicles. MDA is working with the Defense Cost and Research Center to adapt kill vehicles and other MDA hardware systems into 881C.

All cost estimating WBSs are approved by the DOC Director, prior to implementation. When required, the WBS is tailored for specific program use. The estimator will also choose the best estimating method for each WBS element and identify potential cross-checks for likely cost and schedule drivers.

5. Identify Ground Rules and Assumptions

Identifying ground rules and assumptions is another major key to a comprehensive, credible and accurate cost estimate. Ground Rules and Assumptions incorporate:

- What the estimate includes and excludes;
- Global and program-specific assumptions
  - Estimate's base year
  - Time-phasing
  - Life cycle, etc.;
- Program schedule information by phase;
- Program acquisition strategy;
- Schedule and budget constraints;
- Inflation assumptions;
- Travel costs;
- Specification of equipment the government is to furnish;
- Use of existing facilities or new modification or development;
- Prime contractor and major subcontractors;
- Technology refresh cycles, technology assumptions, and new technology to be developed;
- Commonality with legacy systems and assumed heritage savings;
- Anticipated effects of new ways of doing business, etc.;
- Systems test hardware and the number of production units; and
- Interdependencies with other programs.

Ground rules and assumptions may vary by WBS. Documentation requirements for ground rules and assumptions are covered in Step 10, below. Every aspect of how the data was collected, analyzed, referenced, or altered is addressed. An estimate's weakest support is usually found in the documentation of its ground rules and assumptions.

Program office buy-in on ground rules and assumptions is critical. Ensure all functional organizations are on-board with ground rules and assumptions including: systems engineering, test, logistics, production/deployment, construction, scheduler, program management, and finance. Having comprehensive approval for the ground rules and assumptions plays a crucial role in the estimate's credibility. Managers or executives may disagree with the results, which are based upon the collective inputs and assumptions provided to the cost estimator by the functional organizations

6. Obtain Data

The sixth step is to create a data collection plan, identify the best possible sources for the data, and collect the relevant technical, programmatic, cost, and risk data. The data collection plan can be both broad and specific depending on the WBS element being estimated, as long as the list is complete and addresses all the data needed to perform a credible cost estimate. Once the data are collected and normalized for cost accounting, inflation, learning, and quantity adjustments, another analyst may double check analyses and results to ensure the estimate is comprehensive. The estimator must analyze the data for cost drivers, trends, and outliers and compare results against rules of thumb and standard factors derived from historical data. Where applicable, Subject Matter Expert (SME) data sources are interviewed and all pertinent information documented including an assessment of data reliability and accuracy. It is good practice to use more than one SME. There should be an interview sheet with questions and responses, along with the SME's degree, background, experience, current position, and any other relevant experience qualify this point of contact as an SME. Additionally, uncertainty analysis must be captured and sensitivity analysis performed on the SME's input to the cost estimate. This comprehensive process adds to the analyst's and the cost estimate's credibility.

7. Develop Point Estimate

If the previous six steps are followed, the point estimate will be as accurate as possible. Each WBS element will have been estimated using the best methodology from the data collected, including all estimating assumptions.

The point estimate is expressed in Constant Year (CY) dollars and time-phased in the years they are expected to occur, based on the program schedule. The WBS elements should sum to a total cost to develop, produce, support, and dispose of the program or system being estimated. One of the key elements in this step is to validate the estimate by checking for errors (i.e., double counting or cost omission) using the cross-check matrix for the WBS. If OSD CAPE has conducted an ICE, compare the estimate against the ICE and examine where and why there are differences. Update the model as more data become available or as changes occur and compare results against previous estimates. Keeping the estimate current makes it as accurate as possible given all updated available data.

8. Conduct Sensitivity Analysis

Step 8 covers sensitivity of cost elements to changes to estimating input values and key assumptions and, determines which assumptions are key cost drivers and which cost elements are affected most by changes. This step increases the credibility of the cost estimate. It is commonly used during "what-if" drills and budget exercises. The most common sensitivity analysis performed is the analysis of the effect resulting from changing the program schedule or quantities. The sensitivity analysis is completed prior to submitting the estimate to a cost lead, Division Chief, etc., and is included in the cost reviews for approval. More detailed information is presented in Chapter 7, Sensitivity Analysis.

9. Conduct Risk and Uncertainty Analysis

A budget should be based upon the cost estimate since it is the most accurate representation of the requirements of the program over a certain time period. Program managers should use the cost estimate with risk, and budget at a confidence level greater than or equal to 50%. Cost analysts document which estimate was presented to leadership for the budget, and document the confidence level of the estimates that are used for budget submissions. More detailed information is presented in the Chapter 8, Cost Risk and Uncertainty.

10. Document the Estimate

Inadequate documentation is the biggest problem with most cost estimates. Cost analysts must document as much detail as possible:

- Purpose of the estimate;
- Team that prepared it;
- Who approved the estimate and on what date;
- Description of the program;
- Program schedule;
- Technical baseline used to create the estimate;
- Time-phased life-cycle cost;
- Ground Rules and Assumptions;
- Auditable and traceable data sources for each cost element and document for all data sources;
- How data were normalized;
- Estimating methodology and rationale used to derive each WBS element's cost a description of the results of the risk, uncertainty, and sensitivity analyses; and
- Documentation of how the estimate compares to the funding profile, how this estimate compares to previous estimates.

Note that these requirements are consistent with the GAO recommendations described above on pages 34 and 35. Documentation is scrutinized by the DOC leadership during all cost reviews. Comprehensive and credible estimates may be replicated. A comprehensive documentation package is the key to its replication.

11. Present Estimate to Management for Approval

Following documentation completion, the analyst develops a briefing to present the life-cycle cost estimate. MDA has a specific format for this presentation and DOC has a comprehensive approval process. Within each of the Programs, a Cost Lead is responsible for all cost estimating activities and reports directly to the Program Manager or Program Director. All estimates within the program must first be approved by the Cost Lead. After the Cost Lead approves the estimate, both the Division Chief and the Technical Director review and approve the estimate. The formats for these reviews are discussed in detail in the Chapter 2, Documentation. The estimate is then presented to the DOC Director for final approval. Upon final approval, the PM or PD is briefed on the material. The cost lead resolves any issues or concerns, and may alter the estimate based upon clarification of the requirements by the program office functional personnel. Any changes to the estimate from the Program Office are validated by the DOC. This follow-up review can be fast-tracked. This multi-tier review and approval process is one of the most comprehensive processes within the MDA.

12. Update the Estimate to Reflect Actual Costs and Changes

Once the cost estimates are approved, they are continually maintained and updated to incorporate changes to technical or program assumptions; or to actual data as the program passes through new phases or milestones. Cost estimates are reviewed by MDA leadership prior to submission of the BAR to Congress and prior to quarterly BERs. The purpose for each BAR is to provide Congress information regarding the status of MDA's progress toward implementing a BMDS.

Many Service programs submit progress reports to Congress, called Selected Acquisition Reports (SARs). MDA also submits a SAR annually, but the scope of the MDA's SAR submission is for the entire BMDS program. For Congress to have insight into the larger efforts within the BMDS, MDA also submits annual BARs for major BMDS subsystems (e.g., THAAD weapon system). BAR submissions are planned each year for the February time frame. A comprehensive program cost estimate review is required by MDA cost estimating leadership for each program for which a BAR submission is required. This cost estimate review typically occurs a minimum of 90-120 days prior to the BAR submission. MDA currently schedules quarterly BERs to manage its programs. These quarterly updates provide real-time changes to the cost estimates as scope, schedules, and quantities are always in the trade-space to balance the resources within the Agency.

As the cost estimate changes, the cost review process is conducted. DOC has specific formats for the quarterly BER cost reviews. For more information on the BER reviews see the Chapter 2, Documentation. MDA continually update its estimates to reflect programmatic changes so that the estimates maintain the highest level of accuracy possible.

By following the 12 steps to a high quality estimate, and after completing the cost estimate approval process, MDA's estimates are comprehensive, credible, and accurate.

CHAPTER 4
GROUND RULES AND ASSUMPTIONS

Ground rules and assumptions specify the scope of the estimate and the conditions under which the estimate may be considered credible. Ground rules and assumptions restrict the scope of the cost estimate to a manageable and workable set of conditions. While it is important to include enough ground rules and assumptions, a balance must be maintained since if many scope limitations may generate an estimate of limited utility. Select Ground rules that are practical and applicable so that the estimate produces meaningful results. Ground rules and assumptions are related but have distinct roles, so they are defined separately.

Ground rules are concise statements that describe the basis from which the estimate is made. “This estimate includes functions a, b, and c only; no costs associated with travel are included” is an example of a ground rule (Galorath, 2008). Ground rules represent a common set of agreed-to estimating standards that provide guidance and that minimize definition conflicts.. When conditions are directed, they become the ground rules by which the team will conduct the estimate. The technical baseline requirements represent cost estimate ground rules. Therefore, a comprehensive technical baseline provides the analyst with all the necessary ground rules for conducting the estimate (GAO, 2009).

Assumptions are suppositions that describe known variables which may affect an estimate. “This estimate assumes the software developer will use development system X” is an example of an assumption. When it is confirmed that “development system X” will be employed, this proven assumption is restated as a ground rule. More information is available in the article “Step Two: Establish Technical Baseline, Ground Rules, and Assumptions” by Dan Galorath, Oct 2008 (Galorath 2008)

Assumptions represent a set of judgments about past, present, or future conditions postulated as true in the absence of positive proof. Cost estimators must brief management and document all Assumptions, so management can fully understand the conditions on which the estimate was structured. Failure to do so may lead to overly optimistic assumptions that heavily influence the overall cost estimate, to cost overruns, and to inaccurate estimates and budgets (GAO, 2009). Cost estimators make only those assumptions necessary to develop a cost estimate, and should not use assumptions too liberally to avoid limiting scope unnecessarily.

Cost estimates are typically based on limited information and therefore need to be bound by the constraints that make estimating possible. These constraints usually take the form of assumptions to focus the estimate’s scope, establishing baseline conditions from which the estimate will be built. Since there are many unknowns, cost analysts create a series of statements made in the form of ground rules and assumptions that define the conditions on which the estimate is to be based (GAO, 2009). The ground rules and assumptions are a critical step in any estimate and are be clearly prominent in all documentation and presentation material that the estimator prepares. A comprehensive list of the ground rules and assumptions is a major element of a cost estimate. Ground rules and assumptions are important to define the program clearly and for estimators to be able to understand what costs are being included and excluded for the current estimate and future comparisons. By spending time developing and socializing accurate ground rules and assumptions, problems can be avoided that may cause an inaccurate or misleading estimate (NASA Cost Estimating Handbook, 2002).

In the early stages of the cost estimate, ground rules and assumptions are preliminary and highly uncertain. Ground rules and assumptions, as the foundation of the cost estimate, must be credible and well-documented, and all assumptions should be reviewed and redefined regularly as the cost estimate progresses through the life-cycle phases. As the program moves from the Material Solution Analysis (MSA) phase through the Operations and Support (O&S) or the Disposal phase, the ground rules and assumptions that accompany life cycle cost estimates change drastically.

By reviewing the technical baseline and discussing the ground rules and assumptions with customers early in the cost estimating process, analysts can flush out any potential misunderstandings. Ground rules and assumptions help to:

- Satisfy requirements for key program decision points;
- Answer detailed and probing questions from oversight groups;
- Make the estimate complete and professional;
- Present a convincing picture to people who might be skeptical;
- Provide useful estimating data and techniques to other cost estimators;
- Provide for reconstruction of the estimate when the original estimators are no longer available;
- Provide a basis for the cost estimate that documents areas of potential risk that can eventually be resolved.

Ground rules and assumptions are either global or element-specific. Global ground rules and assumptions apply to the entire estimate; element-specific ground rules and assumptions are driven by each WBS element's detailed requirements. Ground rules and assumptions are more pronounced for estimates in the development phase, where there are more unknowns. They become less prominent as the program moves through development into production. While each program has a unique set of ground rules and assumptions, there are some general ground rules and assumptions that every estimate should address.

Each estimate should at a minimum define the following global ground rules and assumptions:

- Program schedule;
- Cost limitations (e.g., unstable funding stream or staff constraints);
- High-level time phasing;
- Base year;
- Labor rates;
- Inflation indexes;
- Participating agency support; and
- Government Furnished Equipment (GFE).

Defining a realistic schedule is of critical importance. It may be difficult to perform an in-depth schedule assessment early to uncover the frequent optimism in initial program schedules.

Ideally, members from manufacturing and the technical community are involved in developing the program schedule, but often information is insufficient and assumptions must be made. It is important the assumptions note the confidence the team has in its ability to achieve the schedule so it can be documented and presented to management.

Sometimes, management imposes cost limitations because of budget constraints. In such cases the ground rules and assumptions must clearly explain these limitations and how they affect the estimate. Usually, cost limitations are handled by delaying program content or by a funding shortfall if program content cannot be delayed. In many cases, such actions will both delay the program and increase its final delivered cost. Management needs to be fully apprised of how funding limitations affect the estimate.

Other aspects of the estimate need to be clearly documented in the ground rules and assumptions. In particular:

- Peaks and valleys in time-phased budgets must be explained;
- Inflation index, source, and approval authority must be identified;
- Dependence on participating agencies, interdependencies with other BMDS programs, the availability of government furnished equipment, and the effects if these assumptions do not hold must be identified;
- Items excluded from the estimate must be documented and explained; and
- Technology should be mature before it was included - if its maturity was assumed, the estimate must address the effect of the assumption's failure on cost and schedule.

Estimates are time-phased because program costs usually span many years. Time phasing spreads a program's expected costs over the years in which they are anticipated to aid in developing a proper budget. There are numerous time-phasing methodologies available. Depending on the activities included in the schedule for each year, some years may have more costs than others.

Depending on the type of funding, the cost analyst must explain incremental (RDT&E) vice full-funding (Procurement). Great peaks or valleys in annual funding are be investigated and explained since staffing is difficult to manage with major variations from one year to another. Unusual peaks and valleys from year-to-year are easily discovered when the estimate is time-phased. Cost limitations may also affect an estimate's time phasing if there are budget constraints for a given fiscal year. Additionally, changes in program priorities will affect funding and timing. These conditions are addressed by the estimate and their effects adequately explained.

The Base Year (BY) is used as a constant dollar reference point to track program cost growth. MDA follows the OSD inflation guidance. Expressing an estimate in BY dollars removes the effects of economic inflation and allows for comparing separate estimates "apples to apples." Thus, a global ground rule is to define the BY dollars that the estimate will be presented in and the inflation index that will be used to convert the base year costs into then-year dollars that include inflation. At a minimum, the inflation index, source, and approval authority are clearly explained in the estimate documentation. Escalation rates are standardized across similar programs, since they are all conducted in the same economic environment. Priority choices between them should not hinge on different assumptions about what is essentially an economic scenario common to all programs.

Some programs result from two or more agencies joining together to achieve common program goals. For example, the SBX O&S cost estimate is a *joint* cost estimate performed with the Navy. When this happens, agreements specify each agency's area of responsibility. An agency's failing to meet its responsibility could affect the program's cost and schedule. In the ground rules and assumptions section, these conditions are highlighted to ensure that management is firmly aware that the success of the estimate depends on the participation of other agencies.

Equipment the government agrees to provide to a contractor can range from common supply items to complex electronic components to newly developed engines for aircraft. Because the estimator cannot predict whether deliveries of such equipment will be timely, assumptions are usually made that it will be available when needed. It is important that the estimate reflect the government-furnished items it assumes, so that the risk to the estimate if items are delayed can be modeled and presented to management. In general, schedules represent delivery of material from external sources, including the government, with date-constrained milestones. A better approach is to include the supplier's work to produce the product by a summary activity in the schedule, examine the possibility of delayed delivery, include that risk in a schedule risk analysis, and monitor the work of the supplier as the date approaches. For example, the MDA Targets and Countermeasures program uses excess solid rocket motors as the propulsion system stages for targets used in flight tests.

In addition to global ground rules and assumptions, estimate-specific ground rules and assumptions are tailored for each program, including

- Life-cycle phases and operations concept;
- Maintenance concepts;
- Acquisition strategy, including competition, single or dual sourcing, and contract or incentive type;
- Industrial base viability;
- Quantities for development, production, and spare and repair parts;
- Use of existing facilities, including any modifications or new construction;
- Savings for new ways of doing business;
- Commonality or design inheritance assumptions;
- Technology assumptions and new technology to be developed;
- Technology refresh cycles;
- Security considerations that may affect cost; and
- Items specifically excluded from the estimate.

The cost estimator must work with members from the technical community to tailor these specific ground rules and assumptions to the program. Information from the technical baseline and WBS dictionary help determine some of these ground rules and assumptions, like quantities and technology. The element-specific ground rules and assumptions carry the most risk and therefore are checked for realism and well-documented to insure a credible estimate result.

Examples of Global Ground Rules include:

- Estimate will be in BY12$M
- FY12 OSD inflation indices are used to calculate inflation

An example of a Global Assumption includes:

- There will be replenishment of assets to ensure 20-year system operational life
- Satellite design life is 5 years

Examples of Phase-Specific Ground Rules include:

- Initial Operation Capability (IOC) date is Sept 9, 2011 (X% of total fleet or the first asset delivered)
- Full Operation Capability (FOC) date is Sept 9, 2015 (i.e., quantity requirement can be defined by Modeling & Simulation for footprint coverage)
- O&S period is from IOC though 2030
- No Pre-Planned Product Improvement Programs (P3I) will be included

An example of an Element-Specific Ground Rule is:

- Contractor Logistic Support (CLS) will be used rather than Organic Depot Maintenance

The MDA/DOC Scorecard (detailed in Chapter 1) is used to grade all cost estimates performed by MDA/DOC personnel.

All ground rules and assumptions are:

- Developed by estimators with input from the technical community;
- Based on information in the technical baseline and WBS dictionary;
- Vetted and approved by upper management;
- Documented to include the rationale behind the assumptions and historical data to back up any claims; and
- Accompanied by a level of risk of each assumption's failing and its effect on the estimate.

Risk is discussed in detail in Chapter 8, however an overview as it pertains to ground rules and assumptions is provided here. There are numerous types and sources of risk (program, technical, schedule, cost, funding, etc). Risk is an integral part of all cost estimates and every cost estimate addresses cost risk and uncertainty. Cost risk analysis is intended to provide decision makers with information to help them successfully manage projects and mitigate risk.

To provide program management the information they need to mitigate risk:

- All ground rules and assumptions are placed in a single spreadsheet tab so that risk and sensitivity analysis may be performed quickly and efficiently.
- All potential risks including cost, schedule, technical, and programmatic (e.g., risks associated with budget and funding, start up activities, staffing, and organizational issues) are identified and traced to specific WBS elements.
  - A schedule risk analysis is performed to determine the program schedule's realism.
  - A cost risk analysis, incorporating the results of the schedule risk analysis, is performed to determine the program's cost estimate realism.

Cost estimators meet with technical staff to obtain the information to determine risk distributions; the distributions should be used in sensitivity and uncertainty analyses of the effects of invalid assumptions. Management is then briefed, and the results documented.

CHAPTER 5
DATA

Data are the foundation of every estimate and are what drive cost estimates. It is critical to the cost estimator/analyst to understand the importance of data, types of data, considerations when using data, the data collection process, sources of data, and data normalization.

Importance of Data

The quality of data is critical to the estimate's credibility. Poor data lead to poor estimates, as encapsulated in the maxim "garbage in, garbage out." The best documentation, methodology, risk analysis, etc., are futile efforts without a basis in sound, applicable well-documented data. Depending on the quality, an estimate can range anywhere from a mere guess to a highly defensible cost position.

Data provide information on cost trends over a variety of related programs; insight into cost structures; and the information used to develop Cost Estimating Relationships (CERs), parametric estimates, and models. The paradigm that "what has happened in the past repeats itself" and that "the future will resemble the past" are the basis for all cost estimating. Past historical data is the only means for deriving future estimates.

Data are often viewed as the lowest level of abstraction from which information and knowledge are derived. It is common to see the relationship between data and information represented as a pyramid (Figure 5.1) with data as the base rising through ground rules, assumptions, and analysis to the cost estimate at the apex.

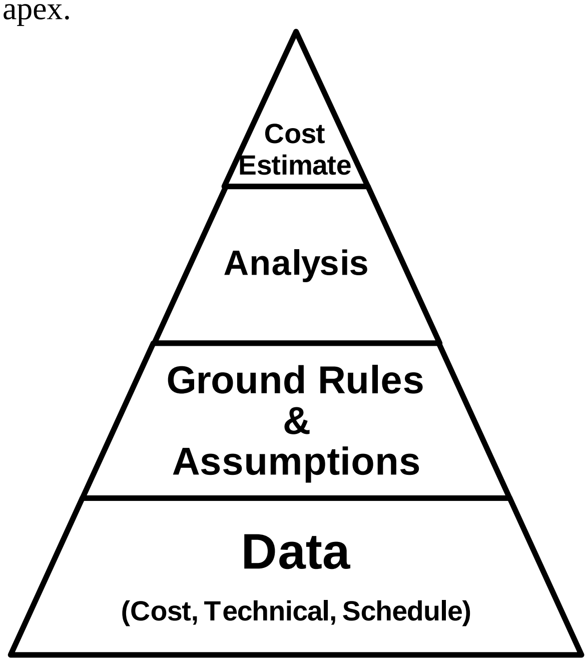

Figure 5.1. Data Relationship Pyramid

Cost, Technical, and Programmatic Data

Cost data represent costs ($) and/or hours (labor) associated with activities or materials.

Technical and programmatic data provide the basis for and drive cost. Program and technical data provide a context for cost data, since without this the cost data may be meaningless. It is essential that cost estimators gain access to cost, technical, and programmatic information in order to develop a complete understanding of what the data represent. Without this understanding a cost estimator may not be able to correctly interpret the data, leading to greater risk that the data may be misapplied. It is critical that a cost estimate be consistent with technical and programmatic data.

Technical characteristics define the systems and allow for comparisons. Technical data define the requirements for the equipment being estimated, which include physical and performance attributes such as length, width, weight, horsepower, and size. When technical data are collected, care must be taken to relate the types of technologies and development or production methodologies to be used. These changes over time and require adjustments when estimating relationships are being developed. Technical data also include operational parameters like crew size and composition.

Programmatic data include: schedule; the structure of the value chain for a program; contract types; and the acquisition environment, among others. Schedule data provide parameters that directly affect cost. Examples include lead-time start and duration of effort; delivery dates; outfitting; testing; initial operational capability dates; operating profiles; contract type; multiyear procurement; and sole source or competitive awards.

When collecting data, the analyst identifies sources and includes documented information that provides traceability. This is necessary so that the analyst can match specific technical and programmatic data with the associated cost data. If audited, the auditor should be able to trace back to the analyst's source data.

Primary and Secondary Data

Primary data are those data that are obtained from the original source, that can be traced to an audited document. Secondary data are those which are derived rather than obtained directly from a primary source.

Since secondary data are at least one step removed from a primary data source, the cost estimator must understand how the data were normalized, what the data represent, how old they are, and whether they are complete. Secondary data have some advantages in that extensive normalization may have already been applied, saving the analyst several steps. For example, databases of cost are often normalized for inflation; have been aggregated to subsystem and system levels; and have been segregated into nonrecurring and recurring categories. An analyst using such a database will not have to re-do these steps from the same primary data. The analyst ensures that these secondary sources of data are normalized consistently and are consistent. For example, secondary data from different databases that employ different normalization processes should not be combined.

Sources of historical data include:

- Business plans;
- Catalog prices;
- Contract performance reports;
- Contract funds status reports;
- Cost and software data reports;
- Forward pricing rate agreements;
- Historical cost databases;
- Market research;
- Program budget and accounting data from prior programs;
- Supplier cost information;
- Historical or current vendor quotes; and
- Weight/mass reports.

In the operations and support area, common data sources include:

- DoD's Visibility and Management of Operating and Support Costs (VAMOSC) (*ftp.rta.nato.int/public//PubFullText/RTO/MP/RTO-MP...///MP-096-08.pdf)*;
- Defense Acquisition Management Information Retrieval (DAMIR) (www.acq.osd.mil/damir/);
- Defense Acquisition Automated Cost Information System (DACIMS) (http://dcarc.pae.osd.mil/Dacims/Index.aspx);
- DCARC (http://dcarc.pae.osd.mil/); and
- Naval Center for Cost Analysis (NCCA) (www.ncca.navy.mil/).

Cost estimators collect actual cost data from a list of similar and legacy programs. Since most new programs are improvements over existing ones, data is available that share common characteristics with the new program.

Historical data provide insight into actual costs on similar programs, including any cost growth that has occurred since the original estimate. As a result historical data can be used to challenge optimistic assumptions. For example a review of the average labor rates for similar tasks on other programs is a powerful reality check against assumptions of skill mixes and overall effort. In addition historical data from a variety of contractors can be used to establish generic program costs or cost trends of a specific contractor across a variety of programs.

Historical data also provide contractor cost trends relative to proposal values, allowing the cost estimator to establish adjustment factors if relying on proposal data for estimating purposes. Additionally insights are obtained on cost accounting structures to allow an understanding of how a certain contractor charges things like other direct costs and overhead.

However, historical cost data also contain information about past technologies, so it is essential that appropriate adjustments are made to account for differences between the new system and the existing system such as the type of technology used in the design, design methodologies (for example, newer data points were designed with Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) tools, while older data may have been designed using engineering draft tools by hand), manufacturing processes (automation versus hands-on labor), and types of material used. Statistical methods, like regression, that analyze cost against time and performance characteristics can reveal the appropriate technology-based adjustment. The productivity effect on cost data over time is significant and should be taken into consideration when collecting historical data.

Cost Performance Reports (CPRs) and cost and software data reports (CSDRs) are excellent sources of historical cost data for Department of Defense programs. The CPR is the primary report of cost and schedule progress on contracts containing Earned Value Management (EVM) compliance requirements. It contains the time-phased budget, the actual cost, and earned value, which is the budgeted value of completed work. By reviewing CPR data, the cost analyst gains valuable insights into performance issues relevant to future procurements. For instance, CPR data can provide information about changes to the Estimate At Completion (EAC) (or total expected cost of the program) and the performance measurement baseline. It also it explains the reason for any variances. Before beginning any analysis of such reports, the analyst performs a cursory assessment to ensure that the contractor has prepared them properly. The several ways for analyzing cost data reports all use three basic elements in various combinations:

1. Budgeted cost for work scheduled (BCWS), or the amount of budget allocated to complete a specific amount of work at a particular time;
2. Budgeted cost for work performed (BCWP), also known as earned value, which represents budgeted value of work accomplished; and
3. Actual cost of work performed (ACWP), or actual costs incurred for work accomplished.

Contract cost data reports are often used in estimating analogous programs. Examples of contract data include:

- Contract WBS DI-MGMT-81334;
- CPR, DI-MGMT-81466;
- Contractor Cost Data Reporting (CCDR) DI-FINCL-81565A (DD Form 1921 series);
- Contract Funds Status Report (CFSR), DI-MGMT-81468;
- Integrated Master Plan (IMP);
- Integrated Master Schedule (IMS), DI-MGMT-81650;
- Integrated Logistics Support Plan (ILSP), DI-ILSS-80095 or Integrated Support Plan (ISP) as appropriate; and
- Software Resources Data Report (SRDR) (DD Form 2630-2 and 2630-3).

It is reasonable to expect similar programs at similar contractors' plants to incur similar costs. This analogy may not apply for the costs of hardware or software but may apply to the peripheral WBS areas of data, program management, or systems engineering. If the analyst can then establish costs for the major deliverables, such as hardware or software, a factor may be applied for each peripheral area of the WBS, based on historical data available from cost reports. Sometimes, the data listed in the WBS include elements that the analyst may not be using in the present estimate - spares, training, and support equipment. In such cases, these elements are removed before the data are analyzed.

Rate and factor agreements are negotiated between the contractor and the appropriate government negotiator. Because the contractor's business base may be fluid, with direct effect on these rates and factors, such agreements do not always exist. The agreements represent negotiated rates for direct labor, overhead, general and administrative data, and facilities capital cost of money. These agreements may cover a myriad of factors, depending on each contractor's accounting and cost estimating structure. Factors include material scrap, material handling, quality control, sustaining tooling, and miscellaneous engineering support factors.

The scope of the estimate often dictates the need to consult with other organizations for raw data. For example, after government test facilities have been identified, those organizations are contacted for current cost data, support cost data, and the like. Other government agencies, including the Defense Contract Audit Agency and the Defense Contract Management Agency, are involved with the development of similar programs may be potential sources of data. Additionally, a number of government agencies and industry trade associations publish cost data useful for cost estimating.

Another area for potential cost data are contractor proposals. However, a contractor proposal is a document that represents the contractor's best estimate of cost. Proposals also tend to be influenced by the amount of money the customer has to spend. In a competitive environment, proposal data are often optimistic, to help win the work, by providing an appearance of best value. As a result, ***proposal data are always suspect***. Negotiated prices do not necessarily equate to less optimistic cost estimates on cost plus contracts. Proposal data should never be used as the basis of a credible estimate. Data from a proposal, such as labor rates, and proposed hours, may be used if sufficiently supported.

When using proposal data the cost analyst must consider the limitations of cost data before using them in an estimate. Historical cost data have two predominant limitations: the data represent contractor marketplace circumstances that must be known if they are to have future value, and cost data eventually become outdated.

The first limitation is routinely handled by recording these circumstances as part of the data collection task. To accommodate the second limitation, the cost estimator can either adjust the data (if applicable) or decide to collect new data. In addition, the contract type to be used in a future procurement - for example, firm fixed-price, fixed-price incentive, or cost plus award fee - may differ from that of the historical cost data. Although this does not preclude using the data, the analyst must be aware of such conditions, so that an informed data selection decision can be made. A cost analyst addresses data limitations by ensuring that the most recent data are collected, by evaluating cost and performance data together to identify correlation, ensuring a thorough knowledge of the data's background, and by holding discussions with the data provider.

Because of the potential for bias in proposal data the estimator tests the data to see whether they deviate from other similar data before deciding whether they are useful for estimating. This can be done through a plant visit, where the cost estimator visits the contractor to discuss the basis for the proposal data. As with any potential source of data, it is critical to ensure that the data apply to the estimating task and are valid for use.

During source selection in a competitive environment, for instance, lower proposed costs may increase the chances of receiving a contract award, it is very important to analyze the cost data for realism. A proposal can nonetheless provide much useful information and should be reviewed for the following:

- Structure and content of the contractor's WBS
- Contractor's actual cost history on the same or other programs
- Negotiated bills of material
- Subcontracted items
- Government-furnished equipment compared to contractor-furnished equipment lists
- Contractor rate and factor data, based on geography and makeup of workforce
- A self-check to ensure that all pertinent cost elements are included
- Top-level test of reasonableness
- Technological state-of-the-art assumptions
- Estimates of management reserve and level of risk

Because cost estimates are usually developed with data from past programs, it is important to examine whether the historical data apply to the program being estimated. Over time, modifications may have changed the historical program so that it is no longer similar to the new program. For example, data from an information system that relied on old mainframe technology would not apply to a new program will rely on server technology that processes data at much higher speeds. Having good descriptive requirements of the data is imperative to determine whether the data available apply to what is being estimated.

To determine the applicability of data to a given estimating task, the analyst determines whether or not the data require normalization to account for differences in base years, inflation rates (contractor compared to government), or calendar year rather than fiscal year accounting systems. The analyst decides if the work content of the current cost element is consistent with the historical cost. Also, the data is scrutinized for performance variation over time, such as advances in technologies. Trends of cost and performance over time are examined. Also, the type of data is considered. If the data reflect actual costs, proposal values, or negotiated contracts, then the suitability of the data and its use in estimating is quite varied. Actual costs reflect history and are considered the most reliable for future estimating, since there is no inherent optimism. Next in the hierarchy are contract values. A firm fixed price contract is much more likely to be realized than a cost plus contract. Cost plus contract can have as much optimism as proposals, and should not be used in forward estimating, with a few exceptions.

The exceptions are that negotiated cost plus contracts and proposals often contain data, such as contractor labor rates that can be used as input into a credible cost estimate.

Quantitative and Qualitative Data

Quantitative, or numerical data is preferable because of its objectivity. Quantitative data is ordinal, interval, ratio, or cardinal. Ordinal data represents rank order of the data; for example, 1^{st}, 2^{nd}, 3^{rd}, etc. The only valid comparisons that can be made are greater than or less than in magnitude or scope. Interval data is scaled, such as the year, so that from 1995 to 2005 is twice as long as from 1995 to 2000. Interval data supports relative comparisons more meaningfully that ordinal data, but it can stumble on absolute comparisons. For example, the year 200 is not "twice" the year 1000 in any meaningful way. Ratio data, on the other hand, supports absolute comparisons. However, two million dollars is twice as much as one million dollars, assuming the amounts are in the same base year dollars. Cardinal data are measured in either physical or cost accounting units, such as hours, kilograms, or dollars. Comparisons between and among cardinal numbers is easiest, since all basic arithmetical operations can be applied in a meaningful way.

Qualitative data describe a quality of the program or system, usually in categorical terms called nominal. A program may be labeled as high risk or a system can be described as having a low complexity or a high degree of heritage. Qualitative data may be subjective; however, categorical qualitative data may be objective. Examples include prototype vs. protoflight test approaches.

Data Quality of Cost Types

Actual cost data, or "actuals" for completed programs/contracts are better than Estimates at Completion (EAC) for contracts greater than 90% complete. EACs should improve as the contract nears completion, but one should be careful before accepting the data. Often problematic programs wait until they are beyond the original schedule to re-baseline, so the 90% complete metric is not always a clear benchmark. EACs are better than contract line item prices from Schedule B. Contract line items are not as good as later EACs, because those prices are not what was actually spent. Those prices are generally the EAC at 0% complete. However, contract line item prices from Schedule B are better than historical budget data. Original budget is the lowest quality, because the budget data is not the actual spent cost. Most budget data is at a high level and is not useful at low levels for data collection.

Data Collection Process

The data collection process is a vitally important part of cost estimating, since estimates have no credibility unless they have firm basis in historical data. There are four basic steps:

1. Developing and understanding of the total picture of the estimating task;
2. Establishing a Cost Estimating Structure and boundaries around the estimate;
3. Understanding the estimating techniques to be employed and its associated data collection; and

4. Developing a data collection plan. Successful execution of the plan ensures that the right data are collected efficiently.

Sources of Data

Estimators typically develop estimates for new programs by relying on data from programs that already exist. Collecting valid and useful historical data is a key step to developing a sound cost estimate. This is accomplished by obtaining the most applicable historical data to ensure that the new estimate is as accurate as possible. To find data that already exists, the analyst can access either the current program contract data or a similar program's contract data.

Upon collecting historical data, the analyst ensures that data are applicable. One method is to perform reasonableness checks to see if the results are similar. Performing quality checks takes time and requires access to large quantities of data. This is often the most difficult, time-consuming, and costly activity in cost estimating. Sometimes collecting data can be challenging when there is a poorly defined technical baseline or WBS. This occurs when the contractor has not been required to maintain detailed cost reporting. However, by gathering sufficient data, cost estimators can analyze cost trends on a variety of related programs, which gives insight into cost estimating relationships (CERs) that can be used to develop parametric models.

Knowing the factors that influence a program's cost is essential for capturing the right data. The type of estimate drives the type of data needed. An engineering build up, for example, requires data on applicable labor rates. Parametric estimates require data from similar historical programs. As an example, a missile cost estimating relationship will require historical data on missile programs. A development cost estimate will require development data, and a production estimate will require data about learning, rate effects, and historical production data.

Other examples of data include equivalent source lines of code, number of interfaces for software development, number of square feet for construction, and the quantity of aircraft to be produced. To properly identify cost drivers cost estimators meet with engineers and other technical experts. In addition, by studying historical data, cost estimators determine through statistical analysis the factors that tend to influence overall cost. Obtaining information from schedule analysts can provide valuable knowledge about how much, if any, slack exists in a program's schedule by comparing the program schedule to similar historical programs.

Cost estimates must be based on realistic schedules. Often the cost estimates are in line with the baseline schedule with the early estimates, but they also have to keep in touch with changes in the schedule, since schedule changes can lead to cost changes. Some costs such as labor, quality, supervision, rented space and equipment, and other time-related overheads depend on the duration of the activities they support. These level-of-effort activities are relatively simple to estimate, but require estimators to keep up-to-date with project plans, and understand program execution issues such as burn rates, and require estimators to collect actuals as they become available and roll them into the estimate.

In addition to data for the estimate, backup data is collected for performing cross-checks. This takes time and usually requires travel to meet with technical experts. It is important to plan ahead and schedule the time for these activities. Scheduling insufficient time can affect the estimator's ability to collect and understand the data, which can then result in a less confident cost estimate.

Common issues with data collection include inconsistent data definitions in historical programs compared to the new program. Understanding what is included in historical data is vital to data reliability. For example, are the data skewed because they come from a program that followed an aggressive schedule and therefore instituted second and third shifts to complete the work faster? Or was a new manufacturing process implemented that was supposed to generate savings but resulted in more costs because of initial learning curve problems? Knowing the history behind the data allows for its proper allocation for future estimates.

Another potential issue is data availability. Some agencies may not have any cost databases. Data may be accessible at higher levels but information may not be sufficient to break them down to the lower levels needed to estimate various WBS elements. Data may be incomplete. For instance, they may be available for the cost to build a component, but the cost to integrate the component may be missing. Similarly, if data are in the wrong format, they may be difficult to use. For example, if the data are only in dollars and not hours, they may not be as useful if the labor and overhead rates are not available. When access to data is limited, the analyst may need to coordinate a site visit to the contractor.

Data can be collected in a variety of ways, such as from databases of past projects, engineering build-up estimating analysis, interviews, surveys, data collection instruments, and focus groups. After the estimate is complete, the data needs to be well documented, protected, and stored for future use in retrievable databases. Cost estimating requires a continual influx of current and relevant cost data to remain credible. Cost data is continually supplemented with written vendor quotes, contract data, and actual cost data for each new program. Moreover, cost estimators follow the program acquisition plans, contracting processes, and marketplace conditions, all of which can affect the data. This knowledge provides the basis for credibly using, modifying, or rejecting the data in future cost estimates. Once collected, the data is normalized.

Normalizing and Analyzing Data

Data normalization is a key step to creating a consistent basis for comparison. The purpose of data normalization (or cleansing) is to ensure a given data set is consistent with and comparable to other data used in the estimate. Since data is gathered from a variety of sources, they are often in many different forms and need to be adjusted before being used for comparison analysis or as a basis for projecting future costs. Cost data are adjusted in a process called normalization, stripping out the effect of certain external influences. The objective of data normalization is to improve data consistency, so that comparisons and projections are more valid and other data can be used to increase the number of data points. Data are normalized in several ways.

Cost units are adjusted primarily for inflation. Because the cost of an item has a time value, it is important to know the year in which funds were spent. Costs may also be adjusted for currency conversions. In addition to inflation, the cost estimator needs to understand what the cost represents. For example, does it represent only direct labor or does it include overhead and the contractor’s profit? Finally, cost data have to be converted to equivalent units before being used in a data set. That is, costs expressed in thousands, millions, or billions of dollars must be converted to one format - for example, all costs are expressed in millions of dollars.

Sizing units normalize data to common units - for example, cost per foot, cost per pound, dollars per software line of code. When normalizing data for unit size, it is very important to define exactly what the unit represents: What constitutes a software line of code? Does it include carriage returns or comments? The main point is to clearly define what the sizing metric is so that the data can be converted to a common standard before being used in the estimate.

Key groupings normalize data by similar missions, characteristics, or operating environments by cost type or work content. Products with similar mission applications have similar characteristics and traits, as do products with similar operating environments. For example, space systems exhibit characteristics different from those of submarines, but the Space Shuttle has characteristics distinct from those of a robotic satellite even though they are both space systems. In regard to environmental controls, the requirements for both the Space Shuttle and a submarine are similar, while no analogous system is needed for a robotic satellite. Costs are also grouped by type. For example, costs are broken out between recurring and nonrecurring or fixed and variable costs.

Technology maturity normalizes data according to a program’s life cycle; it also considers learning and rate effects. These effects depend upon a continuous operating production line. The first unit of an end item is expected to cost more than the 1,000th unit, just as a system procured at one unit per year is expected to cost more per unit than the same system procured at 1,000 units per year.

Technology normalization is the process of adjusting cost data for productivity improvements resulting from technological advancements that occur over time. In effect, technology normalization is the recognition that technology continually improves, so a cost estimator makes a subjective attempt to measure the effect of this improvement on historical program costs. For instance, an item developed 10 years ago may have been considered state of the art and the costs would be higher than normal. Today, that item may be available off the shelf and therefore the costs would be considerably less. Therefore, technology normalization is the ability to forecast technology by predicting the timing and degree of change of technological parameters associated with the design, production, and use of devices. Life cycle adjustments to the cost data is very subjective, because it requires identifying the relative state of technology at different points in time.

Using homogeneous groups normalizes for differences between historical and new program WBS elements in order to achieve content consistency. To perform this type of normalization, cost data are gathered that can be formatted to match the desired WBS element definition. This may require adding and deleting certain items to get an apples-to-apples comparison. A properly defined WBS dictionary is necessary to avoid inconsistencies.

After the data are collected and normalized, the data are ready to be analyzed. A preliminary first step in data analysis is to visualize the data. One visualization method is to create a scatter plot shown in Figure 5.2 to obtain a graphical representation of the data. Scatter plotting allows the analyst to quickly determine potential outliers, relationships, and trends. Scatter charts typically treat cost as the dependent variable that is plotted on the y axis, while various independent variables are plotted on the x axis. These independent variables are typically technical, such as weight, lines of code, speed; or operational parameters such as crew size or flying hours. These statistics provide information about the amount of dispersion in the data set, which is important for determining risk.

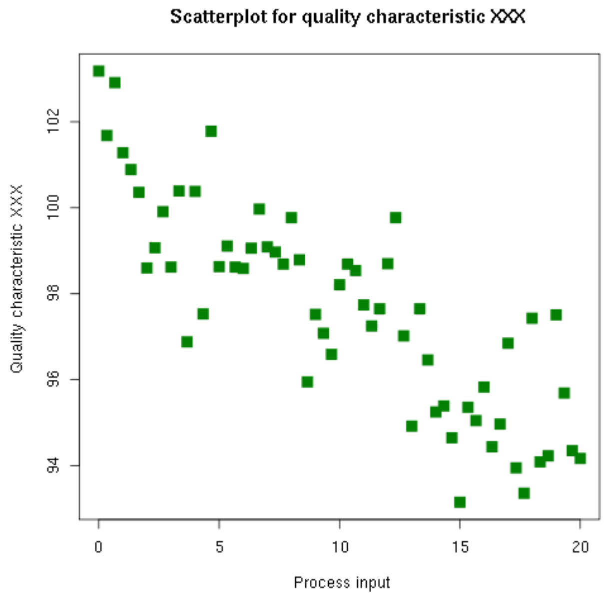

Figure 5.2. Data Scatterplot

The cost estimator first decides which independent variables are most likely to be cost drivers and graphs them separately. The extent to which the points are scattered will determine how likely it is that each independent variable is a cost driver. The less scattered the points are, the more likely it is that the variable is a cost driver. The analyst also uses statistical techniques to distinguish cost drivers, but using scatter charts are an excellent way to perform preliminary filtering to spot potential cost drivers. The correlation between the cost and the independent variables is also calculated, as a visual analysis is often not sufficient to determine statistically significant relationships.

The cost estimator also examines each scatter chart in unit space to determine if a linear relationship exists. If the relationships are not linear the estimator can often perform a transformation to make the data linear. If the data appear to be exponential when plotted in unit space, the analyst plots the natural log of the independent variable on the y axis. If the data appear to represent a power function, the analyst plots the natural log of both the cost and the independent variable. In both cases, the goal is to transform the data appropriately to reveal a linear relationship, because most cost estimating relationships are based on linear regression.

After analyzing the data through a scatter plot, the estimator calculates descriptive statistics to characterize and describe the data groups. Important statistics include sample size, mean, standard deviation, and coefficient of variation. Calculating the mean provides the estimator with the best estimate, because it is the average of the historical data. To determine the dispersion within the data set, the estimator calculates the standard deviation. Finally, the estimator calculates the coefficient of variation so that variances between data sets can be compared. The coefficient of variation is calculated by dividing the standard deviation by the mean. This provides a percentage that can be used to determine which data set has the least variation. After the statistics are derived, visual displays are created to help discern differences among groups. Bar charts, for example, are often useful for comparing averages. Histograms can be used to examine the distribution of different data sets in relation to their frequency.

Many times, estimates are derived by subjective engineering judgment. All engineering judgments are validated before being used in a cost estimate. Judgment validation involves cross-checking the results in addition to analyzing the data and examining the documentation. Graphs and scatter charts can often help validate an engineering judgment, because they can quickly point out any outliers.

An outlier data point is not discarded without first understanding why a data point is outside the expected range. If a data point appears to be an outlier, the technical and programmatic data is analyzed to determine whether or not the data point is consistent with the others, or to determine if there are potential errors in the data. For example, the data may have been skewed due to a strike, a program restructuring, or a natural disaster. However, an outlier should not be removed simply because it appears too high or too low compared to the rest of the data set. It is tempting to remove outliers, because it leads to better statistics and improves the fit. Removing outliers also makes the trend appear stronger than it may actually be. However, such cherry-picking of data undermines the robustness of cost estimating relationships. Carefully pruned data sets lead to cost estimating relationships with little valid foundation in fact. Such cost estimating relationships are not robust. Instead, a cost estimator provides justification documentation for outlier removal. This documentation includes comparisons to historical data that show the outlier is in fact an anomaly. If possible, the documentation describes why the outlier exists. If the historical data show the outlier is just an extreme case, the cost estimator should retain the data point.

Recurring and Non-Recurring Costs

Embedded within cost data are recurring and nonrecurring costs. These are usually estimated separately to keep one-time nonrecurring costs from skewing the costs for recurring production units. For this reason, it is important to segregate cost data into nonrecurring and recurring categories.

Nonrecurring costs are defined as the elements of development and investment costs that generally occur only once in a system's life cycle (SCEA CEBoK 2011). They include all the effort required to develop and qualify an item, such as defining its requirements and its allocation, design, analysis, development, qualification, and verification. Costs for the following are generally Nonrecurring:

- Manufacturing and testing development units, both breadboard and engineering, for

hardware, as well as qualification and life-test units
- Retrofitting and refurbishing development hardware for requalification
- Developing and testing virtually all software before beginning routine system operation
- Nonrecurring integration and test efforts usually end when qualification tests are complete
- Providing services, such as engineering, and some hardware, before and during critical design review
- Developing, acquiring, producing, and checking all tooling, ground handling, software, and support equipment and test equipment

Recurring costs are incurred for each item produced or each service performed (SCEA CEBoK 2011). Costs for the following are generally Recurring:

- Costs associated with producing hardware - that is, manufacturing and testing,
- Providing engineering support for production,
- Spare units or parts,
- Recurring integration and testing,
- Integration and acceptance testing of production units at all WBS levels,
- Refurbishing hardware for operational or spare units,
- Maintaining test equipment, and
- Production support software.

In contrast, maintaining system operational software, although recurring in nature, is often considered part of operating and support costs, which might also have nonrecurring components.

Similar to nonrecurring and recurring costs are fixed and variable costs. Fixed costs are static, regardless of the number of quantities to be produced. An example of a fixed cost is the cost to rent a facility. A variable cost is directly affected by the number of units produced and includes such things as the cost of materials or overtime pay. Knowing what the data represent is important for understanding anomalies that can occur as the result of production unit cuts.

The most important reason for differentiating recurring from nonrecurring costs is learning curve theory. Learning curve theory applies only to recurring costs. Cost improvement or learning is generally associated with repetitive actions or processes, such as those directly tied to producing an item again and again. More clarity is added to the data by categorizing costs affected by the quantity of units produced as either recurring or variable.

Inflation

Every February, the executive branch of the U.S. government submits a budget to the U.S. Congress proposing expenditures and revenues. This submission is called the President's Budget (PB). While the budget outlines expenditures for the next fiscal year, starting October 1, many of the proposed programs cover obligations over several years. This makes it necessary to account for inflation.

Inflation is the change in general price levels over time. The Federal Government spends dollars that are appropriated in a given year, but spent over a period of years, which increases the complexity of inflation calculations.

The Department of Defense deals in large sums of money, frequently spent over several years. Even small factors can result in large adjustments for major programs. In order to compare costs across time, inflation rates are used to convert a cost from its current year into a constant base year (BY) so that the effects of inflation are removed. When cost estimates are stated in BY dollars, the implicit assumption is that the purchasing power of the dollar has remained unchanged over the period of the program being estimated. This requires the transformation of historical or actual cost data into constant dollars. Cost estimates are typically prepared in BY dollars to eliminate the distortion that would otherwise be caused by price-level changes.

Current year dollars are valued in the count of dollars that actually make the transaction. Typically these are dollars spent (outlays) in the given year, but Current Year dollars may also represent Budget Authority (BA) or Total Obligation Authority (TOA) for a given year. Current year dollars are also known as Then Year (TY) dollars.

Constant dollars reflect constant purchasing power independent of the passage of time (constant = BY), and actual dollars are estimates of future (or past) cash flows for year *n* that take into account any anticipated changes in amount caused by inflationary (or deflationary) effects (current = TY = actual).

Individual agencies have established their own policies and procedures. The Office of Management and Budget (OMB) uses data prepared by the Bureau of Labor Statistics and the Bureau of Economic Analysis to forecast future inflation rates. The Office of the Under Secretary of Defense (OUSD), Comptroller, publishes the Department of Defense (DoD) Inflation Guidance each January or February each year. The inflation guidance includes specific inflation guidance for Army, Navy, Air Force, as well as Defense Wide. MDA uses the Defense Wide inflation since its systems cross service boundaries, working on land, in the air and space, as well as at sea,

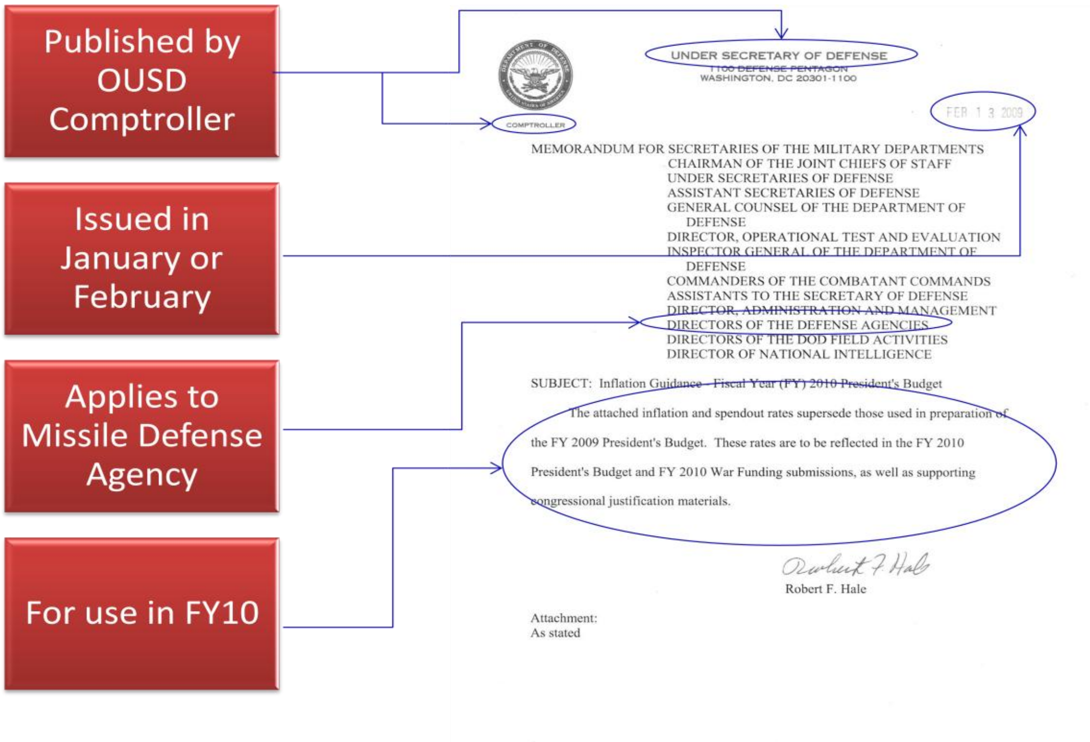

Figure 5.3. Department of Defense Annual Inflation Memorandum for FY2010.

Raw indices are used to change the base year and may also be used for appropriations that do not cover more than one year, such as Military Pay, Civilian Pay, and Fuel. Weighted indices are used for conversions between Then Year and Base Year dollars in appropriations spent down over multiple years, such as Development and Procurement. Table 5.1 delineates when to use raw and when to use weighted indices. Raw indices are used for changing constant dollars in one year to constant dollars in another year. Weighted indices are used for converting between then year dollars and constant year dollars for Total Obligational Authority (TOA) covering multi-year programs.

Raw	Weighted
Constant Year-Constant Year	Then Year-Constant Year
	Then Year-Then Year
	Constant Year-Then Year

Table 5.1: Raw vs. Weighted Indices

When converting between constant and then year dollars, there are four main conversion tasks involving the historical data, each with several variations: 1) converting Constant Year dollars in one year to Then Year dollars in another year; 2) converting Then Year dollars in one year to Constant Year dollars in another year; 3) converting Then Year dollars in one year to Then Year dollars in another year; and 4) converting Constant Year dollars in one year to Constant Year dollars in another year. Raw inflation indices are used for conversions between Constant Year dollars in different years. Weighted indices are used for conversions between Constant Year and

Then Year dollars in either direction, and for conversions between Then Year dollars in one year and Then Year dollars in another year, which is essentially a Then Year to Constant Year conversion coupled with a Constant Year to Then Year conversion.

Constant Year dollars are converted to Then Year dollars to determine the Total Obligational Authority (TOA) needed to cover the costs of a multi-year program due to the effects of inflation. Constant Year dollars are converted to Then Year dollars by multiplying the constant dollar amount by the weighted index of the appropriation in the given year relative to the base year. If the base year is set to 1.000 in the weighted index table, the equation is:

Then Year $ = Constant $ * Weighted Index (TY).

If the base year is not set to 1.000, the more general form of the equation is needed:

Then Year $ = ((Constant $) / Weighted Index (CY)) * Weighted Index (TY).

Then Year dollars are converted to Constant Year dollars to remove the effects of inflation from a multi-year outlay to determine the costs in constant dollar terms. This facilitates comparisons across programs. Then Year dollars are converted to constant dollars by dividing the Then Year dollar amount by the weighted index of the appropriation in the given year relative to the base year. If the base year is set to 1.000 in the weighted index table, the equation is:

Constant $ = Then Year $ / Weighted Index (TY)

If the base year is not set to 1.000, the more general form of the equation is needed, utilizing the raw index for the constant year (CY) to convert from the base year to the constant year:

Constant $ = ((Then Year $) / Weighted Index (TY)) * Raw Index (CY)

Converting Then Year dollars in one year to Then Year dollars in another year can facilitate comparisons in like dollar terms, though in general this will be done with constant dollars. To convert from Then Year dollars in one year to Then Year dollars in another year, multiply the originating then year dollar amount by the ratio of the weighted indices of the target year and the originating year:

Then Year $ (Yr. B) = Then Year $ (Yr. A) * (Weighted Index (B) / Weighted Index (A))

Converting from one Constant Year to another constant year is used to change the base year of constant dollars. This conversion requires the use of raw indices rather than weighted indices like the other conversions. To convert constant dollars from one year to another, simply multiply the constant dollar amount by the raw index of the target year relative to the base year. The equation is:

Constant $ (Year B) = Constant $ (Year A) * Raw Index (Year B)

In the case of actual costs, which occurs when an analyst is normalizing historical data, the raw index should be used. This is due to the fact that actual costs represent the costs accumulated for goods and services purchased in a particular year. Thus, historical costs should be treated as Constant Year dollars. However, historical obligations should be treated as Then Year dollars, thus when obligations are normalized, the weighted index should be used.

When the actual costs are derived from CPR or CCDR data from a particular year, the analyst should use the raw index to convert to Constant Year dollars. Actual costs using a final CCDR without a history of the actual cost accumulation profile will require determining the spending mid-point and treating that year as a Constant Year for the entire program. Thus a raw index is used to convert the mid-point year to another Constant Year.

When the actual costs are derived from budget data, the analyst should use the weighted index to convert to Constant Year dollars.

Documenting Data

After the data have been collected, analyzed, and normalized, they are documented and stored for future use (see Chapter 2, Documentation, for additional details). All data collection activities are documented for: source, work product content, time, units, and assessment of accuracy and reliability. Comprehensive documentation performed during data collection greatly improves quality and reduces subsequent effort required for developing and documenting the estimate. The data collection format serves two purposes - the format provides for the full capture of information to support the analysis; and it provides standards that aid with mapping other forms of cost data.

Data Validation

MDA Directive 5010.06, Contract Data Management Program, dictates all contracts funded primarily by MDA, including both contracts awarded by the MDA Contracting Directorate (MDA/DAC) and contracts awarded by element contracting offices, shall require Contractor Cost Data Reporting (CCDR) (DD Form 1921 series) and Software Resources Data Report (SRDR) (DD Form 2630-2 and 2630-3) subject to the thresholds defined in DoDI 5000.02.

Contractor Cost Data Reporting (CCDR) and Software Resources Data Report (SRDR) are the two principal components of Contractor Cost and Software Data Reporting (CSDR). Responsibility for the CSDR process lies with MDA/DOC. As such, MDA/DOC places Contract Data Requirements List (CDRL) (DD Form 1423-1) for each CCDR and SRDR on each applicable MDA-Funded Contract. DOC representatives on Award Fee Boards use the review and acceptance of each CSDR as a metric for Award Fee determination.

DOC has instituted a validation process to formalize review techniques and ensure the integrity of the information provided through the CSDR process. The process for validating the Contractor Cost Data Reporting (CCDR) (DD Form 1921 series) is illustrated in Figure 5.4.

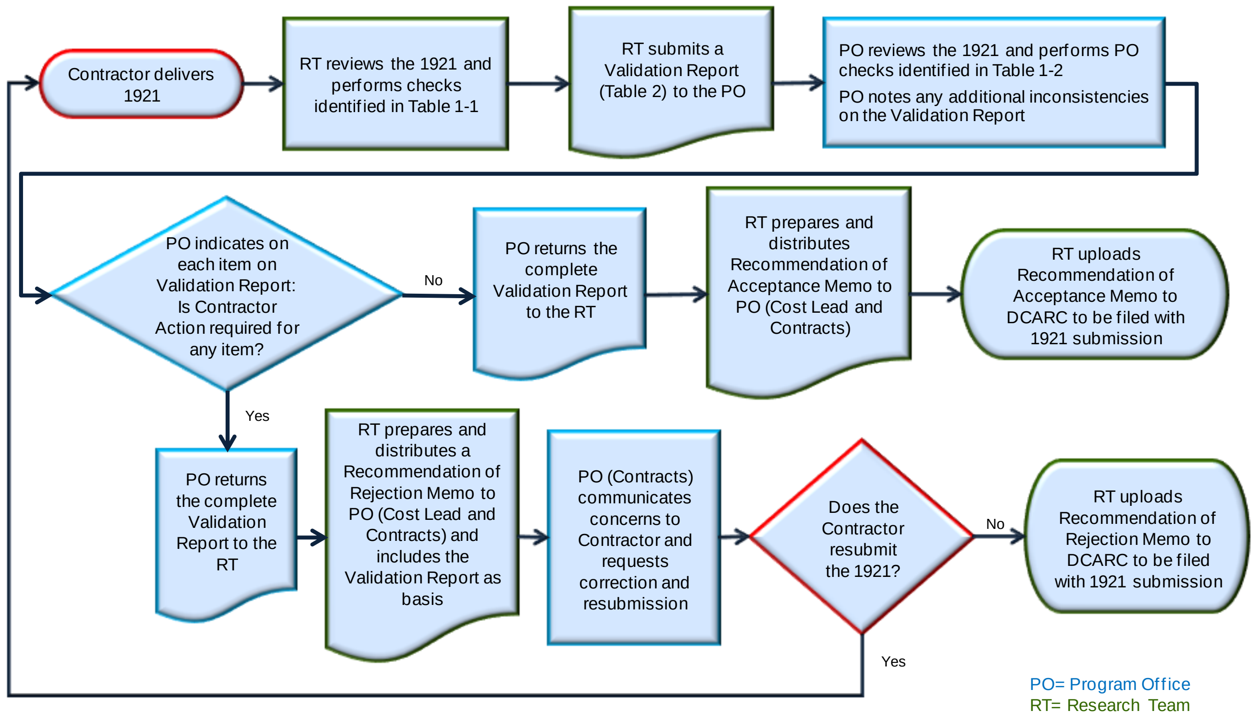

Figure 5.4. Process Flow for Validating Contractor Cost Data Reports.

As illustrated in the flowchart, the process starts when the Contractor delivers the Contractor Cost Data Reporting (CCDR) (DD Form 1921 series) to MDA. Upon delivery, the DOC Research Team performs a series of checks to determine mathematical accuracy, consistency with Contractor Cost and Software Data Reporting (CSDR) plans, logical progression from previous reports (on interim and final submissions), and completeness. The DOC Research Team then prepares a draft Validation Memo and coordinates with the Program Office to ensure consistency with Cost Performance Reports, correctness of unit quantities, clarity of remarks, and top level validation of nonrecurring and recurring costs, both incurred to data and at completion. The Program Office provides any additional items needing clarification or revision by the Contractor and determines if Contractor action is required for each issue identified. The Research Team then finalizes the Validation Report and prepares one of three Recommendation Memorandums: acceptance, acceptance with request for revision on future submissions, or rejection/request for resubmission. The Research Team provides both the Validation Report and Recommendation Memorandum to the Program Office for communication to the Contractor. If the report is accepted, the Contractor is directed to submit the report to DCARC and the Research Team coordinates filing of the internal validation record with DCARC. If the report is rejected, the Contractor will resubmit and the resubmitted report goes through the validation process from the beginning. All Contractor Cost Data Reporting (CCDR) (DD Form 1921 series), corresponding Validation Reports, and Recommendation Memorandums are indexed and archived in the electronic DOC Research Library.

This validation process provides cost estimators with primary source data of nonrecurring and recurring costs. Close scrutiny of CSDR reports provides higher fidelity data for the development of Cost Estimating Relationships (CERs). This process also ensures the actual historical cost data is consistently documented, archived, and indexed in the DOC Cost Research library to facilitate consolidation and comparison to increase the quality of future estimates.

CHAPTER 6
METHODOLOGY

Cost estimating methodologies are the building blocks of a cost estimate. They translate a program's technical and programmatic requirements into a prediction of future costs. Estimating methods rely upon a combination of statistical properties, logical relationships, and subjective judgment. The analyst's judgment determines the most applicable method. Cost estimating lends itself to creativity, since many estimators often develop or discover new and unique ways of estimating costs.

Generally, there are four primary methods for estimating costs. These include the use of the following:

- Analogies;
- Parametric Cost Estimating Relationships (CERs);
- Engineering build-up; and
- Actual cost data (and extrapolation)

Selection of Appropriate Methodology

The appropriate methodology to utilize largely depends upon two factors:

- Level of accuracy expected for the cost estimate and/or time and effort available to apply to the estimating effort; and
- Availability of sound data which may be used as the basis for the estimating approach/method.

An estimator can never be certain which available methodology will provide the highest degree of accuracy. Assuming there is sufficient information available to make use of any of the four estimating methods, the relative ranking of expected accuracy associated with each method is provided in Figure 6.1.

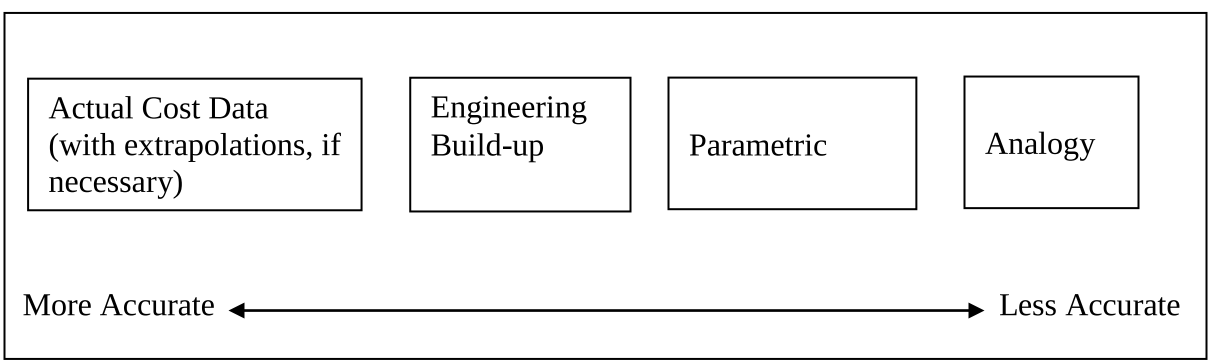

Figure 6.1. Relative Expected Accuracy of Cost Estimating Methods, When Available

The most appropriate selection among cost estimating methods is to use the one that has the highest relative accuracy, as long as sufficient information exists to ensure proper use of the methodology. The point in time during which sufficient information exists depends upon the life cycle phase of the program under study. For example, according to Figure 6.1, actual cost data (with extrapolations, if necessary) is generally the most accurate means of estimating. Actual costs represent expenses that have been accumulated against a specific cost element to be estimated, so the longer the program advances over time, the more likely and more meaningful actual (accumulated) costs become. Figure 6.2 provides insight into the likely appropriateness of selecting each type of methodology based on the point where an MDA program is in its life cycle. Most estimates are a combination of more than one method.

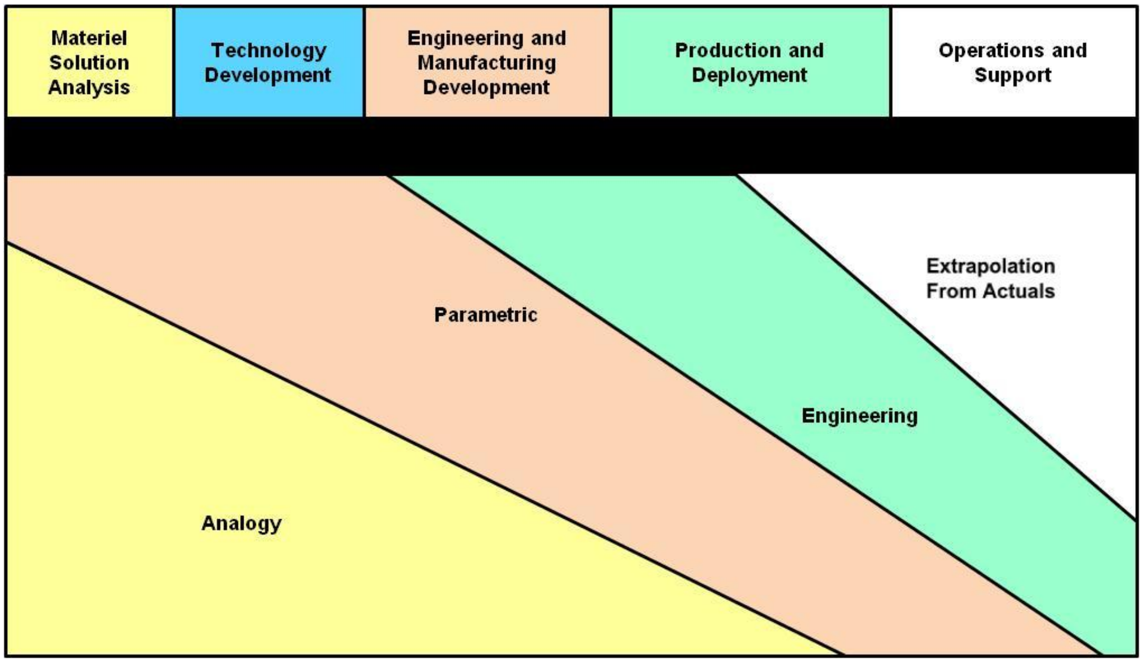

Figure 6.2. Life Cycle Relationship and Possible Estimating Approaches

Analogy Method

The analogy method is based on the concept that the item whose cost is to be estimated is similar (or analogous) to another item whose costs are known. Estimators often use the analogy methodology when few details are available about an item. Such conditions often occur during the early phases of a program's life cycle. Analogy estimating can be performed at the system, subsystem, or component level, and multiple analogies can be used at the lower WBS levels to build up to a higher level estimate. Frequently, adjustments are made to the costs of the item (whose costs are known) in order to better refine the estimate. Such adjustments include those made based on differences in schedules, quantities, performance characteristics, and technical characteristics between the item whose costs are known and the item whose costs are being estimated. Adjustments are made objectively, and this objective adjustment is applied to analogy in a mathematical fashion. As an example, consider that an analogy is being developed for an interceptor booster. The boosters appear to be similar in performance and programmatic characteristics, but the booster whose cost is to be estimated weighs 20% more than the booster whose cost is known. If the cost estimator discovers it is logical to assume that the cost of the new booster generally increases approximately linearly with weight, the estimator would appropriately adjust the cost of the new booster to be 120% of the cost of the old booster – thus, adjusting the cost using a multiplier of 1.20. Mathematically, this is presented as follows:

Cost of New Booster = (Cost of Old Booster) * (1.20)

Whatever the source of the analogy and any adjustments to it, the estimator has the responsibility to ensure logic prevails. All such logic and rationale is included in cost estimate documentation. NASA (2008, pp. 1-31) describes strengths and weaknesses associated with the analogy method in Table 6.1.

Strengths	**Weaknesses**
Based on actual historical data.	May rely on a single data point.
Quick.	Can be difficult to identify appropriate analog.
Readily understood.	Requires "normalization" to ensure accuracy.
Accurate for minor deviations from the analog.	Relies on extrapolation and/or expert judgment for "adjustment factors."

Table 6.1. Strengths and Weaknesses of the Analogy Estimating Method

Parametric Method

Parametrics requires sufficient homogeneous analogous data points. Cost estimates developed using the parametric approach are based on historical data and regression models that relate cost as the dependent variable to certain explanatory (or independent) variables which are believed to influence cost. Such regression models are commonly referred to as cost estimating relationships, or CERs. The use of CERs to estimate costs is especially valuable in the early stages of the life cycle when little is t known about the system to be estimated. CERs require only the knowledge of values associated with the explanatory (i.e., input) variables (e.g., weight, in pounds). The underlying assumption for CER use is that whenever a CER is utilized the input/explanatory variable values and cost for the system being estimating should react in the same manner for the system under study as they did for the systems' data from which the regression model was derived. This is true not only for the system being estimated but the other systems in the database. For example, if historical missile seeker data is used to generate a regression model that appears (based on logic and fit statistics) to provide a reasonable estimate of seeker development costs, then the assumption when using the regression model to estimate seeker development costs for a new seeker is that field of view (in degrees) will similarly influence development costs for the new seeker. Since parametric methods are used to generate costs at either the system or subsystem level (i.e., and not at the lowest WBS levels), an advantage to using this method is that results may be generated relatively quickly. As mentioned previously, another advantage is that very little information about the system or subsystem to be estimated must be known in order to use this method.

The focus of regression analysis is to "fit" a line to historical cost and explanatory variable data. The dependent variable is usually denoted by "*y*." For the case of a simple linear regression model, the equation is expressed as $y = a + b*x$, where "a" is called the "intercept" and "b" is called the "slope." The "a" and "b" parameters are estimated during development of a regression model, most commonly using a method called "ordinary least squares." In most cases, there is a positive correlation between cost and the explanatory variable, thus typically resulting in a positive ("+") slope value. It should be noted that "b" may occasionally take on a negative value (i.e., "-b"), as would be the case when the requirement to miniaturize an item is the leading cost driver.

More complicated linear models may include additional explanatory variables, called multivariate linear regression. The addition of explanatory variables which also have a strong effect on cost (the dependent variable) often results in a more accurate estimating model. Such multivariate linear regression models take the form $y = a + b_1*x_1 + b_2*x_2 + \ldots + b_n*x_n$. In a multivariate regression the constant values (i.e., b_x) are called regression coefficients. Table 6.2 (NASA, 2008) provides an explanation of the meaning of the three regression coefficients for the case of a multivariate linear regression model with three explanatory variables (i.e., x_1, x_2 and x_3).

Regression Coefficient	Meaning
b_1	Impact of a one-unit increase in x_1 on the dependent variable y, holding constant all the other included independent variables (x_2 and x_3)
b_2	Impact of a one-unit increase in x_2 on y, holding x_1 and x_3 constant
b_3	Impact of a one-unit increase in x_3 on y, holding x_1 and x_2 constant

Table 6.2. Multivariate Regression Model: Coefficients Explained

In practice, and especially in an industry such as missile defense, there is often a small data set available for use in development of regression models. In such cases, the size of the data set is considered when selecting the number of explanatory variables to be used in an estimating model. Too high a ratio of explanatory variables to data set size results in too few degrees of freedom, and the end result may be a model which results in "good" fit statistics without proper basis, due to over-fitting the model (Draper, 1981). In addition, the parameters for the system being estimated should lie within the range of parameters used in the CER. Estimating outside of such ranges can lead to inaccurate estimates.

A linear regression model is one in which the dependent and independent variables can be transformed into a linear form. A non-linear regression model is one for which there is no such transformation. More formally, a non-linear regression model is one for which the first-order conditions for least-squares estimation of the parameters are non-linear functions of the parameters. In cost estimating, more common non-linear models take the form $y = a * x ^b$. If multiple explanatory variables are required, the more common non-linear models take the form $y = a * x_1 ^b_1 * x_2^b_2 * \ldots x_n^b_n$. The reason this model form, sometimes referred to as the "power model," is a favorite with cost estimators is that error around the curve which fits the data is distributed according to a constant percentage. This type of error distribution is referred to as "multiplicative." By comparison, with a linear model error around the curve which fits the data is distributed in an additive fashion, such that data with higher cost values have no more influence over the resulting regression equation than do data points representing much less cost.

A word of caution is in order concerning causation between dependent and explanatory variables in regression models. It should be understood by the estimator that "good" correlation statistics between cost and explanatory variable(s) does not confirm causality (i.e., a cause and effect relationship between the explanatory variable(s) and the dependent variable). Fit statistics help express the strength and direction of the quantitative relationships involved (Draper, 1981). In other words, no matter the statistical significance (as measured by fit statistics) of a regression result, causality cannot be proven. Instead, regression analysis is used to estimate and test hypotheses regarding the model's parameters (NASA, 2008).

As an example both shark attacks and ice cream sales at the beach have a high positive correlation. This does not mean an increase in sales of ice cream at the beach is the cause of more shark attacks. Rather it reflects the fact of an underlying root cause that visits to the beach are higher during the summer months.

Although simple linear and multivariate linear and non-linear regression models may be developed "by hand," there are a number of computer applications which perform regression analysis so such tools are commonly used in practice. The benefit of using computer software tools to perform regression analysis increases as the number of explanatory variables increases.

Table 6.3 lists some of the strengths and weaknesses associated with parametric methods (NASA, 2008).

Strengths	Weaknesses
Once developed, CERs are an excellent tool to answer many "what if" questions rapidly	Collecting appropriate data and sufficient statistically representative database generating statistically correct CERs is typically difficult, time consuming and expensive
Statistically sound predictors that provide information about the estimator's confidence of their predictive ability	Often difficult to others to understand the relationships
Eliminates reliance on opinion through the use of actual observations	Must fully describe and document selection of raw data, adjustments to data, development of equations, statistical findings and conclusions for validation and acceptance
Defensibility rests on logical correlation, thorough and disciplined research, defensible data, and scientific method	Lessens predictive ability/credibility outside its relevant data range

Table 6.3. List of Parametric Method Strengths and Weaknesses

An overview of the steps required to develop a regression model include:

- Review the literature and develop the theoretical model;
- Specify the model;
- Select the independent variables(s) and the functional form;
- Hypothesize the expected signs of the coefficients;
- Collect the data;
- Estimate and test the hypotheses regarding the model's parameters; and
- Document the results.

There are a number of statistical tests and data plot analyses typically utilized to determine whether or not a regression model can be expected to be accurate and robust. A thorough discussion of each of these is too technical and focused for a cost estimating handbook, but a list of some of the more common tests and analyses, along with the general purpose for each, is provided below:

- Test for significance of regression – checks the significance of the whole regression model.
- *t*-test – checks for significance of individual regression coefficients.
- Partial F-test – simultaneously checks the significance of a number of regression coefficients (but can also be used to test individual coefficients).
- Cost versus potential explanatory variable plots (scatter plots) – allows the model builder to visually assess if there appears to be correlation between the cost and potential explanatory variables; it also provides insight into the possible need for a non-linear model.

- Plot of regression line versus data – helps the model builder to visually assess the influence of individual data points on the model, the ranges over which the model is likely to better predict costs, the ranges over which the model may not predict very accurately, and the potential benefits for stratifying the data to create separate models for different ranges of data.
- Plot of residuals – allows the model builder to visually assess if residuals appear to be distributed randomly around prediction (i.e., regression) line, where a non-randomly distributed pattern often indicates that a better model (e.g., more or fewer explanatory variables, different explanatory variables, or different form of model) may be preferred.

There are a number of references a cost estimator may use to gain a more detailed understanding of regression modeling, fit statistics, and data plot analysis. One recommended source is the Society of Cost Estimating and Analysis' *Cost Estimating Body of Knowledge* (CEBoK, 2009).

Engineering Build-Up

The engineering build-up method develops cost estimates for higher-level cost elements by summing detailed cost estimates for lower-level cost elements. Although summing (or "rolling up") cost elements to higher level cost elements may be practiced for all other estimating techniques, summing for an engineering build-up involves summing cost elements from the lowest definable levels for which data exists. This method is so named because engineers associated with a product are typically the ones with the most intimate knowledge of details associated with the product, and it is this level of detail that is required for an engineering build-up. This method is also commonly referred to as the "industrial engineering build-up." Because it involves summing estimates from the lowest WBS level up, it is also sometimes called the "bottom-up" approach.

The engineering build-up method is most frequently used when detailed information, such as the number of parts of each type required and the actual cost of each part, for lower cost element levels are either known with a reasonably high degree of certainty (e.g., actuals or based on bids). This method is most applicable in a manufacturing, or touch labor, environment where measurable labor touches (i.e., physically works on) the product. Historical or even hypothesized touch labor can be measured and adjusted to create "labor standards," which may be applied against the number of parts processed by the touch labor. Costs of materials (or purchased components/subsystems) associated with the product may then be added to derived a total direct manufacturing cost. All labor and material overhead costs, general and administrative expenses, and profit/fee may then be added to derive a total manufacturing cost estimate. These same principles may also be applied to non-manufacturing environments, but use of this method is less common outside the manufacturing environment because the precise information required for this method is less likely to be known or available. Typically, cost estimators must work closely with program/technology engineers to develop the cost estimates. This way, the estimator can get the engineer to focus on the task in such a way that the estimate is consistent with all applicable cost estimate ground rules and assumptions (GAO, 2009).

There are occasions when the use of the engineering build-up method outside the manufacturing environment is appropriate, even when details typically required for this method are not available. In such cases, the necessary details are usually assumed, with the assumptions based upon other estimating methods. A common source for “filling in” these details is the use of expert opinion. The underlying basis for the vast majority of expert opinions from SMEs is analogies to the experts’ experiences.

Table 6.4 provides an overview of the strengths and weaknesses of the engineering build-up methodology (NASA, 2008).

Strengths	Weaknesses
Intuitive.	Costly; significant effort (time and money) required to create a build-up estimate.
Defensible.	Not readily responsive to "what if" requirements.
Credibility provided by visibility into the BOE for each cost element.	New estimates must be "built-up" for each alternative scenario.
Severable; the entire estimate is not compromised by the miscalculation of an individual cost element.	Cannot provide "statistical" confidence level.
Provides excellent insight into major cost contributors.	Does not provide good insight into cost drivers.
Reuse; easily transferable for use and insight into individual project budgets and individual performer schedules.	Relationships/links among cost elements must be "programmed" by the analyst.
	Only includes what is known; the expected risks as well as the unknown unknowns are not included.

Table 6.4. Engineering Build-Up Methodology Strengths and Weaknesses

Actual Cost Data and Extrapolation

Using actual (historical) cost data provides an excellent basis of estimate when future requirements are for the same item for which the historical cost data was accumulated. For commercial-off-the-shelf (COTS) goods or services, vendor quotes can be used. Note that vendor quotes represent price not cost because it is the price the government pays. There is never a need to estimate the cost for an item whose actual cost is already known unless the new item will require some type of modification. Vendor quotes must be treated with caution, since they represent the costs of hardware only, and do not reflect the costs required to integrate the hardware into the design, which includes not only direct design work, but also indirect costs such as system engineering and program management.

Extrapolation from actual costs uses historical data from prototypes or complete or partially complete items to estimate the cost of a future item. When the new system is close in design and functionality to a currently existing system, extrapolation can provide the most credible and supportable cost estimate. Care must be taken if the extrapolation is from a system that is no longer in use or production, or the new system is significantly different from the analogy.

Three areas where extrapolation from actual costs is commonly used for an estimate include:

- Averages – the use of simple or moving averages to determine the average actual costs of items to predict the future cost of a number of the same item;
- Learning curves – includes the effects of learning on cost improvement due to learning associated with performing the same activity or producing the same item more than once; and
- Estimate At Completion (EAC), which makes use of actual cost and schedule data to estimate costs at completion using EVM techniques.

Table 6.5 shows the strengths and weaknesses associated with extrapolating from actual costs. (SCEA CEBoK, 2009)

Strengths	Weaknesses
Utilizes actual costs to predict future costs	Work to date may not be representative of work to go
Can be applied to hours, materials, total costs	
Highest credibility and greatest accuracy when properly applied	Extrapolating beyond a reasonable range
Many government bodies require or encourage the use of this technique	

Table 6.5. Strengths and Weaknesses with Extrapolating from Actual Costs

Application of Learning Curves

Learning curve theory states that the more times an activity is repeated, the more efficient (in terms of time) the activity becomes. Learning curves are based on the assumption that as the quantity of items produced doubles, the effort and cost associated with producing the item decreases according to a constant percentage.

Learning curves (sometimes also called improvement or progress curves) are useful for estimating the production cost of large lot buys or production runs. When estimating costs within MDA, the percent decrease assumed typically depends upon the commodity being produced. The learning curve slope is defined as (1 - % learning improvement), and in practice tend to take on values between around 80-95%. As an example, if the assumed learning curve slope for production of a certain commodity (e.g., interceptor seeker) is 90%, then each time the quantity of that commodity produced doubles, there is an assumed 1-90%=10% decrease in cost. Major cost estimating assumptions associated with the application of learning curve theory is that production of the items is not interrupted and there will be no significant changes made to the item being produced during the time period when the learning curve is assumed. Figure 6.3 presents the effect on unit cost for an assumed learning curve slope of 80%.

Figure 6.3. Effects on Unit Cost Assuming 80% Learning Curve Slope

Within learning curve theory there are two basic approaches: cumulative average curve theory and the unit curve theory. Cumulative average curve theory calculates the average unit value for the entire curve to a set point, whereas unit curve calculates the unit value for a specific quantity point. In other words, with cumulative average curve theory, the cumulative average cost is reduced by the same constant percentage; and with unit curve theory, unit cost is reduced by the same constant percentage. In practice, the cumulative average curve equation will show a much greater reduction in cost over the first few units produced than unit curve theory equation using the same slope. This difference in cost decreases as the quantity produced increases. Mathematically, these two theories may be expressed as follows:

Cumulative Average Curve (Calculates Average Unit Value of a Production Lot):

$Y = A * X^{b}$; where

Y = Cumulative average unit value of the X^{th} unit;
A = Theoretical first unit cost (T1);
X = Cumulative Number of Units; and
b = Log(slope)/Log (2)

Unit Curve (Calculates Unit Value of Specific Point on Curve):

$$Y = A * X^{b}; \text{ where}$$

Y = Unit value of the X^{th} unit;
A = Theoretical first unit value (T1); and
b = Log(slope)/Log (2)

Application of Estimate at Completion

Earned value management (EVM) is a project management technique used to objectively track the progress and status of a program, and may be used to forecast future performance. EVM is also used by MDA leadership to integrate risk management with performance, cost and schedule. Because EVM data is collected from cost data submitted by MDA contractors, the use of EVM as an estimating technique requires that a contract be in place and work is progressing under the contract. Three basic elements of EVM include:

- Budget Cost of Work Schedule (BCWS) – also called the Present Value (PV), it represents the total cost of the work scheduled (i.e., planned) as of a certain reporting date.
- Actual Cost of Work Performed (ACWP) – also called the Actual Cost (AC), this is the total cost taken to complete the work as of a certain reporting date.
- Budgeted Cost of Work Performed (BCWP) - also called the Earned Value (EV), this is the budgeted cost of work completed as of a certain reporting date.

In order to calculate the EAC, sometimes also referred to as the Estimate at Completion, the following may also be required:

- Budget At Completion (BAC) – represents the total budget allocated to the program item under study.
- Estimate to Complete (ETC) – represents the estimated cost of the remaining work for the program item under study.
- Cost Performance Indicator (CPI) – an index which represents the efficiency of the utilization of resources for the program item of interest; the CPI may be calculated as CPI = EV / AC.
- Schedule Performance Indicator (SPI) – an index which represents the performance of the program relative to planned schedule; the SPI may be calculated as SPI = EV /PV.
- Schedule Cost Index (SCI) – an index which combines the cost and schedule performance to date; SCI may be calculated as SCI = CPI * SPI

The manner in which the EAC is calculated depends upon which, among three different assumptions, the EVM analyst believes to be the most accurate. A brief description of each assumption, and the formula used for calculating EAC for each assumption, are provided below:

- Cost variances experienced to date are not expected to continue in the future:
  EAC = AC + (BAC – EV)

- Past estimating assumptions are not valid and new estimates must be applied: EAC = AC + ETC
- Cost variances experienced to date will continue to be present in the future: EAC = AC + (BAC – EV) / CPI
- Cost and Schedule performance experienced to date will continue to be present in the future: EAC = (ACWP + ETC) / SCI

Regardless of the means used to derive the EAC, the accuracy of the earned-value derived EAC forecast increases as the contract progresses. Care should be used when considering replacing an estimate generated by parametrics, analogies, or contract actuals, with an earned-valued derived EAC, particularly in the early stages of the fulfillment of a contract.

CHAPTER 7
SENSITIVITY ANALYSIS

Introduction

Sensitivity analysis must be performed for all MDA cost estimates. A sensitivity analysis investigates the effects of changing assumptions and ground rules and presents model outcomes based on these changes. Due to the impact of cost uncertainty, it is necessary to identify the cost model elements that represent the most risk and, if possible, quantify the risk. The GAO states this can be done through both a sensitivity analysis and an uncertainty analysis. (GAO 2009, pg.147)

Sensitivity analysis will help MDA decision makers and cost modelers to identify key cost drivers for the program. This information will help guide programmatic and technical decisions. For example, a sensitivity analysis will allow a program manager to determine how sensitive a program is to changes in a Best Estimate Test Date (BETD) and at what BETD a program alternative is no longer attractive. By using information from a sensitivity analysis, a program manager can take certain risk mitigation steps, such as assigning someone to monitor the BETD by coordinating range availability dates, ensuring target availability, and/or monitoring progress of hardware/software enhancement schedules. (GAO 2009, pg. 147)

For a sensitivity analysis to be useful in making informed decisions, however, carefully assessing the underlying risks and supporting data is necessary. In addition, the sources of the variation should be well documented and traceable. **Simply varying the cost drivers by applying a subjective plus or minus percentage is not useful and does not constitute a valid sensitivity analysis.** This is the case when the subjective percentage does not have a valid basis or is not based on historical data. (GAO 2009, pg.147)

Sensitivity analysis reveals how the cost estimate is affected by a change in a single assumption. The cost estimator and modeler examine the effect of changing one assumption or cost driver at a time while holding all other variables constant. This strategy allows the analyst to understand which variables most affect the cost estimate. The GAO indicates in some cases, a sensitivity analysis can be conducted to examine the effect of multiple assumptions changing in relation to a specific scenario. (GAO 2009, pg.147)

The GAO notes the difference between sensitivity analysis and risk or uncertainty analysis is that sensitivity analysis tries to isolate the effects of changing one variable at a time, while risk or uncertainty analysis examines the effects of many variables changing all at once. (GAO 2009, pg. 147)

The GAO recommends the sensitivity analysis should focus on the high cost elements. Sensitivity analysis examines how the cost estimate is affected by a change in a cost driver's value. For example, the analysis could evaluate an interceptor production lot cost with different assumptions about theoretical first unit cost, learning curve rates, "step factor" amount, limiting production lot sizes or continuing with a full, uninterrupted production run. (GAO 2009, pg. 147)

GAO best practices state that the sensitivity analysis is conducted by recalculating the cost estimate with different quantitative values for selected input values, or parameters, in order to compare the results with the original estimate. The output result is considered sensitive to the input parameter or assumption if a small change in the value of a cost element's input parameter or assumption yields a large change in the overall cost estimate. A sensitivity analysis provides helpful information for the system designer because it highlights cost sensitive elements. Sensitivity analysis is useful for identifying those areas where more design research could result in less production cost or where increased performance could be implemented without substantially increasing cost. This type of analysis is called a "what-if" analysis and is often used for optimizing cost estimate parameters. (GAO 2009, pg. 147-148)

Examining a variety of scenarios can be useful in developing input ranges for a sensitivity analysis. What-if scenarios can be described by changes to input parameters or those factors which would drive the scenario. For example – a scenario would be described by "what if 10 simulators are purchased and 25% less training flying hours are needed?" That scenario would be described by conducting the sensitivity around the number of simulators vice actual flying hour costs for training purposes. Would the cost of 10 simulators reduce the overall training cost? Could five be the breakeven point? What if the actual flying hour reduction for training purposes was more like 15% vice 25%?

Requirement to Conduct a Sensitivity Analysis

The cost analyst conducts sensitivity analyses as part of the overall cost model and estimate development process. The GAO Cost Estimating and Assessment Guide (GAO 2009) addresses the requirement in order to insure that a sound cost analysis has been conducted. A sensitivity analysis is one of the items the GAO will request during cost-related inquires. Also, the MDA Cost Estimating and Analysis Director (DOC Director) has incorporated sensitivity analysis as part of the overall cost model and estimate "score card" to ensure MDA cost models are using sound and credible cost estimating procedures.

Sensitivity Factors

The GAO indicates that uncertainty about the values of the technical parameters is common early in a program's design and development. MDA engineers and cost analysts make many initial assumptions at the start of a program and these initial assumptions change as the program matures. Therefore, as the point estimate is being developed, it is important to determine how sensitive the total cost estimate is to changes in the initial assumptions and cost drivers. (GAO 2009, pg. 148)

The GAO provides insight into some of the factors often varied in a sensitivity analysis. They are noted below. MDA indicates these factors can be categorized into two subgroups; those which are programmatic-related and those which are parametric and technical factors. (GAO 2009, pg. 148)

- Programmatic factors
  - Potential requirements changes - *(Software Lines of Code (SLOC) changes)*

- Testing requirements – *(number of tests)*
- Configuration changes in hardware, software, or facilities – *(building sizing)*
- Economic life – longer or shorter – *(O&S years)*
- De-scoping the program – *(removing a software build)*
- Acquisition strategies – *(multiyear procurement or dual sourcing)*

- Parametric/Technical factors
  - Increase or decreased learning curve slope, step factors and T1 cost
  - Changes in performance characteristics – (motor thrust)
  - Labor rates; Overhead rates; Wrap rates; Inflation rates

Note there is some overlap between these factors, as changes in programmatic factors may necessitate changes in technical factors. For example, if there is a configuration change in hardware that requires more performance from the system being estimated, then technical factors will also change as a result.

These are just some examples of potential MDA cost drivers. Many of the factors to be tested are determined by the assumptions and performance characteristics outlined in the technical baseline description and ground rules and assumptions. Cost estimators should use the technical baseline and ground rules and assumptions as the basis for looking at the factors to be varied in a sensitivity analysis. When documenting the sensitivity analysis cost estimators must address how the factors included in a sensitivity analysis relate to the ground rules and assumptions and technical baseline. (GAO 2009, pg. 148)

Additionally, the cost estimator always includes the assumptions most likely to change; i.e., an assumption made for lack of knowledge or an assumption outside the control of the program office. (GAO 2009, pg. 148)

Steps in Performing a Sensitivity Analysis

The GAO states a sensitivity analysis addresses some of the estimating uncertainty by testing discrete cases of assumptions and other factors that could change. The GAO recommends the analyst examine each assumption independently, while holding all others constant. The cost analyst can evaluate the results to discover which assumptions most influence the estimate. The GAO also states a sensitivity analysis requires estimating the high and low uncertainty ranges for significant cost driver input factors. To determine the key cost drivers a cost estimator determines the percentage of total cost that each cost element represents. The major contributing variables within the highest percentage cost elements are the key cost drivers to be varied in a sensitivity analysis. (GAO 2009, pg. 149)

Analysts also consider the “Pareto Principle,” first hypothesized by Vilfredo Pareto in the early 20th century: 80% of the effects come from 20% of the causes. This is also known as the “80/20” rule. In the case of sensitivity analysis, an analyst may expect 80% of the cost variation would come from 20% of the input factors – hence these would be considered the model’s “cost drivers.” 80/20 may not be the exact ratio in a cost model, but simply stated, there are probably a few variables or factors which drive the overall cost of the model. These input variables are the factors the analysts identify and focus for the analysis.

A credible sensitivity analysis has six steps (GAO 2009, pg. 149):

1. Identify key cost drivers, ground rules, and assumptions for sensitivity testing;
2. Re-estimate the total cost by choosing one of these cost drivers to vary between two set amounts - for example, maximum and minimum or performance thresholds;
3. Document the results;
4. Repeat 2 and 3 until all factors identified in step 1 have been tested independently;
5. Evaluate the results to determine which drivers affect the cost estimate most; and
6. Summarize and present results.

The GAO indicates a sensitivity analysis also provides important information for economic analyses that can result in the choice of a different alternative from the original recommendation. This can happen because an economic analysis is based on assumptions and constraints which may change. It is essential to test how sensitive the ranking of alternatives is to changes in assumptions before choosing the alternative course of action. Sensitivity is determined by how much an assumption must change that will result in an alternative that differs from the one recommended. The GAO provides a rule of thumb - an assumption is considered sensitive if a 10 – 50 % change yields a different alternative and very sensitive if the change is less than 10%. (GAO 2009, pg. 150)

The GAO stresses that assumptions and cost drivers which have the most effect on the cost estimate warrant further study. This will ensure the best possible value is used for that parameter. All the ground rules and assumptions should be reviewed to assure decision makers that sensitive parameters have been carefully investigated and the best possible values have been used in the final point estimate. (GAO 2009, pg. 150)

Sensitivity Analysis Benefits and Limitations

The purpose of cost estimating is to provide senior decision makers with the information they need to make decisions about not only funding but also program alternatives. Sensitivity analysis can provide a clear picture of the range of costs to be expected, with discrete reasons for what drives them. (GAO 2009, pg. 150) As a result, sensitivity analysis is an essential part of the overall flow of information provided to the MDA Director, the Director for Agency Operations and MDA Program Directors.

Cost analysts must present a summary view of the basic model operation by summarizing each of the cost factor effects on the outcome of the cost model. In the example summary below, each of the cost factor inputs (or “dials” in this example) can be either increased or decreased resulting in an expected increase or decrease in the model output. Amounts are not indicated, just the effects of increases and decreases to the model inputs.

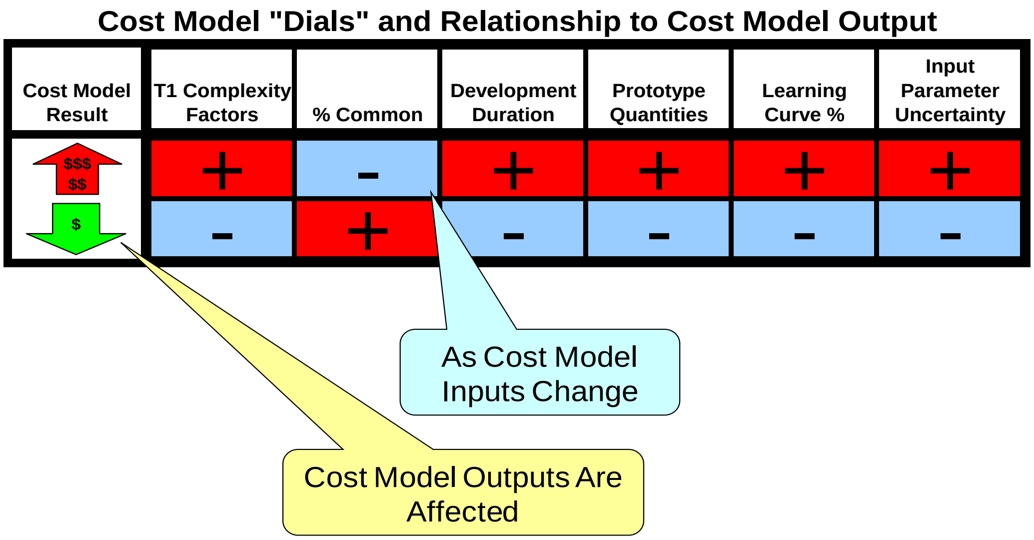

Figure 7.1. Model Output as a Function of Inputs

Consider a notional production cost estimate example with a production lot of 100 interceptors and a learning curve percentage of 90% (for this example, unit learning curves are used.) First compare total cost by varying theoretical first unit cost (T1), then reset the T1 and vary the Learning Curve input. In this example, technical leads have been consulted and they developed a range of 1,800 to 2,500 pounds for the weight of the proposed interceptor, but believe the most likely weight will be 2,000 pounds. Using a notional T1 weight-based CER of y =4.88x+240 with x being weight in pounds and y being cost in thousands of dollars yields a baseline T1 of $10 million. With a low weight of 1,800 pounds, the T1 cost decreases to $9.0 million, while using a high end weight of 2,500 pounds the T1 cost increases to $12.4 million.

Vary Interceptor Weight to Affect Lot Cost

Weight (Lbs)	T1 Cost ($M)	Lot Cost of 100 Interceptors 90% Learning ($M)	Lot Cost % Change
1,800	9.02	524.67	-9.8%
2,000	10.00	581.41	
2,500	12.44	723.28	24.4%

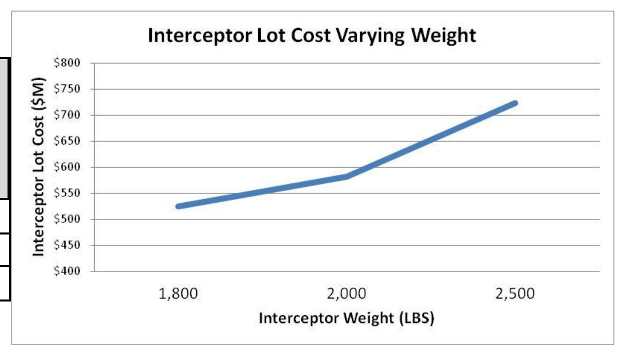

Figure 7.2. Notional T1 Cost Change Case

Using the baseline again and varying the learning curve percentage from 85% to 95% yields the results in Figure 7.3.

Vary Learning Curve Percentage

Learning Curve	T1 Cost	100 Interceptors	% Change
85%	10,000	437,540	-24.7%
90%	10,000	581,411	
95%	10,000	765,865	31.7%

$s in Thousands

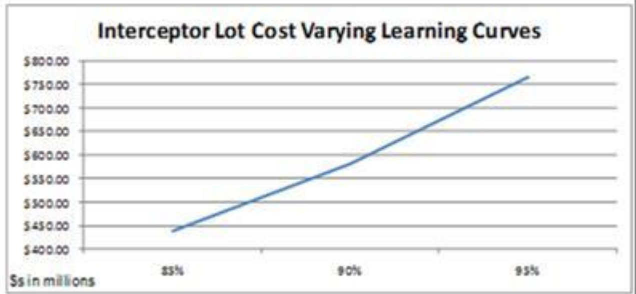

Figure 7.3. Notional Learning Curve Change Case

In Figure 7.4 both variables are included in a single graph to show how sensitivity analysis can give decision makers and cost analysts insight into the operation of a cost model.

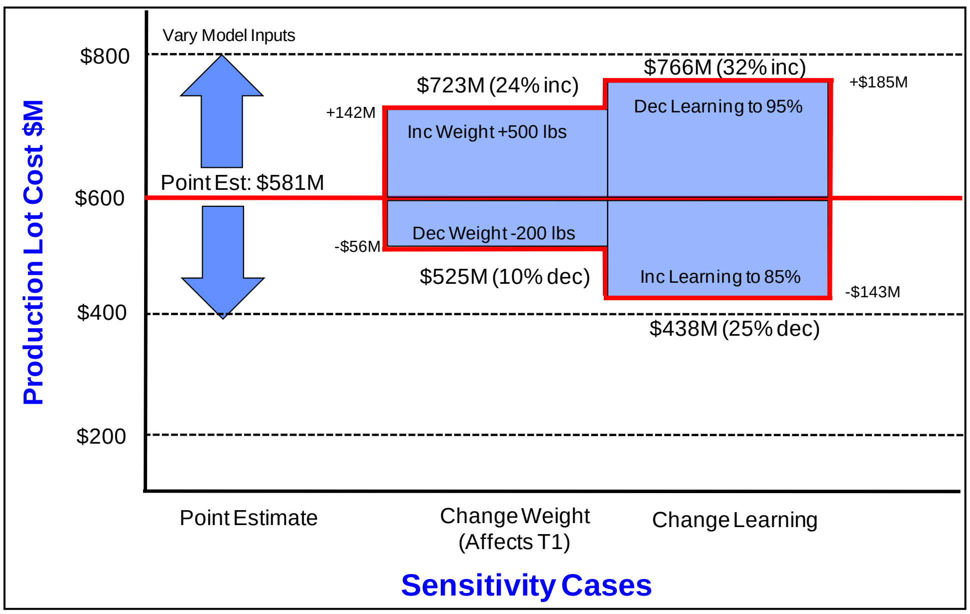

Figure 7.4. Interceptor Production – Notional Cases

In Figure 7.4 it is apparent how these two assumptions affect the estimate. For example, adjusting the learning curve percentage has the bigger effect on the cost estimate - adding $184 million to the point estimate when going to 95% learning while adjusting the learning curve percentage to 85% reduces the cost estimate by $144 million. Using visuals aides can quickly display what-if analyses and helps the cost analyst explain how a model operates and helps management make informed decisions.

The additional information, insight and understanding a sensitivity analysis brings to the final decision is the true value of the sensitivity analysis to MDA decision makers. Sensitivity analysis provides "ranges" around the point estimate, accompanied by specific reasons for why an estimate could vary. This insight allows the cost estimator and program manager to further examine potential sources of risk and develop ways to mitigate them early in the program's life-cycle. The GAO states the sensitivity analysis supports decisions that influence the design, production, and operation of a system to focus on the elements that have the greatest effect on cost. (GAO 2009, pg. 151)

As indicated earlier, the sensitivity analysis examines only the effect of changing one assumption or factor at a time. The GAO indicates the analyst must understand the risk of several assumptions or factors varying simultaneously, and its effect on the overall point estimate. (GAO 2009, pg. 151)

An actual MDA example is displayed in Figure 7.5. Reducing the operational availability of this system below 240 days would not significantly reduce O&S cost. The cost is sensitive between the range of 320 to 240 days. From this example, 240 days underway is a break point since limiting the number of days underway to less than 240 will result in little additional O&S cost savings. There may be other reasons to limit the number of days underway to less than 240, but cost is not a factor in that decision.

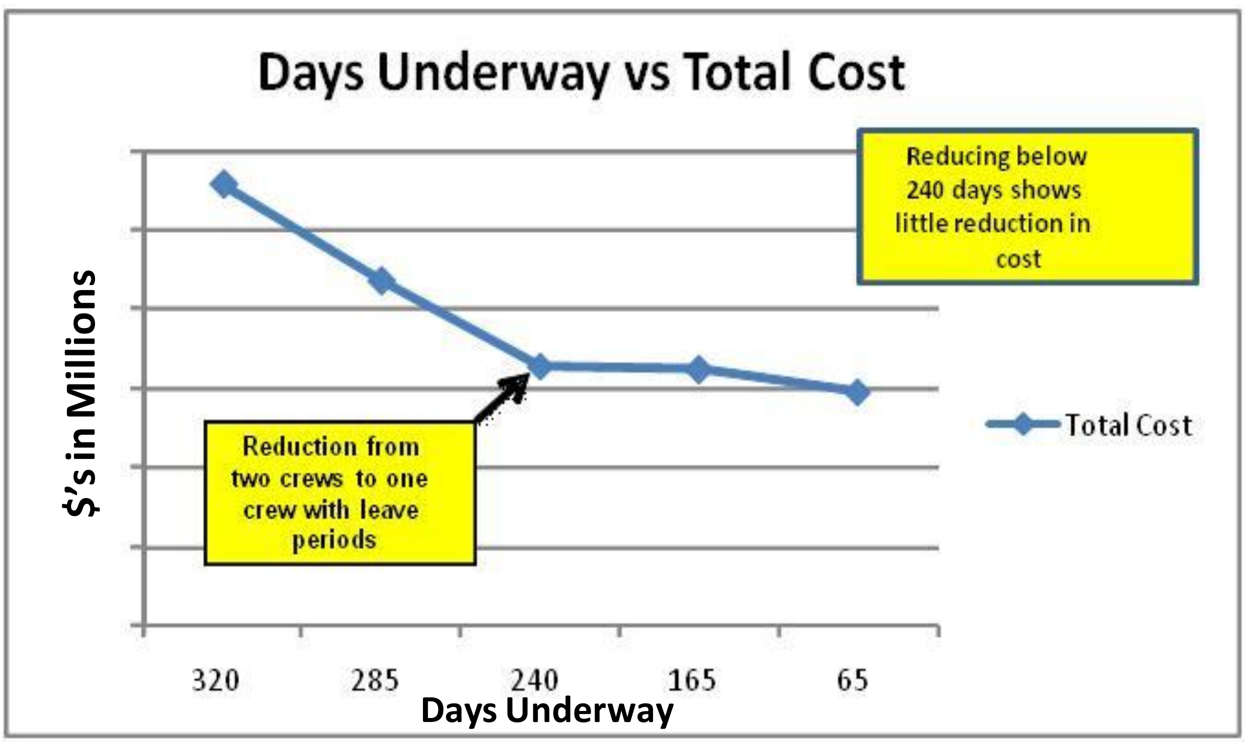

Figure 7.5. MDA Specific Example

GAO and MDA Best Practices Checklist: Sensitivity Analysis (GAO 2009, 151)

- The cost estimate was accompanied by a sensitivity analysis that identified the effects of changing key cost driver assumption and factors.

  – Well-documented sources supported the assumption or factor ranges.
  – The sensitivity analysis was part of a quantitative risk assessment and not based on arbitrary plus or minus percentages.
  – Cost-sensitive assumptions and factors were further examined to see whether design changes should be implemented to mitigate risk.
  – Sensitivity analysis was used to create a range of best and worst case costs.
  – Assumptions and performance characteristics listed in the technical baseline description and GR&As were tested for sensitivity, especially those least understood or at risk of changing.
  – Results were well documented and presented to management for decisions

- The following steps were taken during the sensitivity analysis:

  – Key cost drivers were identified.
  – Cost elements representing the highest percentage of cost were determined and their parameters and assumptions were examined.
  – The total cost was re-estimated by varying each parameter between its minimum and maximum range.
  – Results were documented and the re-estimate was repeated for each parameter that was a key cost driver.
  – Outcomes were evaluated for parameters most sensitive to change.

- The sensitivity analysis provided a range of possible costs, a point estimate, and a method for performing what-if analysis.

CHAPTER 8
COST RISK AND UNCERTAINTY

Introduction

There are numerous types and sources of risk. These include internal factors that are to some extent under a project's control, such as requirements; external factors, such as strikes and acts of nature; and model uncertainty (models don't explain the past perfectly). Cost risk analyses attempt to address some, but not all of these risks. Those typically excluded are extreme events such as the cost consequences of an earthquake occurring in the nation's capital. There are good reasons to leave out some of these. Cost risk analysis is intended to provide decision makers with information to help them successfully manage projects. Inclusion of some extreme events with large impacts will not aid decision makers with project budgeting.. Thus exclusion of some risks is advisable. See Figure 8.1 for a graphical illustration of sources of uncertainty in cost risk analyses (Hunt, 2006).

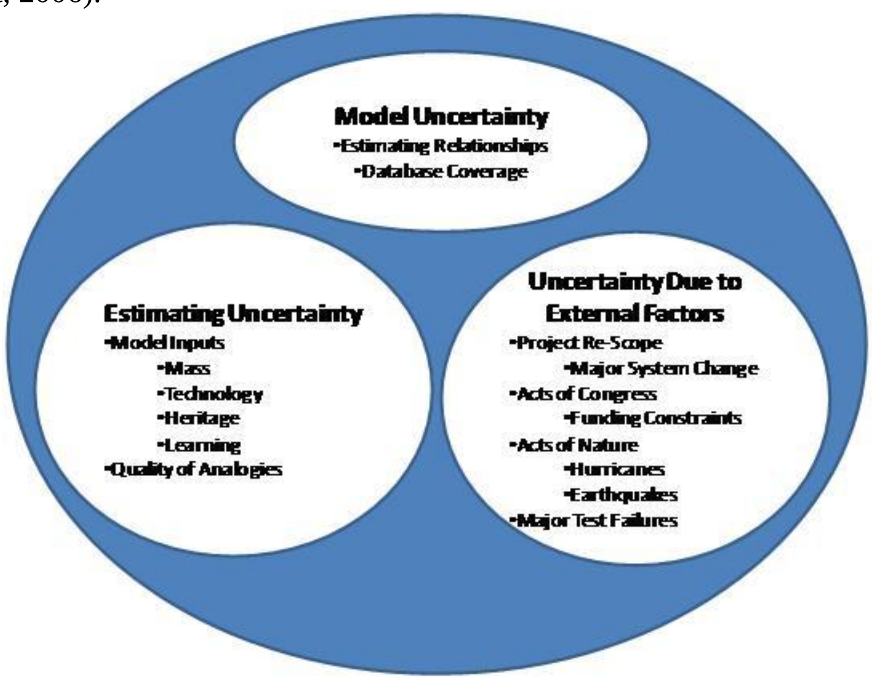

Figure 8.1. Sources of Uncertainty in Cost Estimates

Estimating uncertainty accounts for the fact that before project completion most facets of a project are only known within a range. There is a projected most likely value, but significant uncertainty exists around project weight, the degree of technology maturation, the amount of heritage which can be leveraged from past projects, the amount of learning to take place in production, etc. Estimating uncertainty is typically included in cost risk analyses, in cost risk modeling and with those analyses conducted for NASA and Department of Defense agencies.

The primary approach is to include ranges around the model inputs by allowing them to vary. This is done with probability distributions. The probability distributions are determined by examining historical data for the model inputs or by soliciting expert opinion and engineering judgment on the high and low inputs around the most likely values. These also include such factors as uncertainty surrounding future inflation and test item quantities.

Model uncertainty is the variation in cost attributed to the fact that the models used to predict cost do not explain all of the variation in the data. This is due to having limited, finite samples which do not capture every particular scenario, and in some cases captures random effects seen in the past that cannot be systematically captured in a formal model. Also, what is being estimated may not be similar to the data used to develop the cost model. For example, some argue that using robotic satellite cost data to model launch vehicle costs introduces additional uncertainty since there are aspects of launch vehicle systems which are not similar to small robotic satellites. While many of the electronics may be similar at the component level, the structures are significantly different. Also launch vehicles are not produced on a frequent basis, so using older data to estimate a new launch vehicle development program introduces additional uncertainty. These types of uncertainties are often modeled, but not always. Some cost models do not include any model uncertainty in their risk analysis capabilities, therefore hamstringing their users from including this important source of risk.

Uncertainties due to hard-to-foresee scenarios include major program re-scopes and acts of nature. These are typically not included in project risk estimates. This is reasonable, since the purpose of cost risk analyses is to provide project management with useful information for decision making. These decisions affect those factors within a project manager's purview, so including only those factors impacting management's decisions is often ideal for a project estimate. Independent estimates may include some of these to provide higher-level authorities, such as Congress, with information on what a project may actually cost in practice, since it is likely, over the course of a major development, that some of these external factors may impact costs across the agency, e.g., a Shuttle failure impact like the Challenger incident. The Challenger incident in 1986 increased development costs for numerous satellites due to re-designs necessary to find other launch options, and launch vehicle delays, which had a ripple effect which increased costs across NASA into the early 1990s. More recently, however, the emergence of commercial launch companies indicate that the trend may be towards lower cost launch options.

While it is good to exclude some categories of uncertainty, cost analysis as a profession tends to go too far in the opposite direction. Many of these factors, such as model uncertainty, are ignored in developing cost risk estimates. The greater uncertainty inherent when small data sets are used is often ignored as well. And the extent to which requirements will change, the degree of heritage from previous, similar programs that can be relied upon, and the amount of technology development necessary to be conducted are greatly underestimated. Early project plans sometimes have more in common with science fiction than science fact. For example, one satellite project several years ago maintained it was developing an apogee kick motor for a project that would be a near carbon copy of a previously used apogee kick motor, but the new motor would be twice the size as the "close" analogy. But when looking at the final cost, it was obvious a relatively large amount of design cost was required. This inherent optimism of engineers seems to be common, and also reflects the need for project managers to sell their project in the initial stages of a project's life cycle. This should be taken into consideration when modeling cost risk.

The competitive bidding process has an impact as well, since contractors know requirements will be changed numerous times during development. They are confident they can bid low, and then make up for it as change orders are processed and additional money is negotiated for each additional change once cost-plus contracts are signed. As a society, we are risk blind.

> *"There is a blind spot: when we think of tomorrow we do not frame it in terms of what we thought about yesterday or the day before yesterday. Because of this introspective defect we fail to learn about the difference between our past predictions and the subsequent outcomes. When we think of tomorrow, we just project it as another yesterday."*
> (Taleb 2007)

The results of a cost risk analysis are typically presented as cumulative distribution function, or an "S-curve," which is so named because of the way the graphic is displayed. This is a useful format since the cumulative probabilities (referred to in cost analysis as "confidence levels") can be easily read directly from the graph. See Figure 8.2 for a notional example of an S-curve.

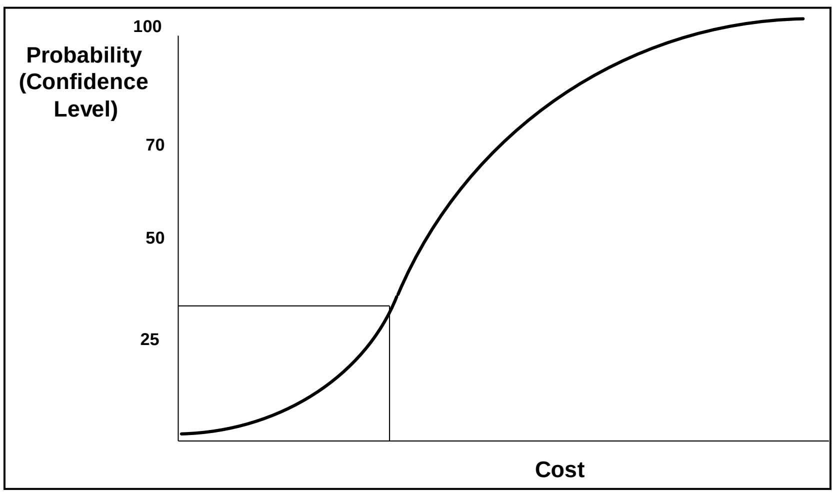

Figure 8.2. Notional Example of an "S-curve"

Basic Terms

A *Point Estimate* is a cost estimate that does not consider risk; in other words it is a non-risk adjusted cost estimate. It is typically calculated with all model inputs at their most likely value.

Uncertainty is the indefiniteness about the outcome of a situation. It includes both favorable and unfavorable events. The favorable events are also referred to as *opportunities*, because they are opportunities to save money.

Risk is the chance of loss or injury.

Cost Risk is a measure of the chance that, due to unfavorable events, the planned or budgeted cost of a project will be exceeded.

Cost Uncertainty Analysis is a process of quantifying the cost estimating uncertainty due to variance in the cost estimating models as well as variance in the technical, performance and programmatic input variables.

Cost Risk Analysis is a process of quantifying the cost impacts of the unfavorable events.

Probabilistic Cost Estimate is a cost estimate that includes risk and can be represented as a probability distribution. A probabilistic cost estimate is a range of values, rather than a single number.

The Cost Risk Analysis Process

The cost risk analysis process follows the same steps as the basic process for developing an estimate, with a few exceptions. Like a non-risk-adjusted point estimate, risk is assessed at the WBS level, taking both cost driver and cost model uncertainty into account. Once risk is *assessed* for all WBS elements, the risk distributions must be *aggregated* across the WBS. This process is similar to summing the costs for individual WBS elements in a point estimate, but the aggregation process is more complicated when risk is considered. Then, once risk is aggregated, there is a range of values rather than a single point. The budget request can be set at only one point, so a *risk measure* must be chosen at which to set the budget. This total level budget request is not sufficient. At MDA, the top level budget consists of many constituent elements. This list of ***N*** items is called, logically enough, a ***1-N*** list. Because the summation of risks is not the same as simply summing individual point estimates, but budget ***1-N*** lists are set at the WBS level, the total risk measure must be *allocated* back to WBS elements, or to the ***1-N*** list level.

See Figure 8.7 for a flowchart of this process.

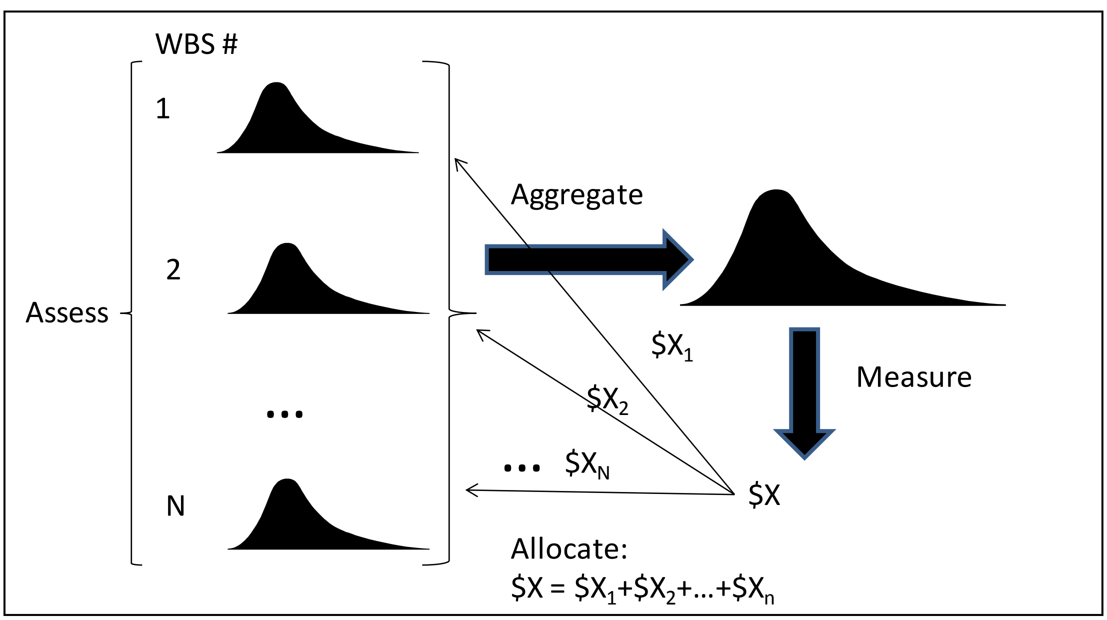

Figure 8.7. The Cost Risk Analysis Process Flow

For early concept (pre-Materiel Solution Analysis (MSA)) estimates and quick-turn drills there may not be sufficient information or time to develop a detailed risk analysis. In this case, historical data can be used to assign a top-level distribution around a point estimate. This process is discussed in Smart (2011).

Risk Assessment at the WBS Level

The way in which risk is assessed at the WBS level is based on the method used for estimating the cost: parametric, analogy, or expert opinion.

Cost estimates are often based on parametric cost models. These cost models take project characteristics or “parameters” as inputs and produce an estimate of cost as the output. Since the final cost of a project at its beginning is unknown, a common way to approach the estimation of cost is to use values (also known as parameters) planned, or included in project requirements.

An important parameter used to estimate cost is the weight of the hardware to be developed and produced. Weight-based parametric estimating models have been in use for over 50 years. The first models were entirely weight-based. The approach is simple. Cost is used as the dependent variable and weight as the independent variable in a (transformed) linear regression to fit the power equation $\boldsymbol{Y = aX^b}$. This has worked in practice because weight has historically been highly correlated with cost, and an estimate of hardware weight is usually known early in a program’s life cycle. While not a cost driver itself, weight often serves as a proxy for the most important top-level driver of cost – the scope or size of a program.

Even though weight explains much of the variation in cost, there is significant variation about the prediction line. Incorporating multiple independent variables is a tremendous advance over simple weight-based estimates since it allows for the introduction of true cost drivers into the estimate and it helps reduce the variation in the actual cost versus the estimate.

The NASA/Air Force Cost Model (NAFCOM) is a parametric estimating tool that is widely used across the Air Force and NASA centers. NAFCOM includes weight, management rating (MR), technical rating (TR), new design (ND), and attribute variables for mission type as independent variables in its CERs. MR is a weighted average of several management parameters. TR is a weighted average of several subsystem-specific technical parameters and incorporates the effect of productivity on cost. Productivity is an important effect to consider and incorporating it into a cost model allows for the inclusion of older data points. These cost drivers are based on input from NASA cost estimators, engineers, project managers, and research performed by the NAFCOM development team. The NAFCOM development team has performed extensive statistical analysis to ensure that the cost drivers are reasonable and that the regression equations are robust. See Figure 8.8 for an example of the multivariate structures CER from NAFCOM. Note that the R^2 is 98.1%, a marked improvement over using weight as the sole cost driver. Also, there is a wider variety of spacecraft included, including planetary robotic spacecraft, launch vehicles, and human flight systems.

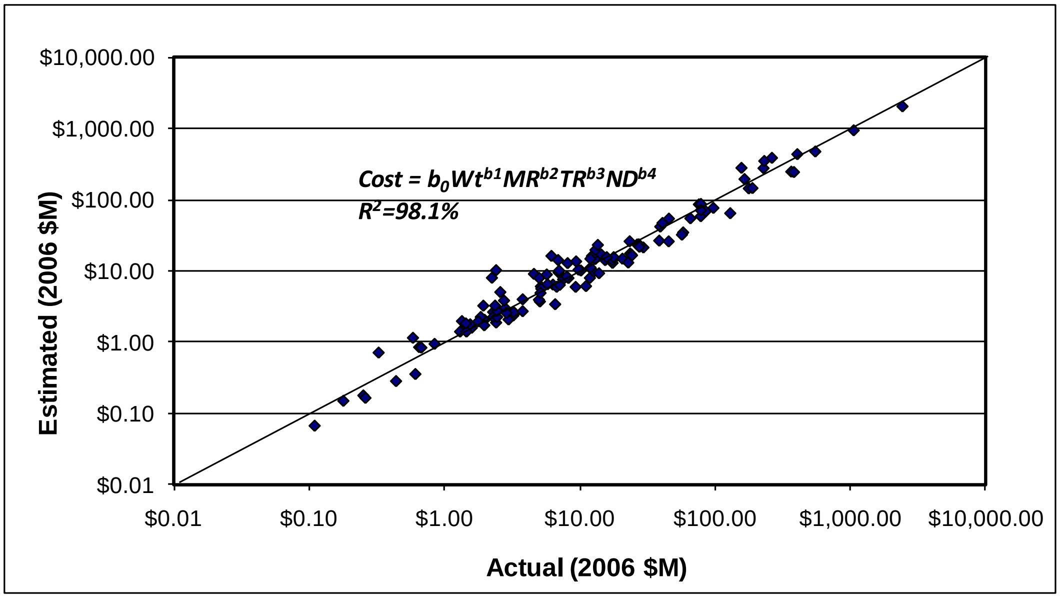

Figure 8.8. Actual & Estimated Costs for Structures & Mechanisms Subsystems using NAFCOM 2006 Multiple Cost-Driver CER

Because there are multiple cost drivers included in the multivariate estimating equation, the actual cost is plotted against the estimated cost in Figure 8.8. The closer the data point is to the line, the closer the actual cost is to the estimated cost. The farther the data point is from the line, the farther the actual cost is from the estimated cost.

Cost model inputs are not known with certainty in advance. Indeed weight often grows from a project's beginning to its completion. As noted in a study on weight growth, this can be significant, with an average over several unmanned satellites equal to almost 30% (Anderson 2003). This is an example of uncertainty denoted "estimating uncertainty" in the sources of uncertainty in Figure 8.1. This is also referred to as "input uncertainty" because weight or mass is an input to parametric cost models.

Cost estimating relationships are subject to another source of uncertainty. Such models do not capture all past variation perfectly. This is easy to see from Figures 8.8, as only a few historical data points are predicted with perfect accuracy. This inability to perfectly capture all variation in the historical data used to develop a CER is another source of uncertainty, which is an example of "model uncertainty." For the linear model and a set of n data points

$$(\boldsymbol{x_1}, \boldsymbol{y_1}), (\boldsymbol{x_2}, \boldsymbol{y_2}) \ldots (\boldsymbol{x_n}, \boldsymbol{y_n}),$$

the residual value that represents the difference between the actual and estimated cost is represented by the Greek letter epsilon $\boldsymbol{\epsilon}$ and for the i^{th} data point is defined as

$$\boldsymbol{\epsilon_i} = \boldsymbol{y_i} - (\boldsymbol{a} + \boldsymbol{b}\boldsymbol{x_i}).$$

Turning this around, and writing this equation so the dependent variable is on the left-hand side of the equation yields for the generic form of the model with residual

$$\boldsymbol{Y = a + bX + \epsilon}.$$

The Greek letter epsilon is often used in mathematics to denote small quantities, and is used in this context in the hope that the actual and the estimated costs will differ by a small amount.

In the case of the power equation, two residual term forms have been considered. Similar to least squares, an additive term form has been considered, viz.,

$$\boldsymbol{Y = aX^b + \epsilon}.$$

However, it is often the case that government projects have a wide range in terms of scope, and hence, cost. Some projects are measured in the tens of millions of dollars, while others are in the range of hundreds of millions, and some may be in the billion-dollar range. In such a case, the goal is not to estimate within a specific dollar value, such as $10 million, but rather within a percentage, such as that the actual is within 20% of the estimated cost. In this case, the interest lies in measuring the error of the actual relative to the estimate, that is, as

$$\boldsymbol{\epsilon = \frac{Y}{aX^b}}$$

The error is measured with the actual cost in the numerator and the estimated cost in the denominator so the error is as a percentage of the estimate. If the two were reversed, with the estimated cost in the numerator, the error would be expressed as a percentage of the actual cost. Since the estimated cost is the only one known upfront when developing an estimate, it is clearly better to express the error as a percentage of the estimate. Rearranging terms, in the multiplicative error case the actual cost can be expressed as the product of the estimate and the error, that is,

$$\boldsymbol{Y = aX^b \cdot \epsilon}$$

Since the error term, or residual, varies for each data point, the residuals are treated as random variables. Because the residuals, or errors, are not all zero, this indicates the model does not explain all variation in the sample used to develop the model. This is a major source of uncertainty, and is what is referred to in Figure 8.1 as “model uncertainty.”

See Figure 8.9 for a comparison of scatter plots that indicate patterns that follow additive vs. multiplicative residuals. In the additive case it is apparent the error is more or less constant as X increases. In the multiplicative case, the residuals increase in absolute value as X increases.

For a comparison of how these error specifications arise in practice, consider the structures and weight data set for small and medium-sized earth orbiting satellites displayed in Figure 8.8.

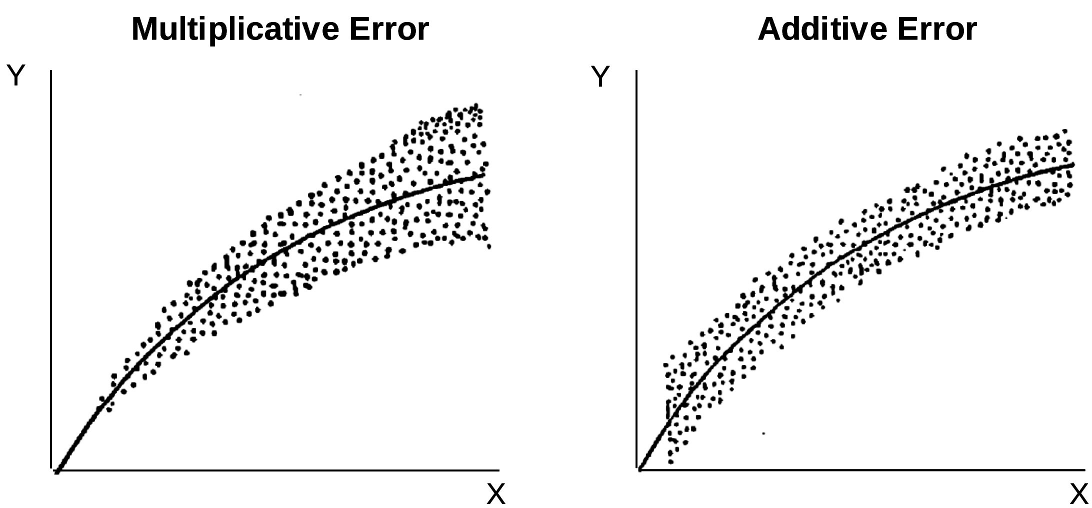

Figure 8.9. Comparison of Multiplicative and Additive Residuals (Eskew and Lawler, 1994)

These data were fit to both a linear equation and the initial power equation and the results of these fits are displayed in Figure 8.10. Note that both the x- and y-axes are graphed on a logarithmic scale, where powers of 10 are equidistant. Note that the power curve appears as a straight line when graphed on a logarithmic scale on both axes ("log-log" scale). In Figure 8.10 the linear equation provides similar fits to the power equation for the large weight data points, but the fits for the straight line are not as good for the lower weight data points. This is because of the nature of the data set, and the fact that the residuals increase as the weight increases. The linear equation gives too much influence to the larger data points at the expense of the lower weight data points because of the use of additive residuals. In this case it is clearly better to model the residuals as a percentage of the estimate (multiplicative) rather than as an absolute difference (additive).

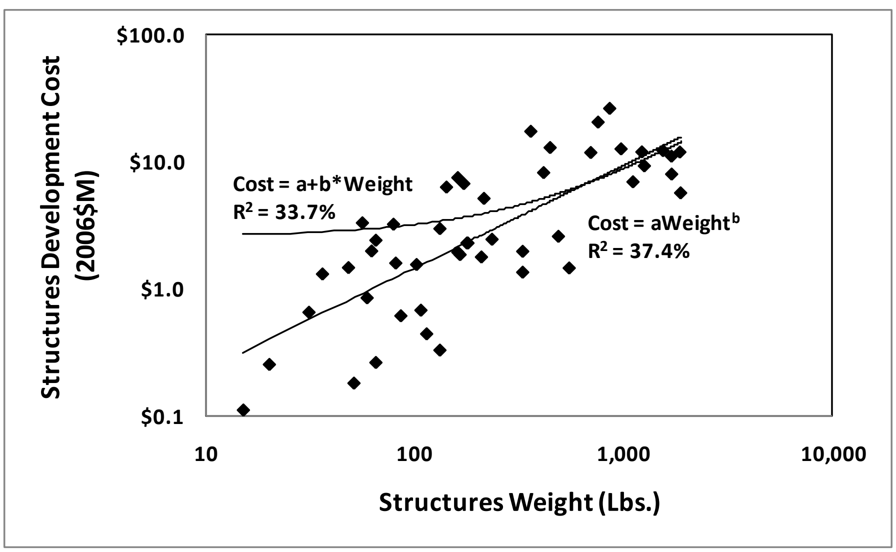

Figure 8.10. Regression between Structures & Mechanisms Subsystem Cost and Weight for a Sample of NASA Missions, Logarithmic Scale on Both Axes

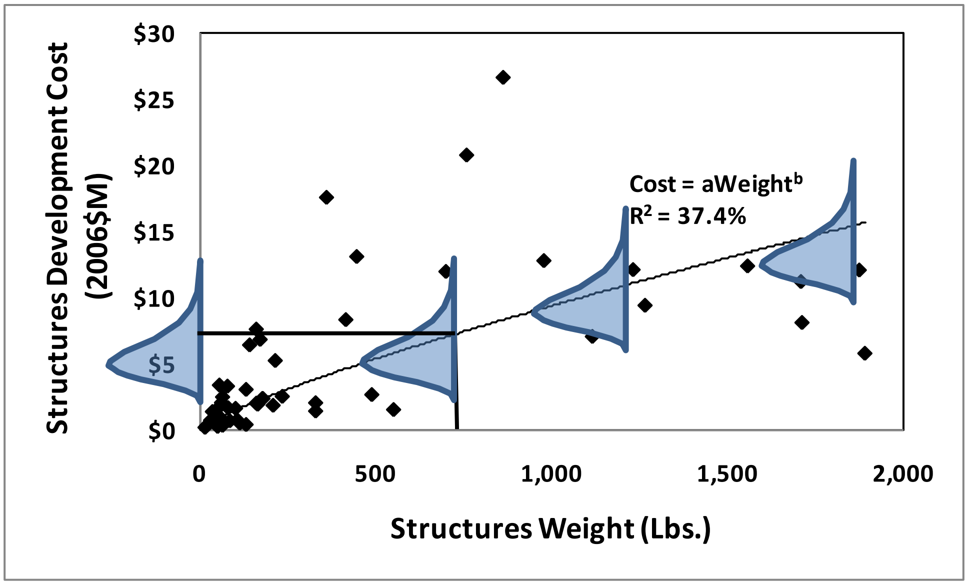

Figure 8.11. Variation about the Estimate

In Figure 8.11 the probability distributions reflect the variation around three different estimated values. Each of these represents variation in estimated cost, as measured in U.S. dollars ($). For example, when the structures weight equals 700 lbs., the estimated cost is equal to

$$0.0354 * 700^{.8074} \approx \$7.0\ million$$

which is a single estimate, but only one point on a lognormal distribution. What point on the distribution does this represent? Depending on the method used, this may represent a measure at or near the "center" of the distribution, such as the mean or the median.

In addition to the variation about the estimate there is also variation to consider in the model inputs. Until a project is completed, none of the parameters is known with certainty. There is a tremendous amount of weight growth in satellite systems, for example. Discussed in "Remaining Weight Growth of Satellite Systems" (Anderson, 2003), the **average** weight growth for a sample of satellite programs from project inception to launch was 28.5% - the maximum was over 50%. So there is a great deal of uncertainty and risk in parametric parameters. As a result, uncertainty distributions should also be assigned to all independent variables included in a CER.

Analogy and Calibration

If an analogy is used to calibrate a CER, uncertainty about the input parameters should be characterized and those are unchanged. However, depending upon the quality of the analogy, the estimating uncertainty may be reduced.

Calibration adjusts the cost estimating relationship so it intersects the analogy. For an equation of the form $Y=aX^b$ this means an adjustment to the "a" value of the equation. One data point is being used for an analogy but any number of data points can be used. Figure 8.12 shows an example of using three data points (A, B and C) and then calculating an average a-value for the calibrated CER.

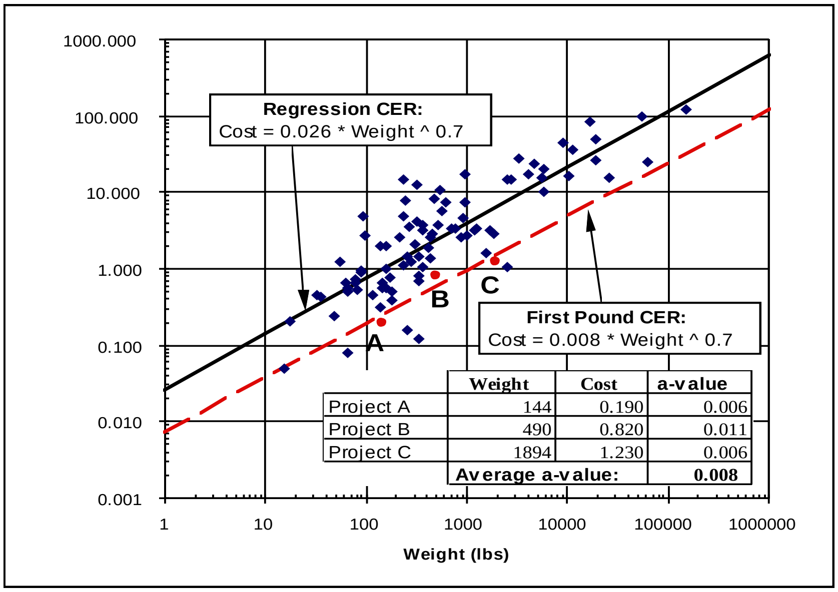

Figure 8.12. Example of CER Calibration

If an estimator is adjusting the a-value of the equation, or calibrating, because he knows something about the program that makes it more similar to what is being estimated than the average data point in the CER data set, then the estimating error should be reduced by this additional insight. There is additional information available to the estimator, and the estimator believes he can improve upon the quality of the estimate by adjusting the a-value. Note this estimating uncertainty is distinct from variation in the model parameters – this adjustment is to reduce the amount of estimating uncertainty. It is not reducing the amount of uncertainty in the model parameters, since the equation already reflects changes in cost due to changes in model parameters. Thus calibration only reduces estimating uncertainty. Parameter uncertainty should still be fully reflected in the cost risk estimate.

Understanding the extent to which estimating uncertainty is reduced can be understood by looking at the difference between the standard error of the estimate and the standard error of the slope. In the power equation $Y=aX^b$, calibration to a highly analogous data point should reduce most, if not all, of the uncertainty due to the a-value, or equation intercept, leaving only the standard error of the slope. When transformed linear least squares is used to estimate the equation's coefficients, there is a simple relationship, in log space, between the standard error of the estimate and the standard error of the slope. That relationship can be expressed mathematically as

$$SE(b) = SE(Y)/Sqrt(SS(XX))$$

That is, the standard error of the slope is equal to the standard error of the estimate divided by the square root of the sum of squares of the X-values and the average X-value. In the case of a weight-based CER, X = weight. Note the standard error is in $ (or log($)), so the standard error of the slope is in log$/log(lbs.). Hence, to translate the units back to log$, SE(b) should be multiplied by the average of the log-transformed weights. This smaller uncertainty value can then be used to calculate the standard deviation of a lognormal distribution that reflects the adjusted slope-only estimating uncertainty of the CER.

The context for why the analogy varies significantly from the trend line should be understood. This difference could be due to differences in overhead rates or labor rates. For example, a satellite developed by a university using graduate students to design the bus should have lower direct and indirect labor costs than a prime contractor occupying expensive real estate and utilizing highly experienced engineers. If there is a logical explanation such as this one for the variation in cost from the trend line, then the standard error of the slope can be reasonably used to model estimating uncertainty. Conversely, if an analogy is selected simply due to superficial similarities, then care should be exercised in arbitrarily assuming that uncertainty will be reduced because of calibration. For example, if an analyst is estimating the cost for a mission planned for Mars, and an analogy is selected for calibration because the CER database includes both earth-orbiting satellites and planetary spacecraft, and there is only one Mars mission in the database, then the analogous data point should be researched to determine whether or not differences between the trend line and the cost for the analogy are due to well-understood programmatic factors, or because of cost growth experienced by the analogous program. For example, if the analogy is above the trend line because it experienced 100% cost growth, the confidence level of the point estimate should be adjusted to reflect this. Based on history, the confidence level for such a mission is quite high, above 90%, as discussed in “Covered with Oil: Incorporating Realism in Cost Risk Analysis” (Smart 2011). Table 8.1 provides a set of confidence levels based on historical cost growth discussed in this paper.

Cost Growth	Confidence Level
<-10%	6%
-9.900%	18%
0.1%-10%	30%
10.1%-20%	43%
20.1%-30%	51%
30.1-50%	64%
50.1%-75%	79%
75.1%-100%	84%
100.1%-150%	92%
150.1%-200%	95%
>200%	99%

Table 8.1. Historical Cost Growth and Associated Percentiles

For the data summarized in this table, 30% of missions experienced cost growth less than or equal to 10%, which means if the analogous mission grew by 8%, it is reasonable to expect that the point estimate is close to the 30th percentile of the estimating uncertainty distribution. Once a confidence level is established, the standard error of the estimate can be used to determine a lognormal distribution that characterizes the estimating uncertainty. If X is equal to the Y^{th} percentile, the log-space standard deviation q is equal to the standard error, and the log-space mean p can then be calculated as

$$p = \ln(X)+(z_Y)q$$

Where z_Y represents the inverse of the standard normal distribution evaluated at Y. This is also known as the Z-score which used to be found in tables at the back of college textbooks on statistics.

The arithmetic space mean and standard deviation can be calculated from their log-space equivalents by solving the following formulas for E(X) and Var(X):

$$E(X) = \exp(p+0.5q^2)$$

$$Var(X) = (\exp(q^2)-1))\exp(2p+q^2)$$

As an example, if the point estimate is $200 million and represents the 30^{th} percentile, and the log-space standard error of the estimate is equal to 0.4, then

$$P = \ln(200)+0.4*z_{0.3} = 5.2983+0.4*(-0.5244) \sim= 5.0886$$

Using these formulas for expected value and variance, the mean is approximately $176 million, the variance is $5,354 million, and thus the standard deviation approximately $73 million.

In summary, calibration has a significant impact on risk assessment. It does not affect parameter uncertainty, but should be used to adjust estimating uncertainty. If the calibration is done because the estimate varies from the trend line due to well-understood reasons that make it highly similar to what is being estimated, then the error about the slope should be used in place of the estimating error of the equation, making sure to adjust to the appropriate unit. However, if the analogy is chosen for more superficial reasons, the estimating error of the equation should be used, and the confidence level of the point, or non-risk adjusted, estimate should be set based on the cost growth of the analogous program, using the information in Table 8.1 to determine an appropriate confidence level for the mission being estimated.

Another model used in cost estimating is to use an analogy, and then adjust the analogy by a complexity factor. This is similar to the concept of using a CER, except that supporting data or expert opinion is used to directly adjust the analogy, i.e.,

$$Estimate = Analogy*C.F.$$

where CF denotes the complexity factor. In such a case, there is no CER to assign estimating uncertainty based on statistics. Rules of thumb based on CER uncertainty or expert opinion should be used to assign uncertainty to the analogy, and uncertainty should be placed on the complexity factor based on variation in the data used to develop the factor. See the presentation on "Quick-Turn Risk Analysis" (Smart, 2011) for information on how to assign risk when little or no historical data are available. The presentation was used for point estimates, but the same concept applies equally well to the use of analogies, if there is uncertainty about the quality of the analogy (analogy is not recent, or there are concerns about the applicability of the analogy).

Bottoms-Up Estimates

Bottoms-up estimates are detailed estimates that involve determining the number of personnel, labor rates, and schedule to develop a detailed estimate from the ground up. In such cases, there is some uncertainty about the number of personnel, and labor rates. However, bottoms-up estimates are primarily developed with a short time horizon, so the largest uncertainty is schedule. Schedule, like cost, is subject to a great deal of uncertainty. For a sample of 98 satellite, spacecraft, and launch vehicle development projects, only nine of the projects were completed on time or less than 10% of the time, and the average growth was 38%. Figure 8.13 displays a histogram of the schedule growth.

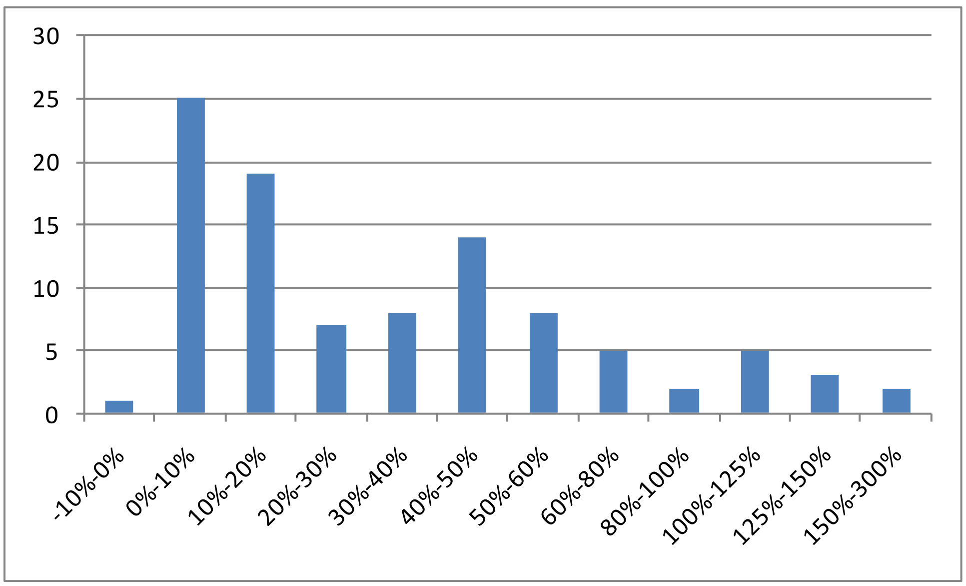

Figure 8.13. Schedule Growth Histogram.

The empirical schedule growth data can be used to develop project-level S-curves which are in line with history. The best fit of the empirical schedule growth data to a probability distribution is a lognormal distribution. The parameters of the lognormal distribution fit to the empirical data are ***location = -13%, mean = 38%, and standard deviation = 46%***. Note that a standard two-parameter lognormal distribution with location parameter *0* has the same standard deviation but with a mean equal to ***0.38+0.13 = 0.51*** so the coefficient of variation is actually ***90%.***

To calibrate, note the calibrated S-curve's log-space standard deviation is completely determined by the coefficient of variation, i.e.,

$$\boldsymbol{\sigma = \sqrt{ln\,(1 + CV^2)} = \sqrt{ln(1 + 0.90^2)} \approx 0.77}$$

Based on history, project schedules overrun 90% of the time. So, a point estimate of schedule is at the 10th percentile of the schedule risk distribution. The 10th percentile of a lognormal distribution, X_0, is equal to

$$X_0 = e^{\mu - 1.28\sigma}$$

Solving for μ yields

$$\mu = ln(X_0) + 1.28\sigma$$

The lognormal is a three-parameter lognormal; hence, the location parameter means that in order to calculate μ from a two-parameter lognormal, X_0 represents the difference between the 10th percentile and the lower bound, which is 0.13. X_0 is the 10th percentile of the project cost risk S-curve multiplied by 0.13. What is actually used in the calibration is

$$\mu = ln(0.13X_0) + 1,28\sigma$$

S-curve values for a lognormal can be calculated in Excel using the formula

"=LOGNORMDIST(Y, μ, σ)"

where ***Y*** varies from 0 to 1. To account for the shift, the calibrated S-curve value is calculated as

"=LOGNORMDIST((X-(1-0.13)*X_0, μ,σ)"

Expert Opinion

Expert opinion is best used on cost driver inputs. The amount of heritage and the level of technology maturity are two examples of qualitative programmatic factor that are often used as cost driver inputs. These factors are often best established by solicitation of information from qualified technical personnel. Expert opinion should be used selectively however, as an over reliance on subject matter experts for risk bounds can lead to questionable cost risk analyses. This method should not be used to assess cost risk in dollar terms. For example, if the analyst has developed a point estimate that is equal to $50 million, expert opinion should not be used to simply decide that the cost could be as low as $30 million or as high as $70 million. Just as cost analysts do not rely on project engineers to develop cost estimates for them, they should not have project engineers develop their risk estimates either.

Other Ways to Assess Uncertainty

1. Rules of Thumb

When triangular distributions are used to model cost risk, expert judgment has been shown to capture only about 70% of the total uncertainty (Air Force, 2007). The uncertainty captured is in the center of the distribution, e.g., between the 15th and 85th percentiles. Rules of thumb can be found in the *US Air Force Cost Risk and Uncertainty Handbook* (Air Force 2007), some of which are reproduced in Table 8.2.

Risk Level	Lower Bound	Point Estimate	Upper Bound
None	100%	100%	100%
Low	90%	100%	110%
Low-Medium	90%	100%	130%
Medium	90%	100%	150%
Medium-High	90%	100%	175%
High	90%	100%	200%
Very High	90%	100%	300%

Table 8.2. Rules of Thumb for Triangular Distributions (Air Force 2007)

As an example of how to apply the rules of thumb in Table 8.2, suppose that the non-risk-adjusted (point) estimate is $100 million, and risk is assessed to be "low" and that it has been decided that a triangular distribution will be used to model cost risk for this estimate. Using the rules of thumb in Table 8.2, and the guidance from the Air Force Cost Risk and Uncertainty Handbook, the low bound for the triangular will be 90% of the point estimate, that is, $90 million (=0.9*$100 million), and the high bound for the triangular will be 130% of the point estimate, that is, $130 million (1.3*$100 million). The "low" bound should be assigned a percentile higher than the absolute minimum, such as the 15^{th} percentile, while the "high" bound should be assigned a percentile less than the absolute maximum, such as the 85^{th} percentile.

It is worth reiterating that the triangular distribution should be used selectively. Many risks do not have definite, absolute bounds, but the cost analyst who uses a triangular distribution is making this assumption. Triangular distributions are often best applied to programmatic aspects that have limited amounts of risk, such as program office support. The number of civil servants typically does not change rapidly over limited time periods, so representing such risk with a triangular distribution, which has hard limits may be realistic.

2. Smart's Quick Risk - Assigning Uncertainty Based on Historical Cost Growth

To gain an understanding of how much additional funding will be required to fund a project, in practice it is useful to examine historical cost growth data. Building upon a data set of 112 NASA missions (Smart 2010), a data set of development cost growth was compiled for 289 NASA and DoD programs and projects (Abata 2004, DAMIR 2010, GAO 1992, 2004, 2009, IDA 2009, Phillips 2004, RAND 2006). The minimum cost growth was -25.2% for SLWT, a super lightweight version of the Shuttle external tank. The negative number means costs under ran their initial budget by approximately one-quarter of the initial budget (contrary to popular belief, missions occasionally come in under budget.) For the study, 47 missions experienced under runs, which is 16.3% of the missions studied. Only six of the missions hit their budget target spot on. Forty-three of the missions were within 5% of the initial budget, and 70 within 10% (either above or below). The maximum cost growth among the missions studied was 475% for the Comanche helicopter program, which was eventually cancelled before development was completed.

A range from -25% on the low side to over 450% on the high end is a wide range. The average cost growth for all missions was 52.0%, with median growth equal to 29.3%. The difference between the mean and median indicates a high degree of positive skew in the data, with most missions experiencing relatively small amounts of cost growth (half experienced growth less than 30%), with some missions experiencing extreme amounts of cost growth. The data are highly skewed (2.54) with a heavy right tail, as the sample kurtosis is 8.50. Overall, 47 missions had cost growth equal to or in excess of 100%, which means cost at least doubled. While representing only 16.3% of the cost growth data, it has been shown (Smart 2009) that growth of this severity while not extremely common occurs often enough to offset any hoped-for portfolio effect. Indeed many of the issues related to cost growth would be largely ameliorated if project managers could keep cost growth contained within 100%. This would require discipline to contain requirement growth, and realism about the heritage and the technology readiness in the early development stages. See Figure 8.14 for a graphical summary of these data. The data in Figure 8.14 include a wide variety of NASA and Department of Defense programs from the 1980s to the 2000s.

As stated earlier, cost risk is the probability that an estimate will exceed a specified amount, such as $100 million or $150 million. Cost growth and cost risk are thus intrinsically related. Historical cost growth provides an excellent means for determining the overall level of risk for cost estimates.

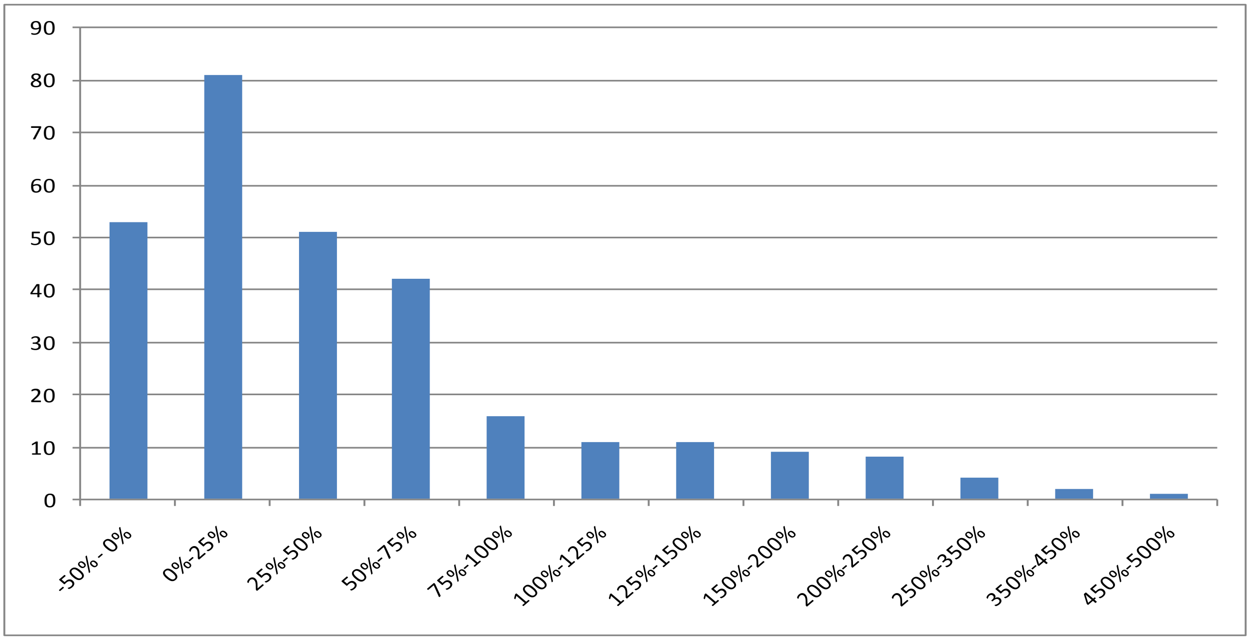

Figure 8.14. Summary of Cost Growth Data for 289 NASA and DoD Programs

For example, if 95% of past programs have experienced less than 100% growth, one should expect the ratio of actual cost to the initial estimate to be less than 100% with 95% confidence. Thus cost growth is the impact of cost risk in action. Because of uncertainty in historical data, cost models, program parameters, etc., the term “cost risk” is redundant. Thus characteristics of this cost growth data set determine characteristics seen in a cost risk distribution that is consistent with cost growth.

The cost growth data were fit to a variety of standard probability distributions using Crystal Ball, an Excel add-in. Crystal Ball uses maximum likelihood estimation to fit probability distributions, which works well when a large number of data points are available, as in this instance. To assess the fit of the distributions, the Anderson-Darling, Chi-Square, and Kolmogorov-Smirnov (K-S) statistics were calculated for each distribution. The statistics for the top three, as ranked by the Anderson-Darling statistic, are displayed in Table 8.3.

Distribution	**Anderson-Darling**	**Chi-Square**	**Kolmogorov-Smirnov**
Lognormal	**0.7221**	**21.6090**	**0.0471**
Gamma	**2.8967**	**37.6782**	**0.0736**
Weibull	**5.9722**	**54.7439**	**0.1330**

Table 8.3. Comparison of Best-Fitting Distributions for Cost-Growth Data

Each of these tests can be thought of as a measure of deviation from a perfect fit for the data. Thus for all three, a smaller test-statistic value indicates a better fit. These three tests focus on slightly different aspects of a distribution's fit. Anderson-Darling is focused on the fit at the tails of the distribution, K-S measures the maximum difference between the actual data and the fitted distribution, and Chi-Square is a sum of squares deviation measure.

Note: the lognormal distribution is the best-fitting distribution according to all three tests, and since the two-parameter lognormal is bounded below by zero and the cost growth data includes a significant number of data points with negative values, a three-parameter lognormal distribution is used in this case. The third parameter sets the minimum location for the distribution.

The empirical cost growth data can be used to develop project-level S-curves that are in line with reality. Based on the evidence that the lognormal distribution is best for describing cost growth and thus for modeling cost risk, a lognormal distribution is recommended for representing project risk. The parameters of the lognormal distribution fit to the empirical data are ***location = -31.8%, mean = 51.5%, and standard deviation = 72.1%***. A standard two-parameter lognormal distribution with location parameter *0* has the same standard deviation but with a mean equal to ***0.515+0.318 = 0.833*** so the coefficient of variation is actually ***86.6%.*** To calibrate, the calibrated S-curve's log-space standard deviation is completely determined by the coefficient of variation, i.e.,

$$\boldsymbol{\sigma = \sqrt{ln\,(1 + CV^2)} = \sqrt{ln(1 + 0.866^2)} \approx 0.748}$$

In cost analysts' experience and as shown anecdotally in the examples discussed, project budgets and cost estimates are similar, since both are based on project inputs, insight, and opinion. Project budgets tend to be on average at the 20th percentile, since roughly 80% of projects experience cost overruns. Project budgets, which are build ups of lower level elements and do not include risk, or correlation between WBS elements, are typically below the mode of a project cost risk analysis, so setting the overall confidence of the calibrate confidence to the 20th percentile of the project cost risk analysis seems to be a reasonable anchoring point. The 20th percentile of a lognormal distribution, X_0, is equal to

$$X_0 = e^{\mu - 0.8416\sigma}$$

Solving for μ yields

$$\mu = ln(X_0) + 0.8416\sigma$$

The lognormal is a three-parameter lognormal; hence, the location parameter means that to calculate μ from a two-parameter lognormal, X_0 represents the difference between the 20th percentile and the lower bound, which is 0.318. X_0 is the 20th percentile of the project cost risk S-curve multiplied by 0.318. What is actually used in the calibration is

$$\mu = ln(0.318X_0) + 0.8416\sigma$$

S-curve values for a lognormal can be calculated in Excel using the formula

"=LOGNORMDIST(Y,μ,σ)"

where ***Y*** varies from 0 to 1. In order to account for the shift, the calibrated S-curve value is calculated as

"=LOGNORMDIST((X-(1-0.318)*X_0, μ,σ)"

3. Garvey's Scenario-Based Method

Another way to assess cost risk and uncertainty is to examine various scenarios. The estimator develops a scenario estimate while developing the baseline point estimate, which typically represents a most likely estimate. The scenario method extends that to develop point estimates for an optimistic case and a pessimistic case. These are relative to the point estimate, e.g., the pessimistic case should be a case where the basis for the cost estimate is pessimistic relative to the most likely point estimate. This pessimistic case represents a scenario against which the project would like to protect.

The end result is a set of three estimates – optimistic, most likely, and pessimistic. These three values can be used to develop a triangular distribution, or another distribution, such as a three-parameter lognormal distribution. For more information see "Cost Risk Without Statistics" (Garvey 2005).

Methods for Aggregation of Cost Risk

1. *Simulation*

Monte Carlo simulation is the most common way to aggregate a cost risk analysis. It is a popular method for solving problems that are analytically intractable. It arose during the Manhattan project as a means to model the interactions inside an atom during nuclear fission which allowed for more sophisticated mathematical modeling of atomic phenomena that involves repeated random sampling. Most computer packages use pseudo-random number generators that produce seemingly random results from an initial seed. An example is the linear congruential generator

$$X_{n+1} = (aX_n + b) \bmod m$$

WBS cost risk is represented by a probability distribution. The most common method for sampling from a probability distribution is the inverse method. This involves obtaining a simulated random value from a uniform distribution and then inverting this through the cumulative distribution function (CDF) to obtain the simulated value.

Consider a uniform distribution on the interval [0,100]. The probability density function is

$$f(x) = \frac{1}{100}$$

The cumulative distribution function (i.e., “S-curve”) is

$$F(x) = \frac{x}{100}$$

To invert the distribution, solve the S-curve equation for ***x***, yielding

$$x = 100F(x)$$

Applying the inverse and noting that by definition

$$F^{-1}F(x) = x$$

Yields

$$F^{-1}(x) = 100x$$

To randomly sample a value from the distribution a random number between 0 and 1 is generated, and then the inverse is applied. If the random number generated is 0.5, then the inverse is equal to ***100*0.5 = 50***.

An example of how this process works is shown in Figure 8.15.

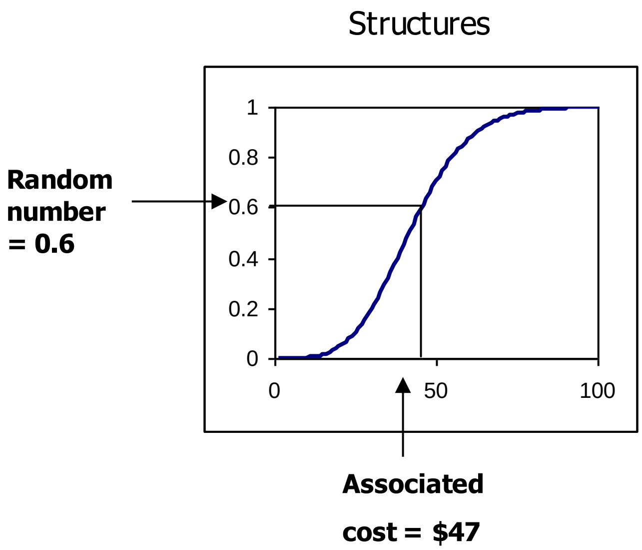

Figure 8.15. Simulating from the Inverse of the S-curve

Monte Carlo simulation involves a repeated number of trials, or iterations. The greater the number of trials, the more accurate the simulation will approximate the overall cost risk behavior of the system. After 100 trials, a histogram of the simulation outcomes typically looks like the one in Figure 8.16 - very jagged.

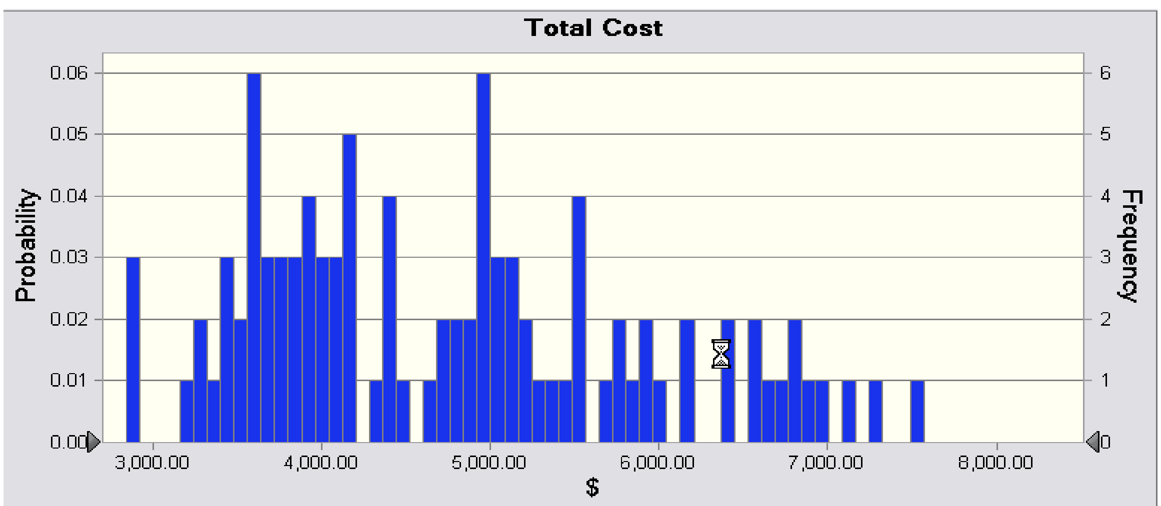

Figure 8.16. Example of Simulation Outcomes after 100 Trials

For the same example simulation, adding to the number of trials gives a more accurate depiction of the overall results as seen in Figure 8.17.

1,000 Trials

10,000 Trials

50,000 Trials

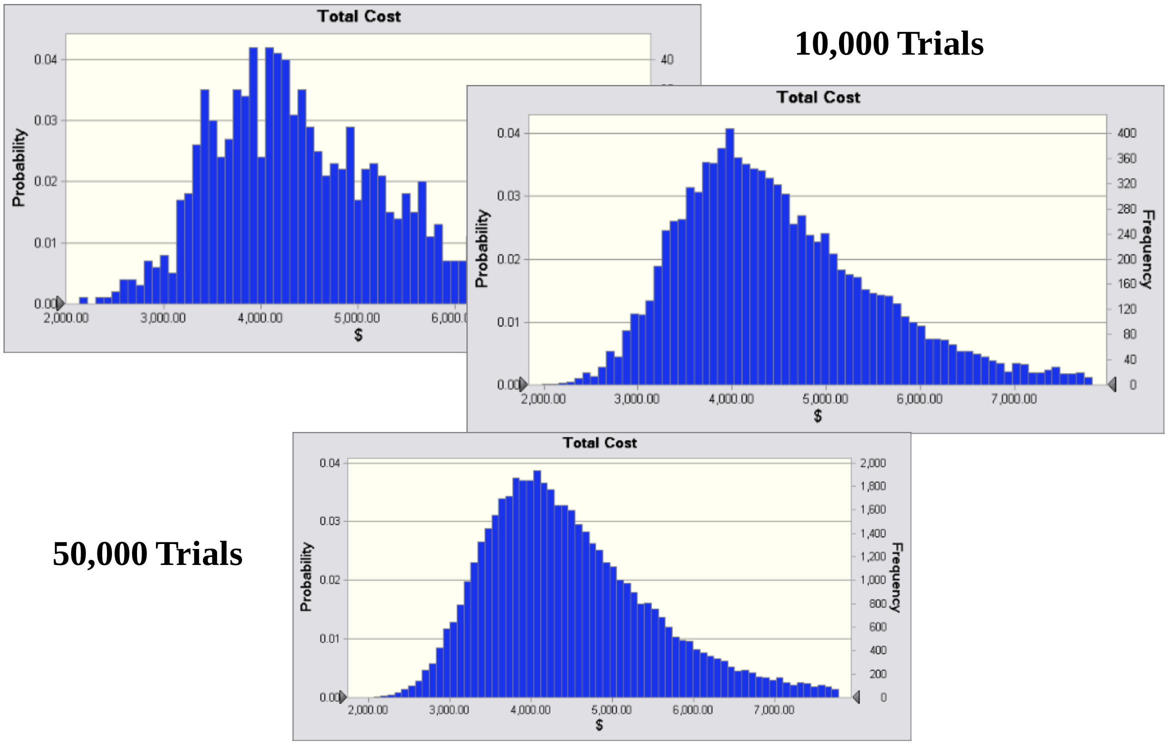

Figure 8.17. Adding Trials Yields More Accurate Depiction of Expected Simulation Outcome

To simulate the underlying mean within 1%, with 95% confidence, the following is required

$$0.95 = \Pr\left(0.99\mu \le \overline{X}_n \le 1.01\mu\right)$$

$$= \Pr\left(\frac{-0.01\mu}{\sigma/\sqrt{n}} \le \frac{\overline{X}_n - \mu}{\sigma/\sqrt{n}} \le \frac{1.01\mu}{\sigma/\sqrt{n}}\right)$$

$$= \Pr\left(\frac{-0.01\mu}{\sigma/\sqrt{n}} \le Z \le \frac{1.01\mu}{\sigma/\sqrt{n}}\right)$$

where Z is a standard normal distribution, by the Central Limit Theorem (CLT).

This means the number of trials required is determined by

$$\frac{.01\mu}{\sigma/\sqrt{n}} = 1.96$$

Solving for n, at least

$$38{,}416\frac{\sigma}{\mu}$$

trials are needed.

Note: this term involves the coefficient of variation of the distribution, which means distributions with less dispersion require fewer trials to accurate simulate.

Simulating percentiles requires more trials than for simulating means. Let P_n represent the number of trials in the sample at or below the 70th percentile of the underlying distribution (suppose this is known). By the CLT, P_n/n follows a normal distribution with mean equal to the 70th percentile, and variance equal to

$$\frac{F_{0.70}(1-F_{0.70})}{n}$$

By a similar process for the mean, the number of trials needed to simulate the 70th percentile within 1% with 95% confidence is

$$38{,}416\frac{n-P_n}{P_n}$$

If $P_n = 0.70$ for all n, then n is approximately

$$38{,}416\frac{n-P_n}{P_n} = 3(8{,}416)\left(\frac{n-0.7n}{0.7n}\right) = 38{,}416\left(\frac{0.3}{0.7}\right) = 16{,}464$$

For the sake of comparison, suppose the coefficient of variation is equal to 0.3. Then the number of trials needed to simulate the mean with the same accuracy is "only" 11,525 more trials are needed to accurately simulate percentiles than means.

The bottom line is that at least 10,000 trials are needed to accurately simulate the mean and percentiles of a cost risk analysis within 1%, with 95% confidence, and 20,000 is more likely the number of trials required.

Monte Carlo simulation is a standard term for simulation. However, there is a refinement on the standard Monte Carlo sampling notion that improves the accuracy of the results of a simulation for a given number of trials. This is called Latin Hypercube sampling. It is similar to basic Monte Carlo simulation, but Latin Hypercube requires an equal number of draws are taken from a set of subintervals; for example, dividing the interval (0,1) into [0.0,0.01), [0.1,0.2),…, [0.9,1.0]. Instead of 10 trials from [0,1], there is one trial from each subinterval. A rule of thumb is Latin Hypercube takes 30% fewer trials to achieve similar accuracy to basic Monte Carlo sampling. Latin Hypercube sampling is an option included in most commercial simulation packages.

2. Method of Moments

A viable alternative to simulation for aggregating WBS-level risks is to use an analytic approximation technique. Analytic approximation avoids doing a full simulation by approximating the sum of random variables. For example, if all the WBS elements were normally distributed, the top-level risk could be calculated by summing the means, and summing the variances (taking correlation into account). The sum of the means is the mean of the sums, and the top-level variance can be calculated as the sum of the variances, with an additional cross term to account for correlation. Specifically, for an n-element WBS in a cost risk estimate, let μ_i and σ_i represent the mean and standard deviation for the normal distribution that represents WBS element i, i = 1,…n., and ρ_{ij} represent the correlation between any two WBS element pairs i and j, i = 1,…,n and j = 1,…,n. Then the total cost means and standard deviations are calculated as:

Total Cost Mean = $\sum_{k=1}^{n} \mu_k$

Total Cost Standard Deviation = $\sqrt{\sum_{k=1}^{n} \sigma_k^{\,2} + 2\sum_{k=2}^{n}\sum_{j=1}^{k-1} \rho_{jk}\sigma_j\sigma_k}$

When all the variables are normally distributed the sum is also normally distributed. This is an important property of the normal distribution and is called *stability*. The only other stable distributions are the Cauchy, and the class of Levy-stable distributions. See Smart (Smart 2011) for a discussion on the use of Levy-stable distributions in cost risk analysis.

In the case of non-normally distributed random variables the sum of the random variables can be approximated by a normal or lognormal distribution by the method of moments, that is define a normal or lognormal by the top-level aggregate mean and variance. This will also work for any distribution which is completely defined by its mean and variance.

The advantages of analytic approximation is that it is computationally simple, calculates the correct top-level means and standard deviations, is faster than Monte Carlo, and allows full access to the correlation matrix.

Analytic approximation was explained thoroughly by Garvey (Garvey 2000). It was implemented in the Formal Risk Assessment of System Cost Estimates (FRISK) tool and in the NASA/Air Force Cost Model (NAFCOM) (Book and Young, 1992, Smart 2005). NAFCOM offers the analyst the opportunity to approximate the total-cost distribution by both normal and lognormal distributions. According to statistical theory, the normal distribution should provide a better approximation to a statistical sum of triangular distributions than would the lognormal distribution under three circumstances: there is a large number of WBS elements, so the CLT of statistics applies; the triangular distributions are not very skewed, so convergence of their sum to the (symmetric) normal distribution does not require very many WBS elements; or there is little or no correlation between WBS elements, so each WBS element contributes fully to the statistical sum, thereby achieving acceptable convergence with a smaller number of elements.

The normal approximation has been recommended by (Simpson and Grant, 2001).

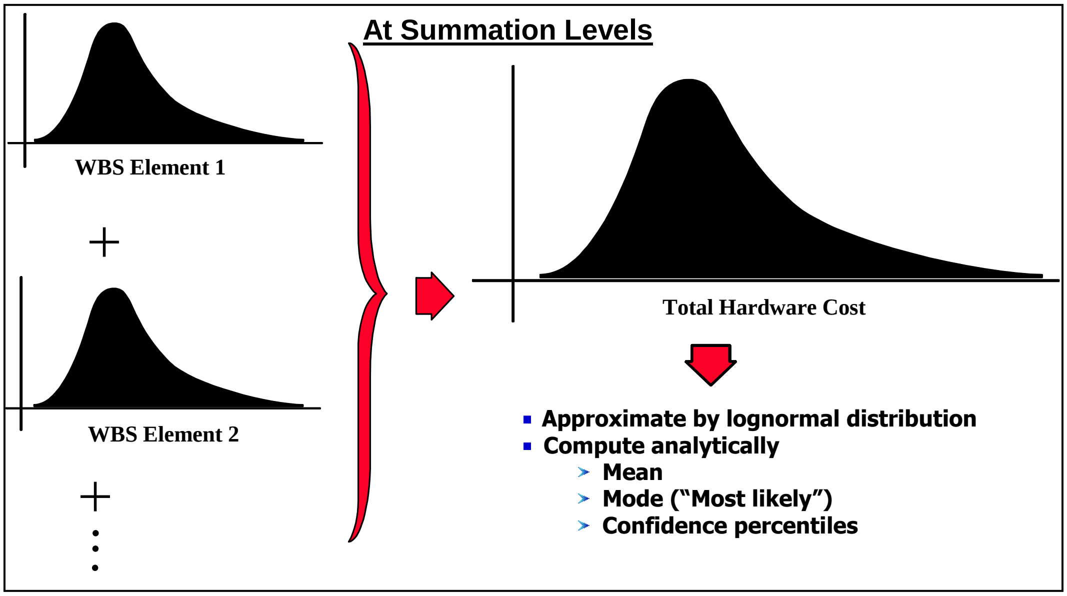

Figure 8.18. Graphical Illustration of the Method of Moments

There is no consensus in the cost analysis community on whether Monte Carlo simulation or analytic approximation is more accurate. Recent studies by Tecolote (Smith, 2004) and MCR (Alexander et al., 2004) show the two methods provide similar results. In 2004 the author conducted a comparison of method of moments with Monte Carlo simulation. The results were extremely close. Even for the worst case, the 5th and 95th percentiles were within 10% of one another. The results of these tests add evidence to other studies cited above that Monte Carlo simulation and analytic approximation provide similar results.

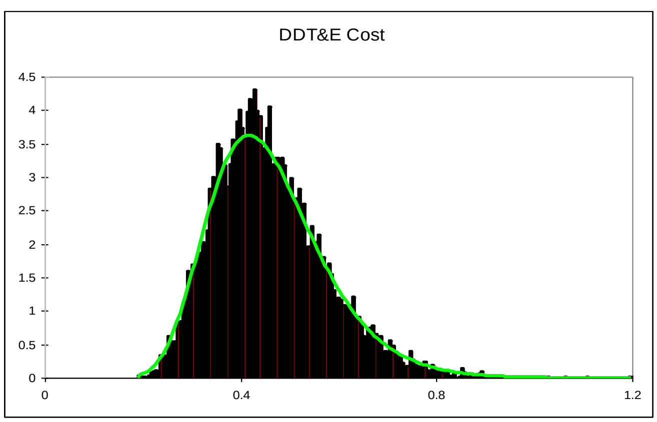

Figure 8.19. Comparison of Method of Moments and Monte Carlo Simulation - PDFs. (Smart, 2005)

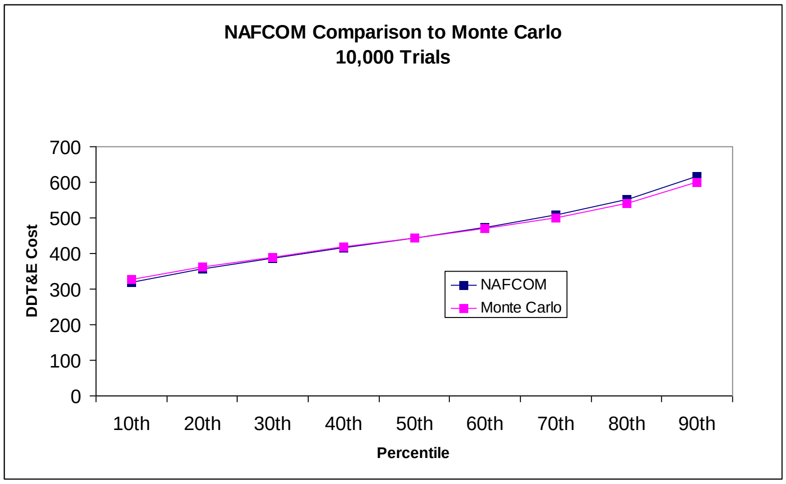

Figure 8.20. Comparison of Method of Moments and Monte Carlo Simulation - CDFs. (Smart, 2005)

3. Correlation

Correlation in cost between two events is the tendency for those costs to move in tandem. It can be positive when there is a tendency for one WBS element's cost to increase when another WBS element's cost increases. It can also be negative, which means there is a tendency for one WBS element's cost to decrease whenever another WBS element's cost increases, and vice versa.

Correlation is often ignored in cost risk analysis. However WBS elements are not independent, which is the underlying assumption when correlation is ignored. The analyst who ignores correlation is implicitly assuming all WBS elements are independent, which is not the case.WBS elements can directly influence one another. For example, if the diameter of a missile increases, additional thermal coatings will necessarily increase. Thus an increase in structures cost can directly lead to an increase in thermal control cost. Also, there are underlying common cause factors for cost growth. A budget constraint that leads to an increase in schedule will affect all WBS elements equally.

It is impossible to not make a choice about correlation. As in the song "Free Will" by the rock band Rush – "Even if you choose not to decide you still have made a choice," so the estimator who ignores correlation is making a choice about correlation: the wrong choice, since assuming complete independence will lead to underestimation of total, aggregate risk. See Figure 8.21 for a chart of how much the total standard deviation will be underestimated when correlation is assumed to be zero. For example, for a 100-element WBS, if the actual correlation is 20%, but it is assumed to be zero between all elements, then the total standard deviation will be underestimated by 80%.

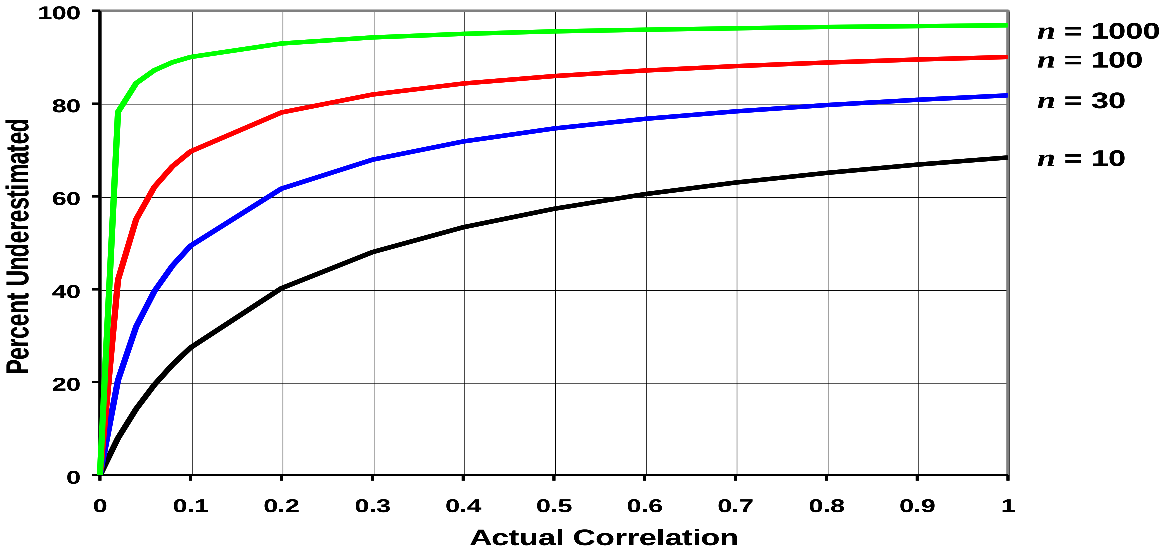

Figure 8.21. The Impact of Correlation on Risk (Book 2005).

Functional correlation is the correlation that is implicit when one cost estimate is a function of another cost estimate. For example, system engineering cost is often modeled as a function of hardware cost. In such a case, when simulation is used to measure and aggregate risk, the variation in hardware cost naturally results in a functional correlation with system engineering cost. In this case, correlation is handled without assigning correlation values and no correlation between hardware cost elements and system engineering needs to be assigned. However, unless structures and thermal control are modeled as functions of a single underlying phenomenon, then correlation between WBS elements needs to be explicitly modeled.

Notice in the graph in Figure 8.21 there is an apparent knee in the curve around 20%. Above 20% correlation the consequence of assuming less correlation begins to dwindle. This graph is the basis for assuming 20-30% for default correlation for elements between which there is no functional correlation.

However, a robust approach to assigning correlations would be to use the value that results in the least amount of error. The percent error in total standard deviation between the assumed and actual correlation values, denoting the assume correlation by ρ_1 and the actual correlation by ρ_2 is

$$\frac{\sqrt{n}\sigma\sqrt{1+(n-1)\rho_2}-\sqrt{n}\sigma\sqrt{1+(n-1)\rho_1}}{\sqrt{n}\sigma\sqrt{1+(n-1)\rho_2}}=\frac{\sqrt{1+(n-1)\rho_2}-\sqrt{1+(n-1)\rho_1}}{\sqrt{1+(n-1)\rho_2}}$$

A robust default measure of correlation would be a value for correlation that would minimize the error when your assumption differs from the actual underlying correlation. Assuming 0% correlation is wrong (as indicated true from experience) and 100% is also wrong; a value of 40% minimizes the sum of absolute errors over a range of WBS sizes. See Table 8.7 for an example.

	Assume Y, Actually X										
X/Y	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
10%	27.5%	0.0%	-21.4%	-39.5%	-55.6%	-70.1%	-83.5%	-96.0%	-107.7%	-118.8%	-129.4%
20%	40.2%	17.6%	0.0%	-15.0%	-28.2%	-40.2%	-51.2%	-61.5%	-71.1%	-80.3%	-89.0%
30%	48.0%	28.3%	13.0%	0.0%	-11.5%	-21.9%	-31.5%	-40.5%	-48.9%	-56.8%	-64.4%
40%	53.4%	35.7%	22.0%	10.3%	0.0%	-9.3%	-18.0%	-26.0%	-33.5%	-40.7%	-47.4%
50%	57.4%	41.2%	28.6%	18.0%	8.5%	0.0%	-7.9%	-15.2%	-22.1%	-28.6%	-34.8%
60%	60.5%	45.5%	33.9%	24.0%	15.2%	7.3%	0.0%	-6.8%	-13.2%	-19.2%	-25.0%
70%	63.0%	49.0%	38.1%	28.8%	20.6%	13.2%	6.4%	0.0%	-6.0%	-11.7%	-17.0%
80%	65.1%	51.9%	41.6%	32.8%	25.1%	18.1%	11.7%	5.6%	0.0%	-5.3%	-10.4%
90%	66.9%	54.3%	44.5%	36.2%	28.9%	22.3%	16.1%	10.4%	5.1%	0.0%	-4.8%

Table 8.7. Measure of Correlation

See Figure 8.22 for a graph of the average absolute percentage error. The graph reaches its lowest level at 40%, but at 30% and 50% also provide similar amounts of accuracy.

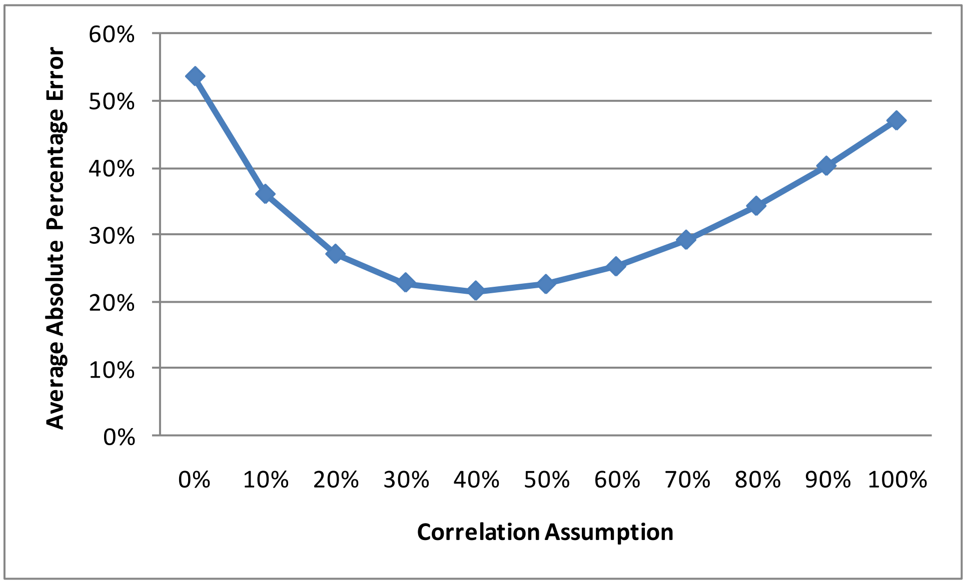

Figure 8.22. Correlation Assumption and Average Error

Thus 40%, in the absence of any other information, would be a logical choice for a default correlation value. However, there is empirical evidence to assign correlation at the 20% level. The average correlation values for NAFCOM version 2004 was 20% for RDT&E costs (see Table 8.8). These correlation values were calculated by correlating the residuals between the CERs, as discussed in the Aerospace Corporation's "Correlation Tutorial" (Covert and Anderson, 2005).

					Design and Development Correlation Matrix							
DD	ADCS	CCDH	EPS	Structures	Thermal	RCS	IACO	STO	GSE	SEI	PM	LOOS
ADCS	1	0.36	0.38	0	0.25	0.09	0.17	0.27	0.06	0.07	0.05	0.19
CCDH		1	0	0.15	0.05	0	-0.16	0.52	0.05	0.04	0.06	0.06
EPS			1	-0.04	-0.04	0.14	-0.17	0.54	0.06	0.06	0.07	0.19
Structures				1	0.32	0.24	-0.01	0.14	0.06	0.06	0.06	0.09
Thermal					1	0.11	0.16	-0.11	0	0.01	0.03	0.25
RCS						1	0.07	-0.03	0.09	0.09	0.11	0.22
IACO							1	-0.26	0.79	0.83	0.83	0.73
STO								1	0.1	0.1	0.1	0.24
GSE									1	1	0.69	1
SEI										1	1	1
PM											1	0.46
LOOS												1

Table 8.8. Correlations in NAFCOM v 2004 for RDT&E (previously unpublished, developed by Smart) – Average = 21.3%

				Flight Unit Correlation Matrix					
FU	ADCS	CCDH	EPS	Structures	Thermal	RCS	IACO	SEI	PM
ADCS	1	0.5	-0.12	-0.26	0.58	0.24	0.16	0.07	0.09
CCDH		1	0.14	0.01	0.13	-0.03	-0.04	-0.05	-0.04
EPS			1	0.08	-0.12	-0.09	0.16	0.12	0.14
Structures				1	0.21	-0.1	0.06	0.11	0.11
Thermal					1	0.1	0.22	0.17	0.17
RCS						1	0.27	0.32	0.33
IACO							1	0.71	0.71
SEI								1	1
PM									1

Table 8.9. Correlations in NAFCOM v 2004 for Theoretical First Unit (previously unpublished, developed by Smart) – Average = 16.8%

	ADCSNR	AGENR	COMMNR	EPSNR	IATNR	PROGNR	STRCNR	THERNR	TT CNR	ADCST1	AKMT1	COMMT1	EPST1	IATT1	LOOST1	PROGT1	STRCT1	THERT1	TT CT1
ADCSNR	1.000	-0.067	-0.096	-0.035	0.035	0.012	0.413	0.605	0.121	-0.095	0.983	-0.122	0.099	0.564	0.139	0.089	-0.047	-0.057	0.092
AGENR		1.000	-0.028	0.525	-0.079	0.127	0.091	-0.230	-0.125	0.416	0.001	0.085	-0.043	-0.163	-0.189	0.033	0.146	0.151	0.232
COMMNR			1.000	0.888	0.884	0.966	0.762	0.281	0.850	-0.166	0.305	-0.176	0.157	0.368	0.884	-0.158	0.109	0.037	-0.004
EPSNR				1.000	0.265	0.604	0.409	0.003	0.337	0.237	0.011	-0.275	0.076	0.342	0.021	-0.049	0.465	0.123	0.035
IATNR					1.000	0.721	0.615	0.331	0.747	-0.037	0.391	-0.133	-0.028	0.501	0.265	-0.145	0.113	-0.014	-0.189
PROGNR						1.000	0.697	0.222	0.868	-0.065	0.145	-0.191	-0.044	0.444	0.329	-0.191	-0.000	-0.125	0.019
STRCNR							1.000	0.837	0.761	-0.001	0.117	-0.214	-0.113	0.418	0.173	-0.018	0.220	-0.103	0.069
THERNR								1.000	0.077	-0.200	0.662	-0.171	-0.053	0.514	0.102	-0.010	-0.063	-0.165	0.092
TT CNR									1.000	-0.149	0.475	-0.118	-0.071	0.519	0.294	-0.178	-0.111	-0.095	0.022
ADCST1										1.000	-0.100	0.614	0.421	-0.262	-0.354	0.543	0.676	-0.029	0.655
AKMT1											1.000	-0.006	0.292	0.855	0.286	0.176	-0.003	-0.027	0.052
COMMT1												1.000	0.266	-0.454	-0.088	0.777	0.729	0.126	0.391
EPST1													1.000	-0.150	-0.145	0.381	0.388	-0.007	0.520
IATT1														1.000	0.448	-0.144	-0.224	-0.014	-0.320
LOOST1															1.000	-0.336	-0.097	-0.074	-0.169
PROGT1																1.000	0.421	-0.039	0.481
STRCT1																	1.000	-0.175	0.285
THERT1																		1.000	-0.140
TT CT1																			1.000

Table 8.10. Average correlation for the Unmanned Spacecraft Cost Model v 7, average = 16% (Covert and Anderson, 2005)

Default correlation values in the range 20-30% are recommended.

Risk Measurement

"Western Europe conquered the world because of a technological revolution that started because of attempts to measure the world." (Jorion 2007) In the same way, attempts to measure risk will lead to better project management.

A *risk measure* is defined as a single number from a probabilistic cost estimate's distribution that represents program cost. For example, the mean is a risk measure for a probabilistic cost estimate. The mode, or most likely value of a probabilistic cost estimate, is another commonly used risk measure at which funding is set. While some government agencies fund at the mean and the mode, many government agencies fund at a percentile. Indeed NASA policy explicitly mentions budgeting at the 70th percentile, at funding projects at no less than the 50th percentile. The 80th percentile is mentioned in the Weapon Systems Acquisition Reform Act (WSARA).

Thus percentile funding is the most common risk measure. One aspect that various percentile funding (50th, 70th, 80th) and the mean have in common is that they are values from the probability distribution. Percentile (or VaR) funding has some merits. It can be used to compare the funding requirements of different projects. It can be easily understood by decision makers who may not be fluent in the details of probability and statistics. Risk reserves can be defined in terms of it. It is currently part of NASA and DoD policies and is commonly used even in the banking industry. However risk management shouldn't stop at that point because, for example, even funding at the 70th percentile means that there is almost a one-in-three chance of experiencing an overrun. And not only that, but funding at the 70th percentile provides no information about what may happen above that level.

The many limitations inherent in percentile funding as well as appealing alternative risk measures are described in detail in "Here There Be Dragons: Incorporating the Right Tail in Risk Management" (Smart 2010). The portfolio effect was discussed in detail in the risk aggregation section. Also expected shortfall avoids the Lognormal Paradox as discussed in "The Fractal Geometry of Cost Risk (Smart, 2008).

Risk Allocation

Once risk is measured at the project level, it is a non-trivial exercise to determine how much of that total risk is attributable to each individual WBS element. This is because, even though total cost is the sum of the costs for each WBS element, most risk measures do not add. For example if percentile funding is used for risk measurement, it is often (but not always) the case that the sum of the percentiles will be greater than the percentile of the sums of the individual WBS elements. As an example consider two independent and normally distributed random variables, X_1 and X_2 with $X_1 \sim N(100,20)$ and $X_2 \sim N(300,80)$. To combine these two distributions the means and the variances are (separately) aggregated, so that the total mean is $100+300 = 400$, and the total variance is $20^2+80^2 = 6800$. The standard deviation is the square root of this latter value, which is approximately 82.5. The combined random variable, X_1+X_2, is also normally distributed with mean equal to 400 and standard deviation equal to 82.5, i.e., $X_1+X_2 \sim N(400,82.5)$. The 80th percentile of X_1 can be calculated as

$$p_{.80} = \mu + z_{.80}\sigma \approx 100 + 0.8416 \cdot 20 \approx 116.8$$

where $z_{.80}$ is equal to the inverse of the standard normal distribution at the 80th percentile.

Similarly, the 80th percentile of X_2 is approximately 367.3, and the 80th percentile of X_1+X_2 is approximately 469.4. Thus the sum of the 80th percentiles for X_1 and X_2 is *116.8+367.3=484.1*, which is larger than the 80th percentile of the sum X_1+X_2. In other words, percentiles do not add. One cannot add the 80th percentiles and expect this sum to be equal to the 80th percentile of the sum of the random variables. To see why this is the case in general for the sum of two independent normally distributed variables note that the percentiles are determined by the mean and standard deviation. The sum of the means of random variables is equal to the mean of the sum of the random variables, regardless of the distribution type, so the difference lies with the variance. For combining independent normal random variables, the variances are added rather than the standard deviations, which is key, since the sum of the variances, where the standard deviations of the individual normal random variables are denoted by a and b, is equal to a^2+b^2. The standard deviation of the sum is the square root of this quantity, i.e., $\sqrt{a^2+b^2}$**.** Note that since $a^2+b^2 \le a^2+2ab+b^2$**,** it follows that $\sqrt{a^2+b^2} \le a+b$, with strict inequality unless at least one of a or b is equal to zero. Note that $\sqrt{a^2+b^2}$ represents the risk of the combined distributions. The quantity $a+b$ represents the sum of the individual risks. Thus in this case, combining the independent elements is a diversification of risk. The total portfolio is not as risky on a relative basis as each individual project.

Since percentiles do not add, when funding at specific percentiles, risk allocation becomes a non-trivial exercise. More generally, risk measures are not typically additive, so whatever risk measure is being used at the total project level, some care is required to effectively and fully allocate risk. The goal of risk allocation is to apportion the total estimate to individual WBS elements so each is funded in a manner such that the sum of the individual WBS allocations equals the total risk measurement. Risk allocation should also take into consideration the impact of correlation. However, at least one widely used method does not take correlation into account.

Standard Deviation-Based Methods for Allocating Risk

The current established state-of-the-practice methods for allocating risk are based on standard deviation as the measure of risk. The first method is conceptually simple. It involves apportioning the risk by setting the amount allocated for a WBS element equal to its ratio to the sum of the total standard deviations. For example for a project with two elements with standard deviations equal to 100 and 200, the sum of the standard deviations is 300, and the ratio of the first element to the sum is 100/300 = 1/3; it is allocated one-third of the total risk reserve, while the second is allocated the remaining two-thirds. This method, which is referred to as the proportional standard deviation method, is easy to understand and easy to implement in a spreadsheet. In the past it has typically been used to allocate risk when risk is measured as a percentile.

Allocating percentile funding via proportional standard deviation begins with calculating the specified percentile, such as the 70th or 80th. When a normal or lognormal probability distribution is used to represent cost risk the mean and standard deviation describe the distribution and are typically used as the parameters to define it. Note: in the case of *n* independent WBS elements the total standard deviation can be calculated as

$$\boldsymbol{\sigma_{Total}} = \sqrt{\sum_{i=1}^{n} \boldsymbol{\sigma_i^2}}$$

For normal and lognormal distributions, once the mean and standard deviation have been determined, a percentile, such as the 80th percentile, may be calculated. For a normal distribution the calculated 80th percentile is

$$\boldsymbol{\mu_{Total} + z_{0.80}\sigma_{Total}}$$

If the mean is used as the point estimate (i.e., the non risk-adjusted cost estimate), since the sum of the individual WBS elements' means is the total mean, the risk dollars to be allocated back is simply

$$\boldsymbol{\mu_{Total} + z_{0.80}\sigma_{Total} - \mu_{Total} = z_{0.80}\sigma_{Total}}$$

These risk dollars are what is allocated back to each individual WBS element, and amounts to the risk reserve above the mean.

Now that the risk dollars have been determined, calculate the WBS element's portion of this total, i.e.,

$$\boldsymbol{p_i = \frac{\sigma_i}{\sum_{j=1}^{N} \sigma_j}}$$

These risk dollars are then allocated to each specific WBS element. In the case of a normal or distribution the amount of risk dollars assigned to a specific WBS element is

$$\boldsymbol{\mu_i + p_i(z_{0.80}\sigma_{Total})}$$

These individual amounts add to the total 80th percentile since

$$\begin{aligned}\sum_{i=1}^{n} \boldsymbol{\mu_i + p_i(z_{0.80}\sigma_{Total})} = \sum_{i=1}^{n} \boldsymbol{\mu_i} + \sum_{i=1}^{n} \boldsymbol{p_i(z_{0.80}\sigma_{Total})} &= \boldsymbol{\mu + (z_{0.80}\sigma_{Total})} \sum_{i=1}^{n} \boldsymbol{p_i} \\ &= \boldsymbol{\mu + z_{0.80}\sigma_{Total}}\end{aligned}$$

and the allocation weights $\boldsymbol{p_i}$ sum to **1**.

Allocating via proportional standard deviation is not an optimal way to allocate risk when percentile funding is used as the risk measure. For more information, refer to "Cost Risk Allocation Theory and Practice" (Smart, 2011).

The proportional standard deviation method has some drawbacks. The most obvious is that summing the standard deviations is a heuristic without basis in theory. The sum of standard deviations is not the total standard deviation for example, or really any useful statistic at the total project level. (However in a later section it will be shown that under some specific circumstances this is an optimal way to allocate risk). Another glaring drawback is that it ignores correlation, and so may allocate risk to individual elements in a non-optimal manner. Also, the proportional standard deviation method equates risk with standard deviation. However, the two are not the same. When risk is high, uncertainty is also necessarily high, but the converse is not always true. It may be the case that uncertainty is high but risk is low. Consider the example of two triangular distributions displayed in Figure 8.23 due to Book (Book 2006).

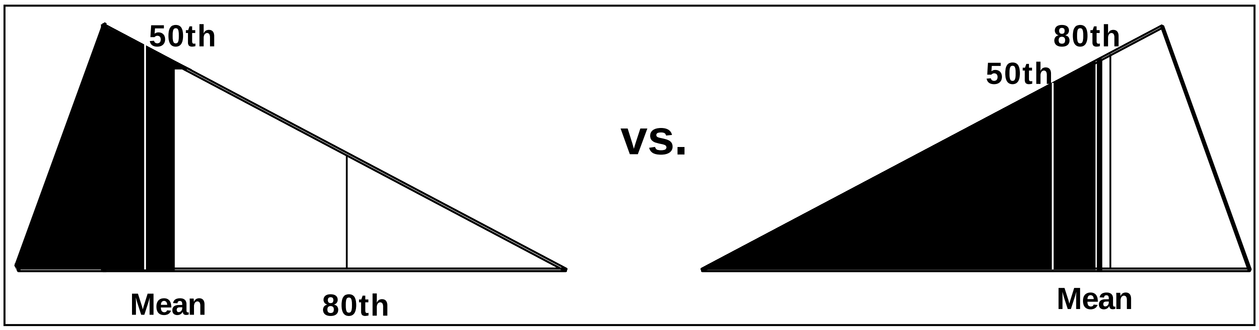

Figure8.23. Triangular Distributions: Equal Uncertainty but Different Risk Amounts

The two triangular distributions displayed in the figure are mirror images of one another and hence have the same amount of uncertainty and the same standard deviation. However, if the point estimate is represented by the mean and risk is measured as the 80th percentile, then the triangular distribution on the left has much more risk than the triangular distribution on the right. As is evident from the graph the triangular distribution on the right requires few risk dollars above the mean to achieve the 80th percentile.

The correlation issue can be overcome; the method could be changed to one based on covariance contributions. The covariance principle is based on the notion that in the general case when one considers correlation among WBS elements, the total variance is equal to

$$\boldsymbol{Total\,Variance} = \boldsymbol{\sigma}^{\boldsymbol{T}}\boldsymbol{P}\boldsymbol{\sigma}$$

where $\boldsymbol{P}$ is the $\boldsymbol{N} \times \boldsymbol{N}$ correlation matrix, and $\boldsymbol{\sigma}$ is the $\boldsymbol{N} \times \mathbf{1}$ vector of standard deviations for the individual WBS elements. The amount the i^{th} WBS element contributes to the total variance is equal to

$$\boldsymbol{\Gamma_i} = \boldsymbol{\sigma_i}\sum_{\boldsymbol{j}=\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{\rho_{ij}}\boldsymbol{\sigma_j}$$

where $\boldsymbol{\rho_{ij}}$ is the correlation between the i^{th} and j^{th} WBS elements. The covariance principle then allocates risk as

$$\boldsymbol{p_i} = \frac{\boldsymbol{\Gamma_i}}{\boldsymbol{Total\,Variance}}$$

Since

$$\sum_{i=1}^{N} p_i = \sum_{i=1}^{N} \frac{\Gamma_i}{Total\,Variance} = 1$$

the risk allocation fully distributes the risk to the WBS elements. This is the only specific requirement of these risk allocation schemes, which is that they are complete – they distribute the total risk dollar among the elements, no more and no less. There are others that will be considered when optimal allocation is covered. Another potential issue is the possibility of a negative allocation if negative correlations are present (Hermann 2010). While not a conceptual problem, it may be hard to communicate with management. Even though the covariance principle overcomes the specific issue of correlation not considered by the proportional standard deviation method, it too does not distinguish between downside opportunities for cost savings and upside risk of cost growth. To distinguish between upside risk and downside opportunity, the notion of need was introduced (Book 2006). This idea is based on the concept of semi-variance. Semi-variance only looks at the second moment above the mean. For a continuous random variable $\boldsymbol{X}$ this is defined as

$$\int_{-\infty}^{\infty} (x-\mu)_+^2\, f(x)dx = \int_{\mu}^{\infty} (x-\mu)^2\, f(x)dx$$

where $Y_+ = max(Y, 0)$.

The notion of need considers the difference between a selected percentile, such as the 80th, and a point estimate, such as the mean. The difference between these two values at the total project level is the amount of risk dollars. Similar to covariance, the total need base is calculated as

$$Need\ Base = \sum_{i=1}^{N}\sum_{j=1}^{N} \rho_{ij} Need_i\, Need_j$$

For the i^{th} element, if the project's percentile risk measure (denoted by π_i) is lower than the reference point estimate (denoted by c_i), e.g., the mean, then the need for the i^{th} element is $\boldsymbol{0}$. Otherwise the need for the i^{th} element is positive, and the need contribution of the i^{th} element to the total need is calculated as

$$\sum_{j=1}^{N} \rho_{ji} Need_j Need_i$$

where

$$Need_i = \max(0, \pi_i - c_i)$$

The percentage of risk dollars allocated to the i^{th} element is then calculated as

$$p_i = \begin{cases} \frac{\sum_{j=1}^{N} \rho_{ji} Need_j Need_i}{Need\ Base} & if\ Need_i > 0 \\ 0 & if\ Need_i = 0 \end{cases}$$

The need concept also has its drawbacks. Negative correlation can lead to negative need allocations, just as with the covariance principle. More importantly, the concept of need ignores the tail of the distribution (Sandberg 2007). This is an important consideration in risk measurement, as discussed in a recent ISPA/SCEA presentation (Smart 2010). First brought to the attention of the cost community by Book (Book 2007), Sandberg (Sandberg 2007) leverages this idea by proposing using semi-variance at the element level to allocate risk and replaces the need at the element level with the positive semi-variance. The idea of using semi-variance to measure risk is a long-standing one. One of the first proponents of semi-variance in finance was the Nobel Prize-winning economist Markowitz (Markowitz 1959). While taking into account the right tail of the distribution, Sandberg does not consider the relationship between the sum of the semi-variance contributions, and the total semi-variance, so again risk allocation and risk measurement are considered as two separate, independent problems. Sandberg (Sandberg 2007) considers the issue of optimization but only in the narrow context that the method he proposes by definition minimizes a specific quantity.

The needs method is recommended as being near optimal when percentile funding is used as the risk measure.

Incorporating Program Risks

Just as a point, i.e., non risk-adjusted, estimate for cost must be consistent with a program's technical baseline, so too a cost risk assessment must incorporate the cost impacts of the major risks that are tracked by the program's quality engineering staff.

Quality/reliability engineers assess and track major programmatic risks. These risks are major if the program considers them to be significant and something the program should guard against and work to mitigate. These risks are assessed and tracked by using a 5x5 risk matrix which considers both the likelihood and the consequence of an event's occurrence. In 2009, a test failure occurred during FTT-11, when an air launch target built by Coleman Aerospace Corporation (CAC) failed to ignite, as reported in *Space News* on December 14 of that year (http://www.spacenews.com/military/091214-target-failure-halts-thaad-test.html). The MDA found specific and systemic issues with CAC engineering and production capability. As a result of the failure review board's investigation, MDA imposed a moratorium on the use of CAC targets until these problems were resolved and a demonstration flight completed. The risk is that CAC would not be able to overcome these issues, resulting in a termination of the targets planned for future tests. As a relatively low-cost alternative, realization of this risk would result in increased cost and schedule delays. See Figure 8.24 for the associated 5x5 risk matrix.

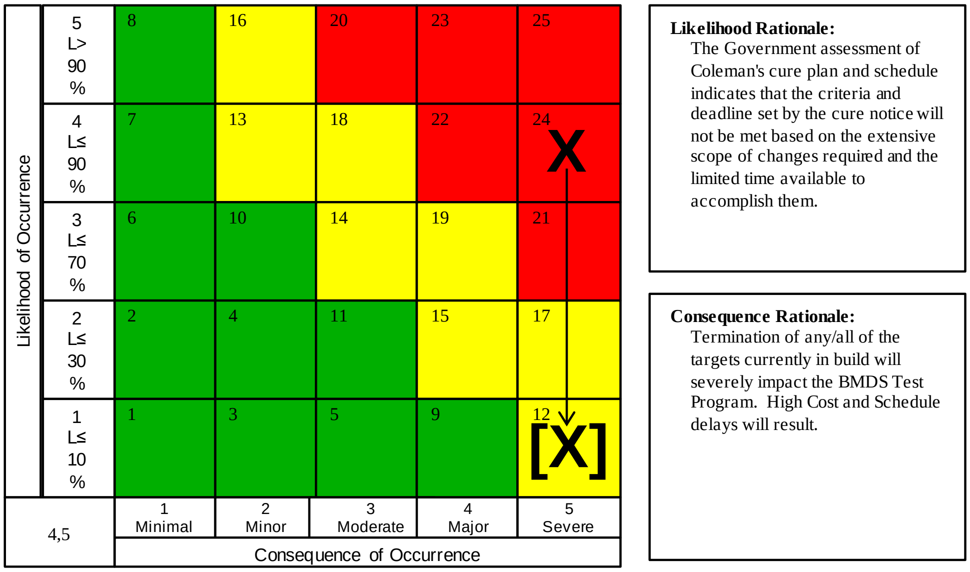

Figure 8.24. Example of a 5x5 Risk Matrix

To incorporate this risk in a cost estimate, the estimator works with technical personnel to understand the likelihood and cost consequence of occurrence. Once a probability of occurrence is assigned, say $\boldsymbol{p}$, and a cost estimate for the consequence of this risk is calculated, say $\boldsymbol{c}$, then the expected additional cost will be

$$\boldsymbol{p} * \boldsymbol{c}$$

This is simulated using Monte Carlo analysis with a binomial distribution for the likelihood of occurrence (either the event occurs or it does not), and a range around the expected cost. This uncertainty is then be incorporated in the WBS elements associated with that particular risk, and aggregated along with the other WBS items included in a Monte Carlo simulation.

GAO Checklist on Cost Risk (GAO, 2009)

(a) A risk and uncertainty analysis quantified the imperfectly understood risks that are in the program and identified the effects of changing key cost driver assumptions and factors.
   i. Management was given a range of possible costs and level of certainty in achieving the point estimate.
   ii. A risk adjusted estimate that reflects the program's risk was determined.
   iii. A cumulative probability density function (S curve) mapped various cost estimates to a certain probability level and defensible contingency reserves were developed and included supporting documentation.
   iv. Periodic risk and uncertainty analysis was conducted to improve estimate uncertainty.

(b) Program cost drivers and associated risks were determined, including those related to changing requirements, cost estimating errors, business or economic uncertainty, and technology, schedule, program, and software uncertainty.

i. All risks were documented for source, data quality and availability, and probability and consequence.
ii. Risks were collected from staff within and outside the program to counter optimism. Risks included reflect program risks (5x5 matrix risks are included).
iii. Uncertainty was determined by cost growth factor, expert opinion (adjusted to consider a wider range of risks), statistics, technology readiness levels, software engineering maturity models and risk evaluation methods, schedule risk analysis, risk cube (P-I matrix) method, or risk scoring.

(c) A probability distribution modeled each cost element's uncertainty based on data availability, reliability, and variability.

i. A range of values and their respective probabilities were determined either based on statistics or expressed as 3-point estimates (best case, most likely, and worst case), and rationale for choosing which method was discussed.
ii. Documentation of the rationale for choosing the probability distributions was provided.
iii. Probability distributions used reflect the risk shape and the tails of the distribution reflect the best and worst case spread as well as any skewness. Distribution bounds were adjusted to account for stakeholder bias using organization default values when data specific to the program were not available.
iv. If the risk driver approach is used, the data collected, including probability of occurrence and impact, were applied to the risks themselves.
v. Prediction interval statistical analysis was used for CER distribution bounds.

(d) Correlation between cost elements was incorporated.

i. The correlation ensures that related cost elements move together during the simulation, resulting in reinforcement of the risks.
ii. Cost estimators examined the amount of correlation already existing in the model. If no correlation is present, a default of 20% was used.

(e) A Monte Carlo or method of moments model was used to develop a distribution of total potential costs and an S curve showing alternative cost estimate probabilities was developed.

i. High priority risks were examined and identified for risk mitigation.
ii. Strength of correlated cost elements were examined and additional correlation was added if necessary to account for risk.
iii. The S-curve was documented, along with associated total risk statistics, including mean, standard deviation, 5^{th}, 95^{th} and deciles (10^{th}, 20^{th}, 30^{th}, etc).
iv. Coherent risk measures such as expected shortfall (conditional tail expectation) have been calculated.
v. The confidence level associated with the point estimate was identified.

vi. Contingency reserves were recommended for achieving the desired confidence level.

1. Budgeting to at the mean of the distribution or higher is necessary to guard against potential risk.
2. The cost risk and uncertainty results were vetted through a core group of experts to ensure the proper steps were followed.
3. The estimate is continually updated with actual costs and any variances recorded to identify areas where estimating was difficult or sources of risks were not considered.

vii. The risk-adjusted cost estimate was allocated, phased, and converted to then-year dollars for budgeting, and high-risk elements were identified to mitigate risks.

viii. A risk management plan was implemented with the contractor to identify and analyze risk, plan for risk mitigation, and continually track risk.

1. A risk database watch list was developed, a contractor's EVM system was used for root cause analysis of cost and schedule variances, monitoring worsening trends, and providing early risk warning.
2. Event-driven reviews, technology demonstrations, modeling and simulation, and risk-mitigation prototyping were implemented.

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APPENDIX A
ACRONYM LIST

A	
AC	Actual Cost
ACEIT	Automated Cost Estimating Integration Tool
ACWP	Actual Cost of Work Performed
AN/TPY-2	Army Navy/Transportable Radar Surveillance – Model 2
B	
BAC	Budget at Completion
BAR	BMDS Accountability Report
BCA	Business Case Analyses
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
BER	Baseline Execution Review
BETD	Best Estimate Test Date
BMDS	Ballistic Missile Defense System
BY	Base Year
C	
CAC	Coleman Aerospace Corporation
CAD/CAM	Computer-Aided Design and Computer-Aided Manufacturing
CAPE	Cost Assessment Program Evaluation
CARD	Cost Assessment Requirements Description
CARD-MTDS	CARD-Minimum Technical Data Set
CCDR	Contractor Cost Data Reporting
CCEA	Certified Cost Estimator Analyst
CCM	Common Cost Methodology
CDF	Cumulative Distribution Function
CEBoK	Cost Estimating Body of Knowledge
CEMM	Cost Estimate Methodology Matrix
CER	Cost Estimating Relationships
CETM	Cost Element Trace Matrix
CFSR	Contract Funds Status Report
CLS	Contractor Logistics Report
CLT	Central Limit Theorem
COCOM	Combatant Command
COTS	Commercial-Off-The-Shelf
CPI	Cost Performance Indicator
CPR	Contractor Performance Report
CSDR	Cost and Software Data Reports
CTE	Conditional Tail Expectation
CWBS	Common Work Breakdown Structure
D	
DA	Acquisition Management Directorate
DACIMS	Defense Acquisition Automated Cost Information System

DAMIR	Defense Acquisition Management Information Retrieval
DAU	Defense Acquisition University
DBR	Development Baseline Review
DCARC	Defense Cost and Resource Center
DDM	Development Decision Memorandums
DE	Engineering Directorate
DO	Agency Operations Directorate
DOB	Budget Directorate (MDA)
DOC	Cost Estimating and Analysis Directorate
DoD	Department of Defense
DOI	Resource Planning Directorate (MDA)
DOR	External Review
E	
EAC	Estimate At Completion
EMD	Engineering, Manufacturing and Development
ETC	Estimate to Complete
EV	Earned Value
EVM	Earned Value Management
F	
FOC	Full Operations Capability
FPIF	Fixed-Price Incentive Fee
FYDP	Future Years Defense Program
G	
GAO	Government Accountability Office
GFE	Government Furnished Equipment
GMD	Ground-Based Midcourse Defense
GR&A	Ground Rules and Assumptions
H, I	
ICE	Independent Cost Estimate
IFCM	Integrated Financial Cost Model
IGE	Independent Government Estimate
ILSP	Integrated Logistics Support Plan
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
IMTP	Integrated Master Test Plan
IOC	Initial Operational Capability
ISG	Integration Synchronization Group
ISP	Integrated Support Plan
ISPA	International Society of Parametric Analysis
J, K	
JCE	Joint Cost Estimates
K-S	Kolmogorov-Smirnov
L	
LCCE	Life Cycle Cost Estimate
ln	Natural Logarithm

M	
MDA	Missile Defense Agency
MDEB	Missile Defense Engineering Board
MR	Management Rating
MSA	Materiel Solution Analysis
N	
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NCCA	Naval Center for Cost Analysis
ND	New Design
O	
OSD	Office of the Secretary of Defense
O&S	Operations and Support
P	
P3I	Pre-planned Product Improvement
PB	Program Budget
PCB	Program Change Board
PCL	Prioritized Capabilities List
PD	Program Director
PE	Program Element
PERS	Program Execution Reviews
PM	Program Manager
POM	Program Objective Memorandum
PPBE	Program Planning and Budget Execution
PV	Planned Value
Q, R	
RDT&E	Research, Development, Test & Evaluation
RFI	Request For Information
RFP	Request For Proposal
ROM	Rough-Order of Magnitude
S	
SAR	Selected Acquisition Reports
SBX	Sea-Based X-band Radar
SCEA	Society of Cost Estimating and Analysis
SCI	Schedule Cost Index
SLOC	Software Lines of Code
SME	Subject Matter Expert
SPI	Schedule Performance Indicator
SRDR	Software Resources Data Report
T	
TBR	Technology Baseline Review
THAAD	Theater High Altitude Air Defense
TR	Technical Rating
TY	Then Year
U, V, W, X, Y, Z	

VAMOSC	Visibility and Management of Operating and Support Costs
WBS	Work Breakdown Structure
WSARA	Weapon Systems Acquisition Reform Act