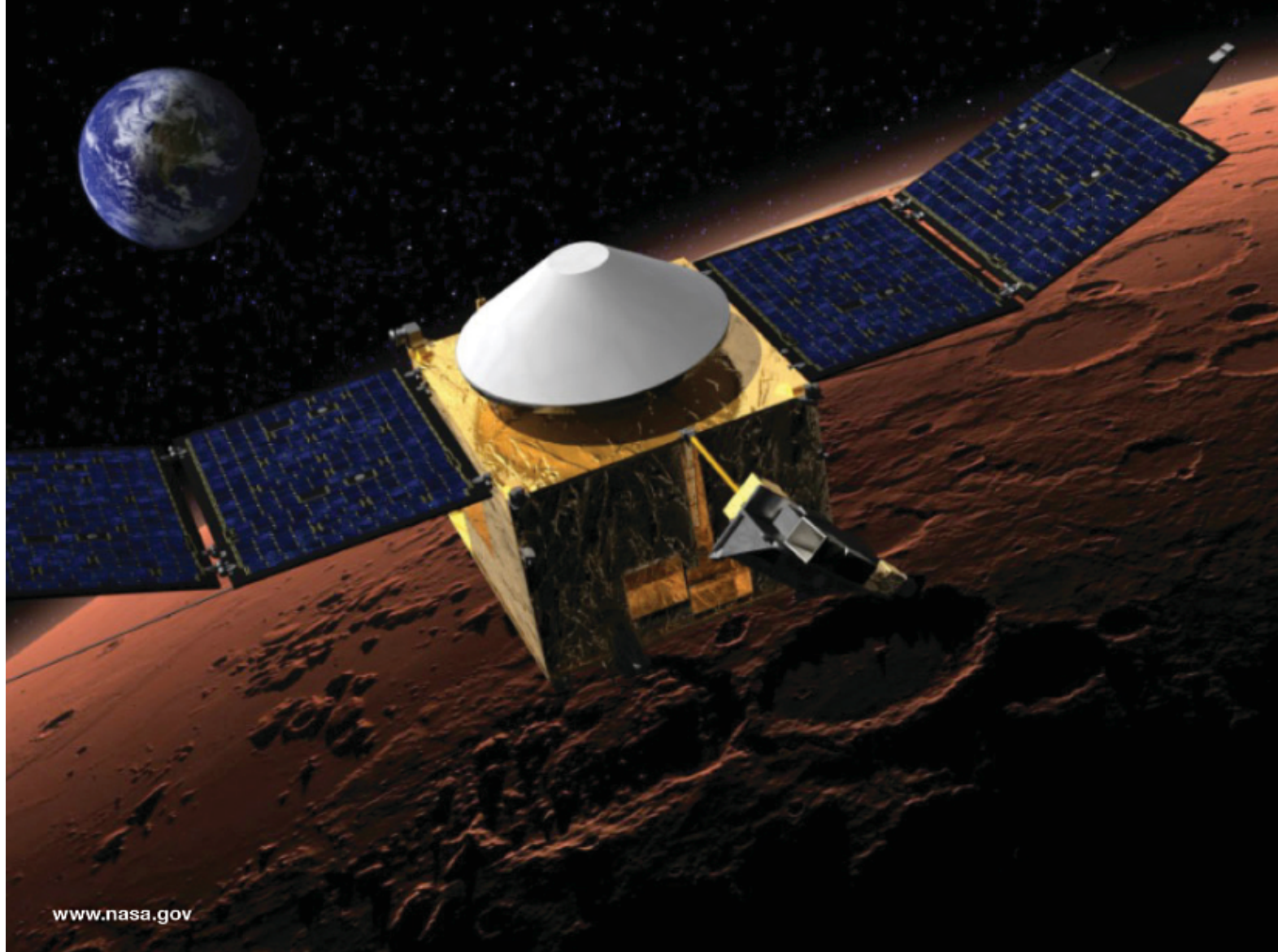


National Aeronautics and Space Administration



# NASA Cost Estimating Handbook

Version 4.0



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*The image on the cover is the MAVEN spacecraft in orbit around Mars, looking back at Earth. MAVEN launched on November 18, 2013, and, following a roughly 10-month trip of over 442 million miles, reached Mars on September 21, 2014. The MAVEN project successfully implemented the principles in this handbook to produce their JCL analysis. MAVEN was launched on schedule and delivered under its budget commitment.*

# Acknowledgments

Many people contributed to the development of the Version 4.0 edition of the Cost Estimating Handbook (CEH). The members of the NASA Executive Cost Analysis Steering Group (ECASG) are the foundation of NASA's cost estimating expertise and provided valuable discussion and materials from their personal wealth of NASA experience. They also spent many hours reviewing and commenting on the handbook. The information from these sources helped identify topics that needed to be enhanced, updated, or created in order to preserve the CEH's usefulness for NASA estimators, contractors, and customers.

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Our thanks go to all contributors as we acknowledge their important inputs to this edition of the NASA CEH and the cost estimating community.

# Welcome to the NASA Cost Estimating Handbook, Version 4.0

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This is the fourth edition of the National Aeronautics and Space Administration (NASA) Cost Estimating Handbook (CEH), updating the 2008 edition. The purpose of this handbook is to serve as a guide for cost estimating at NASA. The intended audience covers the non-estimating professional and the new cost estimator, as well as experienced analysts. The intent of this revision is to provide an update reflecting significant policy changes since the 2008 edition.

## Revision Highlights

This revision includes the addition of an Appendix J addressing Joint Cost and Schedule Confidence Level (JCL) analysis and is intended to be a reference for cost estimating best practices at NASA. Other new topics have been added, and the document layout has been updated. This revision has been developed with the input and participation of the members of the Executive Cost Analysis Steering Group (ECASG), a multi-Center group that coordinates the internal NASA cost estimating and analysis community; ensures that appropriate policy is adopted; and promotes best practices are being developed, communicated, and used across the Agency.

This update to the CEH provides current information on NASA cost estimating policy, including requirements for probabilistic estimating at Key Decision Points (KDPs) in the project<sup>1</sup> life cycle. The information on how to develop probabilistic cost and schedule ranges for KDP-B (approval to start preliminary design) is provided in Appendix C and a JCL calculation in support of KDP-C (approval to start final design) is provided in Appendix J. For probabilistic estimating, the NASA cost community has found it necessary to incorporate active consideration of risk, schedules, and performance and to develop methods of incorporating these factors into cost estimates.

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<sup>1</sup> The term “project” is used throughout this handbook for ease of reading, but it may be interpreted as “program” or “project” in accordance with NPR 7120.5E.

## Using the Handbook

Version 4.0 of this handbook is designed to be an electronic resource, but every effort has been made to provide a layout that enables the user to print out a hard copy.

The main body provides a standalone summary of the process for developing cost estimates; individual appendices cover a variety of additional subjects in more detail.

This CEH belongs to a community of NASA handbooks that include the following:

- EVM Implementation Handbook, Integrated Baseline Review (IBR) Handbook, and Work Breakdown Structure (WBS) Handbook (which are all available at <http://evm.nasa.gov/handbooks.html>);
- Schedule Management Handbook ([http://www.nasa.gov/pdf/420297main\\_NASA-SP-2010-3403.pdf](http://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf));
- NASA Risk-Informed Decision Making Handbook ([http://www.hq.nasa.gov/office/codeq/doctree/NASA\\_SP2010576.pdf](http://www.hq.nasa.gov/office/codeq/doctree/NASA_SP2010576.pdf));
- Systems Engineering Handbook (<http://www.acq.osd.mil/se/docs/NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf>);
- Project Management Handbook ([http://www.nasa.gov/offices/oce/documents/NPR7120-5\\_pm\\_handbook.html](http://www.nasa.gov/offices/oce/documents/NPR7120-5_pm_handbook.html)); and
- Risk Management Handbook ([http://www.hq.nasa.gov/office/codeq/doctree/NHBK\\_2011\\_3422.pdf](http://www.hq.nasa.gov/office/codeq/doctree/NHBK_2011_3422.pdf)).

## Updating the Handbook

Please send feedback or suggested improvements via the form located on the CEH website at [http://www.nasa.gov/sites/default/files/files/NASA\\_Cost\\_Estimating\\_Handbook\\_Recommended\\_Revision\\_Submission\\_Form\\_Tagged.pdf](http://www.nasa.gov/sites/default/files/files/NASA_Cost_Estimating_Handbook_Recommended_Revision_Submission_Form_Tagged.pdf). CAD intends to make periodic updates to the CEH and/or individual appendices as needed (will review annually), and will rely on feedback and input from the community of CEH users as an important source for identifying areas for improvement or addition.

For any general information requests, please submit them to [hq-cad@nasa.gov](mailto:hq-cad@nasa.gov).

# Cost Estimating Handbook

## Table of Contents

---

1. Introduction
  - 1.1. The Need for Cost Estimating and Cost Analyses
  - 1.2. The NASA Acquisition and Management Processes
2. The Cost Estimating Process
  - 2.1. Part 1: Project Definition Tasks
    - 2.1.1. Task 1: Receive Customer Request and Understand the Project
    - 2.1.2. Task 2: Build or Obtain a Work Breakdown Structure (WBS)
    - 2.1.3. Task 3: Define or Obtain the Project Technical Description
  - 2.2. Part 2: Cost Methodology Tasks
    - 2.2.1. Task 4: Develop Ground Rules and Assumptions
    - 2.2.2. Task 5: Select Cost Estimating Methodology
    - 2.2.3. Task 6: Select/Build Cost Model/Tool
    - 2.2.4. Task 7: Gather and Normalize Data
  - 2.3. Part 3: Cost Estimate Tasks
    - 2.3.1. Task 8: Develop the Cost Estimate
    - 2.3.2. Task 9: Develop and Incorporate the Cost Risk Assessment
    - 2.3.3. Task 10: Document the Cost Estimate
    - 2.3.4. Task 11: Present the Cost Estimate Results
    - 2.3.5. Task 12: Update the Cost Estimate as Required
3. Joint Cost and Schedule Confidence Level Analysis
  - 3.1. JCL Process Flow
    - 3.1.1. Step Zero: Identify Goals of the JCL Analysis
    - 3.1.2. Step One: Develop a Summary Analysis Schedule
    - 3.1.3. Step Two: Load Cost onto the Schedule Activities
    - 3.1.4. Step Three: Incorporate the Risk List
    - 3.1.5. Step Four: Conduct Uncertainty Analysis
    - 3.1.6. Step Five: Calculate and View Results
  - 3.2. JCL Policy and Usage
4. Analyses for Decision Support
  - 4.1. Sensitivity Analysis
    - 4.1.1. Steps To Perform Sensitivity Analysis
    - 4.1.2. The Pros and Cons of Sensitivity Analysis
  - 4.2. Trade Studies
    - 4.2.1. Trade-Study Analysis
    - 4.2.2. Make-Versus-Buy Analysis
    - 4.2.3. Lease-Versus-Buy Analysis
  - 4.3. Affordability Analysis
  - 4.4. Cost As an Independent Variable
  - 4.5. Economic Analysis
    - 4.5.1. What Is Economic Analysis?
    - 4.5.2. OMB Economic Analysis Guidance
    - 4.5.3. The Concept of Discounting
  - 4.6. The Economic Analysis Process
    - 4.6.1. Steps for Performing an Economic Analysis
    - 4.6.2. The Challenge of Quantifying Benefits
    - 4.6.3. Use of Net Present Value To Rank Alternatives
    - 4.6.4. Documentation and Review of an Economic Analysis

## Tables

Table 1. Strengths, Weaknesses, and Applications of Analogy Cost Estimating Methodology

Table 2. Strengths, Weaknesses, and Applications of Parametric Cost Estimating Methodology

Table 3. Strengths, Weaknesses, and Applications of Engineering Build-Up Methodology

Table 4. Cost Models and Tools Utilization Guide

Table 5. Data Types and Sources

Table 6. Inflation and Escalation Terms

## Figures

Figure 1. Project Life Cycle Milestone Chart

Figure 2. The NASA Cost Estimating Process

Figure 3. Four Critical Elements Related To Conducting Cost Estimates

Figure 4. Standard Flight Project Level 2 Work Breakdown Structure

Figure 5. Use of Cost Estimating Methodologies by Phase

Figure 6. Parametric Cost Modeling Process

Figure 7. Scatterplot and Regression Line of Cost (Y) Versus Weight (X)

Figure 8. Method for Developing Engineering Build-Up Estimate

Figure 9. Summary Schedule

Figure 10. Cost-Loaded Schedule

Figure 11. Schedule with a Discrete Risk

Figure 12. Schedule with Uncertainty

Figure 13. JCL Scatterplot

Figure 14. Annual Cost Uncertainty Example Displays Cost Risk Statistics Over Time in Comparison to Available Annual Resources

Figure 15. Cost As an Independent Variable

Figure 16. Steps for Performing an EA

# Cost Estimating Handbook

## Appendices

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[Appendix A. Cost Analysis Data Requirement \(CADRe\) and One NASA Cost Engineering \(ONCE\) Database Overview](#)

[Appendix B. Work Breakdown Structure \(WBS\)](#)

[Appendix C. Cost Estimating Methodologies](#)

[Appendix D. Estimating the Cost of Technology Development](#)

[Appendix E. Models and Tools](#)

[Appendix F. Phasing of Cost Estimates](#)

[Appendix G. Cost Risk and Uncertainty Methodologies](#)

[Appendix H. Documenting and Presenting the Results](#)

[Appendix I. Using Performance Information to Adjust Estimates](#)

[Appendix J. Joint Cost and Schedule Confidence Level \(JCL\)](#)

[Appendix K. Schedule Estimating Relationship \(SER\) Development and Model Inputs](#)

[Appendix L. Estimating the Cost of Construction of Facilities \(CoF\) and Ground Support Equipment \(GSE\)](#)

[Appendix M. Software Cost Estimating](#)

[Appendix N. Analyses for Decision Support](#)

[Appendix O. References](#)

[Appendix P. Acronyms](#)

[Appendix Q. Glossary](#)

# 1. Introduction

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The needs of the cost estimating community are as varied as the projects being undertaken at NASA. NASA has a wide range of mission requirements and a variety of expectations and tools that are used to plan and execute those requirements. Cost estimators and cost analysts may be asked to support activities ranging from the development of estimates for competitive proposals to the development of independent estimates. These estimates can be used either for the selection of proposals or the approval to proceed to the next life-cycle phase. NASA requires cost estimating for major acquisition programs. Resources are increasingly scarce, and space systems are increasingly expensive. Informed decisions are critical.

## 1.1. The Need for Cost Estimating and Cost Analyses

NASA and many external organizations are consumers of cost estimates and analyses. The Agency needs estimates for Project Office formulation and implementation phases, nonadvocate cost estimates, source selections, what-if exercises, affordability studies, economic analyses, and Analysis of Alternatives (AoA), as well as to support numerous types of decisions related to projects. System cost must be a design variable to help focus on major cost drivers during design and to challenge estimates that deviate strongly from history. The cost estimating process defined in this handbook will provide the decision maker with a clear understanding of the cost risk inherent in the project, cost of alternatives within the project, and information to make resource allocation decisions. Once the decision is made to proceed with the project, cost estimates provide management with critical cost-risk information to improve the control of resources in the present and the future as well as provide insight into the impact of project changes on the program budget. The cost estimating process must therefore be adaptable and flexible while holding firm to the principles, objectives, and practices of cost estimating. The following groups are informed by cost estimates:

- Projects, programs, Centers, Mission Directorates, and the Agency as a whole
- External stakeholders (e.g., Congress and the Office of Management and Budget [OMB])
- Auditors (e.g., the Government Accountability Office [GAO] and the NASA Office of Inspector General [OIG])
- Taxpayers

## 1.2. The NASA Acquisition and Management Processes

The acquisition process helps projects meet programmatic, institutional, technical, cost, schedule, and performance commitments. NASA's acquisition policy for funding space missions, NASA Policy Directive (NPD) 1000.5 ([http://nodis3.gsfc.nasa.gov/lib\\_docs.cfm?range=1](http://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=1)), outlines the policy and process expectations for the acquisition process. The acquisition policy is supported by NASA Procedural Requirement (NPR) documents, such as NPR 7120.5E (<http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>), which describes how space flight programs and projects are to be managed throughout their life cycles. All NASA cost estimators should be familiar with both NPD 1000.5 and NPR 7120.5E. While the focus of the CEH is on cost estimates for

flight projects, the same guiding principles apply to other types of programs or projects, such as information technology (IT), technology development, and Construction of Facilities (COF).<sup>2</sup>

The Project Life Cycle Milestone Chart, Figure 1, defines the roadmap for identifying points in the project life cycle where cost estimates may be needed to support the justification, formulation, approval, and implementation of the project. For a project to progress through its project life-cycle phases successfully, it must provide cost estimates at each review leading up to the next Key Decision Point. The policy document NASA Systems Engineering Processes and Requirements, 7123.1B

(<http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7123&s=1>), details the complete entrance and exit criteria for each review. This process defines the activities to which the cost estimator's product contributes. In most cases, a project's schedule and cost uncertainties decrease over the project's life cycle as the project matures. It is important for the estimator to understand and communicate not only cost and schedule estimates but also uncertainties associated with these estimates. This is covered in more detail in section 2.

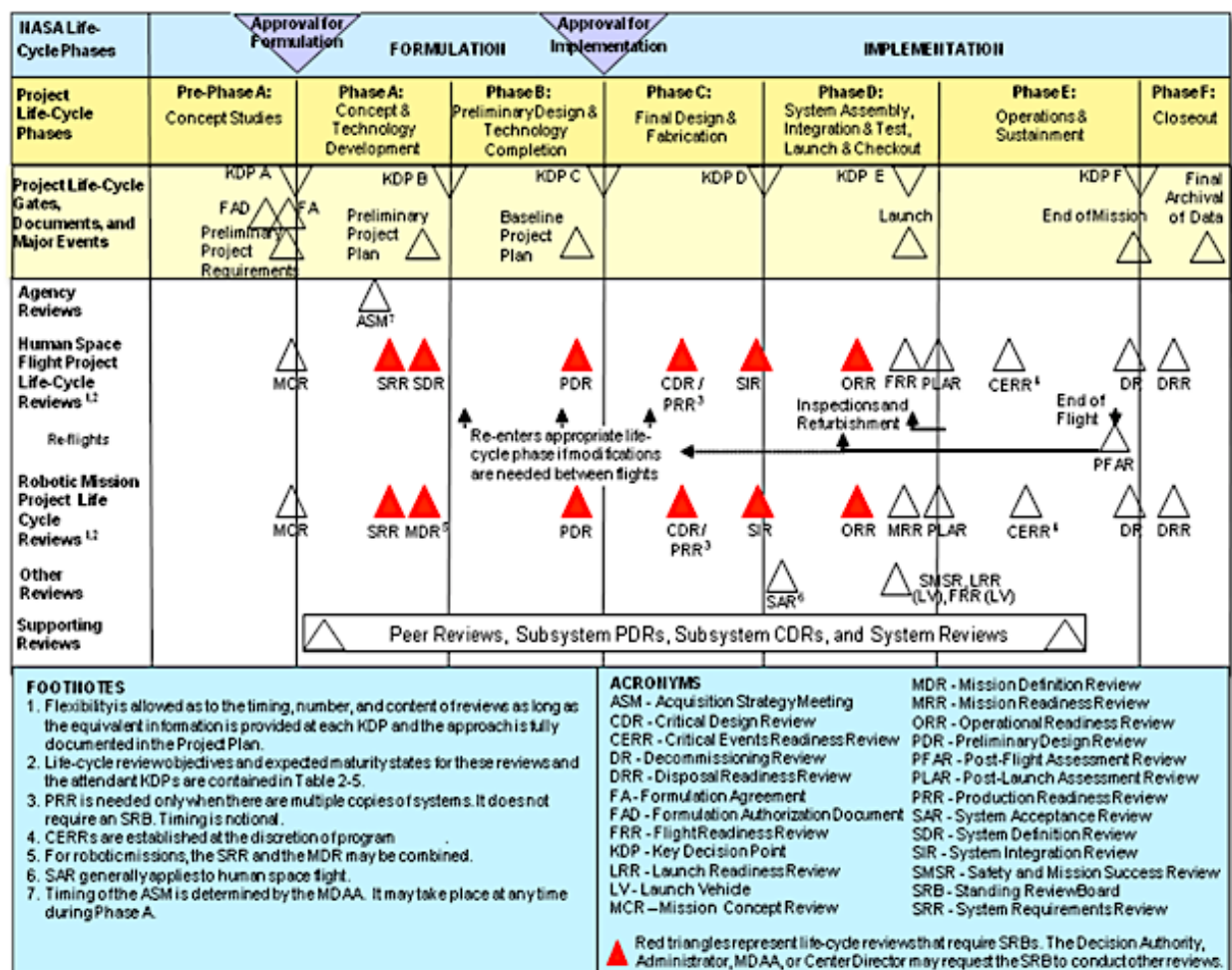


Figure 1. Project Life Cycle Milestone Chart<sup>3</sup>

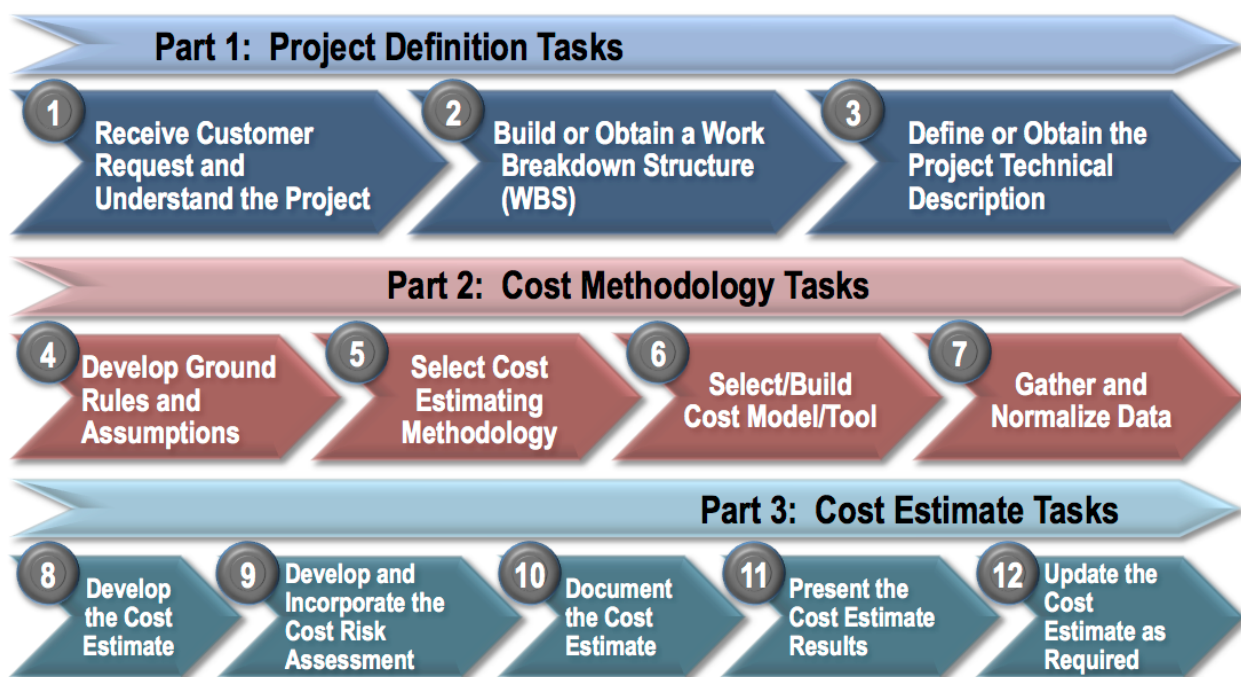
<sup>2</sup> For additional guidance, visit the NASA Online Directives Information System (NODIS) at [http://nodis3.gsfc.nasa.gov/main\\_lib.html](http://nodis3.gsfc.nasa.gov/main_lib.html). See Appendix L of this document for more information on Construction of Facilities.

## 2. The Cost Estimating Process

This section presents the how-to, start-to-finish details of the cost estimating process. As shown in Figure 2, there are three main parts to the NASA 12-step cost estimating process: Part 1—Project Definition, Part 2—Cost Methodology, and Part 3—Cost Estimate. This process is consistent with the cost estimating processes in NASA's 2002, 2004, and 2008 Cost Estimating Handbooks, and it is substantively consistent with the GAO's process<sup>4</sup> but tailored to fit NASA's needs.

### Cost Estimating Process as Applied

The Cost Estimating Process described in Figure 2 is shown as a series of successive steps for instructional convenience. However, in practice it is often an iterative process that is rarely linear. Steps are performed as opportunity, data, and need arise.



**Figure 2. The NASA Cost Estimating Process**

The first part of the NASA cost estimating process is called the *Project Definition*. During this part, the estimator clarifies the reason for the estimate, defines expectations, and begins to understand the project that will be estimated. As the estimate is being defined and data are gathered, a Work Breakdown Structure and technical description are obtained. These items help define the project and form the foundation for the estimate. As the estimator continues through the estimating process, these steps may be revisited as new information is obtained.

<sup>3</sup> Figure 1 is taken from NASA Procedural Requirement 7120.5E (<http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>).

<sup>4</sup> See box on following page, and more information at <http://www.gao.gov/products/GAO-09-3SP>.

Part 2 of the cost estimating process, the *Cost Methodology*, includes four tasks that create the approach and framework for the estimate. Developing the ground rules and assumptions will be the most revisited task in this part of the process. As methodologies are selected and the data are gathered, the ground rules and assumptions, methodologies, and even the cost model may be refined, as appropriate.

Part 3 of the cost estimating process, the *Cost Estimate*, has five tasks that include the actual conduct, presentation, and maintenance of the cost estimate. All of these tasks are important in their own right, and together, they become critical for a defensible and complete estimate.

As noted above, the cost estimating process, described in detail below, is shown as a series of successive steps. It is in practice often an iterative process that is rarely linear. For example, the initial estimating results may be revised one or more times because of changes to the technical and programmatic baselines, questions about the sensitivity of results, changes in ground rules and assumptions, or indications that the estimate is not complete. The revised results and findings are then documented and, along with the estimating models and data, made available for subsequent estimating and analyses.

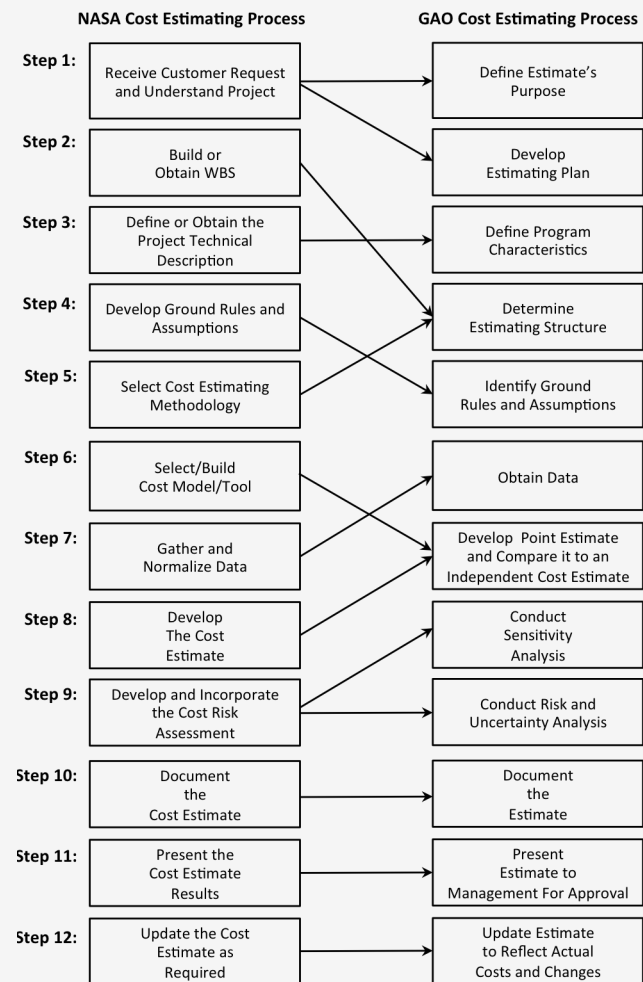
## 2.1. Part 1: Project Definition Tasks

To properly estimate the cost of a project, it is vital that the project be thoroughly defined and understood by the estimators. Therefore, the initial stage of the cost estimating process is dedicated to:

- Receive the customer's request and understand the project;
- Build or obtain a WBS; and
- Obtain/participate in the development of the project's technical description.

### Consistency of the NASA Cost Estimating Process with the GAO Cost Estimating Process

NASA's cost estimating process is consistent with the estimating process recommended within GAO's Cost Estimating and Assessment Guide (<http://www.gao.gov/products/GAO-09-3SP>). This mapping of the processes is depicted below:



To take a deeper look into this mapping schema, it is recommended to first read sections 2.1 through 2.3 of this handbook, which provide a detailed description of each step of the NASA cost estimating process. After reading these sections, use the illustrated map as a guide to compare task descriptions in this handbook to "Associated Tasks" in Table 2 of the 2009 GAO Cost Estimating and Assessment Guide.

NASA has retained the structure of its general cost estimating process flow for consistency and tailoring purposes, rather than exactly duplicate the GAO process.

### 2.1.1. *Task 1: Receive Customer Request and Understand the Project*

**The goal of this task is to communicate sufficiently with the customer to gather enough project information to generate a quality estimate.**

There are three major activities associated with understanding the project:

1. Identify the customer(s) and stakeholder(s) who will use the results of the estimate.
2. Document expectations for program/project by (a) identifying the purpose of the estimate; (b) specifying mission needs, objectives, and goals; and (c) assessing the operating environment and life-cycle phase.
3. Gather and review all relevant project data for evaluation (e.g., an existing technical baseline or Cost Analysis Data Requirement [CADRe], previous estimates, lessons learned and customer feedback, budget data, and programmatic data such as schedules). Discuss schedule, data, expectations, and resource requirements with the requesting customer.
  - a) When a request for a cost estimate is received, the supervisor of the cost group must ascertain if there are adequate resources to accept the assignment based on the understanding of the expectations of the estimate.
  - b) The estimator then determines the magnitude of the workload required (i.e., the type of estimate, the due date(s), and relative priority of the request). If the request is accepted, the supervisor will notify the requester and assign an estimator (or estimators) to the task. If the supervisor has issues with the request, it will be negotiated with the requestor.

#### **NASA's Cost Analysis Data Requirement (CADRe)**

The CADRe is a three-part document that captures detailed programmatic, technical, and cost data in a single document for NASA-funded space missions. The document is prepared six times during the life cycle of a project at major milestones: SRR, CSR or Project PMSR; PDR; CDR; SIR; Launch and EOM.

The CADRe initiative began in 2005 as a way to systematically collect and archive programmatic, technical, and cost information. The CADRe program satisfies a basic cost estimating need to provide historical cost data that are vital to performing estimates for future systems. In performing this task, data across all major flight projects at NASA are captured, including major instruments that fly on foreign international partner spacecraft.

The CADRe program has captured dozens of key historical missions looking back approximately 10 years where the data are available. As the number of CADRes on current and completed missions grows, a better understanding of key programmatic changes and their associated cost and schedule impacts is attained, resulting in more advanced costing practices and tools. Completed CADRes are available on the One NASA Cost Engineering (ONCE) database. Incorporating CADRe into the ONCE database, in turn, facilitates fast searches and easy retrieval to support cost engineering development.

For more information on CADRe, refer to Appendix A.

As illustrated in Figure 3, there are four critical elements to any estimate that need to be understood and agreed upon between the cost estimator and the decision maker before a methodology can be chosen and an estimate developed. These four elements are resources, data, schedule, and expectations.

<p><b>Data</b></p> <ul style="list-style-type: none"> <li>• What data do you need?</li> <li>• Are the data readily available?</li> <li>• If the data are not readily available, what are your alternatives?</li> <li>• Are the organizations you need to collect the data from cooperative &amp; accessible?</li> <li>• Are non-disclosure agreements required?</li> </ul>	<p><b>Expectations</b></p> <ul style="list-style-type: none"> <li>• What is your expectation of the estimate?</li> <li>• What is the expected outcome or usage of the estimate? (based on estimate type)</li> <li>• What is the customer's expectation of the estimate?</li> <li>• What is the team expectation of the estimate?</li> <li>• What is the Agency-wide expectations of the estimate outcome and usage?</li> </ul>
<p><b>Resources</b></p> <ul style="list-style-type: none"> <li>• How many people are required to conduct the estimate?</li> <li>• How many people are available to conduct the estimate?</li> <li>• What is the budget required to conduct the estimate?</li> <li>• What is the available budget to conduct the estimate?</li> </ul>	<p><b>Schedule</b></p> <ul style="list-style-type: none"> <li>• How long have you been given to complete the estimate?</li> <li>• How long do you need to complete the estimate, given the available resources and data?</li> <li>• Do you have the resources needed to conduct the estimate with the allotted schedule?</li> <li>• Do you have the time to collect the required data and analyze the data?</li> </ul>

**Figure 3. Four Critical Elements Related To Conducting Cost Estimates**

In early life-cycle phases of a project there will be many unknowns. It is the role of the cost estimator to ask insightful questions that help the project management staff make decisions regarding key aspects not normally considered in an early stage (e.g., maintenance concept, testing strategy) and to address issues such as personnel, schedule, technologies, and cost drivers that can have a major impact on risk. Data gathering is no less important in later phases of a project, when more is known and overlooking any element could affect the estimate's outcome.

### **2.1.2. Task 2: Build or Obtain a Work Breakdown Structure (WBS)**

**The objective of this task is to provide a consistent structure that includes all elements of the project that the cost estimate will cover.**

As confirmed by NPR 7120.5E, the WBS is a key element of project management. The purpose of a WBS is to divide the project into manageable pieces of work to facilitate planning and control of cost, schedule, and technical content. A WBS ensures that all work to be performed on the project is organized and aligned in accordance with the total scope of a program, using a hierarchical structure. Each element in the cost estimate represents the cost to do that work. This structure becomes the cost estimator's framework for ensuring full coverage (without double counting) of the project's objectives, including the following:

- Project and technical planning and scheduling;
- Cost estimation and budget formulation (in particular, costs collected in a product-oriented WBS can be compared to historical data collected for the same products);
- Definition of the scope of statements of work and specifications for contract efforts;
- Project status reporting, including schedule, cost, workforce, technical performance, and integrated cost/schedule data (such as EVM and Estimate at Completion [EAC]); and

- Creation of plans such as the Systems Engineering Management Plan (SEMP) and other documentation products such as specifications and drawings.

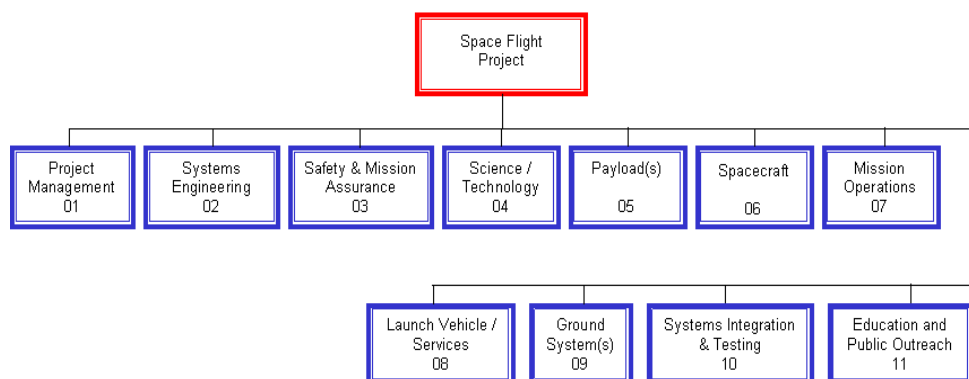
The WBS is also used as a communication tool to present the project's scope in an understandable form that can be easily communicated to the project team and other stakeholders.

There are four activities associated with preparing or obtaining a WBS:

1. Begin with the NASA standard flight project WBS (only to Level 2);<sup>5</sup>
2. Define the WBS elements to the lowest level appropriate to the level of project maturity for the estimate;
3. For a WBS structure below Level 2, refer to the CADRe standard<sup>6</sup> as a reference for suggested lower level breakouts;
4. Create a dictionary to define the WBS elements; and
5. Ensure that the cost estimating WBS is consistent with other project functions including scheduling (the cost estimator is responsible for preparing the cost WBS and mapping it back to the standard WBS). A mapping example is provided in Appendix E.

The type of estimating product varies by program life-cycle phase. In Pre-Phase A, the cost estimator will either obtain a high-level project WBS from the project staff or work with them to develop one. A project WBS is the comprehensive WBS comprising all life-cycle phases, recurring and nonrecurring costs, and components including the hardware for the product; as well as other items such as mission assurance, Systems Engineering and Integration (SE&I), Integration and Test (I&T), mission operations, data analysis, outreach, science team, and project management. At a higher-level WBS (e.g., WBS Levels 1 and 2), it is important to standardize the WBS to not only facilitate data (and data analysis), but also to enable apples-to-apples comparisons to heritage programs.

Figure 4 shows the NASA Level 2 Standard Space Flight WBS that is required for all NASA space flight projects. **For a more detailed recommended WBS, see the box at the end of this section describing the standard CADRe WBS.**



**Figure 4. Standard Flight Project Level 2 Work Breakdown Structure<sup>7</sup>**

<sup>5</sup> For more information, please see the NASA Work Breakdown Structure Handbook, NASA SP-2010-3404, January 2010 (<http://evm.nasa.gov/handbooks.html>).

<sup>6</sup> The CADRe standard WBS is shown in the box at the end of this section and is available on the CAD website at <http://www.nasa.gov/offices/ooo/CAD.html>, and on the ONCE Portal at <http://www.oncedata.com>.

<sup>7</sup> For more information, see the NASA Work Breakdown Structure Handbook (<http://evm.nasa.gov/handbooks.html>).

NASA's standard WBS helps ensure that similar projects within each NASA organization have standard and consistent labels, definitions (i.e., content), and data across different cost disciplines (e.g., CADRe reporting, cost estimating, EVM, cost databases). This consistency will enable improved cost estimation, performance measurement, and project management. Note that a WBS created from NASA Level 2 Standard Space Flight might not necessarily map to the estimating structures found in commercial tools used in the estimating community. Know the tool planned for use before beginning and be prepared to provide a map of the WBS back to the project WBS if there are differences.

The WBS Level 3 goes into greater detail (e.g., individual instruments, spacecraft subsystems) and is typically the level used for estimating the hardware and software elements.

There are many good WBS references including:

- The NASA Systems Engineering Handbook sets forth policies and processes for preparing a WBS (Section 6.1.2.1)<sup>8</sup>
- The NASA Work Breakdown Structure Handbook<sup>9</sup>
- MIL HDBK 881C, "Department of Defense Handbook, Work Breakdown Structures for Defense Materiel Items"<sup>10</sup>
- NASA Space Flight Program and Project Management Requirements (NPR 7120.5E)<sup>11</sup>

A consistent WBS structure across multiple projects/programs is important for data collection, analysis, and communications throughout NASA. This promotes a defensible estimate for the project. More WBS information is provided in Appendix B.

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<sup>8</sup> <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7123&s=1>

<sup>9</sup> <http://evm.nasa.gov/handbooks.html>

<sup>10</sup> <https://acc.dau.mil/adl/en-US/482538/file/61223/MIL-STD%20881C%203%20Oct%2011.pdf>

<sup>11</sup> <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>

## CADRe WBS

The NASA Standard WBS required by NPR 7120.5E only proceeds to level 2. This increases the degrees of freedom for the Program/Project Manager to construct a WBS that best facilitates project accomplishment. However, the cost estimator and project lead must be aware that there are managerial data demands that must map from the project's WBS. Construction of a WBS that considers these requirements may alleviate significant PM level of effort at stages of the project beyond initial WBS formulation.

For each Agency project, the WBS established by the project must use the NSM numbering scheme and also must correlate exactly through level seven to the corresponding financial accounting structure utilized for each project within the NASA Core Financial System.

In addition to the NASA Core Financial System requirements, projects must submit data into the CADRe system under the CADRe WBS format, shown at right. This data is used by the Agency for reference in future cost estimates. Construction of a project WBS that mirrors or easily maps to the CADRe structure will achieve savings in future level of effort and is considered a 'best practice'.

More information on CADRe is available in Appendix A, and the CADRe standard WBS is available on the ONCE Portal at <http://www.oncedate.com>.

### NASA WBS Elements

System Name  
 Project Management  
 Systems Engineering  
 Safety and Mission Assurance  
 Science/Technology  
 Payload(s)  
 Payload Management  
 System Engineering  
 Payload Product Assurance  
 Instrument *n*  
 Instrument *n* Management  
 Instrument *n* Systems Engineering  
 Instrument *n* Assurance  
 Antenna  
 Optics  
 Sensors/Detectors  
 Structures & Mechanisms  
 Thermal Control  
 Electronics  
 Power  
 Pointing Subsystem  
 Harness & Cabling  
 C&DH  
 Ground Support Equip  
 Integration, Assembly Test & Check c  
 Flight System 1 Spacecraft  
 Flight System Project Management  
 Flight System Systems Engineering  
 Flight System Product Assurance  
 Spacecraft  
 Spacecraft Management  
 Spacecraft Systems Engineering  
 Spacecraft Product Assurance  
 Spacecraft Structures & Mechanism  
 Spacecraft Thermal Control  
 Spacecraft Electrical Power &  
 Spacecraft GN&C  
 Spacecraft Propulsion  
 Spacecraft Communications  
 Spacecraft C&DH  
 Spacecraft Software  
 CSCI Name 1  
 CSCI Name 2  
 Software Subsystem I&T  
 Spacecraft I&T  
 Entry/Descent/Lander  
 Rover  
 Spacecraft Retirement & Disposal  
 Launch Vehicle/Services  
 Mission Operations System (MOS)  
 MOS Management  
 MOS Systems Engineering  
 Mission Operations Center  
 Science/Data Operations Center  
 Data Distribution & Archival  
 Communications/Network Infrastruct  
 Training  
 Ground Data System (GDS)  
 GDS Management  
 GDS Systems Engineering  
 Mission Operations Center  
 Science/Data Operations Center  
 Data Distribution & Archival  
 Ground Stations  
 Communications/Network Infrastruct  
 GDS Integration & Test  
 System Integration, Assembly, Test & C  
 Education & Public Outreach  
 Reserves  
 CM&O  
 G&A

### **2.1.3. Task 3: Define or Obtain the Project Technical Description**

**The objective of this task is to establish a common baseline document that thoroughly describes the project to be used by the project team and project estimators to develop their estimate(s).**

The project technical baseline defines and provides quantitative and qualitative descriptions of the project characteristics from which cost estimates will be derived. As such, the project technical baseline ensures that cost projections jointly developed by the Project Offices and the independent review organizations are based on a common definition of the system and project. The objective of this step is to ensure that the estimating team understands and can obtain the documents that thoroughly describe the project to be estimated. The project technical baseline should identify any area or issue that could have a major cost impact (e.g., risks) and, therefore, must be addressed by the cost estimator. If a CADRe has already been created for the system being estimated, it can be used to understand the technical baseline for the estimate. A further benefit derived from the CADRe is its built-in requirement for end-of-contract actual costs and technical parameters (by WBS element) used to update NASA cost models. These values (e.g., key performance parameters [KPPs]) and actual costs at the end-of-contract are ported into the One NASA Cost Engineering database (ONCE) at <http://www.oncedata.com>. See Section 4 and/or Appendix A for more information about CADRe and ONCE.

There are several activities associated with understanding the complete program characteristics, including:

1. Gather and review all relevant project data (e.g., existing technical baseline or CADRe, previous estimates, lessons learned and customer feedback, and budget data as well as other programmatic data such as schedules);
2. Collect system characteristics, configuration, quality factors, security, operational concept, and the risks associated with the system; and
3. Obtain the system's (or the project's) milestones, schedule, management strategy, implementation/deployment plan, including launch, test strategy, security considerations, and acquisition strategy.

The estimating team should work closely with the NASA organization sponsoring the cost estimate for access to pertinent documentation describing the system being estimated.

Every estimate, regardless of size, needs to define what is being estimated. The NASA organization sponsoring a project will prepare, as a basis for life-cycle cost estimates, a description of features pertinent to costing the system being developed and acquired. The type of document used to record this project technical description depends on the following:

- The time available to conduct the estimate;
- The size of the project;
- The technical information available, including the requirements' thresholds and goals (objectives); and
- The phase of the life cycle in which the project exists.

Projects that are smaller in size or earlier in their project lives may only require a simple data sheet with technical requirements provided by the project to support developing a Rough Order Magnitude (ROM) cost estimate.

The project technical description defines and provides quantitative and qualitative descriptions of the project characteristics from which cost estimates will be derived. As such, the project technical description

ensures that cost estimates developed separately by the Project Offices and the independent review organizations are based on a common definition of the system and project. The project technical description should identify any area or issue that could have a major cost impact (e.g., risks) and, therefore, must be addressed by the cost estimator. Actual costs at the end-of-contract are ported into the ONCE database.

## 2.2. Part 2: Cost Methodology Tasks

The next four tasks of the cost estimating process relate to selecting and administering the cost methodology, which will guide the development of the cost estimate. These four tasks are detailed below.

### 2.2.1. Task 4: Develop Ground Rules and Assumptions

**The Ground Rules and Assumptions (GR&A) are intended to communicate the scope, context, and environment within which the estimate is being developed.**

Below are four activities associated with developing the GR&A:

1. Establish a set of programmatic, technical, and schedule GR&A to define the scope of the estimate (i.e., what costs are being included and what costs are excluded);
2. Coordinate and gain agreement/approval from the NASA Program/project Manager (P/pM) (or other cost estimate point of contact);
3. Achieve consensus on the GR&A with stakeholders, vendors, end users, etc., to ensure their applicability and to avoid problems leading to inaccurate or misleading estimates; and
4. Document the GR&A as they evolve during the entire estimate process.

The cost estimator works with the NASA P/pM and members of the technical team to establish and document a complete set of GR&A that are necessary to provide definition to the project and the estimate and to bound its scope. GR&A let everyone involved understand what costs are being included and what costs are excluded in the current estimate. This allows for easy comparisons to future estimates and to ones conducted by independent agencies. GR&A provide cost estimators with the means to bound the estimate, focus attention on the most important elements, and provide temporary resolution of undefined technical and programmatic questions.

Each estimate should have two sets of GR&A: global and element specific. Global GR&A apply to the entire estimate and include ground rules such as base year dollars, schedules, what is and is not included in the cost estimate, and total quantities. Element-specific GR&A are developed as each WBS element is being estimated and are found in the detail section for each WBS element. Element-specific GR&A provide details for each element such as unit quantities and schedules.

Since it is impossible to know every technical or programmatic parameter with certainty before and into the design phase of a project, a complete set of realistic and well-documented GR&A adds to the soundness of a cost estimate. Descriptions of relevant missions and system characteristics, personnel, maintenance, support, and logistics policies are generally included in the GR&A. Global and element-specific GR&A can also be found in the CADRe and should be in sync with the estimate.

GR&A commonly address, but are not limited to, the following topics:

- a) **Scope.** The scope identifies the content that is covered by the cost estimate, including activities, hardware elements, and quantities. The GR&A clarify the scope in relation to acquisition milestones, especially specific items or content excluded from the cost estimate. A typical project includes the costs of designing and fabricating or specifying and purchasing components, integrating and testing

assemblies, transporting project articles to the operating environment, and conducting operations and maintenance, as well as other life-cycle cost (LCC) elements such as the launch vehicle.

- a. **WBS.** As part of the Scope, the WBS organizes the activities and products of a project in a hierarchical structure that matches or maps estimating methods against the elements of the project WBS to ensure that all costs are accounted for without double-counting and/or missing elements.
- b) **Make vs. buy decisions.** Identifies and accounts for costs of either manufactured or purchased items. Manufactured items typically require nonrecurring engineering and design effort, tooling, and production setup prior to production. Purchased items may require effort to ensure their proper integration and testing. GR&A about manufacturers, prices, and availability of procured items will help to simplify the estimating effort. (There is further discussion on make/buy in Section 3.0 and Appendix C.)
- c) **Government Furnished Equipment (GFE)/Government Furnished Information (GFI).** Describes each Government-provided item and its technical capabilities as well as what portion of its costs should be included or excluded from the estimate results. GR&A prescribe when the GFE/GFI will be available and highlight potential risks associated with their availability and performance. Examples of GFE include such items as launch vehicles, communications networks, and spacecraft hardware components. Examples of GFI are software libraries and routines that can be reused with minimal or no modification. Though GFE/GFI can facilitate projects and reduce overall costs, there are usually costs associated with their proper integration and testing.
- d) **Development philosophy.** Plans for how the system will be developed (e.g., prototype or protoflight) as well as the testing philosophy.
- e) **Contractors, subcontractors, and their roles.** Determines cost depending on efficiency, labor rates, and fee of subcontractors that may be used to perform specified activities and deliver specified items for a variety of reasons.
- f) **Amount of test hardware and key system tests.** Varies by project; needs to be known so that an accurate estimate is obtained.
- g) **Budget profile.** Predicts the effect that the budget has on the project's overall cost. In many cases, the availability of fiscal resources in a given period of time may constrain activities and purchases, forcing project delays if the activities and purchases are on the program's/project's critical path. In some cases, the ready availability of funds can enable project efficiencies and discount prices.
  - a. Often, the cost estimator provides an initial budget profile. When this occurs, the cost estimator needs to document how this is performed within the GR&A section of the estimate.
- h) **Schedule and key milestones.** Affect the level of activities and purchases as well as the distribution of estimated costs across time periods. Also affect the project's overall estimated cost and risk. Insofar as point estimating methods are based on historical patterns of expenditures, schedule information permits estimators to assess the applicability of specific analogies or phasing methods to the current project. Includes development and production start and stop dates, Phase B Authorization to Proceed (ATP), Phase C/D ATP, first flight, and Initial Operating Capability (IOC) timeframe for LCC computations, etc.

- i) **Labor resources and rates.** Availability of project-specific information enables the estimator to use nongeneric assumptions about the availability of labor and any associated labor costs. Labor resources are typically characterized as the number of full-time-equivalents (FTEs) needed by specialty or skillset. Assumptions that influence FTEs include if (and when) the specific skill mix is available and the number of persons working full time versus part time. Direct labor rates can be as specific as an hourly rate for a person's given specialty and level of experience. Alternatively, direct labor rates can be as top level as an overall average for all FTEs within a given specialty. It is also important to include GR&A on the added impact of overhead to labor rates (i.e., overhead rate).
- j) **Risks and associated risk reduction or mitigation activities.** Describes risks and likely reduction or mitigation activities to be used by estimators to properly size the project effort. Risk can affect cost in two ways. Realization of a technical, programmatic, or cost estimating risk may increase overall project cost. Such risks, which can have significant effect on cost uncertainty, should be described as a part of the baseline cost estimate. In addition, activities and purchases designed to reduce the probability of a risk or mitigate its effect on a program will increase the project's baseline effort and should be incorporated into the baseline cost estimate. Phasing or spreading the estimate over time should also incorporate risk evaluations.
- k) **Profit/Fee.** Identifies the profit or fee charged by prime contractors and their subcontractors as well as what items and activities are subject to those rates. This can represent a significant portion of overall project cost.
- l) **Design heritage/technology.** Almost all new NASA projects will have some degree of design commonality with a previously flown system—this is also known as “design heritage.” The GR&A section should take new technology and design heritage into account when estimating the cost of system design, development, and testing. The GR&A should indicate the systems with which commonality is assumed and how this is reflected in the estimate. Documenting what parts of the baseline cost estimate leverage design heritage helps improve the Basis of Estimate (BoE). For more information about technology cost estimating, see Appendix D.
- m) **Management and acquisition approach.** Considerations such as whether cost reductions are taken for change in management culture, new ways of doing business, in-house versus contract, etc. Includes percentages (or approach) used for computing program level wraps (i.e., unallocated future expense, program support, other direct charges, Headquarters taxes, Level II Program Office, etc.).
- n) **Production unit quantities.** Includes assumptions regarding spares, long lead items, make or buy decisions, as well as the quantity of development units, prototype, or protoflight units.
- o) **Description of Dollars and Inflation.** Specifies the types of year dollars that are presented in cost estimating analyses and results. Costs can be presented in Base Year dollars (synonymous with Constant Year dollars) and/or Real Year dollars (synonymous with Then Year dollars). Reference the inflation indices source(s) used to convert cost data (e.g., from Constant FY15 dollars to Real Year dollars).
- p) **LCC considerations.** Includes the mission lifetimes; the hardware replacement assumptions; the hardware and software heritage; the launch rates; the number of flights per year and any cost sharing or joint funding arrangements with other government agencies, if any (e.g., partnerships); and the make/buy decisions, outsourcing, or commercialization approach.

- q) **Implementation approach.** Aspects such as integration and test approach/test articles, mission assurance/safety approach, planetary protection approach, launch approval approach, commercialization and outsourcing approach, and partner commitments.
- r) **Facilities.** Use of existing facilities, modifications to existing facilities, and new facility requirements. Refer to Appendix L for more information on cost estimation of facilities.
- s) **Operations Concept.** Includes a description of any systems or efforts that contribute to the overall operation of the system from launch through end-of-mission. This includes, for example, a description of the launch vehicle used; the location of the Mission Control Center (MCC); and the use of the Tracking and Data Relay Satellite System (TDRSS), Deep Space Network (DSN), or other communication systems, etc. It is also important to provide the Operations and Support (O&S) period, the maintenance concept(s), and, if required, the training strategy.

The customer may provide cost estimators with some GR&A. More likely, GR&A are identified during the review of baseline artifacts and during data collection. Because GR&A can have a significant influence on the overall cost estimate, a joint review of GR&A with the customer early in the estimating process can help to eliminate surprises when initial results are presented. All GR&A should be documented, whether they are obtained from the customer or generated by the estimator. GR&A may also be an important consideration in conducting sensitivity analyses as outlined in Task 9.

### 2.2.2. Task 5: Select Cost Estimating Methodology

The goal of this task is to select the most appropriate cost estimating methodology (or combination of methodologies) for the data available to develop a high-quality cost estimate (Figure 5).

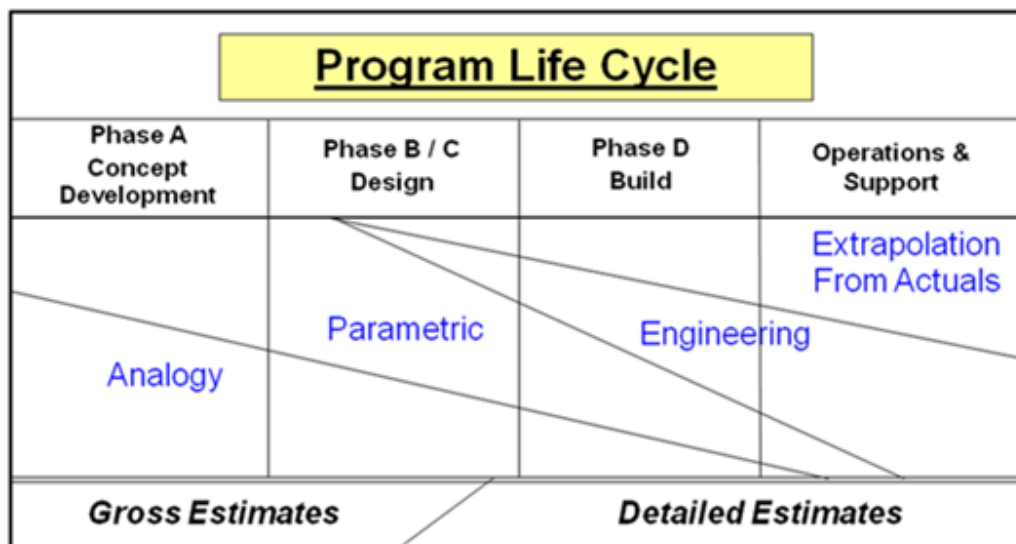


Figure 5. Use of Cost Estimating Methodologies by Phase<sup>12</sup>

<sup>12</sup> Defense Acquisition University, "Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management Framework chart (v5.2)," 2008, as reproduced in the International Cost Estimating and Analysis Association's "Cost Estimating Body of Knowledge Module 2."

Figure 5 shows the three basic cost estimating methods that can be used during a NASA project's life cycle: analogy, parametric, and engineering build-up (also called "grassroots"), as well as extrapolation from actuals using Earned Value Management (EVM).<sup>13</sup> Figure 5 indicates that the prevalent cost estimating methodology changes over the project life cycle. A primary reason for this is that the amount of data available to conduct the project estimate typically changes over time.

A basic explanation of each cost estimating methodology is provided here. Appendix C provides a detailed explanation of each cost methodology.

## Analogy Cost Estimating Methodology

The analogy method uses the cost of a similar system, adjusts for differences, and estimates the cost of the new system. This technique identifies a currently fielded system (comparable system) similar in design and/or operation to the proposed system.

Analogy estimates are based on a comparison and extrapolation to similar items or efforts. Cost data from one past program that is technically representative of the program to be estimated serves as the Basis of Estimate. Cost data is then subjectively adjusted upward or downward, depending upon whether the subject system is more or less complex than the analogous program. Clearly, subjective adjustments compromise the validity and defensibility of the estimate and should be avoided, while historical data and analysis are considered more credible and defensible.

This estimating approach is typically used when an adequate amount of program and technical definition is available to allow for the proper selection, and adjustment, of comparable program costs. An analogous approach is also used when attempting to estimate a generic system with very little definition.

The analogy system approach places heavy emphasis on the opinions of "experts" to modify the comparable system data to approximate the new system and is therefore increasingly untenable as greater adjustments are made. Table 1 provides a list of the strengths and weaknesses of using an analogous system method to develop a cost estimate.

**Table 1. Strengths, Weaknesses, and Applications of Analogy Cost Estimating Methodology**

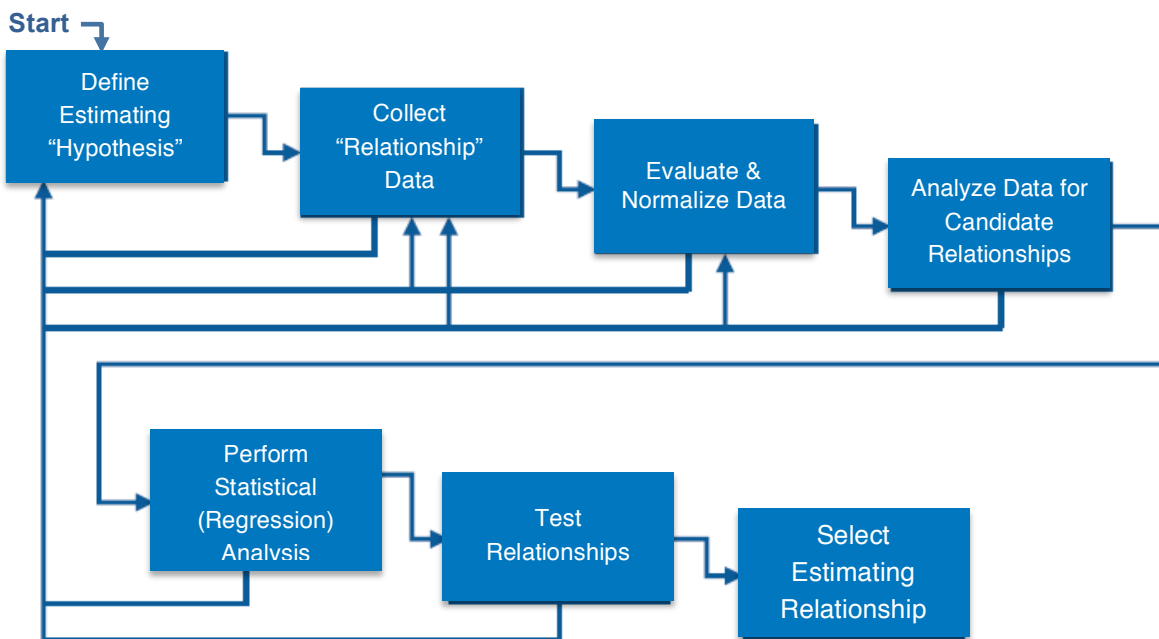
Strengths	Weaknesses	Applications
Based on actual historical data	In some cases, relies on single historical data point	• Early in the design process
Quick	Can be difficult to identify appropriate analog	• When less data are available
Readily understood	Requires "normalization" to ensure accuracy	• In rough order-of-magnitude estimate
Accurate for minor deviations from the analog	Relies on extrapolation and/or expert judgment for "adjustment factors"	• Cross-checking • Architectural studies • Long-range planning

For more information on the analogy method, refer to Appendix C (Cost Estimating Methodologies).

<sup>13</sup> More information on the use of EVM at NASA can be found at <http://evm.nasa.gov>.

## Parametric Cost Estimating

Parametric cost estimates are a result of a cost estimating methodology using statistical relationships between historical costs and other program variables such as system physical or performance characteristics, contractor output measures, or personnel loading. Generally, an estimator selects parametric cost estimating when only a few key pieces of data are known, such as weight and volume. The implicit assumption in parametric cost estimating is that the same forces that affected cost in the past will affect cost in the future. For example, NASA cost estimates are frequently of space systems or software (see Appendix M for more on software). The data that relate to these estimates are weight characteristics and design complexity, respectively. The major advantage of using a parametric methodology is that the estimate can usually be conducted quickly and be easily replicated. Figure 6 shows the steps associated with parametric cost estimating.



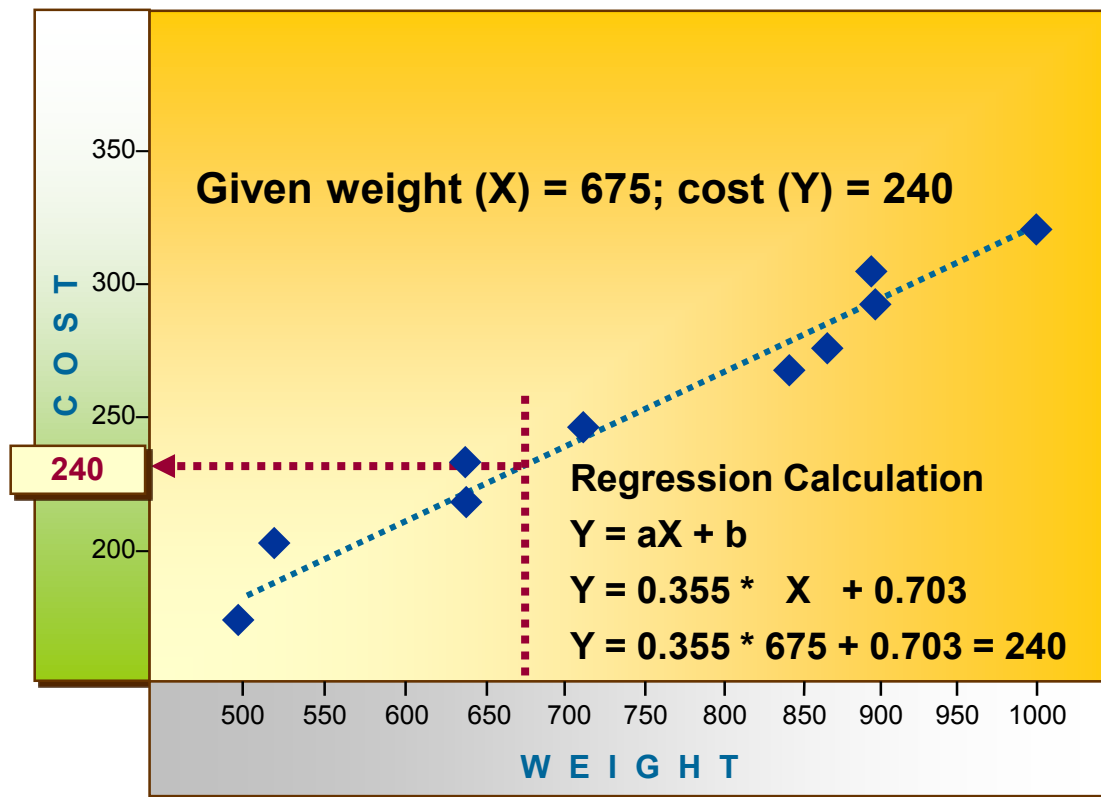
**Figure 6. Parametric Cost Modeling Process**

As part of these seven top-level steps, an estimator performs a regression analysis to develop one or more cost estimating relationships (CERs). The main objective of regression analysis is to generate a CER in the form of an equation that represents a relationship between a “dependent” variable to one or more “independent” variables. The dependent variable is called that because it responds to changes in the independent variable where:

- The value of the dependent variable, designated by the symbol  $Y$ , is calculated;
- The value(s) of the independent variable(s), designated by the symbol  $X$ , is known; and
- The resulting relationship between  $Y$  and  $X$  can be described mathematically.

When working with CERs, the dependent  $Y$  variable typically represents cost, while the independent  $X$  variable(s) represents the parameter(s) of the system or effort being estimated. Independent variables or “cost drivers” should be chosen because there is a strong correlation between these variables and cost ( $Y$ ) and because there are sound principles for the relationship being investigated.

For example, the assumption may be made that the weight of a component drives its total cost. Figure 7 provides an example of how this may be portrayed as a standard Cartesian coordinate graph. The dependent variable is the Y axis (Cost) and the independent variable is the X axis (Weight). By using historical data that compare cost to an independent variable and plotting, we can establish whether there is a relationship between the variables. From these data points, a “line of best fit” can also be plotted (depicted as the blue line in Figure 7). The line of best fit to the data can be tested and used for a CER. Methodology for developing a CER by resolving a line of best fit is covered in more detail in Appendix C.



**Figure 7. Scatterplot and Regression Line of Cost (Y) Versus Weight (X)**

CERs established early must be periodically examined to ensure that they are current throughout the life of an estimate and that the input range of data being estimated is applicable to the system. All CERs should be detailed and documented. If a CER is improperly applied, a serious estimating error could result. Microsoft Excel or other commercially available modeling tools are most often used for these calculations. Table 2 lists some strengths and weaknesses of using parametric cost estimating methodology to develop a cost estimate.

**Table 2. Strengths, Weaknesses, and Applications of Parametric Cost Estimating Methodology**

Strengths	Weaknesses	Applications
Once developed, CERs are an excellent tool to answer many "what if" questions rapidly	Often difficult for others to understand the statistics associated with the CERs	<ul style="list-style-type: none"> <li>• Design-to-cost trade studies</li> <li>• Cross-checking</li> <li>• Architectural studies</li> <li>• Long-range planning</li> <li>• Sensitivity analysis</li> <li>• Data-driven risk analysis</li> <li>• Software development</li> </ul>
Statistically sound predictors that provide information about the estimator's confidence of their predictive ability	Must fully describe and document the selection of raw data, adjustments to data, development of equations, statistical findings, and conclusions for validation and acceptance	
Eliminates reliance on opinion through the use of actual observations	Collecting appropriate data and generating statistically correct CERs is typically difficult, time consuming, and expensive	
Defensibility rests on logical correlation, thorough and disciplined research, defensible data, and scientific method	Loses predictive ability/credibility outside its relevant data range	

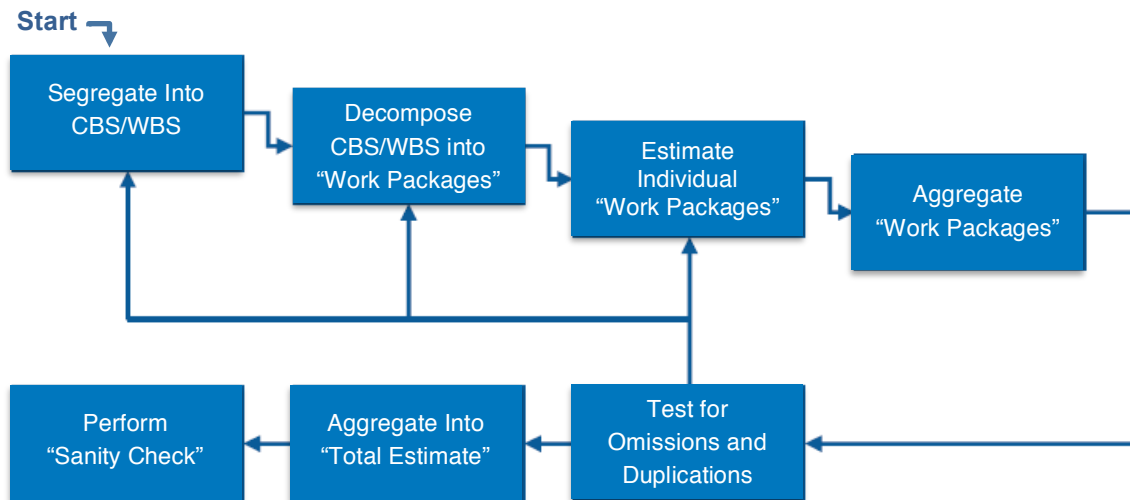
For more information on the parametric cost estimating method, refer to Appendix C (Cost Estimating Methodologies).

## Engineering Build-Up Methodology

Sometimes referred to as "grassroots" or "bottom-up" estimating, the engineering build-up methodology produces a detailed project cost estimate that is computed by estimating the cost of every activity in a Work Breakdown Structure, summing these estimates, and adding appropriate overheads. This costing methodology involves the computation of the cost of a WBS element by estimating at the lowest level of detail (often referred to as the "work package" level) wherein the resources to accomplish the work effort are readily distinguishable and discernable. This is often referred to as the Cost Breakdown Structure (CBS) or the Cost Estimating Structure (CES). In most cases, the labor requirements are estimated separately from material requirements. Overhead factors for cost elements such as Other Direct Costs (ODCs), General and Administrative (G&A) expenses, materials burden, and fee are applied to the labor and materials costs to complete the estimate. A technical person who is very experienced in the activity typically works with the cost analyst, who prepares these engineering build-up estimates. The cost estimator's role is to review the grassroots estimate for reasonableness, completeness, and consistency with the project GR&A. It is also the cost estimator's responsibility to test, understand, and validate the knowledge base and data used to derive estimates.

Figure 8 illustrates a method for deriving an engineering build-up estimate. While this is a simple illustration of the engineering build-up methodology, it is important to remember to conduct other detailed activities such as documenting the Basis of Estimates and schedules and applying wage and overhead rates.

There are also situations where the engineering community provides their "professional judgment," but only in the absence of empirical data. Experience and analysis of the environment and available data provide latitude in predicting costs for the estimator. This method of engineering judgment and expert opinion is known as the Delphi method.



**Figure 8. Method for Developing Engineering Build-Up Estimate**

The cost estimator's interview skills are important when relying on the Delphi method to capture and properly document the knowledge being shared from an engineer's expert opinion. Delphi method usually involves getting a group of experts to converge on a value by iterating estimates using varying amounts of feedback. During this process, individuals are generally not identified to the outside and, in some experiments, not identified to each other. More information is available in Appendix C.

Table 3 provides a list of the strengths, weaknesses, and applications of using the engineering build-up method to develop a cost estimate.

**Table 3. Strengths, Weaknesses, and Applications of Engineering Build-Up Methodology**

Strengths	Weaknesses	Applications
Intuitive	Costly; significant effort (time and money) required to create a build-up estimate Susceptible to errors of omission/double counting	<ul style="list-style-type: none"> <li>• Production estimating</li> <li>• Negotiations</li> <li>• Mature projects</li> <li>• Resource allocation</li> </ul>
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 by itself provide "statistical" confidence level	
Provides excellent insight into major cost contributors (e.g., high-dollar items).	Does not provide good insight into cost drivers (i.e., parameters that, when increased, cause significant increases in cost)	
Reusable; easily transferable for use and insight into individual project budgets and performer schedules	Relationships/links among cost elements must be "programmed" by the analyst	

### 2.2.3. Task 6: Select/Build Cost Model/Tool

The objective of this task is to select the most appropriate model/tool or to create a model to estimate the cost. Factors that influence the selection process include data and resource availability, schedule, and cost.

There are a variety of estimating tools and models available for NASA cost and schedule analysts to use in developing an estimate, including tools that NASA has sponsored and other commercially available tools for which NASA provides licenses. These models and tools are summarized in Table 4, indicating which estimating methodology they may be applicable for, as well as whether they are available on the ONCE Model Portal. Refer to Appendix E for additional information on these primary tools.

**Table 4. Cost Models and Tools Utilization Guide**

Tool Type	Estimating Methodology Applicability			
	Parametric			
	Analogy			
	Build Up			
NASA-Sponsored Models and Tools				
Project Cost Estimating Capability (PCEC)	ONCE Portal <sup>14</sup>	✓		
NASA Air Force Cost Model (NAFCOM)	(Transitioning users to PCEC)	✓		
NASA Instrument Cost Model (NICM)	X	✓	✓	
Technology Cost and Schedule Estimation (TCASE) Tool	X		✓	
Schedule Management and Relationship Tool (SMART)	soon	✓	✓	
Phasing Model	X	✓		
Schedule Estimating Relationship Risk Analysis (SERRA)		✓	✓	✓
Quantitative Techniques Incorporating Phasing and Schedule (QTIPS)		✓	✓	✓
QuickCost		✓		
One NASA Cost Engineering (ONCE) Database	X	✓	✓	✓
REDSTAR Database		✓	✓	✓
Models and Tools with NASA-Provided Licenses				
Polaris <sup>4</sup> (JCL Analysis)	X	✓	✓	✓
Argo (Monte Carlo simulation)	X	✓	✓	✓
Automated Cost Estimating Integrated Tools (ACEIT)	X	✓	✓	✓
CO\$TAT (statistical analysis package)	X	✓	✓	✓
Joint Analysis of Cost and Schedule (JACS)	(JCL Analysis)	X	✓	✓
SEER for Hardware, Electronics, & Systems (SEER-H)	soon	✓		
SEER for Software (SEER-SEM)	soon	✓		
PRICE® TruePlanning™		✓		
PRICE® Estimation Suite (PES)		✓		

As shown in Table 4, many cost estimating models exist, and, as is the case with the estimating methodologies, no single cost model can be used for all purposes. Estimating models can vary significantly in terms of data availability and automation. Some models require the user to create datasets and develop CERs, while other models already include datasets and automate many functions for the cost estimator. A model can also use a variety of estimating methodologies and direct inputs to complete a full estimate.

<sup>14</sup> Current ONCE Model Portal availability as of February 2015. More tools and models will be made available via the ONCE Model Portal at <http://www.oncedata.com> over time.

There are three key activities associated with selecting or constructing a model:

- Review available choices and make a selection. If no suitable alternatives exist, explore the option of creating a model.
- Ensure that the model is validated.
- Be prepared to defend the choice.

For each methodology described in the previous section, the cost estimator can select from a multitude of both commercially available and Government developed or owned models, as summarized in Table 4. Generally speaking, one of these models or tools should help the cost estimator work more efficiently and effectively. In addition, many cost estimators use commercially available spreadsheet software to create their own models when estimating needs cannot be met by commercially available models. Information about many modeling products, including NASA licenses available and recommended for use to the cost estimator, can be found in Appendix E. Included in Table 4 are some tools specific to software estimation, which is addressed in additional detail in Appendix M.

Many commercially available models are parametric models that generate estimates based on specific parameters that drive an estimate's cost. These cost drivers include items such as weight, volume, quantity, and schedule. These models can be used when only a few of these input parameters are known to generate a high-level estimate. If many of the cost drivers have been identified and there are many known technical input parameters, these models can also be used to generate very detailed and complex cost estimates. Commercially available parametric models use normalized industry data sets in generic and sometimes proprietary algorithms. For best results, these models should be calibrated to historical data that is comparable to the system being estimated to ensure that the estimate takes into account factors such as the project environment (e.g., Earth orbiting, planetary, etc.).

If an estimator chooses to build his or her own model, following a disciplined process will ensure a credible product. Once the estimator has identified the need for a model and determined the model type, the model design can begin. The importance of spending time up front to design and understand the model cannot be underestimated. The model developer needs to define the scope of the model, how it will ultimately be used, and the approach for integrating the data collected and new CERs developed. While planning the development, it is important to document the model GR&A.

After the model has been developed and populated with at least preliminary cost data, it must be validated before the estimator uses it. Once the model has been validated and any corrections or updates have been incorporated, it is ready to generate estimates. If the model is going to be distributed to the NASA cost community, user documentation and training should be prepared.

### Three Cost Model Best Practices

1. Before and after running the model, it is important to check and recheck data entry and formulas to ensure accuracy and to document each input and formula for the detailed Basis of Estimate (BOE).
2. Another important step to remember is to conduct a cross-check estimate, using an alternative methodology on your point estimate. This is important to ensure a "sanity check" on the original estimate and to show an alternative estimate view of the data.
3. In addition, keeping the estimate up-to-date helps to defend the estimate, reduce updated estimate turn-around time, and gives the decision-maker a clearer picture for "what if" drills to support major investment and budget decisions.

## 2.2.4. Task 7: Gather and Normalize Data

**The objective of this task is to arm the cost estimator with as much information as possible so that the most accurate and defensible cost estimate can be developed.**

Data collection and data normalization are two cost estimating activities that are critical to the development of a credible and defensible cost estimate. Sufficient time and resources should be planned in advance for these efforts.

### Data Collection

Data collection is one of the most difficult, time-consuming, and costly activities in cost estimating. Data needs are not always clear at the assignment's beginning, and data requirements often evolve during an estimate's development. An estimator needs to recognize that data, once collected, may need to be normalized to support a particular cost model or estimating method.

Because uncertainty is the underlying driver in a cost-risk analysis, it is critical to collect risk data at this time to support the cost-risk assessment. Many of the experts that will be interviewed and the data that will be reviewed in this effort will not only support the cost estimate, but may assist in identifying risks early and potentially save time by reducing data collection during the cost-risk assessment later in the process. Therefore, it is imperative that the cost estimator meet with experts early and often about uncertainty in technology, design, requirements, etc.

As previously noted, data collection can occur in earlier steps, such as collecting data for regression analysis to support a methodology or even earlier in the process when the estimator is understanding the project. The following are potential mechanisms available to the cost estimator for identifying quantitative cost data:

- Surveys and/or questionnaires;
- Model specific data collection/input forms;
- Interviews;
- Focus groups;
- Target research (public domain or otherwise), including reviews, papers, and statistical analysis; and
- Specific cost, technical, and programmatic data from primary and secondary sources (e.g., budget data, contract cost data, labor rates, workforce estimates, etc.).

#### One NASA Cost Engineering (ONCE) Database

The ONCE database is a secure, Web-based application that contains all completed CADRes for easy retrieval and analysis. The database provides advanced search functions to quickly access CADRe data across multiple projects and milestone events. Since CADRes represent snapshots of a project at successive key milestones, the ONCE database captures all of the changes that occurred on a project with the associated cost and schedule impacts.

The ONCE database provides enhanced insight into historical cost and technical data, and provides added capability to manage and organize these data. Such a capability helps advance costing practices and analysis across the Agency. The database is a Web-based ASP.Net application utilizing a Structured Query Language (SQL) server database on the back end. The ONCE server resides behind the Marshall Space Flight Center (MSFC) firewall and complies with all NASA security requirements.

Individuals who need access to the ONCE database can go to the ONCE Web site (<http://www.oncedata.com>) and click on the "request access" link on that page. The requestor must have an account in NASA's Identity Management and Account Exchange (IdMAX) system in order to gain insight.

For more information on ONCE, see Appendix A.

Based upon the resources, the schedule, and the expectations, the estimator should use the most appropriate data collection mechanisms as can be supported. The cost estimator will work with the NASA P/pM and members of the technical team to obtain the technical and programmatic data required to complete the cost estimate. Typically, system requirements are contained in a document or set of documents such as a technical baseline, CADRe, and/or the One NASA Cost Engineering (ONCE) Database.

A well-documented set of project requirements ensures that the cost estimators are estimating the same product being designed by the technical team. If some of the cost model inputs are not explicitly contained in the requirements document, the cost estimator will have to coordinate with the cognizant technical point of contacts to obtain the needed data by interview techniques and/or by survey mechanisms. Often, the cost analyst is estimating conceptual designs, so a requirements document does not exist. However, there is often conceptual design data such as master equipment lists, functional block diagrams, etc. Collecting programmatic data, such as schedules, is also key to data collection efforts. For more information on schedule analysis, see Appendix K.

Table 5 provides a list of typical data types and sources that cost estimators use to collect the data needed to develop an estimate.

**Table 5. Data Types and Sources**

Three Principal Types of Data		
Data Category	Data Type	Data Source
Cost Data	<ul style="list-style-type: none"> <li>• Historical Costs</li> <li>• Labor Costs</li> <li>• Existing Agency CERs</li> </ul>	<ul style="list-style-type: none"> <li>• Basic Accounting Records</li> <li>• Cost Reports</li> <li>• Historical Databases and Libraries</li> <li>• Contracts (Secondary)</li> <li>• Cost Proposals (Secondary)</li> <li>• CADRes</li> <li>• ONCE</li> </ul>
Technical/ Operational Data	<ul style="list-style-type: none"> <li>• Physical Characteristics</li> <li>• Performance Characteristics</li> <li>• Performance Metrics</li> <li>• Technology Descriptors</li> <li>• Major Design Changes</li> <li>• Operational Environment</li> </ul>	<ul style="list-style-type: none"> <li>• Functional Specialist</li> <li>• Technical Databases</li> <li>• Engineering Specifications</li> <li>• Engineering Drawings</li> <li>• Performance/Functional Specifications</li> <li>• End User and Operators</li> <li>• Master Equipment Lists</li> </ul>
Project Data	<ul style="list-style-type: none"> <li>• Development and Production Schedules</li> <li>• Quantities Produced</li> <li>• Production Rates</li> <li>• Equivalent Units</li> <li>• Breaks in Production</li> <li>• Significant Design Changes</li> <li>• Anomalies (e.g., strikes, natural disasters, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>• Project Database</li> <li>• Functional Organizations</li> <li>• Project Management Plan</li> <li>• Major Subcontractors</li> </ul>

As a final note, non-disclosure agreements (NDAs) are required for non-government employee access to Confidential Business Information (CBI), which includes proprietary and competition-sensitive contractor

data. Applicable NDAs must be in place between the originating and requesting organizations before access to such information can be provided. NASA places the highest priority on protection of contractor technical and cost data. Federal employees are subject to the relevant provisions of the Federal Trade Secrets Act. For further information on this subject, contact the Headquarters Cost Analysis Division.

## Normalize Data

Normalizing data for cost includes adjusting for inflation, which makes the raw data set consistent and fit for use in CERs, models, or estimates. Data may be adjusted for inflation again in Task 8 when it has been incorporated into the cost estimate and the estimate as a whole is adjusted for inflation. The full estimate may be adjusted for inflation to show the results in Base Year (BY), Constant Year (CY), or Real Year (RY) dollars. Table 6 defines some common terms used for inflation and escalation.

**Table 6. Inflation and Escalation Terms**

Term	Definition
Base Year (BY) Dollars	A point-of-reference year whose prices form the basis for adjusting costs or prices from other years.
Constant Year (CY) Dollars (ConstY)	Money or prices expressed in terms of values actually observed in the economy at any given time. Constant dollars represent the purchasing power of dollars tied to a particular base year's prices; the base year must be identified (e.g., constant FY13 dollars).
Current Year (CY) Dollars (CurrY)	Money or prices expressed in terms of values actually observed in the economy at any given time. Current dollars represent the purchasing power of dollars at the time they are expended. (This is what NASA calls Real Year dollars, though that term is counter to its usage in DOD and other Federal departments, where Real Dollars means Constant Dollars.)
Then Year (TY) Dollars	Total Obligation Authority (TOA) that includes a slice of inflation to cover escalation of expenditures over a multiyear period.
Real Year (RY) Dollars	Money expressed as spent dollars. Sometimes this is referred to as Then Year Dollars.
Inflation Rate	The percentage change in the price of an identical item from one period to another.
Outlay Profile	In percentage terms, the rate at which dollars in each appropriation is expected to be expended based on historical experience.
Raw Inflation Index	A number that represents the change in prices relative to a base period of 1.0000. Typically, periods are 1 year.
Weighted Inflation Rate	Combines raw inflation indices and outlay profile factors to show the amount of inflation occurring over the entire period needed to expend the TOA.
Composite Inflation Index	A weighted average of the inflation indices for the applicable subappropriations.

The Cost Analysis Division (CAD) in the Office of Evaluation at NASA Headquarters provides an annual update of the NASA New Start Inflation Index (<http://www.nasa.gov/offices/ooe/cad/publications/>) to be used to prepare cost estimates for new projects. The NASA New Start Inflation Index has been created to estimate new efforts and to normalize historical cost from prior missions. The factors contained in this index should not be used to estimate NASA civil servant personnel costs or determine if a contract is currently in place. Defense Contract Audit Agency (DCAA)-approved forward pricing indices should be used for all efforts that are already under contract.

Through escalation, inflation adjusts costs to reflect the decrease in the purchasing power of money over time. The inflation factor is the "multiplier" used to account for the change in the price of a product or service over time. Escalation factor (or weighted inflation) is the "multiplier" that accounts for inflation plus the normal occurrence of allocating money in 1 year and incorporates outlay rates over a number of years. For more information on inflation adjustments, refer to the DOD Inflation Handbook at [https://www.ncca.navy.mil/tools/OSD\\_Inflation\\_handbook.pdf](https://www.ncca.navy.mil/tools/OSD_Inflation_handbook.pdf).

While inflation is the most common data normalization technique to improve consistency in a data set, there are other normalization techniques that can be just as important. Adjustments for learning or cost improvement curves may apply. Production rate (units produced over a time period) may also have an effect on the raw data set, which calls for adjustment. In the case of production rates, there may be patterns or influences in the production of the item, such as facilities or personnel that affect the data. At NASA, there are few projects that involve production rate factors; however, NASA estimates should take into account production considerations for data collected from other sources. Adjustments that may need to be made in order to normalize data include the following:

- Scope consistency between the historical data of a product and the product being estimated;
- Unusual events or anomalies in a project's life, such as extra testing, failures, or labor anomalies;
- Technology improvements and advancements, where the data may need to be adjusted by engineering judgment;
- Raw data from reporting system anomalies or changes, such as a change in rates, factors, or hours for standard reporting; and
- Reporting system differences that may require mapping accounting classifications or categories of data to WBS elements.

Normalized data should be reviewed and validated by the estimator to ensure that a consistent data collection methodology, data collection formats, and procedures to identify data anomalies are in place. Considerations such as data sufficiency to support the estimating methodology selected and documentation to ensure the traceability of adjustments made to the data are also critical. These documented factors assist the estimator with the validation of the data, lead to data reliability, and ultimately contribute to estimate credibility.

If an estimator takes each of these elements into consideration when identifying and collecting data, analyzing schedules, and normalizing data, the repeatability and credibility of the data supporting the estimate will be improved.

## 2.3. Part 3: Cost Estimate Tasks

The last five tasks of the NASA cost estimating process revolve around the actual generation and documentation of the estimate. These Cost Estimate tasks are detailed below.

### 2.3.1. *Task 8: Develop the Cost Estimate*

**The goal of this task is to create an initial LCC point estimate.**

There are eight activities associated with developing a cost estimate:

- Verify the GR&A;
- Populate the model with the normalized data;
- Ensure that the estimate is full cost compliant;
- Run the model to calculate cost;

- Time-phase the estimate;
- Adjust the estimate for inflation;
- Conduct any cross-check estimate or estimate reconciliation; and
- Develop or update the cost track to previous or independent estimate.

Once the model has been selected or constructed and the data have been gathered, the next step is to populate the model with data according to the GR&A. The model is run and a point estimate is calculated. Generating a point estimate is an important step, but it is just the beginning of the cost-risk process.

*It is important to understand that when project costs are being estimated, the costs are uncertain and the point estimate is not definitive and not the only possible estimate.*

## Time-Phasing the Estimate

Next, the cost estimator must properly time-phase the data according to the planned development schedule. This can be done using many techniques, including Beta Curves historical spreads, engineering judgment, or budget constraints. Just as the data needed to be normalized for inflation, the estimate must also be adjusted for inflation over its life cycle.

Baseline cost estimates that are generated in CY dollars can be phased by fiscal year prior to being converted into annual real-year dollars (also known as then-year dollars). Once baseline estimates are adjusted for inflation over the project life cycle, these RY dollars can be used as inputs for the annual NASA budget for the project. There are two main methods to accomplish this, and these are briefly discussed below and addressed in more detail in Appendix F.

The phasing of the cost estimate (which reflects when funds will be expended) needs to be further adjusted to reflect the budget authority, if being used for developing budgets by taking into account when budget authority is needed relative to when those funds will be expended.

## Develop Probabilistic Cost Estimate

The NASA cost community started implementing probabilistic analysis in the early 2000s. NASA embraces probabilistic cost and schedule analysis as a means of improving its delivery of projects and programs on time and within budget. NASA leadership believes that all projects should submit budgets that are based upon a quantification of the risks that could cause the project to take longer or cost more than initially anticipated. Identification and estimation of risk and accommodation of uncertainty, for both cost and schedule, are keys to improving NASA's cost and schedule performance, thereby helping to establish a more credible cost and schedule baseline. By making use of probabilistic techniques, NASA is able to more effectively communicate the impact of changes to planned or requested resources by providing quantified effects on the probability of meeting planned cost and schedule baselines.

The estimation and analysis community has, as a group, moved to the adoption of probabilistic cost estimates rather than deterministic cost estimates. NASA has been a supporter, proponent, and creator of probabilistic cost estimates for more than 10 years. Probabilistic cost estimates attempt to quantify risk and uncertainty. A probabilistic cost estimate provides management with significant insight into the key cost and schedule drivers of the program, allowing them to

### Why do Probabilistic Analysis?

NASA does probabilistic analysis to enable more informed management decisions based on an understanding of risk and uncertainty. NASA deals with complex, one-of-a-kind systems that have a lot of risk and uncertainty associated with them. A probabilistic analysis process helps NASA management understand the risk involved, *informing decisions* on the appropriate amount of risk that the Agency is willing to accept.

actively manage and develop mitigation strategies to reduce cost. In addition to providing insight, probabilistic cost estimates are useful for reporting and analysis purposes, providing valuable information to stakeholders, management, and partners.

The development of a probabilistic estimate can often originate with a point estimate (deterministic estimate), but enhances it by including risk and uncertainty through a variety of techniques. These methods (typically described as inputs based, outputs based, and scenario based) may rely on Monte Carlo simulation or be analytical in nature. In most cases, adding up the most likely point estimates produces an understatement of the total cost because the sum of most-likely estimates does not equal the most likely total.<sup>15</sup> Refer to Appendix C for further explanation.

Conducting a probabilistic analysis involves the identification and quantification of risk and uncertainty. As mentioned above, the method being used to develop the probabilistic analysis may differ, but the fundamental goal and outcomes are the same. Completing a probabilistic analysis as a part of the estimating process ensures that decision makers can view and assess the risk of a project. The successful completion of a probabilistic analysis will produce a range of probable answers for cost, schedule, or both.

Estimators and analysts may choose to develop a Technical Baseline Estimate (TBE) or “point estimate” first before conducting a probabilistic risk analysis. However, this is not a hard requirement. Many estimators and analysts will not perform the activities in serial, but instead will perform them in parallel during the estimating process. Iteration may also be required during the estimating process as data, models, and methodologies are refined.

### **2.3.2. Task 9: Develop and Incorporate the Cost Risk Assessment**

**The objective of this task is to produce a credible project cost cumulative distribution function (CDF, or “S-curve”) for the range of costs of the project.**

#### **Cost-Risk Assessment**

There are six activities associated with developing a cost-risk assessment in order to understand the current confidence level of the project and estimate the amount of unallocated future expense (UFE) necessary to achieve a desired confidence level:

1. Determine the project’s cost drivers and risks with input from the NASA P/pM and staff;
2. Develop probability distributions for the technical and schedule cost drivers;
3. Develop probability distributions for the cost model uncertainty;
4. Run the risk model;
5. Identify the probability that the actual cost is less than or equal to the point estimate; and
6. Recommend sufficient UFE to achieve the desired percent confidence level.

#### **Cost Risk Assessment**

Cost risk must be carefully and quantitatively assessed in developing and presenting any cost estimate for several reasons. First, when trade studies are conducted, a single cost estimate, such as an expected cost, may mislead the trade team by not revealing the potential for overruns. Second, at Confirmation Reviews and Authority to Proceed decision points, the cost estimate must include an appropriately chosen level of unallocated future expense (UFE) to achieve a desired confidence level. The objective of a cost-risk analysis is to produce a credible project cost S-curve (cumulative distribution function) for the cost of the project.

<sup>15</sup> Garvey, Paul R., *Probability Methods for Cost Uncertainty Analysis*, New York, Marcel Dekker, 2000

Cost-risk assessment is the process of identifying and analyzing critical project risks within a defined set of cost, schedule, and technical objectives and constraints. Cost-risk analysis is an analytical process that captures estimating error (or uncertainty); uncertainty in the technical design, requirements, and technology; and project risks to determine a probabilistic range of outcomes. This task also allows the cost estimator to document risks in a manner that accommodates proactive management of project costs. Details about methodologies and how to conduct cost-risk assessments are provided in Appendix G.

Cost-risk analysis quantifies the necessary budgeted UFE necessary to reach an acceptable level of confidence. Risk dollars should be phased in the estimate where they will most likely be needed. Most often, the risk dollars are needed when problems occur between PDR and CDR and then again during Integration and Test.

## **Sensitivity Analysis**

It is recommended that a sensitivity analysis be performed to identify the major cost drivers (i.e., those design parameters whose changes create the greatest changes in cost). Sensitivity analysis helps to determine how sensitive the estimate is to changes in assumptions, technology, or system design. By relating model inputs back to such changes, sensitivity analysis provides the decision maker with added insight into how program decisions can change estimates that cost models produce. For these decision makers, a range estimate with an understanding of the certainty of how likely it is to occur within that range is generally more useful than a point estimate. Due to the nature of the NASA design and development process, there will always be uncertainty about the values of some, if not all, of the technical parameters during the definition phase of a project. Likewise, many of the assumptions made at the beginning of a project's definition phase may turn out to be inaccurate. Therefore, once the point estimate is developed, it is often desirable to determine how sensitive the total cost estimate is to changes in the input data.

While sensitivity analyses can occur at any stage of an estimate, it generally makes sense to derive an unconstrained solution that meets all mission objectives initially and then begin to "back off" that solution in the interest of saving money. Care must be taken, however, not to impact the material solution to such an extent that the benefits derived from that solution are significantly altered through introduction of the changes.

More details on sensitivity analysis can be found in Section 4.1 and Appendix G.

## **Choosing the Level of Unallocated Future Expense**

The level of UFE or UFE percentage should be selected based upon achieving a particular level of confidence from the cost or joint cost and schedule risk analysis. The appropriate level of confidence is chosen by the appropriate NASA management council after the analysis, and the resulting UFE should be identified as the recommended level at all Confirmation Reviews.

For trade studies and formal analyses of alternatives, the cost analyst may choose to add UFE so as to hold the level of confidence constant across all alternatives and report the resulting cost. Or the cost analyst may add UFE so as to hold the cost constant and report the resulting level of confidence.

### **2.3.3. Task 10: Document the Cost Estimate**

**The objective of this task is to capture, concurrently, from project initiation through completion, the LCC results of the cost estimating process, and all of its byproducts (confidence levels, Basis of Estimate (BOE), risk, UFE, etc.).**

The purpose of the cost documentation is to provide a written justification for the program cost estimate. This documentation is typically referred to as a BOE. The BOE documents the ground rules, assumptions, and drivers used in developing the cost and schedule estimates, including applicable model inputs, rationale or justification for analogies, and details supporting cost and schedule estimates. Given the size and importance of programs, the documentation should be viewed as a substantive effort. A general rule of thumb is that the final product should provide sufficient information on how the estimate was developed so that independent cost analysts—or other review team members—could reproduce the estimate.

Although standardization of the content and format of the cost estimate documentation across all NASA Centers is unrealistic, it is recommended that each Center maintain as much consistency internally with respect to the documentation content and format as possible, since this promotes completeness and quality—Agencywide—of the cost estimate's documentation. Cost estimators document the LCC results throughout the entire cost estimating process—not just when the estimate is complete. The final documentation should capture the estimates for each element supporting the point estimate, the inputs used to develop the cost-risk estimate, and a description/analysis of the cost-risk estimation results.

The means by which each part of an estimate has been derived must be fully explained, and the databases employed must be provided in the documentation or clearly identified. A Comparison Cost Track by element to identify and explain any deviations between the estimate and the prior estimate should also be included. If other alternatives are being considered, a brief summary of each alternative should also be included.

In addition to providing a brief description of the system or project being estimated, cost documentation provides:

- The methodology and/or models used;
- Sufficient information on how the estimate was developed to allow independent cost analysts or other review team members to reproduce the estimate if required, including:
  - Inflation and other supporting assumptions;
  - Data sources;
  - BOE (e.g., equations applied, quantities used, labor rates and workforce estimates, schedules);
  - New facilities, initial spares, and other start-up investment costs; and
  - Operations costs with specific operational scenarios.
- The means by which each part of an estimate and the databases used can be fully explained;
- A brief description of the acquisition strategy as it impacts/influences the LCC;
- The cost S-curve and unallocated future expense (UFE) sufficiency analysis;
- The sensitivity analyses; and
- A comparison track to identify and explain any deviations between the current estimate and any prior estimate.

A well-documented estimate provides an understanding of the cost elements so that decision makers can make informed decisions. Other reasons why proper documentation is important in a cost estimate include:

- Experience from formal cost reviews, such as Non-Advocate Reviews (NARs), has proven that poorly documented analyses do not fare well. The credibility of the total project suffers if the analyst is unable to explain the rationale used to derive each of the cost estimates. Conversely, if a reviewer understands your inputs, approach, and assumptions, your estimate remains credible regardless of whether disagreements remain or adjustments are recommended.
- If the BOE is explicitly documented, it is easier to modify key assumptions as they change during the course of the project life cycle, facilitating updates to the estimate and providing a verifiable trace to a new cost baseline. Importantly, this effort supports the requirement imposed by NPR 7120.4 to revalidate the Program Cost Commitment (PCC) annually. A well-documented CADRe not only facilitates the establishment of the baseline PCC, but also aids the revalidation process and the development of an updated PCC.

Documentation should include a reasonable description of each line item, along with risk confidence levels for many, if not all, cost elements. The level of detail varies with the estimate, but the minimum amount of detail should be enough for another estimator to reconstruct the estimate. Supporting data too complex for inclusion in the main documentation should be included in an appendix. It is important for the documentation to be accessible beyond the actual cost model. Whenever sufficient details and data sources are available, consider developing a separate document (e.g., BOE) to sufficiently describe these available data. There should be an accompanying document such as a BOE that provides an explanation of estimate details and data sources.

A peer review is another important part of completing an estimate. Once the estimate has been completed and documented and before the estimate is presented to decision makers, it is important for the estimator to get an outside review. This “sanity check” can provide an outside perspective and a fresh view of the estimate, which can catch any issues with the estimate before presentation. This review can also prepare the estimator for the actual process of briefing the estimate to decision makers. A peer review can be conducted continuously during the cost estimating process or at any point along the way, but it should be completed in full once the estimate is complete and documented.

### Cross Checks

To verify the reasonableness and credibility of the estimate, estimators are encouraged to generate secondary estimates based on the same set of normalized data and inputs, but using different models and techniques. For example, an estimator may compare the results of a parametric model with costs from an analogous program. Another cross-check is to compare the results from one parametric model with those from a different model, or different estimators can run the same model independently and then compare results. The availability of cross-checks, historical data, estimates for similar projects, and expert judgment enables estimators to assess the credibility, reasonableness, and validity of the estimates as a whole and at the detailed level. When issues are identified that lead to questions about the cost estimates, the estimators can apply a cross-check using different methods and tools. They can also conduct sensitivity analyses by identifying key inputs and then varying their values to understand the estimate drivers. The assessment process typically involves a collaboration of estimators and subject matter or technical experts. Many estimators find that a peer review is useful in cross-checking their estimates.

Furthermore, the cost analyst must ensure that the cost estimate meets certain quality standards, including such attributes as traceability, defensibility, and repeatability.

## Cost Documentation Best Practices

- Begin documentation efforts early and continue throughout the cost estimating process. Document sources in the actual models and include these details in the estimate write-up and in the estimate presentations. Provide the data or rationale to support qualitative or subjective inputs, like percent new design or manufacturing complexity.
- When a CER is used, it should be presented, and its source must be cited fully, or the model and the set of data with which it was calibrated must be cited. A cost estimator reviewing the cost documentation should be able to obtain enough information either from the document or from the sources cited therein to reconstruct the CER and evaluate its associated statistics. CER documentation should include descriptive statistics (see Appendix C). This information is necessary to adequately assess the applicability of a CER.
- Where subjective judgments are used to adjust estimates made by analogy with other systems or components of systems, the sources of those judgments must be identified (e.g., cost analysts, engineers) and full citations for the source(s) of the costs of each element in an engineering or grassroots estimate must also be cited.
- Present detailed examples of methodologies used to estimate first and second levels of the cost elements normally included in life-cycle cost estimates (LCCEs) for each phase.
- When used in the estimate, actual cost history from past or present contracts or analogous programs should be provided.
- Areas of uncertainty (such as pending negotiations, concurrency, schedule risk, performance requirements that are not yet firm, appropriateness of analogies, level of knowledge about support concepts, critical assumptions, etc.) must be documented.
- Sensitivity analysis should be performed to include the cost of changing significant input parameters. Risk analysis should include risk-adjusted point estimates. Crosschecks should be included for all high-cost, high-risk portions of the estimate.
- The approach, GR&A, inputs, sources, etc., for the cost-risk analysis must be fully documented.
- Tracking through a comparison or a cost trace is required when an estimate changes. Documentation must include the specific reasons for the change.

See Appendix H for more discussion on documenting the estimate.

### **2.3.4. Task 11: Present the Cost Estimate Results**

**While it may not be realistic to standardize the content and format of the cost estimating briefing charts across all NASA Centers for all estimate types, the objective of this task is to successfully create and communicate a quality cost estimate to decision makers and stakeholders.**

There are three activities associated with presenting/briefing results:

- Create briefing materials and supporting documentation for internal and external presentations, as appropriate.
- Present and defend the estimate.
- Gather and provide feedback to capture improvements for the next estimate.

Consistency in presenting cost estimates across Centers facilitates understanding during the management review process and promotes completeness and quality of the cost estimating and analysis documentation.

The cost estimator should prepare briefing material and supporting documentation for internal and external presentations, as appropriate. It is again recommended that each Center internally maintain as much data formatting consistency as possible, as that will facilitate understanding during the management review process and promote completeness and quality. Thorough documentation is essential for a valid and defensible cost estimate. Cost presentation documentation provides a concise, focused illustration of key points that should direct the reader's attention to the cost drivers and cost results.

### ***2.3.5. Task 12: Update the Cost Estimate as Required***

**The purpose of updating the cost estimate is to improve the estimate as better information becomes available. Doing so can help the estimator defend the estimate over time, reduce updated estimate turnaround time, and give decision makers a clearer picture for major decisions or “what if” drills.**

There are two activities associated with updating the cost estimate:

- Assess and utilize customer feedback along with lessons learned and incorporate this feedback into the next version of the estimate.
- Update the estimate when project content changes and as the project moves through its life-cycle phases and conducts milestone reviews.

It is important to maintain a good project cost baseline as a forward indicator for cost overruns. Cost estimates must be updated whenever project content changes and reconciled to the estimate baseline. By accomplishing a cost estimate on proposed program alternatives, the Project Office can determine the cost impact of the alternatives.

One of the best ways a project team can update its schedule and cost estimates is to adjust these according to its own performance, as discussed in Appendix I. Earned Value Management is recognized as a best practice for making such cost and schedule adjustments (e.g., on a monthly or quarterly basis).<sup>16</sup>

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<sup>16</sup> EVM information available at <http://evm.nasa.gov/>.

## 3. Joint Cost and Schedule Confidence Level Analysis

Joint Cost and Schedule Confidence Level (JCL) is an integrated analysis of cost, schedule, risk, and uncertainty. The result of a JCL indicates the probability that a project's cost will be equal to or less than the targeted cost *and* that the schedule will be equal to or less than the targeted finish.

The development of a probabilistic cost-loaded schedule (PCLS) is the primary methodology for developing a JCL. This method requires the project and the review entity to focus on the project's plan, which in turn improves project planning by systematically integrating cost, schedule, and risk products and processes. It also facilitates transparency with stakeholders on expectations and probabilities of meeting those expectations. Lastly, it provides a cohesive and holistic picture of the project's ability to achieve cost and schedule goals and helps the determination of reserves (or UFE) for cost and schedule to achieve the desired confidence level.

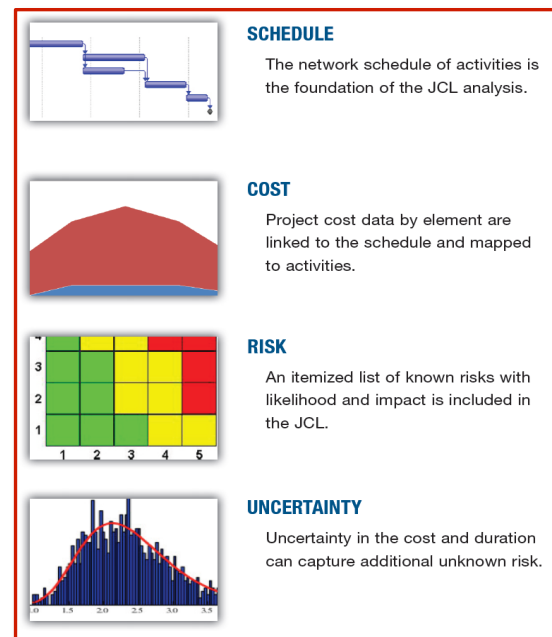
This section presents an overview of the JCL process, outputs, and usage. Appendix J provides more in-depth information and should be referenced by those developing a JCL.

### 3.1. JCL Process Flow

This section gives a broad overview of the JCL process.

In general, there are five fundamental steps in building a JCL and one prerequisite (step 0):

0. Identify goals of the JCL analysis.
1. Develop a summary analysis schedule.
2. Load cost onto the schedule activities.
3. Incorporate the risk list.
4. Conduct an uncertainty analysis.
5. Calculate and view the results.



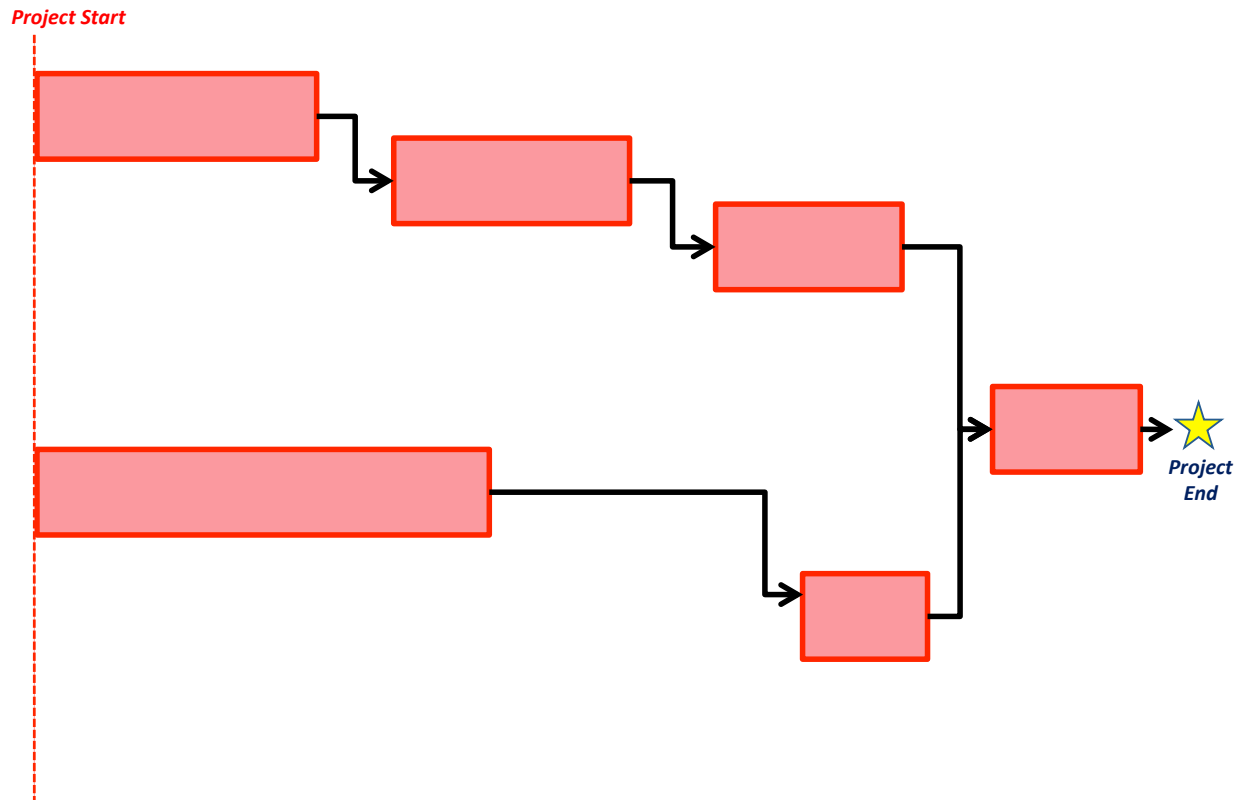
The following sections will walk the reader through a simple illustrative example, describing each of the key steps in the JCL analysis process.

#### 3.1.1. Step Zero: Identify Goals of the JCL Analysis

As stated previously, JCL is a policy requirement, but it can also be a very valuable management tool. There are certain quality standards that must be met to satisfy policy. However, depending on the goals and expectations of the JCL analysis, the cost estimator may want to set up the JCL analysis to assist and be synergistic with other products and processes. When setting up the JCL process, especially the schedule, it is important to think about what questions the JCL should answer, who the primary users and beneficiaries will be, and what fundamental insight the JCL should provide.

### 3.1.2. Step One: Develop a Summary Analysis Schedule

The backbone of the entire JCL analysis is the schedule that includes well-defined activities and logic networking. For more information on developing a schedule, please refer to Appendix K and/or the NASA Schedule Management Handbook ([http://www.nasa.gov/pdf/420297main\\_NASA-SP-2010-3403.pdf](http://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf)). For the purposes of this illustrative example, it is assumed that a project has set up a very simple schedule.<sup>17</sup> Figure 9 shows a simple schedule with two parallel activity streams, one with three tasks and one with two tasks, converging on a single integration task. Once that integration task is complete, the project is complete.



**Figure 9. Summary Schedule**

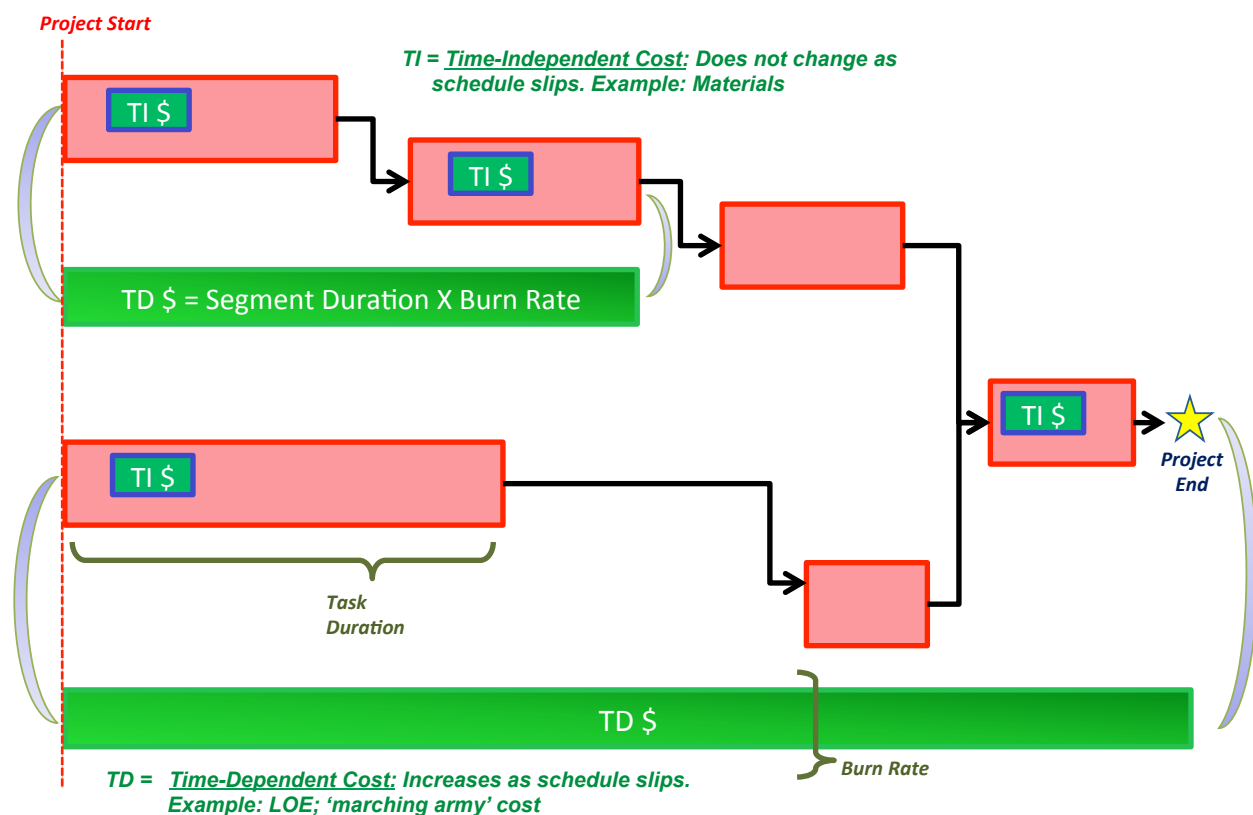
As you will notice, the schedule is logically linked, meaning that you can see the predecessors and successors for every task. You may also notice that the project's milestone—in this case, Project End—is linked in the schedule network, too. Such milestones will automatically adjust as you populate the JCL schedule.

### 3.1.3. Step Two: Load Cost onto the Schedule Activities

Once a robust schedule that accurately portrays project work flow is established, the next step is to cost load the schedule. Cost loading is accomplished by mapping cost to schedule. Cost data can be summarized by a Work Breakdown Structure to aid with mapping.

<sup>17</sup> Note that this example analysis schedule is extremely simplified—a high-level schedule of a typical spacecraft system will have much more detail than this.

Figure 10 shows that time-dependent costs can spread over separate tasks. This example shows two sets of TD costs. One set expands across the entire project. This implies that there is a “standing army” of personnel that will follow the project regardless of where it is in the life cycle (i.e., project management). Another observation is that there are two tasks that do not have TI costs. This is not to imply that there are no costs associated with these tasks—in fact, there are TD costs; it does, however, show that these tasks are level of effort (LOE) tasks that are executed only by the TD resources or costs.



### Figure 10. Cost-Loaded Schedule

### 3.1.4. Step Three: Incorporate the Risk List

So far, the schedule represents the baseline plan for the project (cost and schedule). All durations and cost assumptions may have risk mitigation (for costs and schedule) embedded in the plan, but risk realization from the risk management system has not been incorporated. Traditionally, NASA programs will utilize their risk management system to help populate these risk tasks; however, a JCL analysis does not have to be limited by what is currently being managed in the risk management system. For example, there may be a programmatic risk that does not “make it” into the risk management system but still is of concern to the Project Manager. The JCL analysis allows the project to model the programmatic consequences and expected value of these risks. Figure 11 demonstrates how to incorporate discrete risks into the system. Refer to Appendix G for an in-depth explanation of incorporating risk.

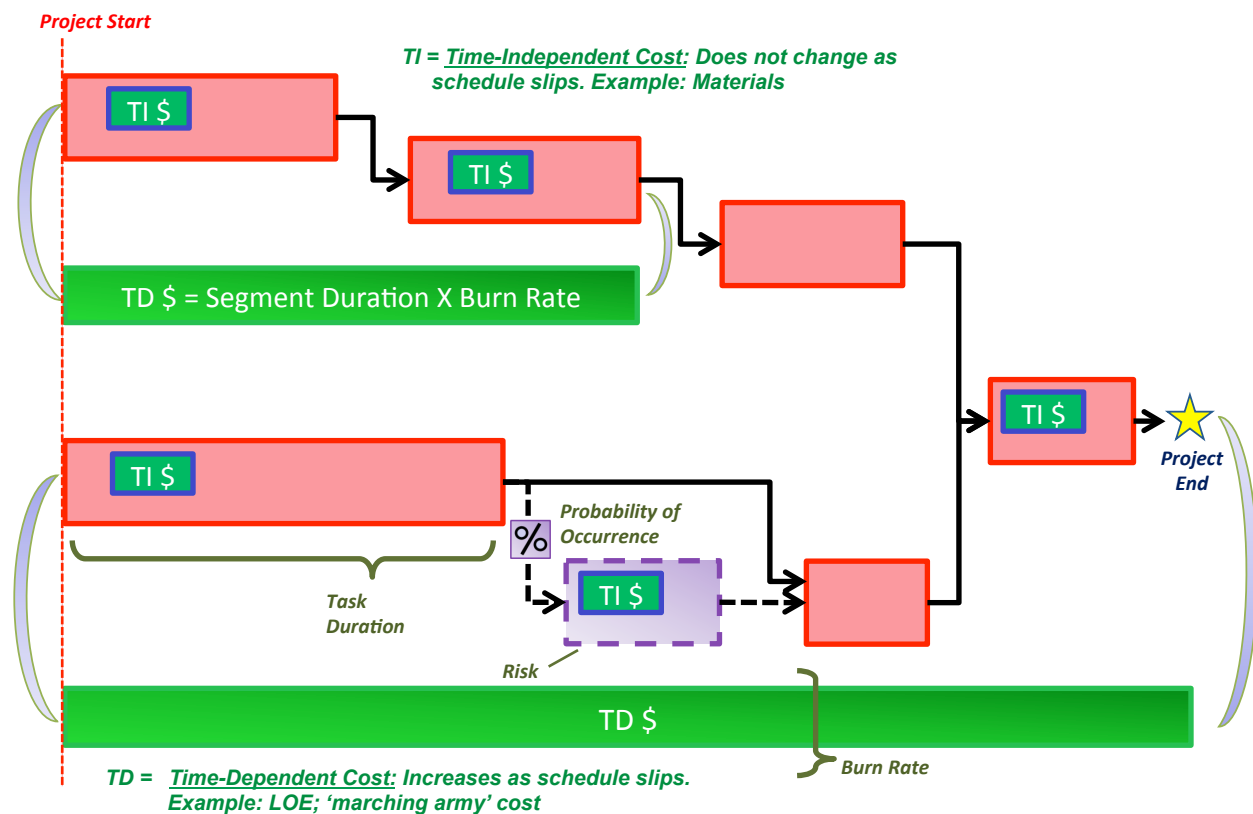


Figure 11. Schedule with a Discrete Risk

### 3.1.5. Step Four: Conduct Uncertainty Analysis

Step 4 in performing a JCL is identifying and implementing the uncertainty. To this point in the JCL process, the primary driver of the JCL results is the quantitative risk assessment and the effect it has on the cost-loaded schedule.

While the risk assessment provides a snapshot in time of potential future events that may cause the project to overrun, it does not account for two key facets that have the ability to drive cost and schedule:

- **Incomplete Risk Register:** Although NASA's Continuous Risk Management (CRM) process aims to create as comprehensive a risk register as possible, it is unrealistic to predict all events that may increase cost or schedule.
- **Uncertainty in the Baseline Estimate:** Disregarding risks altogether, it is impossible to predict the time or budget required to complete various segments of space-vehicle research, development, and production.

In recognition of these two facets, the cost estimator and/or JCL analysts must account for uncertainty in baseline cost and schedule plans. For the purposes of the JCL, it is important to further distinguish between risk and uncertainty, as they are distinct inputs to the JCL model. For JCL analysis, risk and uncertainty are defined as the following:

- *Risk* is an event not in the project's baseline plan that is an undesirable<sup>18</sup> outcome (discrete risk). This definition is similar to what appears in a risk matrix. The event is characterized by a probability of occurring and an expected impact if the event did occur.
- Uncertainty is the indefiniteness about a project's baseline plan. It represents our fundamental inability to perfectly predict the outcome of a future event.

### Tip:

History and experience have shown that the variance in a typical JCL model is driven significantly more by the uncertainty inputs than the discrete risks. With this said, it is essential to consider uncertainty when conducting a JCL analysis.

For a seasoned cost or schedule risk analyst, it is clear that there is an overlap between these two terms. The indefiniteness of a project's baseline plan is partially caused by risks to the project. In the JCL, the analysis risks from the project's risk register are modeled alongside uncertainties applied to the baseline plan. This is done to increase the usefulness of the JCL analysis to a Project Manager; being able to discern the effect each risk has on a project's cost and schedule allows for the development of risk-mitigation plans.

To avoid double-counting, special care must be taken to segregate uncertainty caused by risks already being modeled in the JCL simulation from the underlying uncertainty of the project's plan once these risks have been discounted. Although it is surely the case that this segregation can never account for all aspects of double counting, the benefit of Project Managers seeing the risks outweighs the potential for slight errors in the analysis.

Typically, uncertainty is modeled using a triangular distribution. The low value represents the low extreme of uncertainty, the middle value represents the "most likely" value of the cost or duration, and the high value represents the high extreme of uncertainty. Please note that the baseline plan may not be any of these numbers (low, middle, high) but should fall within the range of low and high. Please refer to Figure 12 for a visual representation.

<sup>18</sup> Risks can also be opportunities if the outcome of the event is a positive outcome.

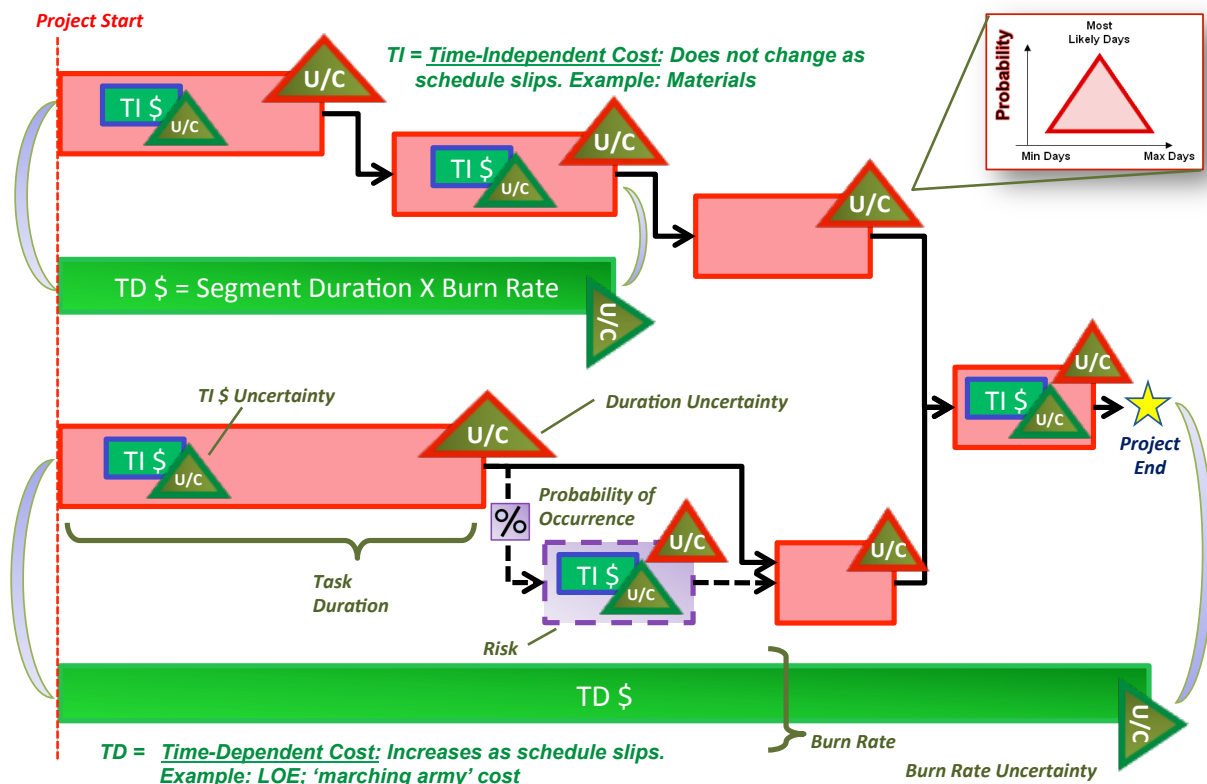


Figure 12. Schedule with Uncertainty

### 3.1.6. Step Five: Calculate and View Results

The process shown above should be considered iterative in that analysts need to ensure that durations and logic make sense and that milestones are achievable. At any point in the JCL iteration process, the final and key step is interpreting the results of the analysis. The JCL model can produce a variety of reports to help an analyst finalize the JCL inputs. This exhaustive list of possible reports is not shown for brevity purposes. With that said, it is important to explain briefly the most commonly used JCL chart: the scatterplot.

The JCL scatterplot in Figure 13 is a standard XY chart with the schedule on the X axis and cost on the Y axis. Each point is the result of the simulation calculation representing a cost and schedule pair.

Establishing a cost and schedule target (where the blue lines intersect in Figure 13) divides the scatterplot into four quadrants. One quadrant contains results that are at or beneath the target (shown in green). Another quadrant contains results that exceed the target (shown in red). The white points represent results that exceed either cost or schedule, but not both. Adding up points in a given quadrant provides an overall confidence level (CL) with respect to the cost and schedule target. For example, the number of data points in the lower left quadrant divided by the total number of points in the scatterplot equals 14.4 percent. In other words, there is a 14.4 percent joint cost and schedule confidence level (JCL)—the probability that the project will end up at or below its cost and schedule target. (In this example, the cost is \$3.5 million and the finish date is July 1, 2013.)

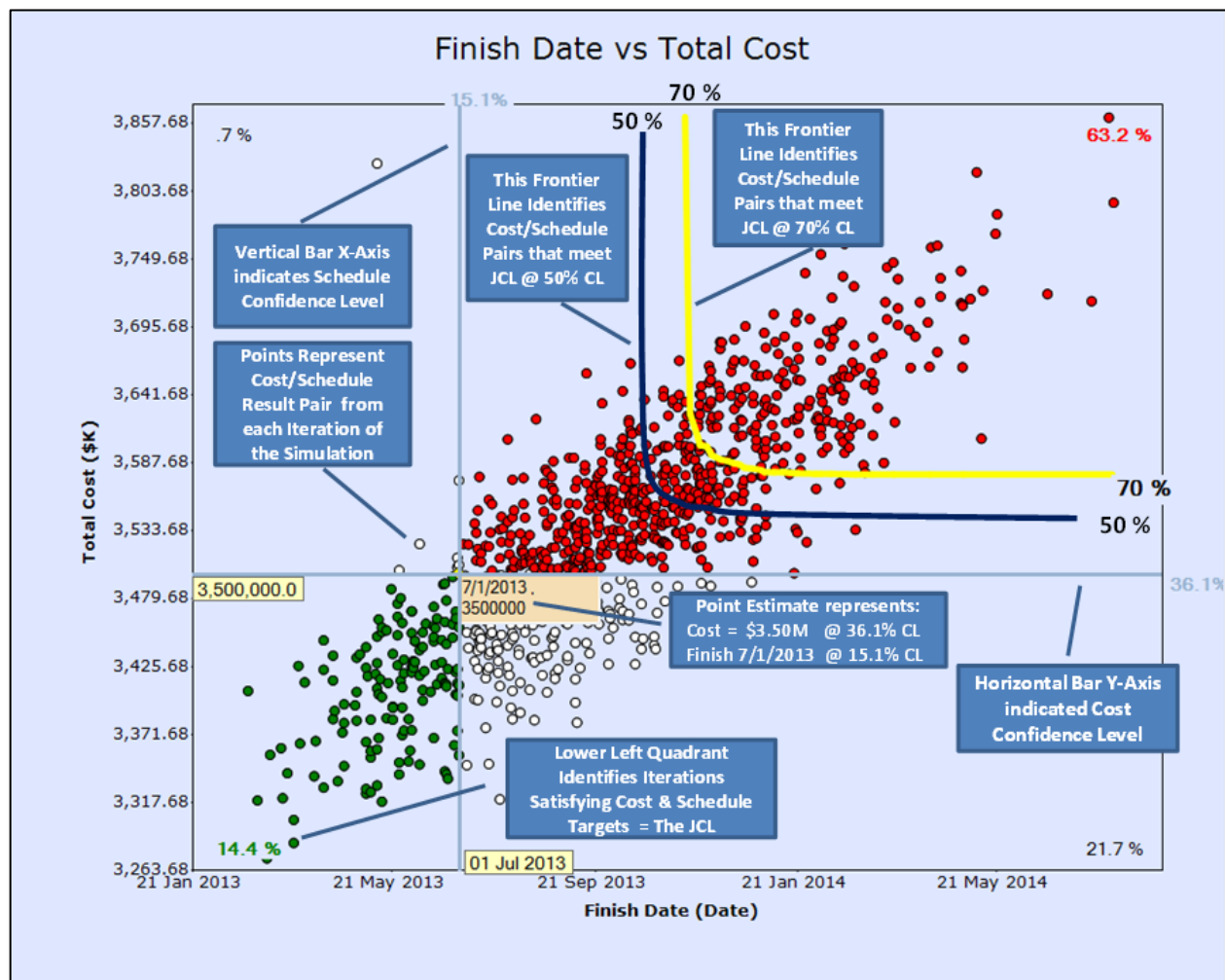


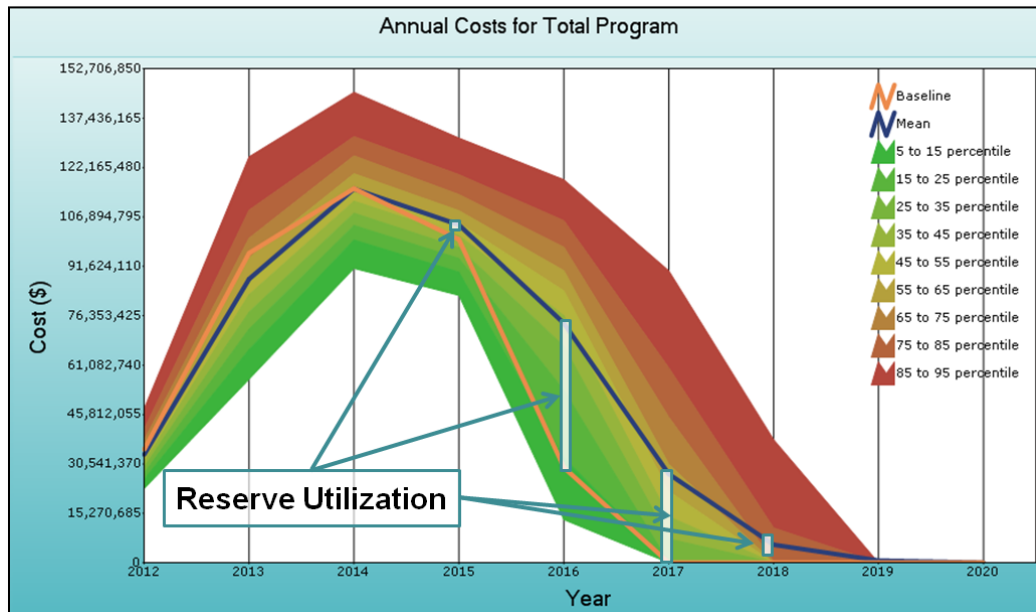
Figure 13. JCL Scatterplot

In addition to the quadrants are frontier lines. Each frontier line represents a separation between all the results from the simulation that meet a desired JCL from those that do not. As seen in Figure 13, the JCL for each frontier line differs from the JCL of the cost and schedule target, where the black frontier line has a chosen JCL of 50 percent and the yellow frontier line has a chosen JCL of 70 percent. Multiple points from the simulation may meet the JCL. In-depth analysis of a JCL scatterplot is provided in Appendix J.

One significant note on the scatterplot: it is *only* valid for the current plan and should be considered a snapshot in time. If the project changes its baseline plan, due to factors such as a funding or schedule increase or technical challenge, this will fundamentally change the project's risk posture and the project team will need to rerun the analysis to generate the current JCL. The scatterplot only illustrates scenarios at specified confidence levels (e.g., at 70 percent JCL to provide sufficient project UFE)—it does not prove guidance and should only be used as a starting point to trade off cost against schedule.

The JCL process yields more useful products than just the JCL scatterplot. Sensitivity analysis from the JCL provides decision makers with awareness of what may affect a project or program as adjustments are made, and the process also allows the analyst to produce Annual Cost Uncertainty results since the

cost, and probabilistic risk results will be phased over the project schedule. As an example in Figure 14, the time-phased probabilistic results of the integrated cost-schedule risk analysis are displayed from the 5th to 95th percentile for the years 2012 through 2020. The years 2015, 2016, 2017, and 2018 are annotated to highlight the likelihood of reserve utilization. In these years, the available annual resources, denoted by the orange line, are significantly less than the mean statistical result from the analysis, denoted by the blue line. Appendix J provides an in-depth analysis of JCL implementation, including advanced products from the analysis.



**Figure 14. Annual Cost Uncertainty Example Displays Cost Risk Statistics Over Time in Comparison to Available Annual Resources**

### 3.2. JCL Policy and Usage

NASA directs projects to generate a probabilistic cost-loaded schedule and to produce a JCL for KDP-I/C<sup>19</sup> for each project to be executable within the available annual resources.<sup>20</sup> This JCL analysis will be evaluated by a non-advocacy body (i.e., the Standing Review Board).<sup>21</sup> The Decision Authority will determine the appropriate JCL (probability) for the associated development and life-cycle cost at which the Agency commits to deliver the program/project. It is policy<sup>22</sup> that the JCL value be at 70 percent for the Agency Baseline Commitment (ABC), with a Management Agreement (MA) value of at least 50 percent (the decision authority may deviate from these values with documented rationale).

In conclusion, by combining its cost, schedule, and risk into a single model, a project's cost estimator can generate a probabilistic assessment of the level of confidence of achieving a specific cost-schedule goal. The rationale for conducting the JCL in support of KDP-C is to help ensure that:

<sup>19</sup> Key Decision Point I or Key Decision Point C. Use KDP-I for programs. Use KDP-C for projects.

<sup>20</sup> See NPR 7120.5E

<sup>21</sup> The NASA Standing Review board handbook is at <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140008530.pdf>.

<sup>22</sup> See NPR 7120.5E.

- 1) The project's plan is well defined and risks are understood, and
- 2) The risk posture is acceptable for the timeframe and cost to which NASA is committing to external stakeholders.

The Agency uses this assessment when considering its external commitment (KDP-C) as one means of ensuring that the project has a robust plan with costs linked to schedule, where both are informed by risks.

## 4. Analyses for Decision Support

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In addition to developing cost estimates, NASA cost estimators are key contributors to providing decision support. Over the life of a project, there are many choices that project personnel must make. Whether these decisions take the form of an LCC analysis, an engineering trade, an architecture selection, or an affordability assessment, decision makers look to the cost estimating community to help inform these choices with data.

This section provides an overview of analytical methods that are commonly used to guide decision makers. These methods are organized into the following five categories:

1. Sensitivity Analysis;
2. Trade Studies;
3. Affordability Analysis;
4. Cost As an Independent Variable (CAIV); and
5. Economic Analysis.

Additional details on how to conduct these analyses with supporting references are supplied in Appendix N.

### 4.1. Sensitivity Analysis

Sensitivity analysis is a technique used to address variations in project requirements. It is used to evaluate the effects of changes in system parameters on the system cost. It is also used to examine variations in the ground rules and assumptions.

#### 4.1.1. Steps To Perform Sensitivity Analysis

There are five steps in a sensitivity analysis:

1. *Compute the point estimate.* The point estimate is a deterministic cost estimate where inputs are fixed values. It is developed using the most-likely inputs from our experts. The point estimate sets the baseline for measuring change.
2. *Select the elements for analysis.* System parameters and requirements, the values of which are likely to change, are usually selected. They are not usually the values we insert into our cost estimating equations, but they impact the values we need. Other things to consider are ground rules or assumptions used for the estimate (e.g., inflation, discount rates for economic analyses, buy quantity, and expected mission life). The focus here is on getting the right requirement. For example, the current requirement for the new office complex is that it must hold at least 500 employees. The question here is will the capacity requirement change over time in either direction? As the capacity changes, the square footage of the building and the associated cost changes.
3. *Determine the range of values for each element selected for analysis.*
4. *Determine the cost impact.* Recompute the estimate using, first, the high, then, the low values of the element in question. In sensitivity analyses, each change is applied one at a time; all other elements remain constant at their baseline values. This procedure is repeated for each element of interest.

5. *Graph or table results.* Once the analyst completes the analysis, graphs or tables can be used to communicate this information.

To demonstrate how to apply these five steps, see the example provided in Appendix N.

### **4.1.2. The Pros and Cons of Sensitivity Analysis**

Sensitivity analysis focuses on individual items that cause large or imbalanced changes in cost. Requirements and parameters that cause large changes in cost are considered to be sensitive. Requirements and parameters that can vary without significantly affecting cost are insensitive. Imbalanced changes are seen in cases where the percentage change in cost is different depending on which direction you move the requirement.

Sensitivity analysis allows managers and decision makers to focus scarce resources by (1) concentrating on the sensitive elements, (2) understanding when to fight against (or push for) change, and (3) identifying events that might change which alternative is the least expensive. One of the cons of this method is that a sensitivity analysis cannot describe the exact likelihood of any value occurring—a particular outcome might be more likely than another, but its exact probability would be unknown. Another drawback of this analysis is that the impact of dependencies, or lack thereof, among elements of the estimate cannot be quantified.

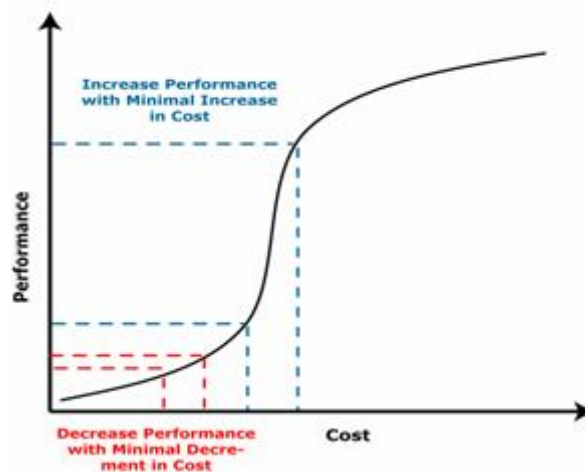
## **4.2. Trade Studies**

This section includes information about trade-study analysis, make-versus-buy analysis, and lease-versus-buy analysis.

### **4.2.1. Trade-Study Analysis**

Cost-performance trade studies are systematic, interdisciplinary examinations of the factors affecting system costs. These studies analyze numerous system concepts to find acceptable ways to attain necessary performance and system requirements that meet an acceptable cost and schedule. The objective of a cost-performance trade study is not necessarily to minimize the cost of the system, but to achieve an optimal balance of performance and cost. Conducting cost-performance trade studies is one of the most effective means used, especially in the early life-cycle phases. These studies help to define a system and help narrow the universe of potential technologies, processes, and/or operational concepts to aid in the definition of the optimal solution.

Trade studies are at the heart of the affordability process, and their solutions are often represented in a multidimensional trade space bounded by a cost element and by one or more performance parameters. Figure 15 illustrates a simplified two-dimensional trade space with a plot connecting candidate design alternatives. At one point on Figure 15, a big gain is made in performance for a small gain in cost. A multidimensional trade space may be substituted to show the interaction of multiple cost drivers, including performance, schedule, and risk. Solutions (data points) at the far left of the trade space may show alternatives that look attractive from a cost perspective but may not satisfy even the threshold (minimal) performance requirements. Similarly, data points at the far right may be alternatives that exceed the threshold cost boundary only to provide performance beyond the requirement, which may not be justified.

**Where is the "biggest bang for the buck"?****Figure 15. Cost As an Independent Variable**

The steps for performing trade studies are presented in Appendix N.

### **4.2.2. Make-Versus-Buy Analysis**

The make-or-buy decision is a strategic choice between producing an item internally (in-house) or buying it from an outside supplier (outsourcing). Make-or-buy decisions may arise when the Agency has the ability to develop or produce a product or part but is having trouble with its workforce and/or current suppliers, has diminishing capacity, and/or has changing demand. Strategic factors such as the desire to maintain quality control, workforce proficiency, or the need to protect proprietary technology may make this decision easy by requiring an in-house build. Aside from these details, operational and cost factors must be considered. Additional make-or-buy guidance and reference information with an example can be found in Appendix N

### **4.2.3. Lease-Versus-Buy Analysis**

A lease-vs.-buy analysis can be performed once the decision is made to acquire an asset. This analysis is commonly used in business cases and applies most often to facilities and information technology projects. While the process of analyzing the economics of buying an asset has been discussed, the analysis behind the lease-versus-buy decision is slightly different. For a lease-versus-buy analysis, various tradeoffs need to be examined.

When analyzing the financial considerations under the lease-versus-buy decision process, the cost analyst needs to consider the LCC of either leasing or buying as well as the O&S cost. The most meaningful financial comparison is the cost of lease financing versus the cost of debt financing. While comparing absolute LCC is important, it is equally critical to take into consideration fiscal budgetary constraints. Guidance on conducting these analyses is provided in OMB Circular A-94,<sup>23</sup> and additional information on the methodology is contained in Appendix N.

<sup>23</sup> OMB Circular No. A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," October 29, 1992 (available at [http://www.whitehouse.gov/omb/circulars\\_a094/](http://www.whitehouse.gov/omb/circulars_a094/)).

Note that in some cases, the sponsor has the capability to make the asset as well. If so, this possibility would have to be assessed along with the other lease-and-buy options. (For more information, see make-versus-buy previously described in Section 4.2.2 and Appendix N.)

### 4.3. Affordability Analysis

Often used in a trade-study analysis, an affordability analysis ensures that the final system, program, project, product, or service can be delivered (or owned, operated, developed, and produced) at a cost that meets previously established funding (or best value) constraints while still meeting all approved requirements (or standards, needs, and specifications). Affordability is a continuous, overarching process applied throughout the program/project life cycle that ensures a program/project is doing the following:

- Optimizing system performance for the total LCC while satisfying scheduling requirements and managing risks;
- Acquiring and operating affordable systems by setting aggressive yet achievable cost objectives and managing those objectives throughout the full program/project life cycle;
- Balancing between cost objectives and mission needs with projected out-year resources, taking into account anticipated product and process improvements;
- Maintaining cost as a principal input variable in the program/project structure and in the design, development, production, operation, and support of a system; and
- Emphasizing cost as more of a constraint, and less of a variable, in the process of developing and supporting affordable systems once system performance and cost targets are determined.

Affordability should be incorporated into all programmatic decisions, as sound affordability practices have proven to be highly beneficial when developed and implemented as part of complex programs and projects.

Much of the LCC associated with NASA's human space systems can occur during program/project O&S. For robotic NASA missions, most of the mission cost is typically incurred during Phases C and D. Therefore, careful attention to affordability, particularly by establishing an affordability process and methodology in the early program/project phases, will help NASA maximize cost savings; define best value solutions to the top-level requirements set; and reduce future program/project operations and sustainment costs.

### 4.4. Cost As an Independent Variable

The purpose of a CAIV study is to ensure that an affordable design solution meets threshold performance requirements. CAIV can be used to evaluate requirements and to assist in performing trade studies. A key tenet of CAIV is that design can converge on cost rather than allowing cost to converge on design. In applying the CAIV process, NASA leadership will be able to demonstrate the following concepts:

- That performance is not sacred and certain performance requirements may be challenged if significant cost savings are possible.
- That the CAIV process continually challenges the requirements when affordability is at stake.

The U.S. Government embraced CAIV in the mid-1990s to counter large program acquisition and sustainment cost overruns. CAIV has been adopted by the aerospace industry including many NASA contractors. A similar process is applied in commercial practice, where it is typically identified as "target costing" or "target pricing." CAIV results can help the project office, working with its acquisition staff, to develop robust incentives proposed within any contract for achieving cost reduction objectives. This

requires a system of performance metrics to facilitate progress tracking and evaluation. Where cost is the independent variable, both performance and schedule requirements will be traded to achieve the cost objectives.

## 4.5. Economic Analysis

The primary basis of an economic analysis (EA) is to develop and compare discounted cash flows (in terms of costs and benefits) of competing alternatives. Generally, an EA considers several proposals having different current and future cost and benefit patterns.

EAs help provide the basis for initiating a project or task by evaluating all possible alternatives in an unbiased manner. EAs are based upon the logic that whenever resources such as money or effort are consumed, they should be in support of a specific organizational need. EAs assist decision makers in the comparison of alternative approaches, options, or projects and consider not only all LCC identified by a LCCE, but also other quantifiable and nonquantifiable benefits.

An EA can help establish the financial or economic justification for a specific program, project, or decision undertaken by NASA. It can provide the reasoning for why the proposed program or project should be undertaken and how that program or project will meet NASA's objectives.

Note that an EA does not make decisions. It *helps* the decision maker by identifying significant factors, clarifying differences and similarities, and quantifying and enumerating characteristics. The decision maker then brings experience, judgment, values, and leadership to bear upon those factors when needed. With an EA, the manager has a much better understanding of investment options, thus, enabling improved decisions.

### 4.5.1. What Is Economic Analysis?

An EA is commonly used within the Federal Government to guide or support decisions on the "worth" of pursuing any form of action that departs from the status quo or do-nothing scenario. For example, an EA can help determine if downstream benefits of startup research, a new acquisition, or a change in maintenance procedures outweigh the near-term costs of implementing the desired changes.

An EA is a technique to give decision makers a means to make more informed decisions. Although EA definitions vary within private, public and academic communities, the following definition captures the common theme of an EA:

Economic analysis is a systematic approach to the problem of choosing the best method of allocating scarce resources to achieve a given objective. A sound economic analysis recognizes that there are alternative ways to meet a given objective and that each alternative requires certain resources and produces certain results. To achieve a systematic evaluation, the economic analysis process employs the following two principles:

1. Each feasible alternative for meeting an objective must be considered, and its life-cycle costs and benefits evaluated.

2. All costs and benefits are adjusted to "present value" by using discount factors to account for the time value of money. Both the size and the timing of costs and benefits are important.<sup>24</sup>

Note that there are three main elements that differentiate an economic analysis from its respective life-cycle cost estimate: an EA (a) applies the concept of discounting, (b) weighs costs against benefits, and (c) produces economic measures of merit (e.g., net present values and benefit-cost ratios).

### **4.5.2. OMB Economic Analysis Guidance**

In October 1992, the Office of Management and Budget published "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs." Such guidance, commonly referred to as OMB Circular A-94, serves as the overall reference for all Federal programs. Included in this document are discount rates (similar to inflation rates) that OMB updates annually.<sup>25</sup>

### **4.5.3. The Concept of Discounting**

One element that differentiates economic analyses from cost estimation is the concept of discounting. In order to understand what discounting is and the reasoning behind it, one must first understand the philosophy of time-value-of-money and how it translates into monetary terms: primarily, interest and interest rates. More details on the concept of discounting are provided in Appendix N.

#### **4.5.3.1. Time-Value-of-Money**

The phrase "money has time value" means that a dollar to be paid (received) today is worth more than a dollar to be paid (received) at any future time. Time value arises because of (a) the opportunity to earn interest on money in hand or (b) the cost of paying interest on borrowed capital.

In OMB Circular A-94, the explanation for the Government use of a discount rate was changed to, simply, the Government cost of borrowing money as represented in Treasury bill rates. This change in policy led to the Federal Government using discount rates that rarely exceeded 7 percent over the past 20 years.<sup>26</sup>

#### **4.5.3.2. Interest Versus Inflation**

It is important to differentiate between the concepts of inflation and the time-value-of-money. They are two different effects. Inflation accounts for the loss of the purchasing power of a dollar due to the general rise of prices in the economy. NASA produces a NASA New Start Inflation Index (NNSI) annually that cost analysts should use in their estimates.<sup>27</sup> The time-value-of-money accounts for the fact that a dollar today is worth more to us than a dollar received in the future, say, a year from now. For example, if you invest a dollar you get today in a fixed-interest account, you will have more than a dollar a year from now because you will have earned interest on the investment.

#### **4.5.3.3. Interest and Interest Rate**

As the previous paragraph illustrates, there are two terms used almost synonymously when discussing the future value of money: interest and interest rate. Interest, when expressed in dollars, represents the money paid or received over time. The interest rate is a percentage that expresses the fraction of cost or

<sup>24</sup> Enclosure (3) of Department of Defense Instruction 7041.3, November 7, 1995 (Subject: Economic Analysis for Decisionmaking).

<sup>25</sup> OMB Circular A-94, October 29, 1992, Appendix C: Discount Rates for Cost-Effectiveness, Lease-Purchase, and Related Analyses.

<sup>26</sup> <http://www.whitehouse.gov/omb/circulars/a094/dischist-2007.pdf>

<sup>27</sup> NNSI is available on the NASA ONCE portal at <http://www.oncedata.com>.

return on the principal over time. For most Federal EAs, the specific interest (discount) rate to use is directed by OMB directives. Interest ( $i$ ) is:

- expressed as a percent (%) or decimal (0.00);
- assessed on the dollar balance (of money borrowed or invested);
- stated for a specified period of time (usually a year); and
- based on the project life and type of analysis (e.g., constant dollar or current dollar).

OMB Circular A-94, dated October 29, 1992, with annual memoranda updates, prescribes specific interest rates depending on the project term. Different rates are also used if the analysis is in base-year (without inflation) or then-year (with inflation) dollars—the difference being an assumed general inflation rate.

Interest rates can be depicted in one of two forms: the nominal rate or the real rate. The nominal rate is the rate of return that is used for payments that include inflation (i.e., cash flows measured in current- or then-year dollars). Nearly all loans and returns provided by financial institutions (e.g., mutual fund companies, banks, credit card companies, mortgage companies) are communicated to the customer as nominal rates. The real rate is the nominal rate adjusted to eliminate the effect of anticipated inflation/deflation, and it is used for payments that are in terms of stable purchasing power (cash flows measured in constant- or base-year dollars). Real rates are primarily used to perform EAs with cash flows depicted in constant (base-year) dollars.

#### 4.5.3.4. Future Value and Present Value

Compound interest occurs when the interest charged (or received) over one period is based upon the balance of principal and interest of the previous period.

The Future Value (FV), representing the total amount received of repayment, is based on compound interest for a single payment or receipt in Present Value (PV). FV is calculated as  $PV(1 + i)^n$  where  $i$  is the interest rate and  $n$  is the number of years from the date of initiation for the project. Another way to describe this calculation is that FV equals the product of PV and *compound interest factor*,  $(1 + i)^n$ .

The PV is an amount that, if invested today at the current interest (or discount) rate, would equal the value of the future cash flow. In essence, the time-value-of-money reflects the fact that money in hand today is likely to be more valuable than an identical amount of money received in the future and that benefits and costs have a greater value if they are realized earlier. Since money today can earn interest, all costs must be adjusted to reflect the inflation rate and then discounted to reflect their PV.

As demonstrated by FV, time-value-of-money can cause a dollar today to become more than a dollar in the future (commonly measured in terms of accrued compound interest). Such mechanics of time-value-of-money can also be applied in reverse. That is, one can compare the value of a dollar in the future (FV) to the value of a dollar held now (PV). This adjustment to a common point in time (traditionally a PV) is called *discounting*.

#### Time-Value-of-Money Example

What if your bank promises you \$11,000 a year from now if you deposit \$10,000 today?

To determine if the “value” of waiting a year is worth the \$1,000 in accumulated interest, you explore other investment options.

It would not be worth it, for example, if you believe a mutual fund will yield an 11% return over the next year (i.e., your \$10,000 investment would grow to \$11,100).

The time-value-of-money increment in this case would equal \$1,100 instead of \$1,000.

The formula for determining FV of money can be adjusted to match the PV formula. This is accomplished algebraically by dividing both sides of the FV by the compound interest factor,  $(1 + i)^n$ . This adjustment of the compound interest formula calibrates the sum of capital at a future time to a present value (PV). The PV is calculated as  $FV / (1 + i)^n$ , where  $i$  is the interest rate and  $n$  is the number of years from the date of initiation for the project. Another way to describe this calculation is that PV equals the product of FV and *discount factor*,  $1 / (1 + i)^n$ .

Given that  $i$  and  $n$  depict an annual interest rate and year, respectively,  $1 / (1 + i)^n$  represents an “End-of-Year” discount factor. Consequently, this discount factor can only be applied to End-of-Year (EOY) cash flows. To discount future values, other conventions are used such as Middle-of-Year (MOY) and continuous discount factors. For more on these discounting conventions, refer to Appendix C.

### Discount Rate

Note that the rate ( $i$ ) associated with compound interest is synonymous with the rate associated with discounting future cash streams (discount rate).

Hence, for simplicity, the notation for the interest rate and the discount rate is left as  $i$ .

The discount rate is the interest rate used to determine the present value of a future cash stream.

The discount rate used represents the opportunity cost of making the investment. The opportunity cost is the rate of return that is given up by choosing one use of funds over another.

## 4.6. The Economic Analysis Process

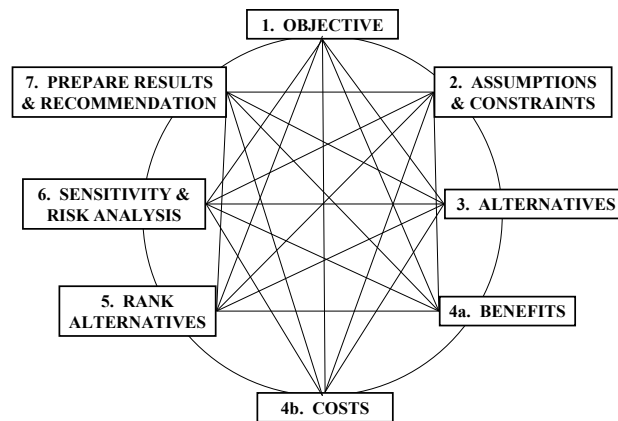
Based on OMB policy, costs and benefits must be viewed from the *perspective of the Federal Government* as a whole. EA cash flows are not limited to only the costs and benefits incurred by the organization for which the analysis is being done.

### 4.6.1. Steps for Performing an Economic Analysis

The basic steps for performing an EA are as follows:

1. Prepare the statement of objective;
2. List the assumptions and constraints;
3. Identify the alternatives;
4. Identify and estimate the benefits and costs;
5. Rank the alternatives using economic measures-of-merit;
6. Perform sensitivity and risk analyses; and
7. Prepare the results and recommendation (documentation).

It is important to note that economic analysis is a process to aid in making resource-allocation decisions. Therefore, an EA commonly goes from a step-by-step process to an iterative one (see Figure 16). There are many interrelationships among the steps in the process. Rather than performing each step in order to completion, the steps may be revisited during the analysis.



**Figure 16. Steps for Performing an EA**

An overview of each EA step is provided in the economic analysis section of Appendix N. Nevertheless, the remainder of this section provides some of the critical aspects that should be accounted for within an economic analysis.

### **4.6.2. The Challenge of Quantifying Benefits**

Space science programs and projects generally do not have easily quantifiable benefits. The value of a science mission is difficult to quantify with any credibility. Therefore, the EA becomes a cost-effectiveness analysis that focuses on the quality and completeness of the LCCE and the quality of the expected science data returned. The qualitative benefits are usually determined by panels of experts in the particular field.

How an EA is structured depends upon the answers to two questions:

- (1) Is the EA for a spaceflight program/project, or is it for an institutional project?
- (2) Are the benefits quantifiable?

If the benefits are quantifiable, the EA can usually be depicted as a feasible set of alternatives, each having its own discounted cash flow (representing a summation of net benefits and net costs).

Quantifiable benefits are more often associated with institutional programs, though they can sometimes be calculated for launch systems or technology programs.

### **4.6.3. Use of Net Present Value to Rank Alternatives**

Each discounted cash flow provides the basis for step 5 (rank alternatives), where economic measures-of-merit are calculated for each alternative. OMB Circular A-94<sup>28</sup> establishes Net Present Value (NPV) as the standard criterion for deciding whether a Government project's cost can be justified on economic principles. The criterion in this case is that the alternative with the "most positive" NPV would be most preferred.

In simple terms, NPV is the amount of dollars that would have to be invested during the base year at the assumed discount (interest) rate to cover the costs or match the revenues or savings at a specific point in the future. All costs and benefits are reduced to a single discounted net value. This allows for a simple comparison of alternatives on an equitable basis.

<sup>28</sup> [http://www.whitehouse.gov/omb/circulars\\_a094/](http://www.whitehouse.gov/omb/circulars_a094/)

NPV is the algebraic combination of the PV of costs and benefits. It allows for the comparison of the costs of different alternatives because it reflects the total cost of an alternative over the given timeframe of analysis in terms of current or normalized<sup>29</sup> dollars. NPV is a way of making costs and benefits occurring in different years comparable. A common way to determine NPV of an alternative is to first calculate net benefits (or costs) from the costs and benefits in each year. Once this net cash flow is created, each individual cash flow is discounted to a present value and summed up to produce NPV. Benefits used in the NPV calculation should be quantified in cost/financial terms. All costs and benefits are adjusted to their PV by using discount factors to account for the time value of money. See Appendix N for additional detail.

Other measures-of-merit, such as Equivalent Uniform Annual Cost (EUAC) and Savings/Investment Ratio (SIR) are also covered in detail in Appendix N.

#### ***4.6.4. Documentation and Review of an Economic Analysis***

It is important to properly document the EA for review by peers, stakeholders, and management. A good documentation package captures all inputs, GR&A, descriptions of the alternatives, analysis approaches, risks and uncertainties, and evaluations of the results. Because an EA is often used to justify major NASA decisions, it is vital that the documentation package be comprehensive, complete, and clear. Major decisions are often subject to review by the NASA Inspector General and outside groups such as the Government Accountability Office (GAO). A well-documented analysis will assist the Agency in responding to these reviews.

For more details on the seven steps of the EA process, refer to Appendix N. For more information on guidance for performing a Government EA, refer to OMB Circular A-94.

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<sup>29</sup> The same year's dollars for all options.

The NASA Cost Analysis Division hopes you find the NASA Cost Estimating Handbook Version 4.0 useful. If you have any questions concerning the material presented in this handbook, suggestions for future editions, or general information requests, please contact us at [hq-cad@nasa.gov](mailto:hq-cad@nasa.gov). In addition, if you would like to make a contribution for possible inclusion in future editions, please send feedback or suggested corrections, additions, or improvements to us via the form at [http://www.nasa.gov/sites/default/files/files/NASA\\_Cost\\_Estimating\\_Handbook\\_Recommended\\_Revision\\_Submission\\_Form\\_Tagged.pdf](http://www.nasa.gov/sites/default/files/files/NASA_Cost_Estimating_Handbook_Recommended_Revision_Submission_Form_Tagged.pdf).

*On the back cover is NASA's Orion spacecraft, pictured as it awaits the U.S. Navy's USS Anchorage for a ride home. Orion launched into space on a two-orbit, 4.5-hour test flight at 7:05 a.m. ET on December 5, 2014, and splashed down safely in the Pacific Ocean, where a combined team from NASA, the Navy, and Orion prime contractor Lockheed Martin retrieved it. Orion is a part of NASA's plan to develop new technologies and capabilities to send astronauts farther than ever before—first to an asteroid, and onward to the Red Planet.*





National Aeronautics and Space Administration  
Washington, DC

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# Appendix A: Cost Analysis Data Requirement (CADRe) and One NASA Cost Engineering (ONCE) Portal Overview

## A.1. CADRe

### A.1.1. Introduction

The Cost Analysis Data Requirement (CADRe) is a formal project document that describes the programmatic, technical, and life-cycle cost and cost/schedule risk information of a project. It is a three-part document that describes a NASA project at major life-cycle milestones and provides a historical record of cost, a schedule, and technical project attributes so that estimators can better estimate future analogous projects. A 2005 initiative, the CADRe is NASA's unique response to the need to improve cost and schedule estimates during the formulation process, providing a common description of a project at multiple given points in time as the project matures through its life-cycle.

#### A.1.1.1. History of CADRe

In 2004, the Government Accountability Office (GAO) released a critical report on NASA titled "Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management" (see Figure A-1). The GAO made a number of recommendations to NASA, including urging the Agency to develop a document to fully describe a project and include the actual costs of the project so that estimators could use that data to better estimate similar future projects. Agency Project Managers (PMs) have historically estimated the cost of their projects using a bottom-up method—otherwise known as "grassroots estimating," which is highly optimistic and tends not to include all potential risks. To combat this tendency, GAO recommended using actual historical costs and building a repository of cost and technical data for use in preparing cost estimates.

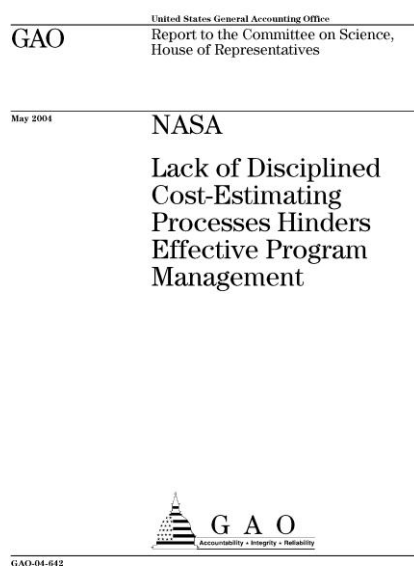


Figure A-1. 2004 GAO Report—The Beginnings of CADRe

In response, the Agency agreed (in line with the GAO recommendations) that all major space projects would develop what is now known as a CADRe. The CADRe would serve as a formal means to capture and archive cost, technical, and programmatic data for use in estimating future NASA projects. Unique templates for each part of the CADRe (A, B, and C) were developed to standardize the development of the document across all of NASA's flight projects. The CADRe document was formally established in 7120.5C, which was a new policy and directive to implement CADRes across all of NASA. The CADRe requirement was further documented in 7120.5D and 7120.5E. With the requirements framework in place, the Cost Analysis Division (CAD) began implementing CADRe on current missions as well as preparing CADRes for many historical missions.

#### **A.1.1.2. CADRe Purpose**

The CADRe effort satisfies a foundational cost estimating need, capturing data across all major flight projects at NASA, including major instruments that fly on foreign partner spacecraft to provide historical cost data, which is vital to performing estimates for future missions. The CADRe provides information to support an Independent Cost Estimate (ICE) as well as actual cost and technical information so that estimators can do a better job of projecting the cost and schedule of future analogous projects. The CADRe tracks and explains changes that occurred from one milestone to the next, and it helps the PM capture, in one document, all the events that occurred during the project both internal and external.

#### **A.1.1.3. CADRe Ownership**

The CADRe is a project-owned document and is signed by the PM; therefore, it does not include any independent assessments or evaluations or opinions about the project. It simply records the known configuration at the specific milestone. CAD at NASA Headquarters provides the necessary funding and support to prepare the document on behalf of the project by using existing project documentation prepared during the milestone review process. In the few cases where a CADRe is prepared for a previously launched mission, CAD will determine if there is enough data, and, if so, will prepare a single Launch or End of Mission (EOM) CADRe.

### **A.1.2. CADRe Structure and Content**

Composed of three parts, the CADRe captures detailed programmatic, technical, and cost data in a standardized format. The document is prepared six times during the life cycle of a project at major milestones (i.e., System Requirements Review [SRR], Preliminary Design Review [PDR], Critical Design Review [CDR], Systems Integration Review (SIR), Launch, and End-of-Mission [EOM]). (See Figure A-2.)

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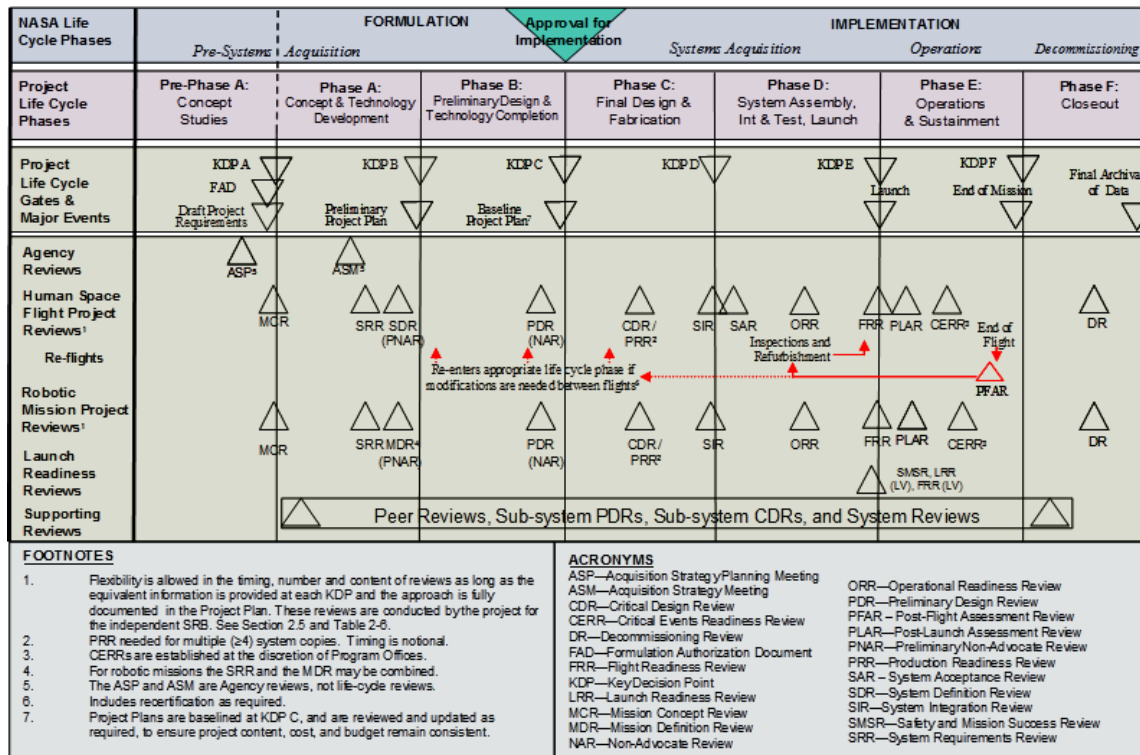


Figure A-2. When CADRes Are Required

The three parts of a CADRe are as follows:

- Part A: Describes the project at each milestone (i.e., SRR, PDR, CDR, SIR, Launch, and EOM) and describes significant changes that have occurred. Part A includes essential subsystem descriptions, block diagrams, and heritage assumptions that are needed for cost-analysis purposes (see Figure A-3). The templates for robotic or human space flight missions can be found at <http://www.nasa.gov/offices/ooe/CAD.html>.

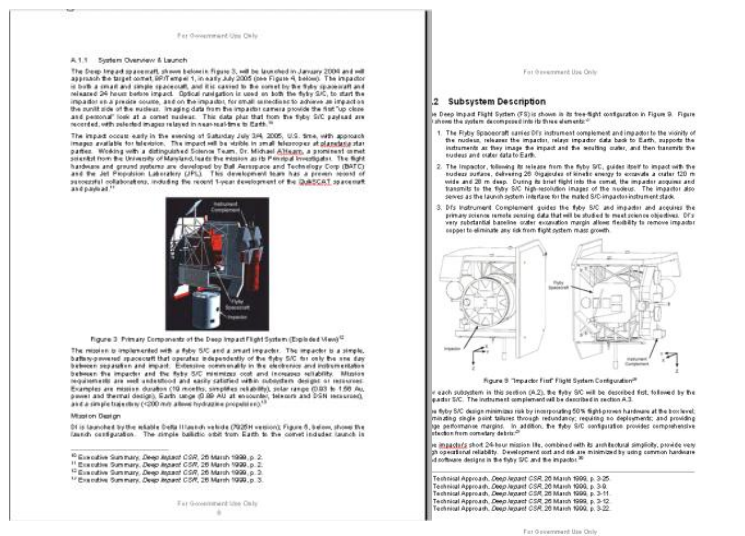


Figure A-3. CADRe Part A Example

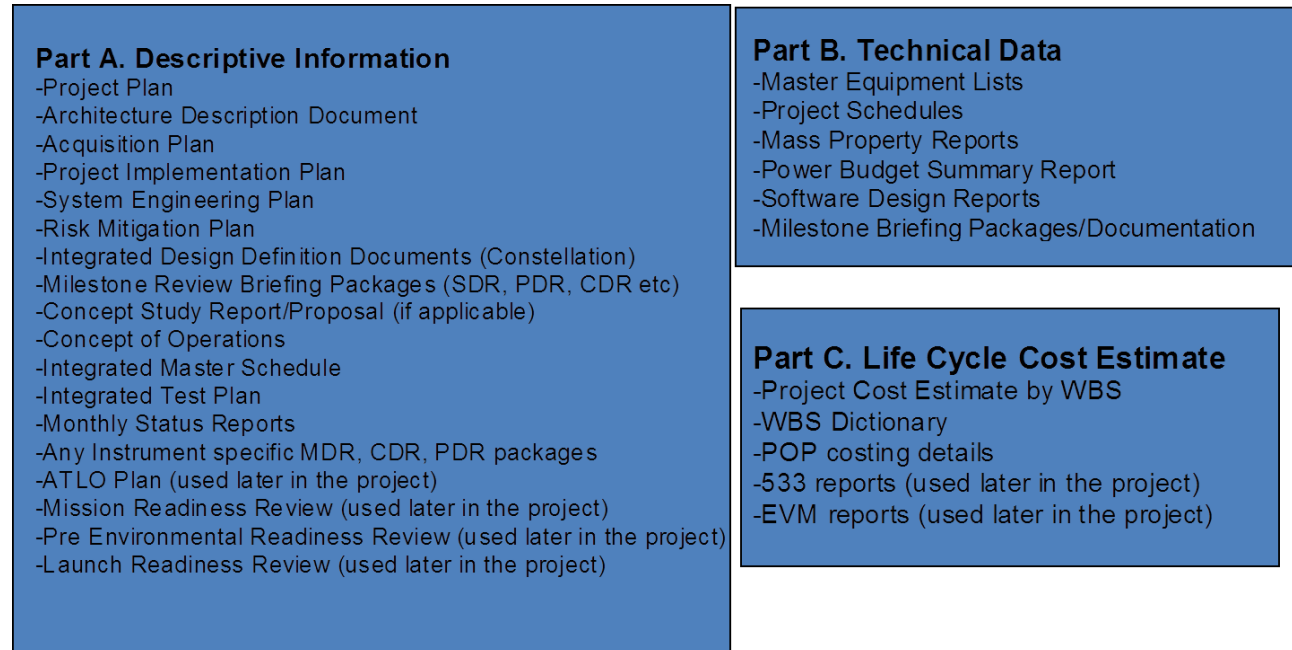
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- Part C: Captures the cost estimate and actual life-cycle costs within the project's Work Breakdown Structure (WBS) in a Microsoft Excel Workbook. This section also captures the project schedule, risks, and ground rules and assumptions (GR&A). (See Figure A-5 and <http://www.nasa.gov/offices/ooo/CAD.html> for more information.)

#	Project WBS Elements		FY2000	FY2001	FY2002	FY2003	FY2004	FY2005	FY2006	Total
1	Project Mission / Mission Analysis / System Effort	1	185	2,187	2,234	1,491	-	-	-	6,103
1.0	Science Team	1	76	520	480	790	330	-	-	3,686
1.0.1	Flight System	1	10,174	42,873	37,244	14,704	1,604	-	-	104,499
1.0.1.1	Program Management	2	1,247	1,004	1,403	1,449	460	-	-	5,723
1.0.1.2	System Engineering	2	192	448	210	180	-	-	-	1,030
1.0.1.3	Instrument	2	3,490	13,177	74,738	1,534	283	-	-	26,445
1.0.1.3.1	Instrument Management	3	549	1,070	1,528	520	44	-	-	3,778
1.0.1.3.2	Instrument Systems Engineering	3	897	763	1,069	799	157	-	-	3,278
1.0.1.3.3	Instrument Product Assurance	3	104	287	471	194	12	-	-	1,068
1.0.2	Telescope	1	15	159	160	-	-	-	-	334
1.0.3	Spectral Camera	3	347	4,474	403	-	-	-	-	5,968
1.0.3.1	Electronic Module	3	349	3,444	105	-	-	-	-	5,243
1.0.3.2	Instrument Software	3	157	771	280	99	22	-	-	2,229
1.0.3.3	HRI	3	50	247	699	-	-	-	-	927
1.0.3.4	MEB	3	52	271	524	-	-	-	-	847
1.0.3.5	Impactor Target Sensor	4	49	331	763	27	-	-	-	1,170
1.0.3.6	Ground Support Equipment	3	-	931	46	-	-	-	-	977
1.0.4	Flyby Spectroast	2	6,430	19,920	20,824	7,022	717	-	-	52,944
1.0.4.1	Program Management	3	3,179	1,540	2,234	2,322	291	-	-	11,566
1.0.4.2	System Engineering	3	620	701	692	480	101	-	-	3,094
1.0.4.3	Product Assurance	3	428	542	700	510	-	-	-	2,180
1.0.4.4	Propulsion	3	403	1,454	1,694	104	197	-	-	3,328
1.0.4.5	Telecommunications	3	723	2,673	1,024	424	9	-	-	5,853
1.0.4.6	Electrical Power	3	144	3,192	2,048	-	-	-	-	6,384
1.0.4.7	Structure	3	764	2,720	3,411	239	-	-	-	7,134
1.0.4.8	CADH	3	148	3,418	2,827	750	-	-	-	7,873
1.0.4.9	ADCS	3	429	927	2,071	419	-	-	-	3,877
1.0.4.10	Thermal	3	239	405	764	192	-	-	-	1,612
1.0.5	Software	3	2,037	764	479	-	-	-	-	3,280
1.0.6	Integration & Test	3	75	252	1,035	997	-	-	-	2,264
1.0.6.1	Ground Support Equipment	3	218	670	477	256	-	-	-	1,591
1.0.6.2	Impactor	2	2,405	7,245	7,315	2,569	29	-	-	20,474
1.0.6.3	Deep Impact Integration & Test	2	-	-	-	1,741	924	-	-	3,777
1.0.6.4	System Integration & Test Management	3	-	-	-	242	21	-	-	305
1.0.6.5	Flyby S/C and Impactor Integration & Test	3	-	-	-	1,035	114	-	-	1,149
1.0.6.6	System MSGE	3	-	-	-	172	172	-	-	344
1.0.6.7	System EDGE	3	-	-	-	-	-	-	-	-
1.0.7	Launch Site & Orbital Operations	1	66	140	243	422	703	-	-	1,473
1.0.7.1	Pre Launch Planning	1	66	140	243	422	67	-	-	773
1.0.7.2	Launch Site Support	2	-	-	-	105	496	-	-	791
1.0.7.3	Flight Operations	2	-	-	-	-	256	-	-	256
1.0.8	Pre-Launch QDS/MOS Development	1	390	391	1,817	2,495	973	-	-	5,916
1.0.9	Mission Operations and Data Analysis	1	-	-	-	3,471	5,424	1,215	-	10,161
1.1	Mission Operations	2	-	-	-	1,572	2,315	199	-	4,086
1.1.1	Phase I Mission Operations	2	-	-	-	1,572	2,315	199	-	4,086
1.1.2	Science Team	2	-	-	-	1,992	3,111	105	-	5,118
1.2	Deep Space Network (DSN) or Other Trading Service	1	-	-	-	-	-	-	-	-
1.0.9	Education and Public Outreach	1	434	499	446	779	693	743	232	4,409
1.0.9.1	Launch Services	1	-	-	-	-	-	-	-	-

February 2015

The CADRe is produced using existing project documents. The CAD does not require any unique documentation to produce the CADRe. This is one of the key aspects of a CADRe that makes it a one-stop source of data. Part A includes documents such as the project plan and milestone briefing charts; Part B uses the project mass and power reports; and Part C uses the project's cost estimates, schedules, and cost reports. See Figure A-6 for many of the key documents used.



**Figure A-6. Key Documents Needed for a CADRe**

CADRe templates may be a significant aid to developing a CADRe submission and should be reviewed early in the project development to ensure awareness of the data reporting requirements as the project matures through its life cycle. Templates can be found in the ONCE Portal at [http://www.nasa.gov/offices/ooe/CADRe\\_ONCE.html](http://www.nasa.gov/offices/ooe/CADRe_ONCE.html).<sup>1</sup>

### **A.1.3. The CADRe Development Process**

The process of preparing a CADRe is as follows: after a kickoff meeting with the PM approximately 60 to 90 days before the milestone, CAD will collect all relevant existing documentation during the life-cycle review process. The CADRe is prepared using existing project documentation that provides descriptive information, mass statements, power statements, schedules, risk list, and life-cycle cost estimates as well as any other technical parameters that tend to drive costs. CAD will deliver the document for the PM's review and signature shortly after a capstone Key Decision Point (KDP) briefing such as the Agency Program Management Counsel (APMC) or the Directorate Program Management Counsel (DPMC)—when the cost and schedule positions are finalized—is held.

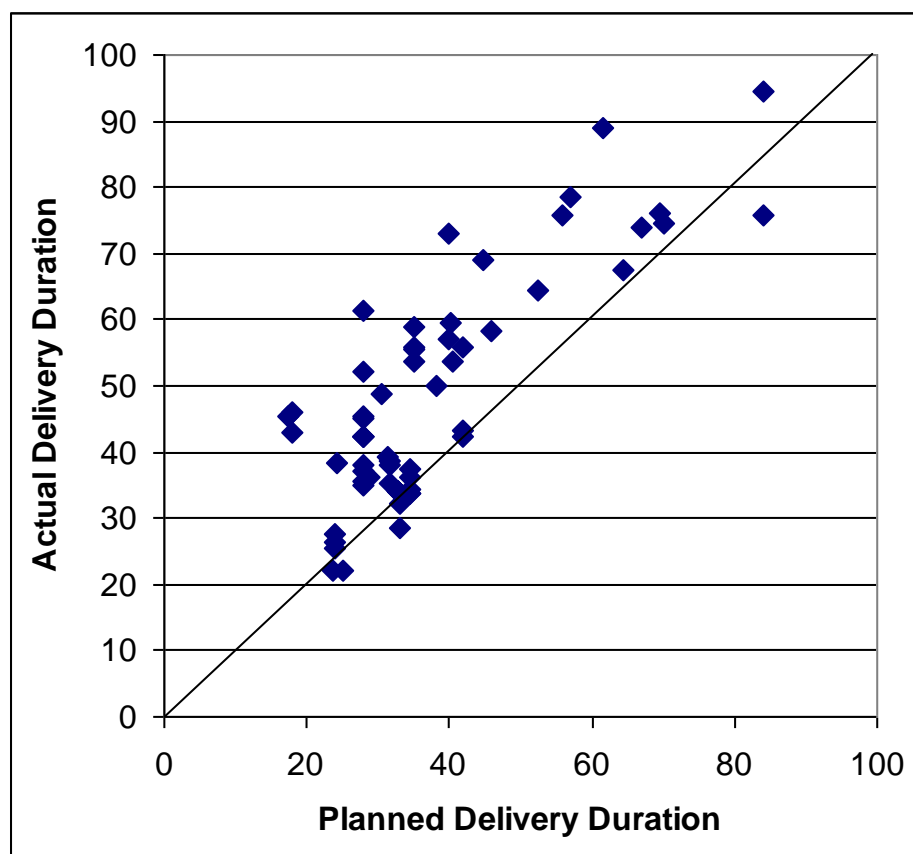
<sup>1</sup> Project and Program Managers may contact the Cost Analysis Division directly for templates and guidance at [hq-cad@email.nasa.gov](mailto:hq-cad@email.nasa.gov).

Completed CADRe data are available from the ONCE portal to facilitate fast searches and retrieval to support cost and schedule estimating.<sup>2</sup>

### **A.1.4. Application of CADRe Data**

The application of CADRe data helps NASA PMs and cost analysts analyze important attributes of projects to help deliver projects within cost, schedule, and technical margins. With a large, historical archive of project data, it is possible to determine trends that may be useful to PMs. Here are some examples:

- 1) Cost engineers use CADRe to estimate the cost of future systems based on known technical parameters such as mass and power. The CADRe data are also used to help evaluate proposals from contractors on new missions.
- 2) System engineers use CADRe information to perform mass architecture trades earlier in concept design by using time-tagged mass data on all major NASA projects.
- 3) Analysis of CADRe data has shown that schedule growth on payload instruments is a significant factor that increases the total cost. On average, instrument development schedule growth was 33 percent or approximately 10 months above the trend line as can be seen in Figure A-7.



**Figure A-7. Planned Versus Actual Delivery Durations for Payload Instruments**

In another example, research of the mass data in CADRe is showing that actual instrument mass often exceeds the planned mass contingencies that are routinely used. An analysis of over 30 NASA instruments showed that the baseline mass contingency was not enough to protect against mass growth.

<sup>2</sup> Information for accessing ONCE can be found at [http://www.nasa.gov/offices/ooe/CADRe\\_ONCE.html](http://www.nasa.gov/offices/ooe/CADRe_ONCE.html).

With this information, PMs of future projects will be able to program more appropriate levels of mass contingency tailored to the type of instrument being developed.

A substantial database of completed CADRes, looking back approximately 15 years, is now available on the ONCE portal, where membership has grown to over 200 users. Furthermore, these data have been used in many cost estimates to develop analog costs. Projects can now determine if they are in a family with other similar projects across cost, schedule, and various technical parameters. As CAD completes more CADRes, CAD expects the use of these data will improve the quality of estimates and lower the cost growth of projects over time and therefore improve NASA's credibility with external stakeholders, including Congress. As the number of CADRes continues to grow, more robust analysis can be accomplished, resulting in more advanced costing practices and tools.

### ***A.1.5. Lessons Learned and the Challenge of Implementing CADRe***

In the early years of implementing a CADRe, there was resistance from the PM community. Many PMs attempted to write "waivers" so they would not have to support the preparation of a CADRe. The CAD worked diligently to build consensus within the PM community by alleviating concerns and misunderstandings about how a CADRe works and by communicating the value and future benefit of having a CADRe document to improve estimating of future project costs. The CAD negotiated exactly what data and project documentation was needed to prepare the CADRe documents, and once the CADRe was prepared, explained how the PM needed to review and sign the document.

A different challenge occurred when CAD undertook the effort to prepare CADRes for historical missions going back 10 to 15 years. A determination was made that anything older than 20 years would not yield functional CADRes simply because the detailed data were not readily available. Still, gathering data on historical missions necessitated customized templates; the creation of something called a CADRe Plus, which is a single CADRe that combines all available data from each milestone as the data become available; and persistence in data collection and in finding the PM to review and sign off on those CADRes.

## **A.2. One NASA Cost Engineering (ONCE) Portal**

The ONCE portal is a secure Web-based application containing all completed CADRes in the ONCE portal for easy retrieval and faster data analysis, as well as tools available to the NASA cost and schedule analysis community. This portal is fully cloud compliant, and the server is located behind the Marshall Space Flight Center (MSFC) firewall. The portal provides advanced search routines to quickly access CADRe data across multiple projects and milestone events. Since CADRes represent snapshots of a project at successive key milestones, the ONCE portal captures all project changes and their associated cost and schedule impacts. The result provides enhanced insight and management of historical cost and technical data, which is helping to advance costing practices and analysis across the Agency. Anyone who needs access to the ONCE portal can go to the ONCE Web site at <http://www.oncedata.com> and click on the "request access" link on that page.<sup>3</sup> The portal is pictured in figure A-8.

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<sup>3</sup> The key requirement for access is a NASA Identity in NASA's IDMAX system.

NASA Cost Estimating Handbook Version 4.0

NE NASA COST ENGINEERING DATABASE (ONCE)  
INSIGHT AND MANAGEMENT OF CADRe DATA

Note: Please Use NDC Credentials

DOMAIN: NDC

User Name:

Password:

User must click on Submit Button

[Access Instructions](#) [Forgot Password](#)

WARNING! This is a US Government computer. This system is for the use of authorized users only. By accessing and using the computer system you are consenting to system monitoring, including the monitoring of keystrokes. Unauthorized use of, or access to, this computer system may subject you to disciplinary action and criminal prosecution.

[NASA Privacy Statement](#)

Figure A-8. ONCE Portal

## Appendix B: Work Breakdown Structure (WBS)

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### B.1. Introduction

The WBS and WBS dictionary are effective management processes for planning, organizing, and administering NASA programs and projects. In accordance with NASA directives NPR 7120.5E (“NASA Space Flight Program and Project Management Requirements”), NPR 7120.7 (“NASA Information Technology and Institutional Infrastructure Program and Project Requirements”), and NPR 7120.8 (“NASA Research and Technology Program and Project Management Requirements”), the WBS and WBS Dictionary are mandatory elements of a project’s management baseline. The goal is to develop a WBS that defines the logical relationship among all program elements to a specified level. The WBS integrates technical, cost, and schedule parameters, giving the Project or Program Manager (PM) a tool to forecast cost and schedule performance, among other management objectives.

With respect to the NASA cost estimator, a project’s WBS will significantly affect two areas: the development of the Cost Breakdown Structure (CBS) and the generation of the required inputs into the Cost Analysis Data Requirement (CADRe) database. The development of a WBS with those requirements considered in the early stages will save significant “mapping” and reconciliation efforts for the cost estimator at a later stage. Accordingly, these items are the focus of this appendix. For complete WBS development guidance that includes the WBS as a basis for assigned project responsibilities, provides project schedule development, simplifies a project by dividing the total work scope into manageable units, and provides a common reference for all project communication, refer to NASA’s WBS Handbook,<sup>1</sup> which follows the guidelines found in NPR 7120.5E<sup>2</sup>.

### B.2. Developing a Product-Oriented WBS

A Product-Oriented WBS, which is what is commonly meant by “WBS,” is a hierarchical organization of all of the hardware, software, services, and other deliverables necessary to successfully complete a space flight project.<sup>3</sup> The purpose of the WBS is to allocate the work content into manageable segments to enable the planning and control of cost, schedule, and technical content. The typical space flight system WBS is product oriented. The product-oriented WBS begins with the end product at the highest level (such as spacecraft) and subdivides the work content into lower-level elements until sufficient detail is achieved for management (or cost estimating) purposes. A WBS relates the elements of work to one another and to the end product. The WBS is the foundation that relates all project disciplines to a common framework that supports the planning, monitoring, and control of progress and status of engineering efforts, cost and schedule resources, and technical progress and performance.

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<sup>1</sup> NASA Work Breakdown Structure Handbook, SP-2010-3404, <http://evm.nasa.gov/handbooks.html>.

<sup>2</sup> NASA NPR 7120.5E, NASA Space Flight Program and Project Management Requirements, w/ Changes 1–10, [http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal\\_ID=N\\_PR\\_7120\\_005E\\_&page\\_name=AppendixB&search\\_term=7120%2E5E](http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_005E_&page_name=AppendixB&search_term=7120%2E5E).

<sup>3</sup> References to WBSes of varying types may be confusing. For the purposes of this document, and due to common usage, a WBS refers to a Product-Oriented Work Breakdown Structure, an FBS refers to a Functional Work Breakdown Structure, and an OBS refers to an Organizational Work Breakdown Structure.

One of the first tasks that must be performed by the cost estimator when developing a new cost estimate is to either obtain or develop the WBS (step 2 in NASA's 12 step cost estimating process). The WBS is critical because it is the primary source for development of a CBS. If composed with cost information, a WBS may serve directly as a CBS. Otherwise, it may be loaded with cost information attributed to its respective elements to create the CBS. If the project has advanced into Phase B, the Project Manager should be able to provide a WBS. If, however, the project is in the early concept study phase (including Analysis of Alternatives [AOA]), the cost estimator may need to develop a WBS.

When the project or study lead provides the WBS, the cost estimator needs to determine if the WBS addresses the total scope of work and is suitable for cost estimating. Depending on the specific cost models or estimating approaches the analyst has chosen, the project WBS may not have sufficient granularity, or misalignment may exist between the WBS and the estimating methods. Any adjustments that are made to the project WBS must be coordinated with the project or study lead to ensure that the changes will not cause issues with understanding or communicating the estimate. If adjustments to the WBS are not feasible, it is the responsibility of the analyst to make whatever

### CADRe WBS

The NASA Standard WBS required by NPR 7120.5E only proceeds to level 2. This increases the degrees of freedom for the Program/Project Manager to construct a WBS that best facilitates project accomplishment. However, the cost estimator and project lead must be aware that there are managerial data demands that must map from the project's WBS. Construction of a WBS that considers these requirements may alleviate significant PM level of effort at stages of the project beyond initial WBS formulation.

For each Agency project, the WBS established by the project must use the NSM numbering scheme and also must correlate exactly through level seven to the corresponding financial accounting structure utilized for each project within the NASA Core Financial System.

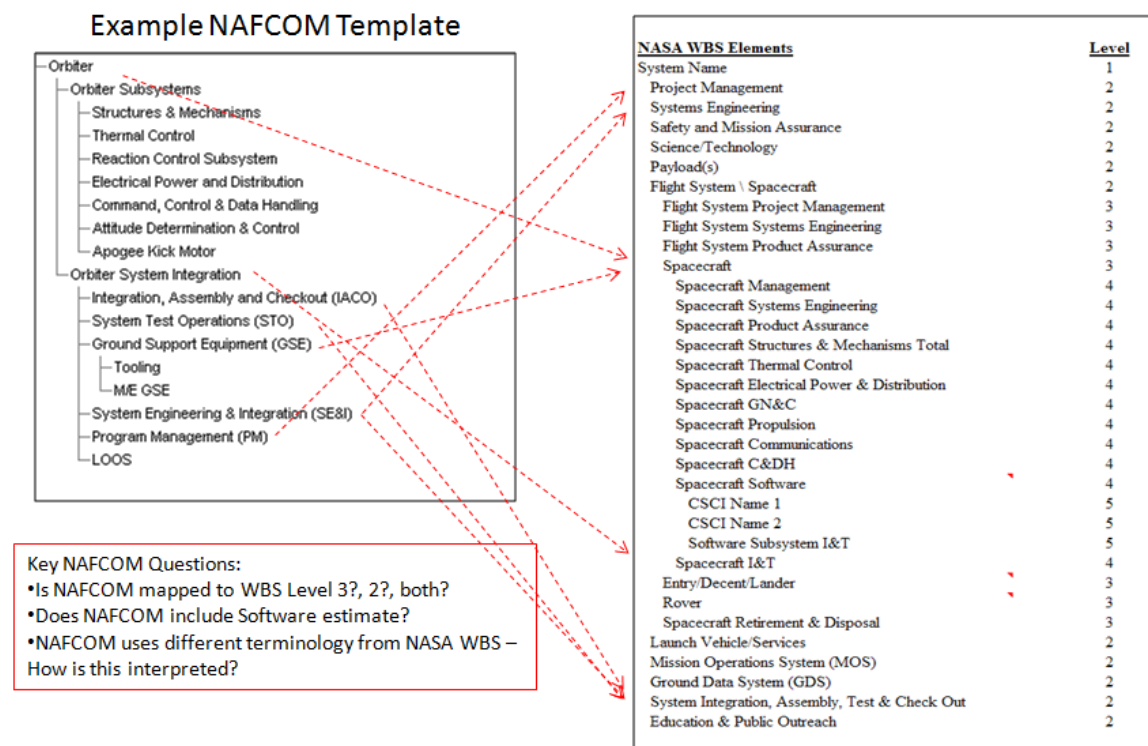
In addition to the NASA Core Financial System requirements, projects must submit data into the CADRe system under the CADRe WBS format, shown at right. These data are used by the Agency for reference in future cost estimates.

Construction of a project WBS that mirrors or easily maps to the CADRe structure will achieve savings in future level of effort and is considered a "best practice."

NASA WBS Elements	Level
System Name	1
Project Management	2
Systems Engineering	2
Safety and Mission Assurance	2
Science/Technology	2
Payload(s)	2
Payload Management	3
System Engineering	3
Payload Product Assurance	3
Instrument <i>n</i>	3
Instrument <i>n</i> Management	4
Instrument <i>n</i> Systems Engineering	4
Instrument <i>n</i> Assurance	4
Antenna	4
Optics	4
Sensors/Detectors	4
Structures & Mechanisms	4
Thermal Control	4
Electronics	4
Power	4
Pointing Subsystem	4
Harness & Cabling	4
C&DH	4
Ground Support Equip	4
Integration, Assembly Test & Check out	3
Flight System 1 Spacecraft	2
Flight System Project Management	3
Flight System Systems Engineering	3
Flight System Product Assurance	3
Spacecraft	3
Spacecraft Management	4
Spacecraft Systems Engineering	4
Spacecraft Product Assurance	4
Spacecraft Structures & Mechanisms	4
Spacecraft Thermal Control	4
Spacecraft Electrical Power &	4
Spacecraft GN&C	4
Spacecraft Propulsion	4
Spacecraft Communications	4
Spacecraft C&DH	4
Spacecraft Software	4
CSCI Name 1	5
CSCI Name 2	5
Software Subsystem I&T	5
Spacecraft I&T	4
Entry/Descent/Lander	3
Rover	3
Spacecraft Retirement & Disposal	3
Launch Vehicle/Services	2
Mission Operations System (MOS)	2
MOS Management	3
MOS Systems Engineering	3
Mission Operations Center	3
Science/Data Operations Center	3
Data Distribution & Archival	3
Communications/Network Infrastructure	3
Training	3
Ground Data System (GDS)	2
GDS Management	3
GDS Systems Engineering	3
Mission Operations Center	3
Science/Data Operations Center	3
Data Distribution & Archival	3
Ground Stations	3
Communications/Network Infrastructure	3
GDS Integration & Test	3
System Integration, Assembly, Test & Check	2
Education & Public Outreach	2
Reserves	1
CM&O	1
G&A	1

accommodations are necessary to the cost estimates in order to provide the alignment between estimating methods and the WBS.

NASA WBS models have been provided in the NASA Air Force Cost Model (NAFCOM) and other Center sources to assist the analyst by furnishing a WBS for the costs estimated by the model. NASA uses NAFCOM for various cost estimating purposes and is transitioning to the Project Cost Estimating Capability (PCEC), as described in the box on page B-3. However, use of the NAFCOM template has resulted in ambiguity when attempting to map the results onto the NASA 7120.5 WBS. Figure B-1 depicts this ambiguity. PCEC addresses this issue by having options for multiple WBSes, including a WBS consistent with the NASA standard WBS and the lower level CADRe standard WBS.<sup>4</sup>



**Figure B-1. Mapping the NAFCOM Template to NASA WBS Created Ambiguity<sup>5</sup>**

As can be seen in Figure B-1, much of the terminology used in NAFCOM differs from that of the NASA WBS. For example, Program Management is listed in the NAFCOM template. The NASA WBS does not include the term 'Program' with 'Management' and lists three levels of Project Management: Project Management (Level 2), Flight Systems Project Management (Level 3), and Spacecraft Management (Level 4). A second example is NAFCOM System Engineering & Integration (SE&I). The NASA WBS contains the following entries: System Engineering (Level 2) and System Integration, Assembly, Test & Check Out (Level 2). Careful examination of Figure B-1 reveals many other inconsistencies.

Due to the ambiguity of mapping between NAFCOM and the NASA WBS, there is concern about the possibility of misinterpreting the NAFCOM output and mapping the results to the incorrect NASA WBS elements. There is also concern about mapping some NAFCOM higher-level elements to the NASA WBS

<sup>4</sup> The templates for a standard CADRe WBS can be found at [http://www.nasa.gov/offices/ooe/CADRe\\_ONCE.html](http://www.nasa.gov/offices/ooe/CADRe_ONCE.html).

<sup>5</sup> Taken from NAFCOM, version 2012. Originally developed for NASA by SAIC.

Spacecraft Level and then double-costing when applying mission wraps to the spacecraft results. The cost analysis must take care to avoid these pitfalls.

The CBS should be consistent with other functions and data sources, such as the budget, the Master Equipment List (MEL), and the Project Management Plan (PMP). The CBS should also be consistent with the appropriate NASA Standard Level 2 WBS template. The analyst must be aware that Pre-Phase A studies may not address all elements in a NASA Standard WBS or provide a cost categorization consistent with the standard WBS terminology.

Per the requirements in NPR 7120.5E, a project should have a preliminary WBS and WBS dictionary by Phase A. The WBS dictionary defines all of the elements in the WBS and is a highly useful document for aligning the project's structure for tracking resources to the content of the cost models. Identifying and resolving differences between these elements is necessary to produce an estimate that accurately reflects the project content.

Once the estimate is complete, the analyst will need to coordinate with the project or study lead to identify the proper WBS level for reporting. Generally speaking, reporting is done at a higher level than the estimate (e.g., reporting the spacecraft estimate at the total level when the estimate is performed at the subsystem level). The costs at the more detailed WBS levels need to be available as backup material to address questions and provide substantiation.

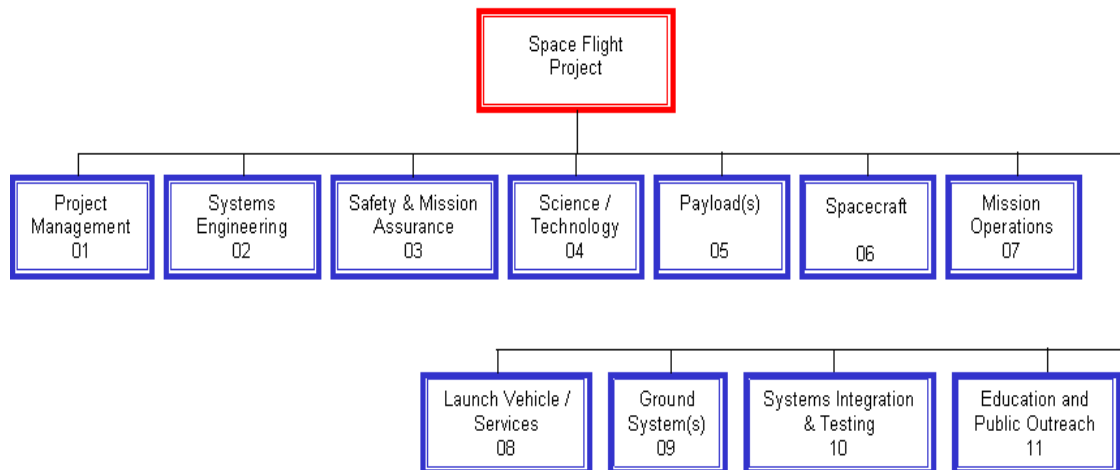
When performing a full Life Cycle Cost (LCC) estimate, the analyst must consider the temporal aspects of the WBS. Ideally, all elements of the WBS will be defined at the beginning of the project life cycle. However, if the project is in the formulation phase, the focus may be on near-term activities such as system development, with less attention being paid to other aspects of the project life cycle. It is incumbent upon the analyst to ensure that all content of a project's life cycle is adequately addressed.

The NASA Space Flight Project Standard WBS, as defined in the NASA Work Breakdown Structure Handbook,<sup>6</sup> is an acceptable approach to ensuring that all LCCs are captured. Since all projects are required to use the NASA Standard WBS, the project's WBS and WBS dictionary must be compatible. The NASA Standard WBS is shown below in Figure B-2.

### **PCEC replacing NAFCOM**

At the time of this report's publication, NAFCOM is still heavily used by the NASA cost estimating community. However, NAFCOM users are in the process of transitioning to the Project Cost Estimating Capability (PCEC), which contains additional information and tools. PCEC incorporates NAFCOM models, as well as models developed by various NASA Centers and directorates. Since most users at this time are more familiar with NAFCOM, this handbook will continue to reference it. The expectation is that the functionality provided to users by NAFCOM and referred to here will continue with PCEC.

<sup>6</sup> [http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110012671\\_2011013098.pdf](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110012671_2011013098.pdf)



**Figure B-2. NASA Standard Space Flight Project WBS**

Note that Figure B-2 only proceeds to level II in its depiction. The standard does not intend that this is the lowest level required. Rather, the standard grants significant freedom to the Project or Program Manager to select which branches require lower levels. In addition to the Flight Projects Standard WBS, there are lower-level standard WBSes defined in NPR 7120.8, Appendix K.<sup>7</sup> The standard CADRe WBS is also consistent with the NASA Standard WBS but goes to more detailed levels. MIL-STD-881C<sup>8</sup> is another resource. PCEC has multiple standard WBS templates that may be helpful to the analyst.<sup>9</sup>

### B.3. Alternative WBSes

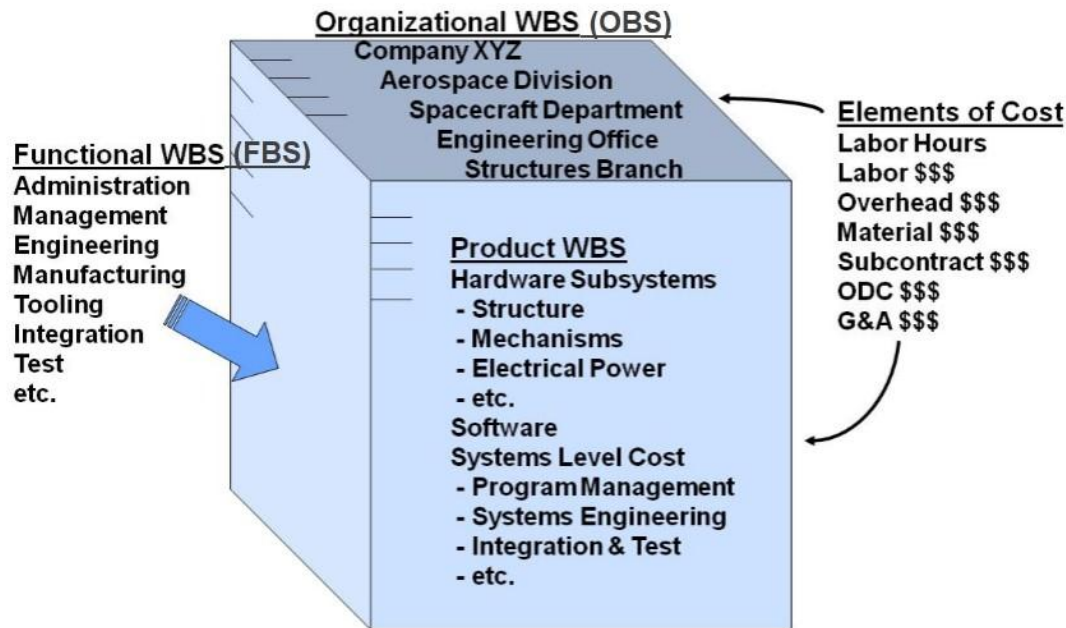
In addition to the product- or cost-oriented WBS, there are alternative ways of organizing the work and presenting the cost. This section discusses three of these approaches: the Organizational Work Breakdown Structure (OBS), the Functional Work Breakdown Structure (FBS), and Elements of Cost (EOC). The relationship between these different breakdown structures is shown in Figure B-3.

<sup>7</sup> [http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal\\_ID=N\\_PR\\_7120\\_0008\\_&page\\_name=AppendixK](http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_0008_&page_name=AppendixK)

<sup>8</sup> MIL-STD 881C Work Breakdown Structure for Defense Materiel Items, 3 October 2011,

<https://acc.dau.mil/CommunityBrowser.aspx?id=482538>

<sup>9</sup> PCEC will contain the following WBS templates: NASA NPR 7120.5, NASA CADRe, NC12 Earth Orbiting Spacecraft, NC12 Planetary Spacecraft, NC12 Uncrewed Spacecraft, NC12 Crewed Spacecraft, NC12 Launch Vehicle Stage



**Figure B-3. Multidimensional WBS Relationships**

Each WBS approach draws on the same cost data but applies a different categorization. Therefore, each dollar spent can be assigned to a product WBS element, an organizational unit, and a function and identified with an element of cost.

It is important for the cost engineer to understand and appreciate these different views. While the estimate is typically tied to the product WBS, other reporting and management systems may use an Organizational Work Breakdown Structure or Functional Work Breakdown Structure, or a combination of the three. Note that performance management systems such as Earned Value Management (EVM) will establish control accounts at a level where individual products intersect with individual organizations, thus linking the product to the OBS.<sup>10</sup>

The following subsections explain each of these alternative WBSes in greater detail.

### **B.3.1. Organizational Work Breakdown Structure (OBS)**

The OBS accounts for the costs via the individual organizational units that perform the work. Since most organizations are structured hierarchically, this approach mimics a WBS in appearance. However, the OBS is used by the performing organization to track fiscal performance, whereas the WBS is the project manager's approach to organizing and tracking the work. For large projects of long duration, it is common for the performing organization to reorganize so that the WBS and OBS are aligned.

### **B.3.2. Functional Work Breakdown Structure (FBS)**

The FBS organizes work by activity (or function). For example, the work to design an avionics box may consist of the following functions: engineering, procurement (of materials), assembly (of the test unit), and testing. The FBS is independent of both product and organization, though there may be overlaps with those two structures. Most WBSes contain enabling functions within their breakdown structure. Typical enabling functions include project management, systems engineering, mission assurance, and systems integration. In NAFCOM, these crosscutting functions are captured as systems integration costs.

<sup>10</sup> More information on the use of EVM at NASA can be found at <http://evm.nasa.gov/>.

FBSes are typically seen in recurring activities. Both mission operations and ground processing lend themselves to an FBS, where the work required to either prepare flight hardware for launch or operate the hardware post launch is best described using action (or functional) terms (vehicle processing, for example).

An FBS is sometimes referred to as an activity-oriented structure. An activity-oriented structure contains all the activities needed to develop a mission. It is also usable for any subset of the mission. It focuses on work that must be done, rather than on end products. The activity-based structure is not tied to any particular architecture because it is a list of the needed functions, not the elements, of the architecture.<sup>11</sup>

The following is an example of an activity-based structure:

- Project Management
- Systems Engineering
- Systems Design
- Detailed Design
- Prototype/Brassboard Manufacturing
- Prototype/Brassboard Integration
- Prototype/Brassboard Qualification Testing
- Protoflight Manufacturing
- Protoflight Recurring Engineering
- Protoflight Quality Assurance
- Protoflight Integration
- Protoflight Testing and Checkout

It should be noted that these activities are performed in support of a number of the aforementioned WBS elements (e.g., payload, spacecraft, and ground systems). Each of the above activities is a part of each of the WBS elements and can even be assigned to individual subsystems or components. The activities are typically performed by different organizations, with engineering performed by the engineering organization and manufacturing by the manufacturing organization. Contractor or civil service labor may be recorded in systems that are first organized by function and then by end item. Data may be available for both. Every contractor manages its projects differently. Some manage by products, some by functional activities, and others by both.

The estimating community has traditionally focused on the cost by WBS, but the activity-based or FBS may be utilized to either develop a grassroots estimate or to normalize data for inclusion in a parametric cost model. With the introduction of JCL (see Appendix J), obtaining actual costs by both WBS and activities will become more critical. So as more data are collected, the Agency will have better historical data to improve future JCL estimates. During project execution, use of activity- or function-based data displays may also provide very useful insight into both plans and actuals and offer analysts the ability to quickly identify problems or disconnects between planned expenditures or staffing and project schedules.

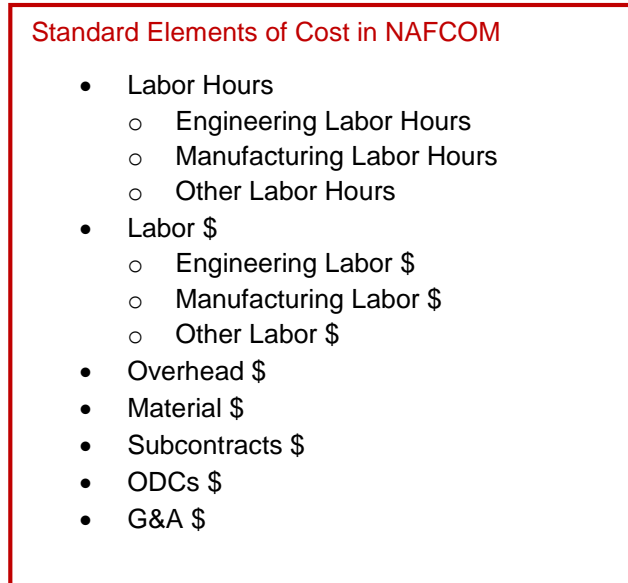
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<sup>11</sup> The Functional Breakdown Structure and its Relationship to Life Cycle Costs," DeHoff, Levack, and Rhodes, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, August 2009.

### **B.3.3. Elements of Cost (EOC)**

An EOC structure is unique in that it can be used as a standalone approach to organizing cost data, or it can be used to provide more detail for other WBS forms. Because it is relatively standard, elements of cost are often aligned with the accounting system and focus on capturing cost and other resource data at the lowest possible level. A typical EOC breakdown will look similar to the NAFCOM EOC shown in Figure B-4.

**Example: EOC in NAFCOM:** In addition to estimating by WBS, cost models such as NAFCOM, PCEC, PRICE, and SEER can produce cost estimates by EOC. NAFCOM assumes a standardized cost element breakdown, including cost for labor, material, overhead, subcontracts, Other Direct Charges (ODCs), and General and Administrative (G&A) expenses for each element in the WBS. The cost element breakdown is computed using default labor, overhead, and G&A rates, as well as average percent-of-total factors derived from an analysis of historical missions. The analyst is able to further refine the cost estimate with user-defined labor, G&A, and overhead rates. In addition to cost, labor is also reported in hours separated into engineering, manufacturing, and other (quality control, tooling, facilities labor) categories.



**Figure B-4. Standard Elements of Cost Used in NAFCOM**

The data and research performed result in the default labor rates; percent-of-total factors for engineering labor, manufacturing labor, other labor, material, and Other Direct Charges; default make percentage; G&A percentage; and overhead percentage. Data are obtained representing different spacecraft types, agencies, and reporting methods. The standard cost elements identified above provide consistency for allocating various reporting types into similar groupings. Definitions for these elements of cost are provided in the next subsection.

### **B.3.4. Cost Element Definitions**

**Engineering Labor**—Engineering labor is generally defined as the direct labor expended by engineering employees while performing all scientific investigations, technical processes, research, development and design, system engineering, testing, logistics, and support for the manufacturing process of a specific product.

**G&A**—General and administrative costs are indirect expenses, including the costs required to maintain a company's general and executive offices; the cost of staff services such as legal, accounting, public relations, financial, and similar expenses; and other general expenses related to the overall business that are not assignable to overhead areas.

**Labor Hours**—The skill or labor categories that can be used for analysis are divided into three suggested groupings: engineering, manufacturing, and other.

**Manufacturing Labor**—Manufacturing labor is generally defined as the direct labor performed on the end item or the processing of parts used in the finished product, as well as the functional testing of the product. It normally covers fabrication, assembly, and manufacturing support activities. Manufacturing labor also sometimes includes tooling and quality control labor; however, for the functional breakdown analysis, tooling and quality control labor are considered other labor.

**Materials**—The raw materials, purchased parts, and overhead costs that are attributable to purchasing, receiving, storing, warehousing, delivering, or expediting materials.

**Other Direct Charges**—ODC covers costs not usually listed under direct material, labor, or overhead, including such things as computer usage, travel, freight, consultants, remote activities, taxes, and interdivisional support costs.

**Other Labor**—Other labor includes program management, data labor tooling, quality control labor, and facilities labor.

**Overhead**—Overhead includes costs that, because of their incurrence for common or joint objectives, are not readily subject to treatment as a direct cost. Such indirect cost is incurred to benefit the total direct cost or business base of a contractor. In NAFCOM, fringe benefits are included in overhead and not in labor.

**Subcontracts**—Subcontracts include the procurement of major components or subsystems that require the subcontractor to do extensive design, development, engineering, and testing to meet a prime contractor's procurement specifications. This cost category does not include the procurement cost for the buy percentage of the subsystem—such cost must be added separately as throughputs.

## Appendix C: Cost Estimating Methodologies

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The cost estimator must select the most appropriate cost estimating methodology (or combination of methodologies) for the data available to develop a high quality cost estimate. The three basic cost estimating methods that can be used during a NASA project's life cycle are analogy, parametric, and engineering build-up (also called "grassroots") as well as extrapolation from actuals using Earned Value Management (EVM). This appendix provides details on the following three basic cost estimating methods used during a NASA project's life cycle:

### **C.1. Analogy Cost Estimating**

### **C.2. Parametric Cost Estimating**

#### **C.2.1. Simple Linear Regression (SLR) Models**

#### **C.2.2. Simple Nonlinear Regression Models**

#### **C.2.3. Multiple Regression Models (Linear and Nonlinear)**

#### **C.2.4. Model Selection Process**

#### **C.2.5. Summary: Parametric Cost Estimating**

### **C.3. Engineering Build-Up Cost Estimating (also called "Grassroots")**

#### **C.3.1. Estimating the Cost of the Job**

#### **C.3.2. Pricing the Estimate (Rates/Pricing)**

#### **C.3.3. Documenting the Estimate—Basis of Estimate (BOE)**

#### **C.3.4. Summary: Engineering Build-Up Cost Estimating**

For additional information on cost estimating methodologies, refer to the GAO Cost Estimating and Assessment Guide at <http://www.gao.gov/products/GAO-09-3SP>.

Figure C-1 shows the three basic cost estimating methods that can be used during a NASA project's life cycle: analogy, parametric, and engineering build-up (also called "grassroots"), as well as extrapolation from actuals using Earned Value Management (EVM).

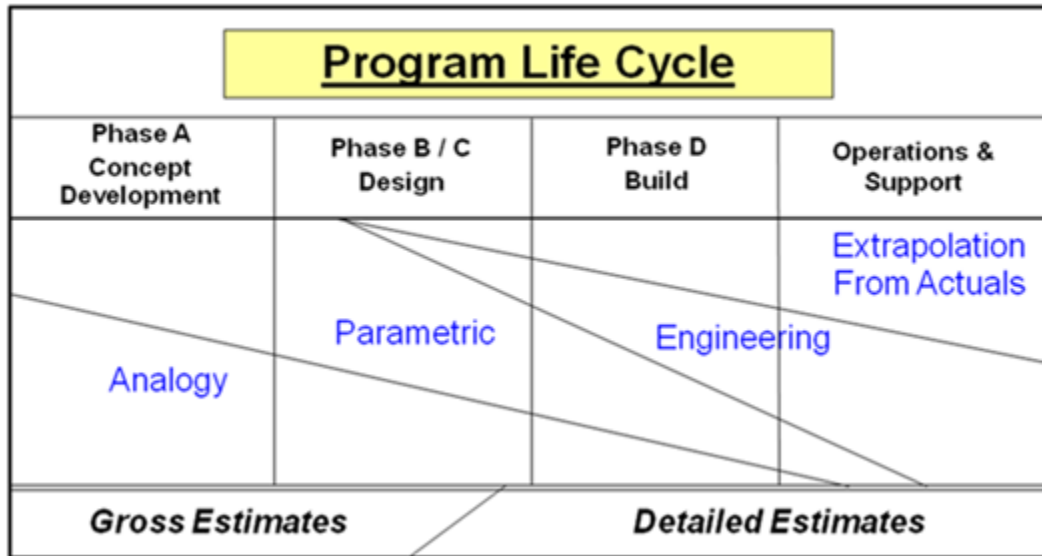


Figure C-1. Use of Cost Estimating Methodologies by Phase<sup>1</sup>

When choosing a methodology, the analyst must remember that cost estimating is a forecast of future costs based on the extrapolation of available historical cost and schedule data. The type of cost estimating method used will depend on the adequacy of Project/Program definition, level of detail required, availability of data, and time constraints. The analogy method finds the cost of a similar space system, adjusts for differences, and estimates the cost of the new space system. The parametric method uses a statistical relationship to relate cost to one or several technical or programmatic attributes (also known as independent variables). The engineering build-up is a detailed cost estimate developed from the bottom up by estimating the cost of every activity in a project's Work Breakdown Structure (WBS).

Table C-1 presents the strengths and weaknesses of each method and identifies some of the associated applications.

<sup>1</sup> Defense Acquisition University, "Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management Framework chart (v5.2)," 2008, as reproduced in the International Cost Estimating and Analysis Association's "Cost Estimating Body of Knowledge Module 2."

Table C-1. Strengths, Weaknesses, and Applications of Estimating Methods

Methodology	Strengths	Weaknesses	Applications
<b>Analogy Cost Estimating</b>	Based on actual historical data	In some cases, relies on single historical data point	<ul style="list-style-type: none"> <li>• Early in the design process</li> <li>• When less data are available</li> <li>• In rough order-of-magnitude estimate</li> <li>• Cross-checking</li> <li>• Architectural studies</li> <li>• Long-range planning</li> </ul>
	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"	
<b>Parametric Cost Estimating</b>	Once developed, CERs are an excellent tool to answer many "what if" questions rapidly	Often difficult for others to understand the statistics associated with the CERs	<ul style="list-style-type: none"> <li>• Design-to-cost trade studies</li> <li>• Cross-checking</li> <li>• Architectural studies</li> <li>• Long-range planning</li> <li>• Sensitivity analysis</li> <li>• Data-driven risk analysis</li> <li>• Software development</li> </ul>
	Statistically sound predictors that provide information about the estimator's confidence of their predictive ability	Must fully describe and document the selection of raw data, adjustments to data, development of equations, statistical findings, and conclusions for validation and acceptance	
	Eliminates reliance on opinion through the use of actual observations	Collecting appropriate data and generating statistically correct CERs is typically difficult, time consuming, and expensive	
	Defensibility rests on logical correlation, thorough and disciplined research, defensible data, and scientific method	Loses predictive ability/credibility outside its relevant data range	
<b>Engineering Build-Up</b>	Intuitive	Costly; significant effort (time and money) required to create a build-up estimate; Susceptible to errors of omission/double counting	<ul style="list-style-type: none"> <li>• Production estimating</li> <li>• Negotiations</li> <li>• Mature projects</li> <li>• Resource allocation</li> </ul>
	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; 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 (e.g., high-dollar items).	Does not provide good insight into cost drivers (i.e., parameters that, when increased, cause significant increases in cost)	
	Reusable; easily transferable for use and insight into individual project budgets and performer schedules	Relationships/links among cost elements must be "programmed" by the analyst	

## C.1. Analogy Cost Estimating

NASA missions are generally unique, but typically few of the systems are completely new systems; they build on the development efforts of their predecessors. The analogy estimating method takes advantage of this synergy by using actual costs from a similar program with adjustments to account for differences between the analogy mission and the new system. Estimators use this method in the early life cycle of a new program or system when technical definition is immature and insufficient cost data are available. Although immature, the technical definition should be established enough to make sufficient adjustments to the analogy cost data.

Cost data from an existing system that is technically representative of the new system to be estimated serve as the Basis of Estimate (BOE). Cost data are then subjectively adjusted upward or downward, depending upon whether the subject system is felt to be more or less complex than the analogous system. Clearly, subjective adjustments that compromise the validity and defensibility of the estimate should be avoided, and the rationale for these adjustments should be adequately documented. Analogy estimating may be performed at any level of the WBS. Linear extrapolations from the analog are acceptable adjustments, assuming a valid linear relationship exists.

Table C-2 shows an example of an analogy:

**Table C-2. Predecessor System Versus New System Analogy**

	Predecessor System	New System
Solar Array	A	B
Power	2.3 KW	3.4 KW
Solar Array Cost	\$10M	?

Assuming a linear relationship between power and cost, and assuming also that power is a cost driver of solar array cost, the single-point analogy calculation can be performed as follows:

$$\text{Solar Array Cost for System B} = 3.4/2.3 * \$10M = \$14.8M$$

Complexity or adjustment factors can also be applied to an analogy estimate to make allowances for year of technology, inflation, and technology maturation. These adjustments can be made sequentially or separately. A complexity factor usually is used to modify a cost estimate for technical difficulty (e.g., an adjustment from an air system to a space system). A traditional complexity factor is a linear multiplier that is applied to the subsystem cost produced by a cost model. In its simplest terms, it is a measure of the complexity of the subsystem being priced compared to the single point analog data point being used.

This method relies heavily on expert opinion to scale the existing system data to approximate the new system. Relative to the analog, complexities are frequently assigned to reflect a comparison of factors such as design maturity at the point of selection and engineering or performance parameters like pointing accuracy, data rate and storage, mass, and materials. If there are a number of analogous data points, their relative characteristics may be used to inform the assignment of a complexity factor. It is imperative that the estimator and the subject matter expert (SME) work together to remove as much subjectivity from the process as possible, to document the rationale for adjustments, and to ensure that the estimate is defensible.

Complexity or adjustment factors may be applied to an analogy estimate to make allowances for things such as year of technology, inflation, and technology maturation. A complexity factor is used to modify the cost estimate as an adjustment, for example, from an aerospace flight system to a space flight system due to the known and distinct rigors of testing, materials, performance, and compliance requirements

between the two systems. A traditional complexity factor is a linear multiplier that is applied to the subsystem cost produced by a cost model. In its simplest terms, it is a measure of the complexity of the subsystem being estimated compared to the composite of the cost estimating relationship (CER) database being used or compared to the single point analog data point being used.

The following steps would generally be followed to determine the complexity factor. The cost estimator (with the assistance of the design engineer) would:

- Become familiar with the historical data points that are candidates for selection as the costing analog;
- Select that data point that is most analogous to the new subsystem being designed;
- Assess the complexity of the new subsystem compared to that of the selected analog in terms of:
  - Design maturity of the new subsystem compared to the design maturity of the analog when it was developed;
  - Technology readiness of the new design compared to the technology readiness of the analog when it was developed; and
  - Specific design differences that make the new subsystem more or less complex than the analog (examples would be comparisons of pointing accuracy requirements for a guidance system, data rate and storage requirements for a computer, differences in materials for structural items, etc.).
- Make a quantitative judgment for a value of the complexity factor based on the above considerations; and
- Document the rationale for the selection of the complexity factor.

Table C-3 presents the strengths and weaknesses of the Analogy Cost Estimating Methodology and identifies some of the associated applications.

**Table C-3. Strengths, Weaknesses, and Applications of Analogy Cost Estimating Methodology**

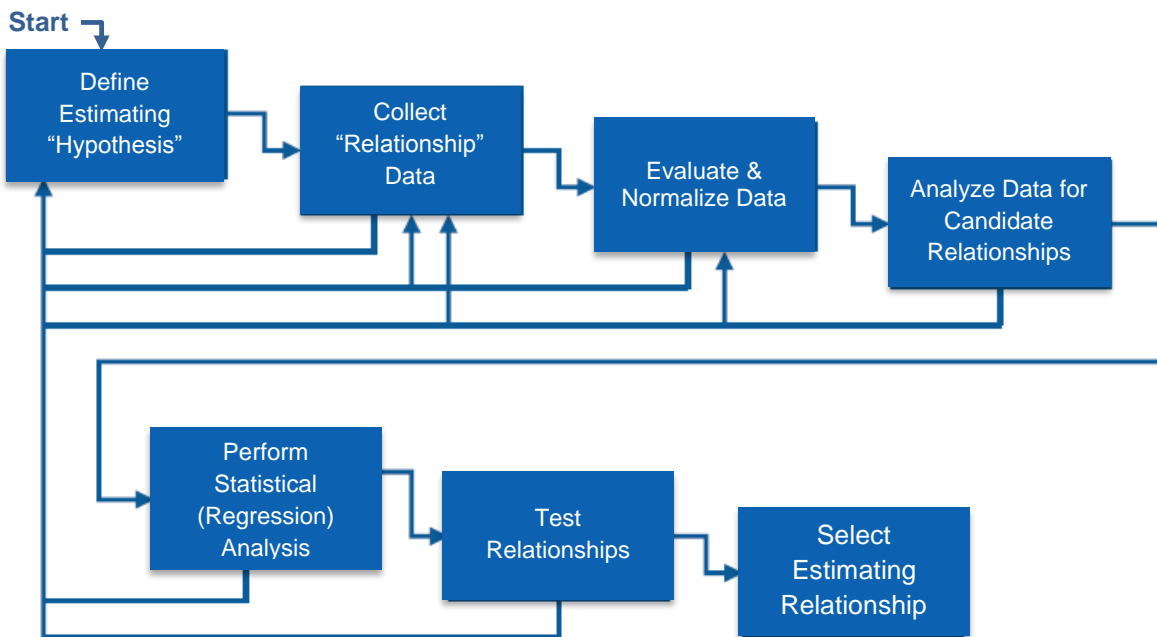
Strengths	Weaknesses	Applications
Based on actual historical data	In some cases, relies on single historical data point	<ul style="list-style-type: none"> <li>• Early in the design process</li> <li>• When less data are available</li> <li>• In rough order-of-magnitude estimate</li> <li>• Cross-checking</li> <li>• Architectural studies</li> <li>• Long-range planning</li> </ul>
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"	

## C.2. Parametric Cost Estimating<sup>2</sup>

Parametric cost estimates are a result of a cost estimating methodology using statistical relationships between historical costs and other program variables (e.g. system physical or performance

<sup>2</sup> The information in this section comes from the GAO Cost Estimating and Assessment Guide – Best Practices for Developing and Managing Capital Program Costs, GAO-09-3SP, March 2009.

characteristics, contractor output measures, or personnel loading) to develop one or more cost estimating relationships (CERs). Generally, an estimator selects parametric cost estimating when only a few key pieces of data are known, such as weight and volume. The implicit assumption in parametric cost estimating is that the same forces that affected cost in the past will affect cost in the future. For example, NASA cost estimates are frequently of space systems or software. The data that relate to these estimates are weight characteristics and design complexity, respectively. The major advantage of using a parametric methodology is that the estimate can usually be conducted quickly and be easily replicated. Figure C-2 shows the steps associated with parametric cost estimating.



**Figure C-2. Parametric Cost Modeling Process**

In parametric estimating, a cost estimator will either use NASA-developed, commercial off-the-shelf (COTS), or generally accepted equations/models or create her own CERs. If the cost estimator chooses to develop her own CERs, there are several techniques to guide the estimator.

To develop a parametric CER, the cost estimator must determine the drivers that most influence cost. After studying the technical baseline and analyzing the data through scatter charts and other methods, the cost estimator should verify the selected cost drivers by discussing them with engineers, scientists, and/or other technical experts. The CER can then be developed with a mathematical expression, which can range from a simple rule of thumb (e.g., dollars per kg) to an equation having several parameters (e.g., cost as a function of kilowatts, source lines-of-code [SLOC], and kilograms) that drive cost.

Estimates created using a parametric approach are based on historical data and mathematical expressions relating cost as the dependent variable to selected, independent, cost-driving variables. Generally, an estimator selects parametric cost estimating when only a few key pieces of data, such as weight and volume, are known. The implicit assumption of parametric cost estimating is that the same forces that affected cost in the past will affect cost in the future. For example, NASA cost estimates are frequently of space systems or software. The data that relates to estimates of these are weight characteristics and design complexity, respectively.

The major advantage of using a parametric methodology is that the estimate can usually be conducted quickly and be easily replicated. Most estimates are developed using a variety of methods where some general principles apply.

Note that there are many cases when CERs can be created without the application of regression analysis. These CERs are typically shown as rates, factors, and ratios. Rates, factors, and ratios are often the result of simple calculations (like averages) and many times do not include statistics.

- A rate uses a parameter to predict cost, using a multiplicative relationship. Since rate is defined to be cost as a function of a parameter, the units for rate are always dollars per something. The rate most commonly used in cost estimating is the labor rate, expressed in dollars per hour. Other commonly used rates are dollars per pound and dollars per gallon.
- A factor uses the cost of another element to estimate a new cost using a multiplier. Since a factor is defined to be cost as a function of another cost, it is often expressed as a percentage. For example, travel costs may be estimated as 5 percent of program management costs.
- A ratio is a function of another parameter and is often used to estimate effort. For example, the cost to build a component could be based on the industry standard of 20 hours per subcomponent.

Parametric estimates established early in the acquisition process must be periodically examined to ensure that they are current throughout the acquisition life cycle and that the input range of data being estimated is applicable to the system. Such output should be shown in detail and well documented. If, for example, a CER is improperly applied, a serious estimating error could result. Microsoft Excel and other commercially available modeling tools are most often used for these calculations. For more information on models and tools, refer to Appendix E.

The remainder of the parametrics section will cover how a cost estimator applies regression analysis to create a CER and uses analysis of variance (ANOVA) to evaluate the quality of the CER.

**Regression analysis** is the primary method by which parametric cost estimating is enabled. Regression is a branch of applied statistics that attempts to quantify the relationship between variables and then describe the accuracy of that relationship by various indicators. This definition has two parts: (1) quantifying the relationship between the variables involves using a mathematical expression, and (2) describing the accuracy of the relationship requires the computation of various statistics that indicate how well the mathematical expression describes the relationship between the variables. This chapter covers mathematical expressions that describe the relationship between the variables using a linear expression with only two variables. The graphical representation of this expression is a straight line. Regression analysis is the technique applied in the parametric method of cost estimating. Some basic statistics texts also refer to regression analysis as the Least Square Best Fit (LSBF) method, also known as the method of **Ordinary Least Squares (OLS)**.

The main challenge in analyzing bivariate (two variable) and multivariate (three or more variables) data is to discover and measure the association or covariation between the variables—that is, to determine how the variables relate to one another. When the relationship between variables is sharp and precise, ordinary mathematical methods suffice. Algebraic and trigonometric relationships have been studied successfully for centuries. When the relationship is blurred or imprecise, the preference is to use statistical methods. We can measure whether the vagueness is so great that there is no useful relationship at all. If there is only a moderate amount of vagueness, we can calculate what the best prediction would be and also qualify the prediction to take into account the imprecision of the relationship.

There are two related, but distinct, aspects of the study of association between variables. The first, regression analysis, attempts to establish the nature of the relationship between variables—that is, to study the functional relationship between the variables and thereby provide a mechanism for predicting or

forecasting. The second, correlation analysis, has the objective of determining the degree of the relationship between variables. In the context of this appendix, we employ regression analysis to develop an equation or CER.

If there is a relationship between any variables, there are four possible reasons.

1. The first reason has the least utility: chance. Everyone is familiar with this type of unexpected and unexplainable event. An example of a chance relationship might be a person totally unfamiliar with the game of football winning a football pool by correctly selecting all the winning teams. This type of relationship between variables is totally useless since it is unquantifiable. There is no way to predict whether or when the person would win again.
2. A second reason for relationships between variables might be a relationship to a third set of circumstances. For instance, while the sun is shining in the United States, it is nighttime in Australia. Neither event caused the other. The relationship between these two events is better explained by relating each event to another variable, the rotation of Earth with respect to the Sun. Although many relationships of this form are quantifiable, we generally desire a more direct relationship.
3. The third reason for correlation is a functional relationship, one which we represent by equations. An example would be the relationship:  $F = ma$ , where  $F$  = force,  $m$  = mass, and  $a$  = acceleration due to the force of gravity. This precise relationship seldom exists in cost estimating.
4. The last reason is a **causal** relationship. These relationships are also represented by equations, but in this case a cause-and-effect situation is inferred between the variables. It should be noted that a regression analysis does not prove cause and effect. Instead, a regression analysis presents what the cost estimator believes to be a logical cause-and-effect relationship. It's important to note that each causal relationship enables the analyst to imply that the relationship between variables is consistent. Therefore, two different types of variables will arise.
  - a. There will be unknown variables called **dependent** variables designated by the symbol  $Y$ .
  - b. There will be known variables called **independent** variables designated by the symbol  $X$ .
  - c. The dependent variable responds to changes in the independent variable.
  - d. When working with CERs, the  $Y$  variable represents some sort of cost, while the  $X$  variables represent various parameters of the system.

As noted above in #4, regression analysis is used not to confirm causality, but rather to **infer causality**. In other words, no matter the statistical significance of a regression result, causality cannot be proven. For example, assume a project designing a NASA launch system wants to know its cost based upon current system requirements. The cost estimator investigates how well these requirements correlate to cost. If certain system requirements (e.g., thrust) indicate a strong correlation to system cost, and these regressions appear logical (i.e., positive correlation), then one can **infer** that these equations have a causal relationship—a subtle yet important distinction from proving cause and effect. Although regression analysis cannot confirm causality, it does explicitly provide a way to (a) measure the strength of quantitative relationships and (b) estimate and test hypotheses regarding a model's parameters.

Prior to performing regression analysis, it is important to examine and normalize the data as follows<sup>3</sup>:

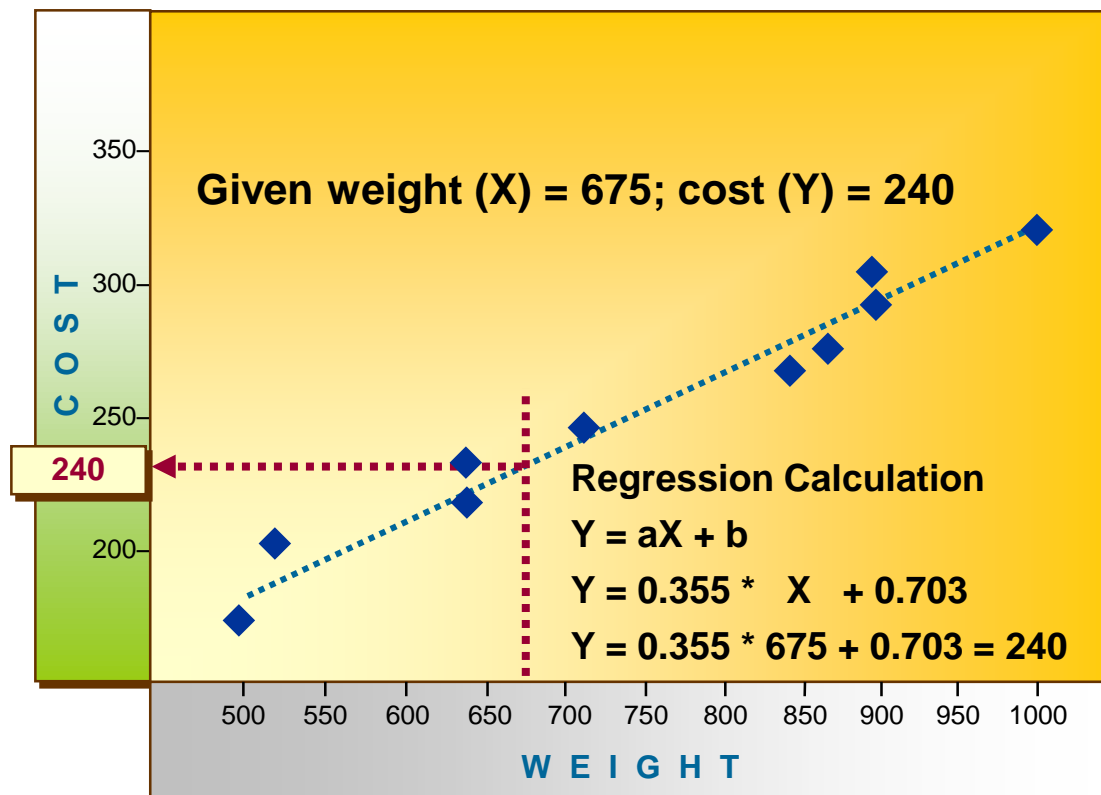
- (1) Make inflation adjustments to a common base year.
- (2) Make learning curve adjustments to a common specified unit, e.g., Cost of First Unit (CFU).
- (3) Check independent variables for extrapolation.
- (4) Perform a scatterplot analysis.

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<sup>3</sup> For more details on data normalization, refer to Task 7 (Gather and Normalize Data) in section 2.2.4 of the Cost Estimating Handbook.

- (5) Check for database homogeneity.
- (6) Check for multicollinearity.

The first step of the actual regression analysis is to postulate what independent variable or variables (e.g., a system's weight, X) could have a significant effect on the dependent variable (e.g., a system's cost, Y). This step is commonly performed by creating a scatterplot of the (X, Y) data pairs then "eyeballing" to identify a possible trend. For a CER, the dependent variable will always be **cost** and each independent variable will be a **cost driver**. Each cost driver should be chosen only when there is correlation between it and cost and because there are sound principles for the relationship being investigated. For example, given analysts assume that the complexity (X) of a piece of computer software drives the cost of a software development project (Y), the analysts can investigate their assumption by plotting historical pairs of these dependent and independent variables (Y versus X). Plotting this historical data of cost (Y) versus weight (X) produces a scatterplot as shown in Figure C-3.



**Figure C-3. Scatterplot and Regression Line of Cost (Y) Versus Weight (X)**

The point of regression analysis is to "fit" a line to the data that will result in an equation that describes that line, expressed by  $Y = Y\text{-intercept} + (\text{slope}) (X)$ . In Figure C-1, we assume a positive correlation, one that indicates that as weight increases, so does the cost associated with the weight. It is much less common that a CER will be developed around a negative correlation, i.e., as the independent variable increases in quantity, cost decreases. Whether the independent variable is complexity or weight or something else, there is typically a positive correlation to cost.

The next step in performing regression analysis to produce a CER is to calculate the relationship between the dependent (Y) and independent (X) variables. In other words, see if the data infer any reasonable degree of cause and effect. The data are, in most cases, assumed to follow either a linear or nonlinear pattern. For the regression line in Figure C-1, the notional CER is depicted as a linear relationship of  $\text{Cost} = A + B * \text{Weight}$ .

As noted in the beginning of this section, the most widely used regression method is the OLS method, which can be applied for modeling both linear and nonlinear CERs (when having one independent variable). Through the application of OLS, section C.2.1. provides details on how to model dependent and independent variables in linear equation form,  $Y = Y\text{-intercept} + (\text{slope}) (X)$ . OLS is used again in section C.2.2. to calculate nonlinear models of the form  $Y = AX^B$ . In order to apply OLS in section C.2.2. (on what is thought to be a nonlinear trend), the nonlinear historical (X, Y) data is transformed using logarithms.

Table C-4 serves as a reference for describing key symbols used in regression analysis. This summary table includes not only symbols that make up a regression model but also important symbols used to assess these models.

There are several other regression methods to produce nonlinear models that bypass the need to transform the historical (X, Y) data. These methods, which were developed to address limitations associated with OLS, include:

- Minimum Unbiased Percentage Error (MUPE) Method
- Zero Percent Bias/Minimum Percent Error (ZPB/MPE) Method (also known as ZMPE Method)
- Iterative Regression Techniques

Such nonlinear regression methods are out of the scope of this handbook and, therefore, will not be covered in Appendix C. For more information on the MUPE Method, ZMPE Method, and Iterative Regression Techniques, refer to the “Regression Methods” section of Appendix A of the 2013 Joint Cost and Schedule Risk and Uncertainty Handbook (CSRUH) at <https://www.ncca.navy.mil/tools/tools.cfm>.

The remainder of Section C.2. covers the following steps in performing regression analysis and selecting the best CER:

- (1) Review the literature and scatterplots to postulate cost drivers of the dependent variable.
- (2) Select the independent variables(s) for each CER.
- (3) Specify each model’s functional form (e.g., linear, nonlinear).
- (4) Apply regression methods to produce each CER.
- (5) Perform significance tests (i.e., t-test, F-test) and residual analyses.
- (6) Test for multicollinearity (if multiple regression).
- (7) See if equation causality seems logical (e.g., does the sign of slope coefficient make sense?).
- (8) For remaining equations, down-select to the one with highest  $R^2$  and/or lowest SE.
- (9) Collect additional data and repeat steps 1–8 (if needed).
- (10) Document the results.

These steps begin with how to produce and assess a simple linear regression (SLR) model.

**Table C-4. Summary of Key Symbols in Regression Analysis**

Symbol	Description	Definition	Evaluation
X, Y	Data Observations	Y= dependent variable X= independent variable	Check and correct any errors, especially outliers in the data. If data quality is poor, it may be necessary to opt for an analysis method other than regression.
$\bar{X}$ , $\bar{Y}$	Average or Mean	$\bar{X}$ = mean of actual $X_i$ 's $\bar{Y}$ = mean of actual $Y_i$ 's.	Helpful to describe the central tendency of the data being evaluated
$\hat{Y}_i$	Calculated Y	$\hat{Y}_i$ = dependent variable	Derived using SLR, $\hat{Y}_i$ is the predicted or "fitted" value associated with $X_i$ , and will differ from $Y_i$ whenever $Y_i$ does not lie on the regression line.
$\hat{b}_i$ or $\hat{B}_i$	Estimated Coefficient of Each Independent Variable (i.e., each estimated regression parameter)	Value of y-intercept, each slope in a linear equation, and/or each exponent in a nonlinear equation	If t-stats are below threshold or values seem illogical, re-specify the model (e.g., with other independent variables and/or another functional form).
$e_i$	Error or "Residual"	Difference between an actual Y ( $Y_i$ ) and its respective predicted Y ( $\hat{Y}_i$ )	Check for transcription errors. Take appropriate corrective action.
$R^2$	Coefficient of Determination	Measures degree of overall fit of the model to the data	The closer $R^2$ is to 100 percent, the better the fit.
$R_a^2$	$R^2$ Adjusted for Degrees of Freedom	$R^2$ formula is adjusted to account for contribution of one or more additional explanatory variables.	One indication that an explanatory variable is irrelevant is if the value $R_a^2$ goes down when the explanatory variable is added to the equation.
SST	Sum of Squared Total	$SST = \sum_{i=1}^n (Y_i - \bar{Y})^2$	Used to compute $R^2$ and $R_a^2$ . The higher the SST, the more disperse the actual Y-data is from the mean of Y.
SSR	Sum of Squared Regression (Explained Error)	$SSR = \sum_{i=1}^n (\hat{Y}_i - \bar{Y})^2$	Used to compute $R^2$ and $R_a^2$ . The higher the SSR, the more "different" the regression line is from the mean of Y.
SSE	Sum of Squared Errors (Unexplained Error)	$SSE = \sum_{i=1}^n (Y_i - \hat{Y}_i)^2$	Used to compute $R^2$ and $R_a^2$ . The higher the SSE, the more disperse the predicted Y-data is from actual Y-data.

### C.2.1. Simple Linear Regression (SLR) Models

"Simple" refers to the fact that only **one independent** variable is required to predict the value of Y. In developing CERs, SLR analysis will be used most of the time. Although this may seem like an oversimplification of the problem, there are several good reasons for taking this approach. Costs should

logically, and often do, vary in a linear fashion with most physical and performance characteristics. If not exactly linear, linear approximations are often adequate, especially when considering the accuracy of the data. In addition, many curvilinear and exponential functions can be transformed into a linear form, thereby lending themselves to linear analysis. And finally, our sample size is often so small that we cannot justify using any other form.

In the SLR model, a **dependent**, or explained, variable Y is related to an **independent**, or explanatory, variable X by the following expression:

$$Y = \beta_0 + \beta_1 X + E$$

This expression is an SLR model for a population where  $\beta_0$ , the Y - intercept, and  $\beta_1$ , the slope, are the unknown regression parameters called the population regression coefficients and E is the random error, or residual disturbance term. The dependent variable is Y and the independent variable is X.

Designating the variable as dependent or independent refers to the mathematical or functional meaning of dependence; it implies neither statistical dependence nor cause and effect. We mean only that we are regarding Y as a function of X.

It should be noted that the SLR model cited above has two distinct parts: the systematic part,  $\beta_0 + \beta_1 X$ , and the stochastic or random part, E. This dissection shows that the model is probabilistic rather than deterministic. The stochastic nature of the regression model implies that the value of Y can never be predicted exactly as in a deterministic case. The uncertainty concerning Y is attributable to the presence of E. Since E is a random variable, it imparts randomness to Y.

In order to ensure the validity of using SLR analysis, five assumptions must be made.

1. The functional form is specified correctly. This means a linear relationship exists between X and Y, and that only one independent variable is sufficient to explain the variation in the dependent variable.
2. The independent variables are assumed to be measured without error. This is, in effect, saying that any deviation will be restricted to the dependent variable.
3. The residuals, E, are assumed to be normally distributed about the regression line. This assumption allows us to use certain statistics and tests of significance to evaluate the validity of the regression line. It is known that the difference between two random variables, regardless of their original distribution, tends to be normally distributed.
4. The residuals, E, are assumed to come from an identically and independently distributed random distribution with mean zero and constant variance. This means that the residuals cannot be predicted from a knowledge of the independent variable, X.
5. The database is homogeneous. This means that the items in the database are of the same category of product.

Using the preceding assumptions, we can derive estimators for the unknown regression parameters,  $\beta_0$  and  $\beta_1$ , and inferences by using these estimators. It should be stressed that, in practice, one or more of the assumptions is often violated. Frequently, the independent variables are not measured without error, and the sample size is so small that assumptions about normality are invalid. However, an essential part of regression analysis is to validate these assumptions (or see if they are violated). In the section on residual analysis, we discuss some techniques used to check these assumptions.

The population regression model represents the equation of a straight line. Since sample data will virtually always be used, it is rare when all points in the population are known or identified. The model for the sample data is:

$$\hat{Y} = \hat{b}_0 + \hat{b}_1 X$$

This expression is an SLR model for a sample where the  $\hat{\phantom{x}}$  indicates a predicted (i.e., calculated) value of Y and calculated values of the slope ( $\hat{b}_1$ ) and intercept ( $\hat{b}_0$ ) of the regression line. Similar to the SLR model for a population, X is the independent variable. All predictors are unbiased estimators of their predicted values, meaning they are as likely to be overestimated as they are to be underestimated.

#### C.2.1.1. Calculating Coefficients for a Simple Linear Regression (SLR) Model

As noted in the beginning of Section C.2, basic statistics texts refer to regression analysis as the Least Square Best Fit (LSBF) method, also known as the method of **Ordinary Least Squares (OLS)**. The

following two equations allow us to solve for the slope ( $\hat{b}_1$ ) and intercept ( $\hat{b}_0$ ) of the regression line.

$$\hat{b}_1 = \frac{n \sum XY - (\sum X)(\sum Y)}{n \sum X^2 - (\sum X)^2} \quad \hat{b}_0 = \frac{\sum Y - \hat{b}_1 \sum X}{n}$$

Upon solving the above equations, we fully define the regression line. Therefore, for any value of the independent variable (a value of some parameter of a given system) within the range of the given independent variable, we can determine a predicted "average" value of the dependent variable (a cost). That is,

$$\hat{Y} = \hat{b}_0 + \hat{b}_1 X, \text{ where the } \hat{\phantom{x}} \text{ indicates a predicted (i.e., calculated) value.}$$

Refer to the box on the following page for an example of how to calculate coefficients for a simple linear regression model.

### Regression Analysis Example

At this point, we present an example to use throughout this discussion. NASA is considering buying a newly developed storage tank that weighs approximately 2.2 tons. Data are available on 10 systems that have been procured in the past, giving the weight and first unit cost of each of these tanks. Therefore, a regression line can be computed, and an estimate of the first unit cost of the new tank can be made based on its weight. In this case, the independent variable is weight (X) in tons, and the dependent variable is first unit cost (Y) in thousands (\$K). Table C-5 presents the data for the 10 systems. Before continuing, we must ensure that data normalization requirements (described in Section 2.3.2 of the main body of this handbook) have already been accomplished. Also included are calculations required to create the inputs required to compute, the regression coefficients,  $\hat{b}_1$  and  $\hat{b}_0$ .

**Table C-5. Data Table for Equation Inputs**

X (tons)	Y (\$K)	XY	X <sup>2</sup>	Y <sup>2</sup>
1.0	6	6.0	1.00	36
1.5	11	16.5	2.25	121
2.0	14	28.0	4.00	196
1.8	16	28.8	3.24	256
1.9	20	38.0	3.61	400
2.5	18	45.0	6.25	324
3.0	22	66.0	9.00	484
3.4	30	102.0	11.56	900
3.7	26	96.2	13.69	676
3.9	31	120.9	15.21	961
<b>ΣX = 24.7</b>	<b>ΣY = 194</b>	<b>ΣXY = 547.4</b>	<b>ΣX<sup>2</sup> = 69.81</b>	<b>ΣY<sup>2</sup> = 4354</b>

We will use these formulas to determine the regression equation. We must first calculate the slope because it is required to determine the intercept.

$$\hat{b}_1 = \frac{n \sum XY - (\sum X)(\sum Y)}{n \sum X^2 - (\sum X)^2} \quad \hat{b}_0 = \frac{\sum Y - \hat{b}_1 \sum X}{n}$$

Upon substitution we have:

$$\hat{b}_1 = \frac{[ (10) (547.4) ] - [(24.7)(194)]}{[(10)(69.81)] - (24.7)^2} = \frac{682.2}{88.01} = 7.75 \quad \hat{b}_0 = \frac{[194 - (7.75)(24.7)]}{10} = \frac{2.58}{10} = 0.26$$

and the regression equation is:

$$\hat{Y} = 7.751392 + 7.75 X \quad 0.2654062$$

The units related to the independent variable must be the same as those attached to the X values in the dataset that created the equation. If the weight for the new storage tank is provided in pounds or kilograms, we must first ensure our input is in tons before plugging it into the equation. The units related to the dependent variable are the same as those used for the Y values in the dataset. The predicted average first unit cost for the new system is:

$$\hat{Y} = 0.26 + 7.75(2.2) = \$17.310K \text{ or } \$17,310.$$

Regression analysis coefficients are sensitive to rounding error. The analyst cannot expect these errors to somehow cancel each other. As a general rule, always carry intermediate calculations at least two decimal places further than the number of places desired in the final answer. The reason that regression analysis is especially subject to rounding error is that often it is necessary to calculate two large numbers and the difference between them. If the difference is small, then it may disappear after rounding.

The regression coefficients may or may not have a practical meaning, depending on the problem. In the previous problem, weight was used to predict storage tank cost. The value of the y-intercept, implies that a storage tank with a weight of zero tons would cost \$260. This is illogical. The y-intercept is not a fixed component of cost. The intercept is a reflection of cost variation that is not captured by weight.

### C.2.1.2. Extrapolation Out of the Relevant Range of the CER

Another reason for the inconsistency is that it requires us to predict a cost that is outside the relevant range. Predictions using a CER are only valid when applied within the relevant range of the equation. Relevant range refers to the range of the values of the independent variable contained in the dataset. Based on the above dataset, we can use the CER to predict first unit costs for vehicles weighing between 1.0 and 3.9 tons. A weight of zero tons is outside the range of the data. Extrapolating outside the range of the data is dangerous because we can make no inference as to the behavior of the data beyond the sample range. In this case we may say that as vehicle weight is reduced beyond a certain point, cost may increase.

Extrapolation is used when regressing time-series data because it is assumed that the relationship continues through time.

The regression slope,  $\hat{b}_1$ , is of both theoretical and practical importance. Theoretically, together with  $\hat{b}_0$ , we can determine the position of the regression line by the slope. Also, we use the value to test the significance of the total regression. The slope measures the amount of change (increase or decrease) in the mean value of Y for a one-unit increase in X. Each time the vehicle's weight increases by 1 ton, cost increases by \$7.75K.

### C.2.1.3. Regression Statistics of Simple Linear Models

The discussion thus far has focused on quantifying the relationship between independent and dependent variables. This constitutes only one half of the regression analysis problem. We must now compute the statistics and tests of significance, which measure the validity of the regression line.

Just because we can create a regression equation does not mean that we should use it. Regression statistics help us determine how well the CER predicts the dependent variable. They can also tell us whether a trend exists. To help determine whether or not to use a regression equation, the estimator should at least calculate then assess the regression's coefficient of determination ( $R^2$ ), standard error of the estimate (SE), coefficient of variation (CV), and the "strength" of regression coefficients (hypothesis tests or "t-tests"). These four areas of analyzing the regression output are covered in the next several pages.

#### Calculating the Coefficient of Determination ( $R^2$ ) for Simple Linear Regression (SLR) Equation

The coefficient of determination,  $R^2$ , is the statistic that will be used more than any other as a measure of the accuracy of the regression line fit to the sample data points.  $R^2$  can have a value between 0 and 1 (or 0 percent and 100 percent), where the higher the number, the better the "fit" of the regression line to the actual data. For example, if SLR produces a regression,  $\text{Cost} = 0.34 + 2.7 \text{ Mass}$ , with an  $R^2$  of 0.93; this implies that 93 percent of the variation in Cost can be explained by the variation in Mass—an example where Mass is a very good predictor of Cost.

In order to calculate an  $R^2$ , one first needs to understand these three terms: explained deviation, unexplained deviation, and total deviation. Refer to the regression line,  $\hat{Y} = \hat{b}_0 + \hat{b}_1 X$ , in Figure C-4. As this graphic illustrates, a single deviation of an actual Y-value from the mean value of Y can be split into the two parts: unexplained and explained deviation.

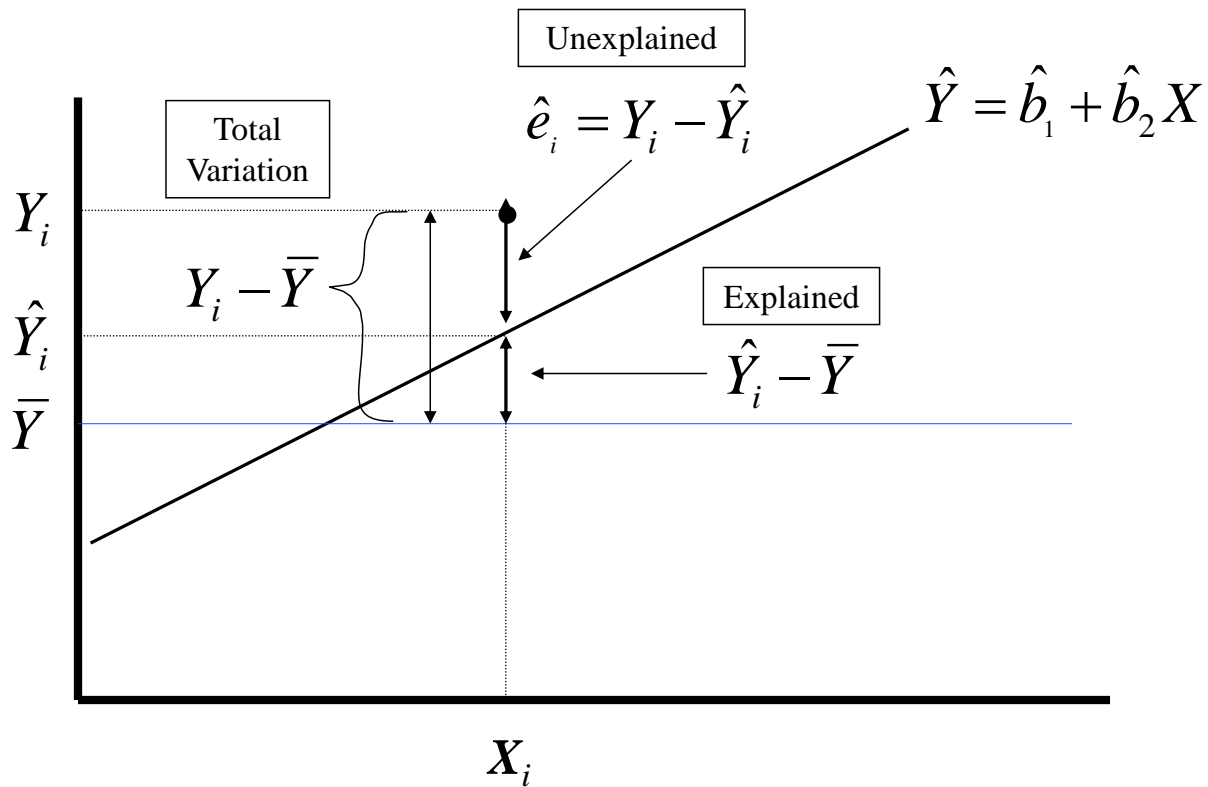


Figure C-4. Illustration of Deviations About the Mean  $\bar{Y}$  and Regression Line  $\hat{Y}_i$ .

Here are a few useful observations that are depicted in Figure C-1:

1.  $X_i$  represents the  $i$ th value of the independent variable.
2.  $Y_i$  is the actual observed value associated with  $X_i$ .
3.  $\hat{Y}_i$  is the dependent variable. Derived using SLR,  $\hat{Y}_i$  is the predicted or "fitted" value associated with  $X_i$  and will differ from  $Y_i$  whenever  $Y_i$  does not lie on the regression line.
4.  $\bar{X}$  and  $\bar{Y}$  are the mean values of the actual  $X_i$ 's and  $Y_i$ 's.
5.  $\bar{Y}$  always crosses somewhere on the regression line.
6.  $\bar{Y}$  serves as a reference point from which to measure each "explained deviation" and "total deviation" as a basis for the coefficient of determination,  $R^2$ .

The SLR output in Figure C-1 reveals three basic types of deviations:

1. The first is the explained deviation and is defined as the difference between the predicted value of  $Y$  and the mean value of  $Y$ . It's a measure of how much each  $Y$  value on the **regression line** differs from the mean value of  $Y$ .

$$\text{Explained Deviation} = \left( \hat{Y}_i - \bar{Y} \right)$$

- The second type of deviation is the unexplained deviation, which is defined as the difference between the actual value of Y and the predicted value of Y. It's a measure of how much each actual Y value differs from its respective predicted Y value on the regression line. This unexplained deviation is often referred to as an "**error**" or "residual" of a predicted value of Y.

$$\text{Unexplained Deviation} = \left( Y_i - \hat{Y}_i \right)$$

- The third type of deviation is total deviation, which is defined in one of two ways: (a) as the difference between the actual value of Y and the mean value of Y, or (b) as the total of explained deviation and unexplained deviation.

$$\text{Total Deviation} = \left( Y_i - \bar{Y} \right)$$

$$\text{Total Deviation} = \text{Explained Deviation} + \text{Unexplained Deviation}$$

$$\left( Y_i - \bar{Y} \right) = \left( \hat{Y}_i - \bar{Y} \right) + \left( Y_i - \hat{Y}_i \right)$$

In order to calculate the coefficient of determination,  $R^2$ , each of these three types of deviation must be squared, then summed. As a result, the squaring-then-summing of each:

- explained deviation produces the Sum of Squared Regression (SSR) where

$$\text{SSR} = \text{Sum of (Each Explained Deviation)}^2 = \sum \left( \hat{Y}_i - \bar{Y} \right)^2$$

- unexplained deviation produces the Sum of Squared Error (SSE) where

$$\text{SSE} = \text{Sum of (Each Unexplained Deviation)}^2 = \sum \left( Y_i - \hat{Y}_i \right)^2$$

- total deviation produces the Sum of Squared Total (SST) where

$$\text{SST} = \text{Sum of (Each Total Deviation)}^2 = \sum \left( Y_i - \bar{Y} \right)^2$$

or

$$\text{SST} = \text{SSR} + \text{SSE}.$$

$$\sum \left( Y - \bar{Y} \right)^2 = \sum \left( Y - \hat{Y} \right)^2 + \sum \left( \hat{Y} - \bar{Y} \right)^2$$

The SST formula, **SST = SSR + SSE**, serves as a good starting point to derive the  $R^2$  formula.

Division by the term on the left yields:

$$1 = \frac{\text{SSR}}{\text{SST}} + \frac{\text{SSE}}{\text{SST}}$$

$$1 = \text{Percent of Explained Deviation} + \text{Percent of Unexplained Deviation}$$

Notice that *the Percent of Explained Deviation* is the definition of  $R^2$ . Therefore, we can rearrange the formula to solve for *Percent of Explained Deviation*, aka  $R^2$ .

*Percent of Explained Deviation = 1 – Percent of Unexplained Deviation*

$$\frac{SSR}{SST} = 1 - \frac{SSE}{SST}$$

Since SSR or  $R^2$  is a ratio of a part to the whole, it will range in value from 0 to 1. For use in conjunction with CERs, an  $R^2$  greater than or equal to 90 percent is desirable. The coefficient of determination can be used to compare various regression lines to determine the best fitting line (the regression line with the highest  $R^2$ ).

$R^2 = \text{Percent of Explained Deviation}$

$$R^2 = \frac{SSR}{SST} = \frac{\sum(\hat{Y} - \bar{Y})^2}{\sum(Y - \bar{Y})^2}$$

This statistic essentially measures the ratio of the explained deviation to the total deviation. Since the explained deviation represents the regression line's ability to predict, it should be as big a proportion of the total deviation as possible. In other words, given that SST is constant, the higher the SSR, the higher the value of  $R^2$ .

$R^2 = 1 - \text{Percent of Unexplained Deviation}$

$$R^2 = 1 - \frac{SSE}{SST} = 1 - \frac{\sum(Y - \hat{Y})^2}{\sum(Y - \bar{Y})^2}$$

Taking a closer look at the previous formula, the regression line that best fits the sample data points is defined when the sum of the squares of the unexplained deviations is a minimum. Each unexplained deviation is the vertical distance from the line to the actual data point. This criterion makes the regression line as close to all the points as possible. In other words, given that SST is constant, the smaller the SSE, the higher the value of  $R^2$ .

An alternative way to calculate  $R^2$  is shown below:

$$R^2 = \frac{[\sum XY - n(\bar{X})(\bar{Y})]^2}{[\sum X^2 - n(\bar{X})^2][\sum Y^2 - n(\bar{Y})^2]}$$

This method bypasses the need to calculate SSR, SSE, and SST. Note, however, that SSR, SSE, and SST values are necessary for other regression statistics covered later in this section.

Referring to the earlier example in Section C.2.1. and using the same data, the coefficient of determination is calculated to be:

$$R^2 = \frac{[547.4 - 10(2.47)(19.4)]^2}{[69.81 - 10(2.47)^2][4354 - 10(19.4)^2]} = \frac{4653.97}{5196.11} = 0.895664$$

This would imply that the variations in weight explain about 90 percent of the total variation in storage tank cost. The regression line explains 90 percent of the deviation, leaving only 10 percent to chance.

#### Calculating the Coefficient of Correlation (R)

The coefficient of correlation is a statistic that is essentially the same measure as the coefficient of determination. It is symbolized by R and is, in fact, plus or minus the square root of the coefficient of determination. Using the coefficient of correlation will yield one piece of information not given by the coefficient of determination. For a regression line with a negative slope, R is negative. For a regression line with a positive slope, R is positive. Obviously, the range of R differs from that of  $R^2$  since R can vary from -1 to +1. The computational formula for R is as follows:

$$R = \sqrt{R^2} \text{ or } \frac{\sum XY - n\bar{X}\bar{Y}}{\sqrt{\sum X^2 - n\bar{X}^2} \sqrt{\sum Y^2 - n\bar{Y}^2}}$$

For the example problem, since the slope is positive, we know that R is positive. The coefficient of correlation is:

$$\sqrt{R^2} = \sqrt{0.90} = 0.948 \cong 0.95$$

#### Calculating the Standard Error of the Estimate (SE)

The standard error of the estimate is analogous to the sample standard deviation. It is a measure of the deviation of the sample points from the regression line or the disturbances from the regression line.

Although both R and  $R^2$  also measure the goodness of fit of the regression line to the data points, they are only relative measures and are affected by the slope of the regression line. The standard error of the estimate is an absolute measure of the deviation and its sign is unaffected by the slope of the regression line. The standard error of the estimate is the square root of the sum of the squares of the unexplained deviations divided by the degrees of freedom and is symbolized by SE.

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{n - k - 1}} = \sqrt{\frac{SSE}{n - k - 1}} = \sqrt{MSE}$$

where:

n is the sample size,

k is the number of independent variables, and

MSE stands for "Mean Squared Error"

Since  $\hat{b}_0$  and  $\hat{b}_1$  are both determined from the same data points from which SE is calculated, there are two restrictions on the data and, thus,  $n - 2$  degrees of freedom when calculating the standard error of the estimate. The term k refers to the number of independent variables contained in the CER. For simple linear equations, there is only one independent variable that must be used to predict Y and therefore only

one slope value that must be calculated. The numerator of the SE equation  $\sum (Y - \hat{Y})^2$  is called the sum of the squared (unexplained) errors, or simply SSE. SSE divided by the degrees of freedom is called the mean squared error (MSE), which is the variance of the error term.

As previously mentioned, SE is an absolute measure of the deviation. It will, therefore, have the units that are associated with the dependent variable. The only magnitude restriction on SE is that it cannot be negative. Because of these facts, the standard error of the estimate cannot be used by itself to evaluate a regression line. It can only be used to compare different regression lines. The standard error of the estimate is also used to calculate other statistics and tests of significance. Since SE is a measure of unexplained error, it should be as small as possible. The computational formula for SE is as follows:

$$SE = \sqrt{\frac{\sum Y^2 - \hat{b}_0 \sum Y - \hat{b}_1 \sum XY}{n - 2}}$$

Considering the example problem and using the computational formula for SE, the standard error of the estimate is calculated as follows:

$$SE = \sqrt{\frac{4354 - 0.26(194) - 7.75(547.4)}{10 - 2}} = \$2.77K$$

#### Calculation of the Coefficient of Variation (CV)

The coefficient of variation (CV) is a statistic that allows us to use the standard error of the estimate to evaluate a regression line. It is actually a relative standard error of the estimate since it becomes a dimensionless quantity. The formula for CV is

$$CV = \frac{SE}{\bar{Y}}$$

When developing a CER by regression analysis, the CV should be less than or equal to 20 percent, and preferably less than 10 percent. The coefficient of variation for the example problem is

$$CV = \frac{2.77}{19.4} = 0.14$$

The CV is particularly appropriate for deciding among competing CERs that seem otherwise appropriate. The one with the lowest CV is preferred, as long as both CERs are logical and have sufficient coefficients of determination and significant slopes.

#### Inferences about Population Regression Coefficients for SLR Models (Hypothesis Tests)

Having obtained the sample regression equation and having concluded that the regression equation may be a useful one on the basis of the standard error of the estimate and the coefficient of determination, the analyst might assume the equation to be a valid predictive device. However, the equation may still contain some error. Predictions may not be precise due to sampling error.

The significance of the sampling error associated with the regression coefficients  $\hat{b}_0$  and  $\hat{b}_1$  may be evaluated by testing the sample distributions of both the intercept and the slope, assuming they are

approximately normal. This assumption of normality allows the analyst to perform a hypothesis test for the significance of the intercept or the slope.

From a practical standpoint, the significance of the intercept is of little importance. As previously stated, it is usually outside the range of the data and represents extrapolation. On the other hand, the significance of the value of the slope should be tested. The hypothesis test might be used to determine if the slope is significantly different from any value. In practice, a hypothesis test is performed to determine if the coefficient of the independent variable (the slope) is significantly different from zero. A slope of zero would imply that the relationship is purely chance. A slope that was not significantly different from zero would mean that knowledge of the value of X would be of no use in predicting the value of Y.

In order to be able to perform this test, another statistic, the standard error of the slope, must be computed. It is symbolized by  $S_1$  and is computed as follows. Most statistical packages give  $S_1$  as an output value.

$$S_1 = \frac{SE}{\sqrt{\sum X^2 - n\bar{X}^2}}$$

Steps in performing a hypothesis test on the slope coefficient are much simpler than those described in testing the mean of a population.

(1) Establish the null and alternative hypotheses. When testing the slope this step is always set up as follows:

- (a) The null hypothesis is  $H_0: b_1 = 0$ .
- (b) The alternative hypothesis is  $H_1: b_1 \neq 0$ .

(2) Determine the level of significance ( $\alpha$ ) desired for the test.

(3) Find  $t_p = t_{(1-\alpha/2, n-2)}$  from the t - table. Because the alternative hypothesis is always a “not equal to,” we always have a two-tailed test.

(4) Calculate  $t_c = \frac{\hat{b}_1 - b_1}{S_1} = \frac{\hat{b}_1 - 0}{S_1} = \frac{\hat{b}_1}{S_1}$ .

(5) Make a decision based on the following decision rules.

(a) If  $|t_c| > |t_p|$ , reject the null hypothesis.

Conclude that the slope coefficient **is** statistically significant.

(b) If  $|t_c| \leq |t_p|$ , do not reject the null hypothesis.

Conclude that the slope coefficient **is not** statistically significant.

Following the steps above, the example problem will yield the following results.

$$(1) H_0: b_1 = 0$$

$$H_1: b_1 \neq 0$$

$$(2) \alpha = 0.05$$

$$(3) t_p = t_{(1-0.05/2, n-k-1)} = t_{(0.975, 9)} = 2.306$$

$$(4) \text{ To calculate } t_c, \text{ we must determine } S_1 = \frac{2.77}{\sqrt{69.81 - 10(2.47)^2}} = 0.935362$$

$$t_c = \frac{7.75}{0.93} = 8.287054$$

$$(5) \text{ Since } |t_c| > |t_p|, \text{ we reject the null hypothesis.}$$

Conclude that the slope coefficient is statistically significant.

In general, retain the sample regression equation as a predictive model if  $b_1$  is found to be significantly different from zero; otherwise the sample regression equation should be discarded.

#### C.2.1.4. Residual Analysis of Simple Linear Regression (SLR) Models

Once we develop a fitted regression model, we need to examine the model's appropriateness for its application. Recall the assumptions of SLR discussed earlier in this chapter (the residuals should be independent, normally distributed, random variables with mean of zero and constant variance). Graphical residual analysis allows us to see whether the errors satisfy these assumptions. The analysis is made easy by use of automated statistics packages. The plot in Figure C-5 of the residuals against the independent variable helps us to evaluate the model.

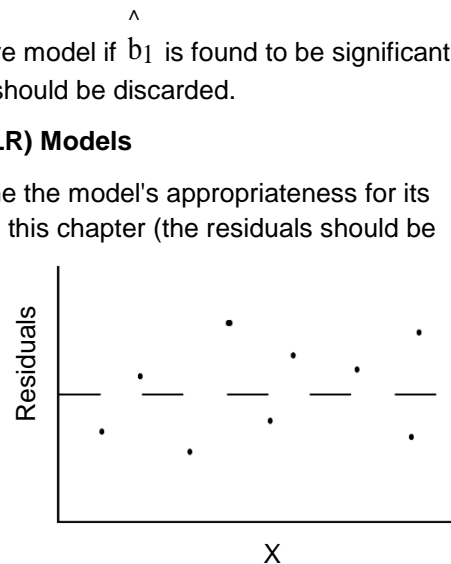


Figure C-5

The plot, a random scatter about the zero line, indicates that the errors are independent and random. Also, the points fall within an equal band above and below the zero line, indicating a mean of zero and constant error variance. This indicates that the regression function used is an appropriate model for the data.

The normal probability plot in Figure C-6 helps in studying the normality of the error terms. The plot shows that the points form a reasonably linear pattern and are close to the line of identity. The assumption of normally distributed error terms in the regression model seems reasonable.

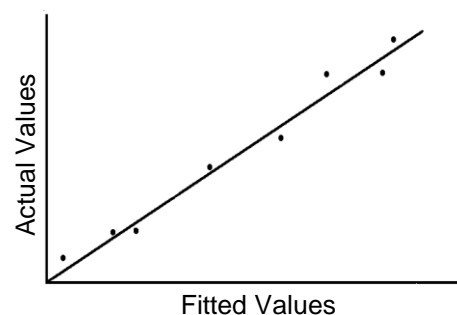


Figure C-6

### C.2.1.5. Confidence and Prediction Intervals of Simple Linear Regression (SLR) Models

The confidence interval and prediction interval are two different intervals on the regression line that give different information. The confidence interval gives a region into which the true (population) regression line can be expected to fall with a probability of  $1 - \alpha$ . This interval actually gives boundary limits for the slope of the population line. It says nothing about the range into which a future prediction might fall. The prediction interval describes an interval into which a given percentage of the population is expected to fall. Because of this feature, prediction intervals can be used to predict the values of future dependent variables within a given range and a given confidence level.

The prediction interval exists due to the variance between the predicted value of the dependent variable,  $\hat{Y}$ , and the actual value,  $Y$ . The standard deviation of this distribution is

$$SE \sqrt{\frac{n+1}{n} + \frac{(X_0 - \bar{X})^2}{\sum X^2 - n\bar{X}^2}}$$

where  $X_0$  is the value of  $X$  for which we are computing the prediction interval.

With this information, the procedure for constructing a prediction interval about a regression line is outlined as follows.

- (1) Determine the significance level ( $\alpha$ ).
- (2) Find  $t_p = t_{(1-\alpha/2, n-2)}$  from the  $t$  table.
- (3) Determine the standard error of the estimate,  $SE$ .
- (4) Select at least three values of  $X$  (called  $X_0$ ) to evaluate. Include the mean and one value on either side of the mean.
- (5) Construct the prediction interval for each value of  $X_0$ .

$$PI = \hat{Y}_0 \pm t_p SE \sqrt{\frac{n+1}{n} + \frac{(X_0 - \bar{X})^2}{\sum X^2 - n\bar{X}^2}}$$

For the example problem, a prediction interval will now be constructed according to the outlined procedure.

- (1) Let the significance level be 0.10.
- (2) Find  $t_p = t_{(1-\alpha/2, n-2)}$  from the  $t$  table.  $t_{(0.95, 8)} = 1.86$ .
- (3) Find  $SE = 2.77$  (from previous example).
- (4) For this example, the three values selected were

$$X_0 = X_{\min} = 1.00$$

$$X_0 = \bar{X} = 2.47$$

$$X_0 = X_{\max} = 3.90$$

(5) Calculate the PI.

$$\text{For } X_0 = X_{\min} = 1.00, \hat{Y}_0 = 8.01.$$

$$PI = 8.01 \pm (1.86)(2.77) \sqrt{\frac{11}{10} + \frac{(1.00 - 2.47)^2}{69.81 - 61.01}} = 8.01 \pm 5.98$$

$$PI = 2.03 \leq Y \leq 13.99$$

$$\text{For } X_0 = \bar{X} = 2.47, \hat{Y}_0 = 19.40.$$

$$PI = 19.40 \pm (1.86)(2.77) \sqrt{\frac{11}{10} + \frac{(2.47 - 2.47)^2}{69.81 - 61.01}} = 19.40 \pm 5.41$$

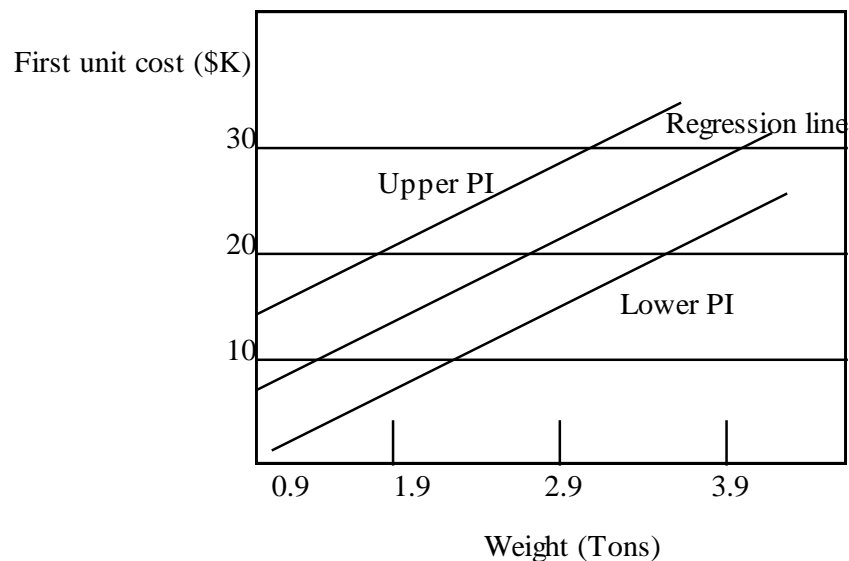
$$PI = 13.99 \leq Y \leq 24.81$$

$$\text{For } X_0 = X_{\max} = 3.90, \hat{Y}_0 = 30.49.$$

$$PI = 30.49 \pm (1.86)(2.77) \sqrt{\frac{11}{10} + \frac{(3.90 - 2.47)^2}{69.81 - 61.01}} = 30.49 \pm 5.93$$

$$PI = 24.56 \leq Y \leq 36.42$$

Figure C-7 shows the regression line and the prediction interval for the sample problem.



### Figure C-7

The prediction interval is very similar to a confidence interval about the regression line. However, the prediction interval will always be slightly wider than the confidence interval. Prediction intervals are usually derived about a specific prediction point with respect to the Y axis, rather than for the regression line as a whole.

#### C.2.1.6. Summary: Simple Linear Regression (SLR) Models

Regression analysis, while a very useful device, often opens up many opportunities for misinterpretation. The most unwarranted interpretation stems from the confusion between association and causation. Regression analysis only shows the degree of association. Many people take the independent variable to be the cause and the dependent variable to be the effect. This is not a necessary condition.

The link between association and causation can be stated as follows: The presence of association does not necessarily imply causation, but true causation always implies association (i.e., correlation). Statistical evidence can only show the degree of association between variables. Whether causation exists or not depends purely on reasoning (logic). For example, there is reason to believe that an increase in the weight of a modern tank “causes” an increase in cost (a direct or positive association). There is also reason to support the premise that a decrease in the weight of an aircraft (range, velocity, and payload held constant) “causes” an increase in cost (an inverse or negative association). Showing that an increase in the inches of padding in the commander’s seat of a tactical vehicle is associated with high cost does not show cause and effect. There is probably a better, more logical predictor of total vehicle cost.

Why is it that association does not show cause and effect? One reason is that the association between variables may be pure chance, such as soil erosion in Alaska and the amount of alcohol consumed in South America. Another reason is that association between two variables may be due to influence of a third common variable. Since 1945, for example, there has been a close relationship between teachers’ salaries and liquor consumption. A plausible explanation is that both variables have been influenced by the continuous increase in national income during the same period. Another possibility is that in the real relationship we may not be able to determine which variable is the cause and which is the effect. It may be that spending more money on education increases the likelihood of a better educated populace, which gets better jobs and thus has a higher per capita income. Which one is the cause and which is the effect?

Regression analysis may lend itself to misinterpretations and spurious results. One reason for spurious results is a flaw in logic, as discussed previously. Spurious conclusions may also result from extrapolations beyond the range of the data. Regression analysis is an attempt to establish a relationship within a range. The relationship may, in fact, change radically over a different range.

Since in regression analysis we are minimizing the deviations about the mean, regression analysis is sensitive to changes in the mean. The mean may be distorted by errors in the sample data or by the presence of outlier observations. Hence, spurious results may occur.

#### C.2.2. Simple Nonlinear Regression Models

A linear function relating the dependent and independent variables frequently does not adequately fit the data. In this event, simple nonlinear regression models should be considered. Often it will be apparent from a scatterplot of the data that a linear model is inappropriate. The analyst should then consider fitting one or more nonlinear models to the data. Fortunately, many nonlinear models are intrinsically linear. That is, by a suitable transformation of the dependent and/or independent variables, a linear relationship

between the variables might be uncovered. The SLR can then be used to fit a straight line to the transformed data. It is important to note, however, that with the modern-day computer, analysts can easily perform nonlinear regression without needing to transform the data (i.e., the computer solves for the lowest sum-squared error using an iterative method).

**Logarithms.** Logarithmic (log for short) transformations can often be used to “straighten out” data that do not plot linearly. The logarithm to the base  $b$  of a number  $X$ ,  $\log_b X$ , is the power to which  $b$  must be raised to yield  $X$ . For example, the logarithm in base 10 of 100 is 2 (i.e.,  $\log_{10} 100 = 2$ ) because  $10^2 = 100$ . Logarithms to the base  $e$  ( $e$  = Euler’s constant = 2.718282 . . . ) are called natural logarithms and are abbreviated  $\ln$ . The natural log of 100 is 4.6 (i.e.,  $\ln 100 = 4.6$ ) because  $e^{4.6} = 2.718282^{4.6} = 100$ . Natural log transformations are used in this unit of instruction.

**Power (Log-Log) Model.** If a scatterplot of the data on ordinary graph paper does not appear linear, the analyst should plot the data on log-log paper. This task is made considerably easier by using the built-in charting capability found with most spreadsheets. If the data appear to “straighten out” on the log-log paper, then a power function in the following form may be appropriate:

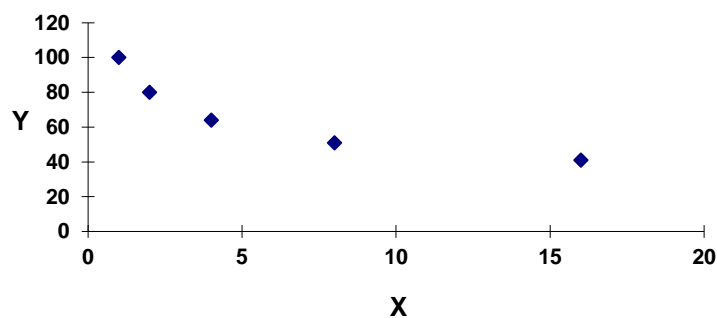
$$Y = AX^B$$

Plotting  $X$  versus  $Y$  on log-log paper is equivalent to plotting  $\ln X$  versus  $\ln Y$  on ordinary graph paper. Consider the data set in Table C-5:

**Table C-5. Power Model Data Set**

$X$	$Y$	$\ln X$	$\ln Y$
1	100	0.0000	4.6052
2	80	0.6931	4.3820
4	64	1.3863	4.1589
8	51	2.0794	3.9318
16	41	2.7726	3.7136

As shown in Figure C-8, a scatterplot of the original data,  $X$  versus  $Y$ , shows a nonlinear relationship.



**Figure C-8**

As shown in Figure C-9, a scatterplot of the transformed data,  $\ln X$  versus  $\ln Y$ , shows an intrinsically linear relationship.

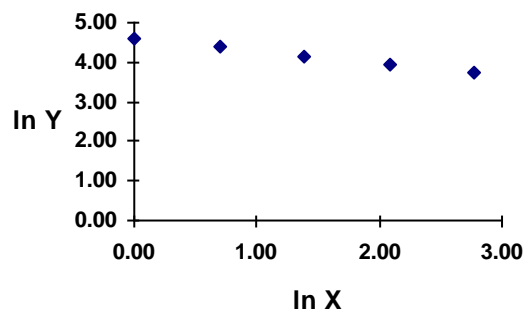


Figure C-9

Assuming that the most accurate model for such data is a power function, taking the natural log of both sides of the power function yields:

$$\ln Y = \ln A + B \ln X$$

This is the equation for a straight line in **fit space**, where the transformed variables “exist,” with slope  $B$  and intercept  $\ln A$ .

#### C.2.2.1. Calculating Coefficients of Simple Nonlinear Regression Models

Now that a nonlinear functional form can be expressed in linear form, the method of least squares can be applied in order to calculate predictive values of slope  $B$ , intercept  $\ln A$ , and  $A$  (i.e., the unit space equivalent of  $\ln A$ ).

To fit a power function, first take the natural log of the sample  $X$  and  $Y$  data. Then apply least squares regression to  $\ln X$  and  $\ln Y$  to solve for the estimated slope ( $\hat{B}$ ) and intercept ( $\ln \hat{A}$ ) using the following formulas:

$$\hat{B} = \frac{n \sum (\ln X \ln Y) - (\sum \ln X)(\sum \ln Y)}{n \sum (\ln X)^2 - (\sum \ln X)^2}$$

$$\ln \hat{A} = \frac{\sum \ln Y - \hat{B} \sum \ln X}{n}$$

$$\hat{A} = e^{\ln \hat{A}}$$

From these estimates for the slope and intercept, the resulting model can be developed in fit space as the equation for a line of the form:

$$\ln \hat{Y} = \ln \hat{A} + \hat{B} \ln X$$

or in **unit space**, where the original or untransformed variables “exist,” as a power model of the form:

$$\hat{Y} = \hat{A} X^{\hat{B}}$$

These equations will now be applied to the data set from Table C-6 using a convenient layout to organize the necessary calculations:

**Table C-6: Power Model Calculation Layout**

X	Y	$\ln X$	$\ln Y$	$\ln X \ln Y$	$(\ln X)^2$
1	100	0.0000	4.6052	0.0000	0.0000
2	80	0.6931	4.3820	3.0372	0.4804
4	64	1.3863	4.1589	5.7655	1.9218
8	51	2.0794	3.9318	8.1758	4.3239
16	41	2.7726	3.7136	10.2963	7.6873
		$\Sigma=6.9314$	$\Sigma=20.7915$	$\Sigma=27.2748$	$\Sigma=14.4134$

$$\hat{B} = \frac{5(27.2748) - (6.9314)(20.7915)}{5(14.4134) - (6.9314)^2} = -0.3222$$

$$\ln \hat{A} = \frac{20.7915 - (-0.3222)(6.9314)}{5} = 4.6050$$

$$\hat{A} = e^{4.6050} = 99.9830$$

$$\hat{Y} = 99.9830X^{-0.3222}$$

### C.2.2.2. Regression Statistics of Simple Nonlinear Models

Similar to the process described for an SLR equation, we proceed to compute the statistics and tests of significance that measure the validity of the nonlinear regression curve. Such statistics can determine how well the CER predicts the dependent variable. They can also tell us whether a trend exists.

#### Calculation of the Coefficient of Determination ( $R^2$ ) for Nonlinear Models

Unlike the calculations shown for a linear equation in section C.2.1.3., the statistics for a nonlinear equation are based upon transformed X and Y data. Analysts should be cautious when interpreting statistics from regression models that involve transformations of the variables, particularly the dependent variable, Y. All spreadsheet regression tools and most statistics packages report regression statistics based on transformed data.

Recall one formula for  $R^2 = \text{Percent of Explained Deviation}$

$$R^2 = \frac{SSR}{SST} = \frac{\sum(\hat{Y} - \bar{Y})^2}{\sum(Y - \bar{Y})^2}$$

For both the power and exponential models,  $R^2$  is calculated based on the natural log transformation of Y. This is not a linear transformation. For example, suppose you transform the values 100 and 10 from unit space to fit space as follows:  $\ln 100 = 4.6$  and  $\ln 10 = 2.3$ . Prior to the transformation, one number is 10 times the other. After the transformation, one number is only twice the other. Therefore, when comparing

a linear model with a nonlinear model,  $R^2$  for the nonlinear model would be larger than  $R^2$  for the linear model, and the nonlinear model would be favored over the linear. This scaling effect distorts the statistic and makes it impossible to accurately compare linear and nonlinear models using transformed  $R^2$ .

A similar problem occurs with other statistics. Recall that the goal of least squares regression is to minimize the sum of squared unexplained errors, SSE.

$$SSE = \sum (Y - \hat{Y})^2$$

The units of SSE are  $Y^2$ . If the dependent variable has been transformed, as with both the power and exponential models, the SSE shown by all spreadsheet regression tools and most statistics packages is in units of  $(\ln Y)^2$ . Therefore, SSEs between linear and nonlinear models are not directly comparable. The standard error of the estimate, SE, is in units of Y for a linear model and in units of  $\ln Y$  for the power and exponential models, so this statistic cannot be directly compared between linear and nonlinear models.

To overcome these problems, use the following guidelines:

- Only compare  $R^2$  between models of the same type (i.e., linear versus linear, power versus power, exponential versus exponential), and only then if the models have the same number of independent variables. If  $R^2$  for each equation is shown in unit space (e.g., output from a statistical computer package), then comparison of  $R^2$  is acceptable, and guidelines (b) and (c) are not necessary.
- Unlike  $R^2$ , unit space SEs are comparable between types of models. The model with the smallest unit space SE would be preferred. To compare models of different types, use a statistics package that reports regression statistics, such as SE, in unit space. The statistics for linear models are always unit space statistics.
- If a computer package that reports regression statistics in unit space is not available, compute unit space SE manually.

#### Calculating the Standard Error of the Estimate (SE) for Simple Nonlinear Models

The definition and application of SE for a nonlinear equation is no different than that for a linear equation. Therefore, refer to section C.2.1.3. for a more detailed description of SE.

To obtain unit space statistics for a nonlinear model like the power model:

- use the equation  $\hat{Y} = \hat{A}X^{\hat{B}}$  to compute a fitted value,  $\hat{Y}$ , for each observed X value
- use the following equation to compute unit space SE:

$$SE = \sqrt{\frac{\sum (Y - \hat{Y})^2}{n - k - 1}}$$

where:

n is the sample size, and

k is the number of independent variables

Continuing with the problem from earlier where the power (log-log) model was developed as  $\hat{Y} = 99.9830X^{-0.3222}$  and using a convenient layout for organizing the necessary calculations, the standard error of the estimate can be readily calculated, as shown in Table C-7.

**Table C-7: Calculating the Standard Error of the Estimate**

X	Y	$\hat{Y}$	$(Y - \hat{Y})^2$
1	100	99.9830	0.0003
2	80	79.9713	0.0008
4	64	63.9650	0.0012
8	51	51.1624	0.0264
16	41	40.9222	0.0061
			$\Sigma=0.0348$

$$SE = \sqrt{\frac{0.0348}{5-1-1}} = 0.1077$$

### C.2.2.3. Summary: Simple Nonlinear Regression Models

This section presented the rationale for using, and the equation for developing, one type of nonlinear regression model: the power (log-log) model. An example demonstrating the development of this model was presented. Following a discussion on various statistics including  $R^2$ , SSE, and SE, the example problems were continued with manual calculations of unit space SE for each model.

### C.2.3. Multiple Regression Models (Linear and Nonlinear)

Many situations require two or more independent variables to adequately describe the process or yield sufficiently precise inferences. For example, a regression model for predicting the demand for repair parts for a particular weapon system may use as independent variables the average operating hours, the average miles driven, and an environmental variable such as mean daily temperature. Regression models containing two or more independent variables are called multiple regression models. This section extends the procedures for SLR to multiple regression and discusses some special considerations when using multiple regression models.

#### C.2.3.1. Regression Coefficients for Multiple Regression Models (Linear and Nonlinear)

The general multiple linear regression model is:

$$\hat{Y} = \hat{b}_0 + \hat{b}_1 X_1 + \hat{b}_2 X_2 + \dots + \hat{b}_k X_k$$

where  $\hat{Y}$  = represents the estimated value of the dependent variable

$X_i$  =  $i$ th independent variable

$k$  = number of independent variables

$\hat{b}_i$  = estimated regression parameters

The general multiple power regression model is:

$$\hat{Y} = \hat{A} X_1^{\hat{B}_1} X_2^{\hat{B}_2} \dots X_k^{\hat{B}_k}$$

where  $\hat{Y}$  = represents the estimated value of the dependent variable

$X_i$  = ith independent variable

$k$  = number of independent variables

$\hat{B}_i$  = estimated regression parameters

To ensure the validity of these models, several assumptions must be checked. The assumptions are similar to those for an SLR model.

- (1) The functional form is specified correctly.
- (2) The values of the independent variables are known without error.
- (3) The residuals or error terms,  $e_i = Y_i - \hat{Y}_i$ , are independent, normally distributed multivariate random variables with mean zero and constant variance.
- (4) The error terms are not correlated.
- (5) The data are homogeneous.
- (6) The independent variables are independent of each other.

The values of the regression parameters are to be estimated by using the sample data. This estimation is done by employing the method of least squares where we seek to minimize the sum of the squares of the error terms. The method leads to a system of normal equations that can be solved simultaneously to obtain the parameter estimates.

### C.2.3.2. Regression Statistics for Multiple Regression Models

As with the nonlinear models, there are new issues that must be accounted for when using multiple regression models.

#### The Adjusted Coefficient of Multiple Determination: Adjusted $R^2$

The **coefficient of multiple determination**,  $R^2$ , is defined analogously to the coefficient of determination in SLR. It measures the proportionate reduction in the total variation from the mean  $Y$  value associated with all the independent variables in the multiple regression model.

$$R^2 = \frac{\sum(\text{Explained Deviations})^2}{\sum(\text{Total Deviations})^2} = \frac{\sum(\hat{Y} - \bar{Y})^2}{\sum(Y - \bar{Y})^2}$$

The coefficient of multiple determination is sometimes modified to recognize the number of independent variables in the model. This modification corrects for the loss of degrees of freedom resulting from adding independent variables. Fundamentally, the  $R^2$  can either increase or remain the same with the adding of additional independent variables. This is because explained deviation can increase or remain the same while total deviation always remains the same. A modified measure is appropriate and recognizes the increase, but it also accounts for the loss of the degree of freedom for each additional independent variable. This measure is the **adjusted coefficient of multiple determination**,  $R_a^2$ .

$$R_a^2 = 1 - \frac{\sum(\text{Unexplained Deviation})^2 / (n - k - 1)}{\sum(\text{Total Deviation})^2 / (n - 1)} = 1 - \frac{(1 - R^2)(n - 1)}{(n - k - 1)}$$

where  $n$  = number of data points

$k$  = number of independent variables

$R_a^2$  may decrease when another independent variable is introduced into a model since the loss of a degree of freedom in the denominator ( $n - k - 1$ ) can more than offset the decrease in unexplained deviation. If all CERs are of the same type (simple linear, nonlinear, multiple) with the same number of independent variables, it is not necessary to calculate  $R_a^2$ .

#### Calculating Standard Error of the Estimate (SE) for Multiple Regression Models (Linear and Nonlinear)

The SE formula (covered in sections C.2.1.3. and C.2.2.2.) can also be applied to multiple linear and/or multiple nonlinear models.

Recall from the previous two sections that the **standard error of the estimate**, SE, is defined as:

$$SE = \sqrt{\frac{\sum(Y - \hat{Y})^2}{n - k - 1}}$$

where:

- $n$  is the sample size,
- $k$  is the number of independent variables, and
- when  $k = 1$ , the formula reduces to the SE formula for simple regression.

The number of independent variables influences the standard error of the estimate. For example, all other things being equal, as the number of independent variables go up, so does the SE. This is because an increase in " $k$ " leads to a decrease in the value of the denominator " $n - k - 1$ ."

For the SE formula to have a "real number" solution, sample size ( $n$ ) must exceed the number of independent variables ( $k$ ) by at least one. For example, if you want a regression model with 4 independent variables ( $k = 4$ ), and your sample size ( $n$ ) is equal to 5, the SE formula denominator will equal the square root " $n - k - 1$ " =  $5 - 4 - 1 = 0$ . This is a case where the SE formula has no solution; you would need to at least (a) collect more actual X and Y data pairs or (b) use less than 4 independent variables.

#### **C.2.3.3. Residual Analysis for Multiple Regression Models (Linear and Nonlinear)**

Once the fitted regression model is developed, the model's appropriateness for its application needs to be examined. Recall the assumptions of multiple regression discussed previously (the residuals should be independent, normally distributed, random variables with mean of zero and constant variance). Graphical residual analysis allows us to see whether the errors satisfy these assumptions. The analysis is made easy by use of automated statistics packages. The plot, as described in Figure C-3, of the residuals against one of the independent variables helps us to evaluate the model. A plot such as this for the residuals versus each independent variable should be examined.

The plot depicted in Figure C-3 of the actual Y values versus the fitted Y values shows that the points form a reasonably linear pattern and are close to the line of identity (45° line). The assumption of normally distributed error terms seems reasonable. Also, plotting residuals against fitted Y values can help identify whether the error variance is constant.

#### Inferences about Population Regression Coefficients for Multiple Regression Models (Hypothesis Tests)

In multiple regression, not only do we test the individual slopes, we also test the overall equation. The F test is used to determine whether the regression relationship between the dependent variable and the set of independent variables is statistically significant.

- (1) Formulate the hypotheses.

$$H_0: b_1 = b_2 = \dots = b_k = 0$$

$$H_1: \text{Not all } b_k = 0$$

- (2) Choose the desired level of significance ( $\alpha$ ).

- (3) Find  $F_{p(1-\alpha, k, n-k-1)}$  from the F distribution table.

$$(4) \text{ Calculate } F_c = \frac{R^2 / k}{(1 - R^2) / (n - k - 1)}$$

(Note:  $F_c$  is generally given in the output from a statistical package.)

- (5) Make a decision using the following rules:

(a) If  $F_c > F_p$ , reject the null hypothesis. Conclude that the regression relationship between Y and the independent variables **is** statistically significant to the degree that such a determination can be made by F tests. Proceed to testing each slope as described in the SLR section.

(b) If  $F_c \leq F_p$ , fail to reject the null hypothesis. Conclude that the relationship between Y and the independent variables **is not** statistically significant. Discard the equation.

Once the existence of a regression relationship has been established, testing of individual regression coefficients can begin. Tests of the individual regression coefficients are done the same way as in simple regression; however, the t statistic must now account for n-k-1 degrees of freedom. Do a t test for each slope coefficient.

- (1) Formulate the hypotheses.

$$H_0: b_i = 0$$

$$H_1: b_i \neq 0$$

- (2) Choose the desired level of significance ( $\alpha$ ).

- (3) Find  $t_{p(1-\alpha/2, n-k-1)}$  from the t distribution table.

- (4) Calculate  $t_c$  (normally given with the computer regression output) .

$$t_p = t_{(1-\alpha/2, n-k-1)} \text{ and } t_c = \frac{\hat{b}_i - b_i}{S_1} = \frac{\hat{b}_i - 0}{S_1} = \frac{\hat{b}_i}{S_1},$$

$$\text{where } S_1 = \frac{SE}{\sqrt{\sum X_i^2 - n\bar{X}_i^2}}$$

(5) Make a decision using the following rules.

(a) If  $|t_c| > |t_p|$ , reject the null hypothesis.

Conclude that the slope **is** statistically significant.

(b) If  $|t_c| \leq |t_p|$ , fail to reject the null hypothesis.

Conclude that the slope **is not** statistically significant.

The test of a single coefficient is a conditional test, since it tests the significance of  $b_i$ , given the presence of the other elements of the model. If we fail to reject the null hypothesis for any slope, then we discard the equation and recompute the regression without that variable.

#### Checking for Multicollinearity within Multiple Regression Models.

When there are exact dependencies between the independent variables (one or more X values can be expressed in terms of another X value or linear combination of X values), then the least squares solution technique fails. This condition in which the sample observations of the independent variables are highly correlated among themselves is called **multicollinearity**. When multicollinearity is present, we encounter two major consequences:

- The estimated value of the regression coefficient,  $b_k$  (for a given independent variable), may vary greatly depending on which other independent variables are in the model. Consequently, the value of the coefficient does not really indicate the contribution of that particular variable.
- The regression coefficients tend to have extremely large standard deviations.

Once the presence of multicollinearity is identified, remedial actions can be taken.

- Obtain additional observations in an attempt to break the pattern of multicollinearity.
- Transform some of the independent variables to lessen the degree of multicollinearity.
- Omit some of the independent variables causing the multicollinearity.

To check for multicollinearity, use the correlation matrix provided by most statistical regression packages, or run linear regressions between all pairs of independent variables. If you are using nonlinear models, transform the variables before performing the linear regression. For any pair of independent variables, if  $R^2 > 0.5$ , ( $|R| > 0.7$ ), then there is a relationship between the independent variables that is likely to affect the regression parameters. The resulting tests for significance and other inferences are invalid. That pair of independent variables should not be used together in a regression model. To check for multicollinearity manually, use the following formula for **each pair** of independent variables.

$$R_{x_1x_2} = \frac{\sum X_1X_2 - n\bar{X}_1\bar{X}_2}{\sqrt{\sum X_1^2 - n\bar{X}_1^2} \sqrt{\sum X_2^2 - n\bar{X}_2^2}}$$

#### C.2.3.4. Summary: Multiple Regression Models (Linear and Nonlinear)

This section presented several multiple regression models that can be used when simple regression is not sufficient to explain relationships between independent and dependent variables. Multiple regression models use two or more independent variables in an attempt to explain the relationship with the dependent variable. Three of the most commonly used multiple regression models in cost estimating are the multiple linear, power, and exponential regression models. Multiple regression analysis should be performed to identify as many of these models as seem appropriate. A model selection procedure for determining the best equation is presented in the next section. A number of statistical tests are available for determining if a regression equation is valid. Residual analysis is used to determine if the errors have a constant variance, are independent, are normally distributed, and are random. F and t tests are utilized to determine the statistical significance of the overall regression relationship and individual regression slope coefficients. Multicollinearity is a condition where pairs of independent variables are highly correlated. Whenever multiple regression is performed, it is imperative to determine if multicollinearity exists.

#### C.2.4. Model Selection Process

This section provides an overview to help the analyst specify the most appropriate regression model. The following steps attempt to ensure good coverage of those principles inherent in sound analysis and model selection. The order in which the steps are performed can be varied. If no automated statistics package is available, it may be more efficient to delay some of the more laborious calculations and graphs until the number of models has been pared down by using the simpler checks. Recall from nonlinear regression that only **unit space statistics** can be used to compare models from different groups (i.e., linear, power, etc.).  $R_a^2$  statistics from transformed models cannot be compared to  $R_a^2$  statistics from untransformed models. If your statistics package does not provide unit space SEs for transformed models, you must calculate SEs manually using the formula

#### Performing Regression Analysis Using Statistical Software

- (1) Consider first trying to fit the (X, Y) data in the form of simple nonlinear model,

$$\hat{Y} = \hat{A}X^{\hat{B}}$$

If the exponent is close to 1.00, then rerun the functional form as a linear regression,

$$\hat{Y} = \hat{b}_0 + \hat{b}_1 X$$

- (2) A similar procedure can also be applied to a multiple nonlinear model,

$$\hat{Y} = \hat{A}X_1^{\hat{B}_1}X_2^{\hat{B}_2} \dots X_k^{\hat{B}_k}$$

If any of the exponents are close to 1.00, then rerun that part of the functional form with no exponent.

Note that such a process could produce a multiple regression model with both linear and nonlinear characteristics. For example:

$$\hat{Y} = \hat{b}_0 + \hat{b}_1X_1 + X_2^{\hat{B}_2}$$

- (3) If all exponents of the multiple nonlinear model are close to 1.00, rerun the regression as a multiple linear model,

$$\hat{Y} = \hat{b}_0 + \hat{b}_1X_1 + \hat{b}_2X_2 + \dots + \hat{b}_kX_k$$

- (4) In all cases above, check if regression statistics and equation logic are reasonable.

described in the nonlinear regression section before comparing SEs (SEs for simple and multiple linear models are already unit space statistics).

- (1) If automated with unit space statistics, choose a model with **maximum  $R_a^2$**  or **minimum SE**.
- (2) If not,
  - (a) Group models by type (linear, power, etc.),
  - (b) Choose model with highest  $R_a^2$  from each group
  - (c) Calculate unit space SE for each model selected in 2(b) above and select the model with the lowest SE.
  - (d) Perform significance tests (if manual). If model fails, go to (b) and choose next highest  $R_a^2$ ,
  - (e) Check for multicollinearity (if manual). If present, go to (b) and choose next highest  $R_a^2$ ,
  - (f) Perform residual analysis (if manual). If bad, go to (b) and choose next highest  $R_a^2$ , and
  - (g) Perform a logic test to ensure that the relationship described in the CER makes sense. If not, go back to (b) and choose the next highest  $R_a^2$ .

Finally, if a good CER does not emerge, be aware of nonparametric techniques. There are many other methods of cost estimating besides the statistical approach.

### C.2.5. Summary: Parametric Cost Estimating

The regression approach depends on adherence to key parametric assumptions, including random data selection, precise measurement of independent variables, correct specification of functional form, and normal distribution of the error terms. In practice, we must sometimes violate those assumptions, yet still produce a useful CER.

It is imperative that the analyst conduct any regression method with normalized data and then proceed in a step-wise fashion to develop and assess the quality of each CER, ultimately selecting the most preferred CER (whenever possible).

## C.3. Engineering Build-Up Cost Estimating

The third type of cost estimate is an engineering build-up, also referred to as a “grassroots-level” approach, or detailed “bottom-up” estimate. The detailed engineering build-up cost estimate is developed from the bottom up by estimating the cost of every activity in a project’s WBS, summing these estimates, and adding appropriate overheads. It is used primarily when there is adequate project maturity to define the scope of work, schedule discrete activities, and determine the resources required to perform those activities. The source and structure of an engineering build-up estimate provides much more detail than estimates by analogy or parametrics. The tradeoff, however, is that producing an engineering estimate is labor intensive, slow and expensive. The strengths, weaknesses, and applications of the engineering build-up method are summarized in Table C-8.

This costing methodology involves the computation of the cost of a WBS element by estimating at the lowest level of detail (often referred to as the “work package” level) wherein the resources to accomplish the work effort are readily distinguishable and discernable. This is often referred to as the Cost Breakdown Structure (CBS) or the Cost Estimating Structure (CES). In most cases, the labor requirements are estimated separately from material requirements. Overhead factors for cost elements

such as Other Direct Costs (ODCs), General and Administrative (G&A) expenses, materials burden, and fee are applied to the labor and materials costs to complete the estimate. A technical person who is very experienced in the activity typically works with the cost analyst, who prepares these engineering build-up estimates. The cost estimator's role is to review the grassroots estimate for reasonableness, completeness, and consistency with the project GR&A. It is also the cost estimator's responsibility to test, understand, and validate the knowledge base and data used to derive estimates.

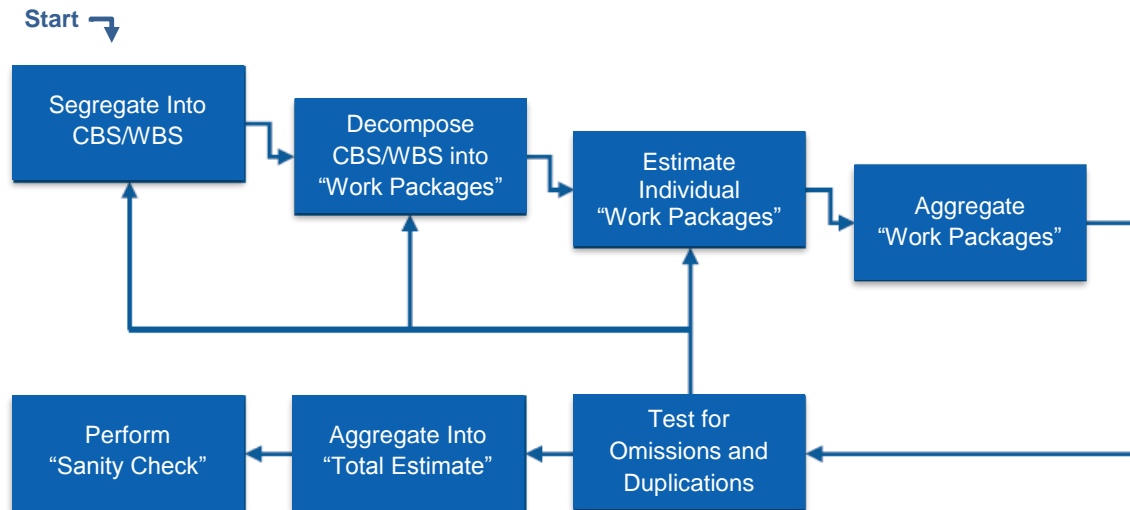
**Table C-8. Strengths, Weaknesses, and Applications of Engineering Build-Up Methodology**

Strengths	Weaknesses	Applications
Intuitive	Costly; significant effort (time and money) required to create a build-up estimate; Susceptible to errors of omission/double counting	<ul style="list-style-type: none"> <li>• Production estimating</li> <li>• Negotiations</li> <li>• Mature projects</li> <li>• Resource allocation</li> </ul>
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 (e.g., high-dollar items).	Does not provide good insight into cost drivers (i.e., parameters that, when increased, cause significant increases in cost)	
Reusable; easily transferable for use and insight into individual project budgets and performer schedules	Relationships/links among cost elements must be "programmed" by the analyst	

Figure C-10 illustrates a method for deriving an engineering build-up estimate. While this is a simple illustration of the engineering build-up methodology, it is important to remember to conduct other detailed activities such as documenting the Basis of Estimates and schedules and applying wage and overhead rates.

The development of the engineering build-up estimate must be preceded by and based on the scope/objectives definition and estimating structure definition, as well as the WBS, normalized data gathering, and the establishment of Ground Rules and Assumptions (GR&A) that are discussed in Section 2.2.1 of the Cost Estimating Handbook.

Cost estimating guidelines should be documented prior to the development of the engineering build-up estimate. The cost estimating guidelines ensure consistency among the estimates by providing a common set of documents to be used for the development of the estimate. The cost estimating guidelines include or identify the location of the technical baseline definition, WBS, WBS dictionary, top-level schedule, Responsibility Assignment Matrix (RAM), GR&A, and instructions as to how the cost information is to be submitted. The estimator can then follow the guidelines, further develop the WBS and the schedule, and use the appropriate source data to identify the resources required to perform each activity. The basis for the resource estimate is then recorded in the BOE document (see section C.3.3).



**Figure C-10. Method for Developing Engineering Build-Up Estimate**

In addition to being used for detailed cost estimates, engineering build-up cost estimates can be used for cross-checks of mission costs if equivalent costs from other approaches (analogy or parametric) are available. Engineering build-up cost estimates can also be used for what-if analyses and trade studies.

### **C.3.1. Estimating the Cost of the Job**

Developing an engineering build-up cost estimate is a two-part process that includes defining the scope of the job and then estimating the resources required to perform the work. The scope of the project/Program must be defined by the p/P Manager. Resources are labor (hours/Full-Time Equivalents [FTEs], Work Year Equivalents [WYE], and labor categories), procurements/subcontracts, travel, General and Administrative (G&A) expenses, indirect, and Other Direct Costs (ODCs). Indirect costs are those derived from general business expense: a business expense that is not directly connected to a specific product or operation. ODCs are those costs that can be related directly and traced to the production of a product or to a particular function or service.

Often the labor requirements are estimated separately from material requirements. Whenever applicable, overhead factors for ODCs, G&A expenses, and materials burden (e.g., storage fees) are applied to labor and material costs to complete the estimate. Where the activity necessitates, a technical person who is very experienced in the activity typically works with the cost estimator, who prepares these engineering build-up estimates.

Life-Cycle Cost (LCC) includes the total of the direct, indirect, recurring, nonrecurring, and other related expenses both incurred and estimated to be incurred in the design, development, verification, production, deployment, prime mission operation, maintenance, support, and disposal of a project, including closeout, but not extended operations. The LCC of a project or system can also be defined as the total cost of ownership over the project or system's planned life cycle from Formulation (excluding Pre-Phase A) through Implementation (excluding extended operations). The LCC includes the cost of the launch vehicle.

#### **C.3.1.1. Defining the Scope of the Job**

To build up the cost, the project must be well understood and broken down into small discrete tasks or activities at the lowest level of the WBS. The discrete tasks may include design, analysis, drawings, board assembly, parts lists, materials, testing, test setup, and chamber time, among many others. The

project/Program Manager must provide all the relevant information to the estimator to facilitate the estimator's understanding of the scope of work. Job definition also includes developing the schedule for the lower-level activities. These schedules are the source data used to build the project Integrated Master Schedule (IMS).

### C.3.1.2. Estimating the Resources

Once the discrete task or activities have been defined and scheduled, the estimator is ready to estimate the direct, time-phased resources for each element of cost (labor, procurements/subcontracts, travel, indirect, and ODCs) required to perform the defined work activities. Table C-9 identifies the direct elements of cost to be estimated, as well as the typical resources and the types of source data that may be used. Examples of data sources are listed starting with the most important source.

**Table C-9. Resources and Source Data by Cost Element**

Element of Cost	Resources	Source Data
Labor	<ul style="list-style-type: none"> <li>FTEs or hours</li> <li>Labor categories</li> </ul>	<ul style="list-style-type: none"> <li>Actual labor hours/labor categories for recent relevant experience</li> <li>Engineering estimate</li> </ul>
Travel	<ul style="list-style-type: none"> <li>Reason for the trip</li> <li>Number of trips, or duration</li> <li>Number of people</li> <li>Destinations</li> <li>Airfare</li> <li>Per diem</li> </ul>	<ul style="list-style-type: none"> <li>Recent experience for specific related work outlined in the solicitation</li> <li>Published Government approved rates for airfare and per diem</li> </ul>
Materials	<ul style="list-style-type: none"> <li>A list of the materials, parts, equipment, and other items required to perform the scope of work. The list includes the vendor name, the price per unit, and the needed quantity and extended price.</li> </ul>	<ul style="list-style-type: none"> <li>Recent vendor quotes</li> <li>Catalogs</li> <li>Web sites</li> <li>Historical data</li> <li>Engineering estimate</li> </ul>
Subcontracts	<ul style="list-style-type: none"> <li>The cost of subcontracts required to perform the scope of work, including the vendor name, description, and dollar value.</li> </ul>	<ul style="list-style-type: none"> <li>Recent quotes</li> <li>Historical data</li> <li>Engineering estimate</li> </ul>
Indirect Cost	<ul style="list-style-type: none"> <li>Traceable cost derived from general business expense: a business expense that is not directly connected to a specific product or operation (e.g., computing, maintenance, security, etc.).</li> </ul>	<ul style="list-style-type: none"> <li>Recent quotes</li> <li>Historical data</li> <li>Valid paid and dated invoicing statements</li> </ul>
Other Direct Cost	<ul style="list-style-type: none"> <li>Traceable cost—not identified in the categories above—to specific services or service centers (e.g., labor, material, fuel, power, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>Recent quotes</li> <li>Historical data</li> <li>Valid paid and dated invoicing statements</li> </ul>

The direct labor hours required to complete the work are estimated from engineering drawings and specifications, usually by an industrial engineer (IE) using company or general industry "standards". The engineers also estimate raw materials and purchase parts requirements. The remaining elements of cost, such as tooling, quality control, other direct costs, and various overhead charges including systems engineering and project management, are factored from the estimated direct labor and/or material content

of the work. The actual portion of the cost estimated directly is thus a fraction of the overall cost of the system.

An IE (or similar specialist) may use a variety of techniques in estimating the direct labor and material cost of each discrete work element. For example, an IE may use an analogy to estimate one work element; a parametric CER based on an industry database of like work elements to estimate a second work element; and a set of work standards based on work activities (e.g., milling .002 inches from a 6 inch diameter rod 3 inches long) to estimate a third work element.

Uncertainty in this type of cost estimate is due to the use of multiplicative factors on the relatively small direct labor/material base that was estimated. This can result in significant error in the total system cost estimate. The uncertainty, however, can be assessed and managed. Another potential problem is that since the cost estimate is the summation of many estimates, it may be hard to maintain the documentation to support the estimate.

Because, in most cases, an engineering build-up estimate is based on standards, either company-specific or industry-wide, the contractor's cost estimate should be "attainable". By definition, standards are attainable values for specific work under given conditions. The engineering build-up estimate is thus a tool for the manufacturer to control the work on the floor (process control). The technique has its greatest value once the design has stabilized and the system is in production.

As NASA systems development programs tend to be on the leading edge of technology, much effort is spent getting the system to work, which translates into redesign and modifications. This design metamorphosis should be reflected in the engineering estimate. However, engineers may, due to the unknown aspects of the program, underestimate the number of design iterations and therefore underestimate the cost of the work element(s).

The engineering build-up cost estimate is most often used during and after Phase C (Final Design and Fabrication). This technique encourages the contractor to do his homework early on and define all the work down to the lowest level of the WBS. It is also a great process control technique at the production facility. The technique, generally accomplished by hardware manufacturers, is the most costly in time and people.

There are also situations where the engineering community provides their "professional judgment," but only in the absence of empirical data. Experience and analysis of the environment and available data provide latitude in predicting costs for the estimator. This method of engineering judgment and expert opinion is known as the Delphi method. The cost estimator's interview skills are important when relying on the Delphi method to capture and properly document the knowledge being shared from an engineer's expert opinion. Delphi method usually involves getting a group of experts to converge on a value by iterating estimates using varying amounts of feedback. During this process, individuals are generally not identified to the outside and, in some experiments, not identified to each other.

### **C.3.2. Pricing the Estimate (Rates/Pricing)**

The resources required for the job are raw information that must be priced and summarized. Pricing the estimate entails the application of rates to the resources that determine the price for the effort. The rates to be used are specific to the individual contractor or Center. It is usually recommended and preferred that approved forward pricing rates be used. In the event that forward pricing rates do not exist, the individual contractor's or Center's published rates should be used. In any case, the rates used for pricing and their source should be fully documented.

### **C.3.3. Documenting the Estimate—Basis of Estimate (BOE)**

The BOE explains how the individual costs used in development of the estimate were derived, including any resources that were determined. The primary components of the BOE are task description, source data, rationale/methodology, documentation, and mathematical calculations.

The following outline expands on the structure and content of what should be included in a BOE:

1. Task Description
  - a. Defines the work being performed
  - b. Cross-references the WBS
  - c. Addresses the specifics of:
    - i. *Who* will perform the work
    - ii. *What* tasks will be performed
    - iii. *Where* and *when* will the work be performed
2. Source Data
  - a. Identifies and describes the sources of data used
  - b. Sources of data may include the following:
    - i. Historical databases
    - ii. Cost models
    - iii. SME input
    - iv. Source quotes and valid paid dated invoice statements
3. Rationale/Methodology
  - a. Documents *why* an estimating technique was used
  - b. Shows *how* the source data were adjusted for similarities and/or differences and also the associated assumptions and judgments used to develop the estimate
4. Mathematical Calculations
  - a. Documents all calculations such as:
    - i. Adjustments to actual costs
    - ii. Application of complexity factors
    - iii. Rates and factors used
    - iv. Escalation from the historical data
    - v. Time-phasing of the current work effort compared to that of the historical data

### **C.3.4. Summary: Engineering Build-Up Estimating**

The project life-cycle phase and the maturity of project definition will impact the level of detail that can be planned in an engineering build-up cost estimate. The available level of detail will impact the number of BOEs and the level of documentation available for the estimate. A simple example of estimating using the Engineering Build-Up method is provided in the box on the following page. The estimator should be aware that an insufficient level of definition will negatively affect the accuracy of the estimate. The estimator may consider a different methodology than engineering build-up estimating, if this is the case, or seek a hybrid estimate.

## Simple Example of Estimating using the Engineering Build-Up Method

Numbers and values associated with WBS, weights and CERs vary from system to system and from service to service. All numeric values shown in this example are for illustrative purposes only. For this example, mass was selected as the unit of measure (UOM). However, there are other commonly used UOMs such as length, square feet, thrust and source lines of code (SLOC).

When estimating by the engineering build-up method for this example, an analyst needs to estimate direct labor hours associated with attaching heat shielding (WBS 06.05.01) to the spacecraft. For example:

### DIRECT LABOR HOURS TO ASSEMBLE & ATTACH HEAT SHIELDING

$$\begin{array}{rclclcl} & \text{Heat Shielding Mass} & \times & \text{Labor CER} & = & \text{Direct Labor Hours} \\ \text{WBS 06.05.01} & 20 \text{ kilograms} & \times & 25 \text{ hours/kg} & = & 500 \text{ Hours} \end{array}$$

Keep in mind that the labor to assemble and attach the heat shielding may be performed by a team of assemblers/integrators. Therefore, for example, the 500 hours of direct labor may actually be completed in a 160 hour work-month if multiple people are performing this task.

The 500 hours of direct labor can be converted to direct labor cost by applying a labor rate as follows:

### DIRECT LABOR COST TO ASSEMBLE & ATTACH HEAT SHIELDING

$$\begin{array}{rclclcl} & \text{Direct Labor Hours} & \times & \text{Labor Rate} & = & \text{Direct Labor Cost} \\ \text{WBS 06.05.01} & 500 \text{ hours} & \times & \$80/\text{hour} & = & \$40,000 \end{array}$$

Overhead cost must also be estimated. This is calculated by applying an overhead rate factor to the direct labor cost:

### OVERHEAD COST TO ASSEMBLE & ATTACH HEAT SHIELDING

$$\begin{array}{rclclcl} & \text{Direct Labor Cost} & \times & \text{Overhead Rate} & = & \text{Overhead Cost} \\ \text{WBS 06.05.01} & \$40,000 & \times & 1.50 & = & \$60,000 \end{array}$$

The cost of direct labor plus overhead results in a total "burdened" labor cost of \$100,000 to attach the heat shielding to the spacecraft.

The cost of the heat shielding material must also be estimated. This example assumes a material cost of \$20,000 per unit kilogram:

### MATERIAL COST OF HEAT SHIELDING

$$\begin{array}{rclclcl} & \text{Heat Shielding Mass} & \times & \text{Material CER} & = & \text{Material Cost} \\ \text{WBS 06.05.01} & 20 \text{ kilograms} & \times & \$20,000/\text{kg} & = & \$400,000 \end{array}$$

The final step in applying the engineering build-up cost estimating method is to add the given WBS' costs of direct labor, overhead and material. For this example, this is denoted as:  $\text{Cost}_{\text{WBS 06.05.01}} = \text{Direct Labor Cost} + \text{Overhead Labor Cost} + \text{Material Cost}$ . Substituting our estimates for each cost category yields  $\text{Cost}_{\text{WBS 06.05.01}} = \$40,000 + \$60,000 + \$400,000$ . Therefore,  $\text{Cost}_{\text{WBS 06.05.01}} = \$500,000$ . Note that  $\text{Cost}_{\text{06.05.01}}$  is just one of many cost elements of the engineering estimate.

- (5) Consider first trying to fit the (X, Y) data in the form of simple nonlinear model,

$$\hat{Y} = a + bX + cX^2 + dX^3 + eX^4 + fX^5 + gX^6 + hX^7 + iX^8 + jX^9 + kX^{10}$$

## Appendix D: Estimating Cost of Technology Development

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NASA is investing in many new technologies that support our mission in space and aeronautics. Understanding the cost for research and development of these technologies and the time it takes to increase the maturity of the technology is important but difficult. Overall, technology estimating may help provide guidance to technology investment strategies to help improve evaluation of technology affordability, and aid in trade studies and decision support. However, the availability of data and tools has been limited, hampering the ability of NASA's cost estimating community for technology estimating.<sup>1</sup> To address this challenge, the CAD engaged in research activities to develop a framework development of a Technology Estimating process in partnership with the Game Changing Technology Program of the Space Technology Mission Directorate. The research project, *Technology Estimating: A Process to Determine the Cost and Schedule of Space Technology Research and Development*, has been documented in NASA technical reports in 2013<sup>2</sup> and 2014.<sup>3</sup>

A result of this research was the development of the Technology Cost and Schedule Estimating (TCASE) tool, which is available to the NASA community via the ONCE Model Portal at [www.oncedata.com](http://www.oncedata.com). The Technology Cost and Schedule Estimation (TCASE) tool generates estimated ranges of cost and schedule duration for a new technology development project. It does so by drawing analogies to historical and current project, or by means of a decision tree model trained on these data. Past performance information for nearly 3,000 technology development projects is stored in an accompanying database. The tool is specifically designed to examine technologies in the range of TRL 1 through TRL 6.

This appendix will be developed in more detail, but the references provided should provide the analyst with the basics to help address the challenge of estimating the cost of technology development.

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<sup>1</sup> Bob Sefcik, Glenn Research Center, Chris Blake, Booz Allen Hamilton, Technology Advancement: Estimating the "Soft" Side 2011 NASA Cost Analysis Symposium August 17, 2011.

<sup>2</sup> Cole, Stuart K.; Reeves, John D.; Williams-Byrd, Julie A.; Greenberg, Marc; Comstock, Doug; Olds, John R.; Wallace, Jon; DePasquale, Dominic; Schaffer, Mark; *Technology Estimating: A Process to Determine the Cost and Schedule of Space Technology Research and Development*, NASA STI Pub. NASA/TP-2013-218145, December 2013. Available at <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140005476.pdf>.

<sup>3</sup> Cole, Stuart K.; Wallace, Jon; Schaffer, Mark; May, M. Scott; Greenberg, Marc W.; *Technology Estimating 2: A Process to Determine the Cost and Schedule of Space Technology Research and Development*, NASA STI Pub. NASA/TM-2014-218251, April, 2014. Available at <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140005340.pdf>.

## Appendix E: Models and Tools

### E.1. Model and Tools Introduction

There are a variety of estimating tools and models available for NASA cost and schedule analysts to use in developing an estimate. This appendix provides a reference to the primary tools available to implement the principles and strategies discussed in other sections of this handbook. NASA makes available a package of models and tools for its cost and schedule user community that includes tools that NASA has sponsored, and other commercially available tools for which NASA provides licenses. These models and tools are summarized in Table E-1, indicating which estimating methodology they may be applicable for, as well as where they are typically used in the project life-cycle.

**Table E-1. Cost Models and Tools Utilization Guide**

Tool Type	Estimating Methodology Applicability			
	Parametric			
	Analogy			
	Build Up			
<b>NASA-Sponsored Models and Tools</b>		<b>ONCE Portal<sup>1</sup></b>		
Project Cost Estimating Capability (PCEC)		✓		
NASA Air Force Cost Model (NAFCOM) <i>(Transitioning users to PCEC)</i>		✓		
NASA Instrument Cost Model (NICM)	X	✓	✓	
Technology Cost and Schedule Estimation (TCASE) Tool	X		✓	
Schedule Management and Relationship Tool (SMART)	soon	✓	✓	
Phasing Model	X	✓		
Schedule Estimating Relationship Risk Analysis (SERRA)		✓	✓	✓
Quantitative Techniques Incorporating Phasing and Schedule (QTIPS)		✓	✓	✓
QuickCost		✓		
One NASA Cost Engineering (ONCE) Database	X		✓	✓
REDSTAR Database		✓	✓	✓
<b>Models and Tools with NASA-Provided Licenses</b>				
Polaris <sup>4</sup> <i>(JCL Analysis)</i>	X	✓	✓	✓
Argo (Monte Carlo simulation)	X	✓	✓	✓
Automated Cost Estimating Integrated Tools (ACEIT)	X	✓	✓	✓
CO\$TAT (statistical analysis package)	X	✓	✓	✓
Joint Analysis of Cost and Schedule (JACS) <i>(JCL Analysis)</i>	X	✓	✓	✓
SEER for Hardware, Electronics, & Systems (SEER-H)	soon	✓		
SEER for Software (SEER-SEM)	soon	✓		
PRICE® TruePlanning™		✓		
PRICE® Estimation Suite (PES)		✓		

Use of a tool or model that is not NASA-sponsored or has a NASA-provided license for estimates supporting Key Decision Point (KDP) reviews should be considered carefully, and the CAD should be consulted prior to proceeding with use of any such tool for those purposes.

<sup>1</sup> Current ONCE Model Portal availability as of February 2015, more tools and models will be made available via the ONCE Model Portal at [www.oncedata.com](http://www.oncedata.com) over time.

The body of knowledge required for gaining expertise in usage of these models and tools can vary greatly, and providing instructional aid for all models and tools referenced here is beyond the scope of this appendix. There is a summary of cost models that address risk in Appendix G, Section G.4. There is also a summary of Schedule Estimating Relationship (SER) models and tools in Appendix K, Section K.4.

If additional information is sought, the NASA Cost Analysis Division, your Center cost leadership, or the tool developer or proprietor can provide assistance in application of a particular tool. Contact CAD with any questions at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

## E.2. Agency-Provided Tools and Models

The NASA Cost Analysis Division (CAD) leads the development, dissemination, and improvement of NASA-sponsored cost and schedule estimating tools and sponsors Agency-wide licenses for key vendor-provided tools. CAD works closely with tool vendors on new enhancements with inputs. CAD standardizes tool use and maximizes efficiency for NASA by establishing Agency-wide licenses that allow programs and projects to complete required cost estimation work without additional expenditure of funds. Additionally, CAD has, in cooperation with Center cost organizations, originated a number of in-house models and tools that are readily available to the user community. For access to these tools, please access the ONCE Portal at <http://www.oncedata.com>, or contact CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

### E.2.1. NASA-Sponsored Models and Tools

**PCEC:** The Project Cost Estimating Capability (PCEC) is an initiative sponsored by CAD and Marshall Space Flight Center Engineering Cost Office to provide robust and consistent analytical capability to the NASA cost and schedule communities. PCEC is based on parametrics and is intended to be the one-stop shop for cost and schedule estimating capability.

Historical NAFCOM functional capability will be replaced by PCEC framework. These include WBS templates, Cost Estimating Relationship (CER) statistics, weight-based CERs, multivariable CERs, learning curve reports, systems test hardware cost, schedule estimating, and time phasing. Other capabilities (to include the NASA Instrument Cost Model (NICM) and QuickCost) will migrate towards integration within the PCEC framework. Historical, current, and future research capabilities will also be incorporated into the PCEC framework.

PCEC Interface will facilitate the use of the PCEC Library information (e.g., inserting CERs, building Work Breakdown Structures) for creating estimates. It will also automate redundant estimating processes. The interface is an Excel add-in. PCEC access is available upon request via CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

**NAFCOM:** The NASA–Air Force Cost Model (NAFCOM) has been the primary cost estimating tool for launch vehicles, Crew Exploration Vehicle (CEV), landers, rovers, and other flight hardware elements. It is now being transitioned to the Project Cost Estimating Capability (PCEC), which incorporates its resources and capability. It has been used by over 800 Government and contractor employees. NAFCOM is a parametric cost model based on over 155 NASA and Air Force space flight hardware projects.

#### PCEC replacing NAFCOM

At the time of this handbook's publication, NAFCOM is still used by the NASA cost estimating community. However, NAFCOM users are in the process of transitioning to the Project Cost Estimating Capability (PCEC), which contains additional information and tools. PCEC incorporates NAFCOM models, as well as models developed by various NASA Centers and directorates. Since most users at this time are more familiar with NAFCOM, this handbook will continue to reference it. The expectation is that the functionality provided to users by NAFCOM and referred to here will continue with PCEC.

**NICM:** The NASA Instrument Cost Model can estimate instrument cost by analogy or by parametric CERs at the system or subsystem level depending on the amount of design information available. NICM is sponsored by NASA Headquarters and actively managed and implemented by the Jet Propulsion Laboratory (JPL). The model can produce probability density functions based on both input parameter uncertainties and CER uncertainties.

A database has been compiled as part of the NICM development. Data have been collected throughout NASA, major NASA vendors, and universities. This database allows for inputs of instrument type (optical, microwave, particles, etc.), destination, mass, power, data rate, etc. Outputs are probabilistic cost distributions at the system and subsystem level, probabilistic schedule distribution, Joint Confidence Level, and cost/schedule estimates by phase. Currently there are two versions of NICM: (1) a Government version that includes modeling capability and underlying data that can be accessed through ONCE and (b) a contractor version that includes system and subsystem estimating capability but no underlying specific data (Sensitive But Unclassified (SBU), proprietary, etc.). For access to NICM, use the ONCE model portal at <http://www.oncedata.com> or contact Joe Mrozinski at [jmrozinski@jpl.nasa.gov](mailto:jmrozinski@jpl.nasa.gov) with the subject line "NICM Access Request."

**ONCE:** The One NASA Cost Engineering (ONCE) database is a secure Web-based application containing all completed Cost Analysis Data Requirement (CADRe) submissions for easy retrieval and faster data analysis. Access is securely provided for NASA users through the Agency Identity Management & Account Exchange (IdMAX) system. ONCE provides enhanced insight and management of historical cost and technical data, which is helping to advance cost estimating practices and analysis across the Agency. The ONCE database is located in the ONCE Portal at <http://www.oncedata.com>.

Beginning in 2014, the ONCE Portal also included a Model Portal for NASA's cost estimating tools and cost models. Examples of models and tools available via the ONCE Model Portal (and as shown in Table E-1) include the NASA Phasing Model, TCASE (Technology Cost and Schedule Estimation), Polaris, ARGO, and ACEIT (which includes JACS), all of which are available for easy download for users with access. ONCE also has a new Library section that includes all original CADRes as well as the CADRe source documents, NASA New Start Inflation tables, and the NASA Cost Symposium presentations from 2006–2014.

For more information on the ONCE database and CADRes, see Appendix A.

**REDSTAR:** The Resource Data Storage and Retrieval System (REDSTAR) Library is funded by Marshall Space Flight Center (Engineering Cost Office) and CAD. The REDSTAR Library is a repository of cost, programmatic, and technical data pertaining to space-related projects and programs. REDSTAR can be used to improve the credibility, fidelity, and consistency of cost estimating products throughout NASA. REDSTAR includes over 38,000 documents, with over 8,000 scanned for distribution in their native format.

Begun in 1971, REDSTAR's document content includes approximately 200 crewed and uncrewed spacecraft missions. Cost, technical, and programmatic data ranging from total program to the subcomponent level can be found pertaining to the spacecraft bus, attached payload, engines, launch vehicles, upper stages, scientific instruments, and aircraft. Additional data pertaining to cost models and cost estimating, schedules, ground and launch operations, mission operations, and business strategy are also found in the database library. REDSTAR Library data are available for use by all NASA employees and members of cost groups from all NASA Centers. A password-protected database of 8,000 full-text documents is available online. Questions concerning access to the REDSTAR database should be directed to Mary Ellen Harris at 256-544-2320.

## E.2.2. NASA-Provided Software Licenses

The Cost Analysis Division provides the NASA cost and schedule communities with Agency-wide licenses for the key estimating tools used by the community. CAD seeks to standardize tool use and maximizes efficiency for NASA through these licenses, and works closely with the tool vendors on new enhancements. These tools are validated for use in Agency reviews, and their use is highly encouraged.

Use of other tools should be carefully considered if an estimate is being prepared for compliance with NASA Procedural Requirement (NPR) 7120.5E. ***Consult CAD prior to using any software for these purposes that is not provided by CAD through an Agency-wide license.***

### Toolsets and Licenses:

NASA CAD currently has an Agency license agreement for two JCL analysis tools (ACEIT JACS and Polaris). Training on these tools has been and will continue to be provided to Agency personnel. It is recommended that all JCL analysis be performed on one of these two tool platforms. If you are a project that is considering using another toolset, please contact CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov). For details on how to obtain these tools or for more assistance on tool selection, please refer to <http://www.nasa.gov/offices/ooe/CAD/>.

CAD is working to have all tools eventually available through the ONCE Model Portal at <https://oncedata.msfc.nasa.gov>, and access can also be requested from CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov). Tools with NASA-provided licenses currently include:

### Polaris

Polaris is program analysis software provided by Booz Allen Hamilton. Polaris integrates cost, schedule, and risk artifacts into a single model, enabling better project performance through real-time simulations. Polaris integrates cost estimates, schedules, and risk registers into a single analytical model that provides a cohesive view across all three project control functions. Polaris is a primary JCL tool and is validated and approved for milestone reviews.<sup>2</sup>

For more information, visit <http://www.boozallen.com/consulting/products/software/polaris> or contact [polaris@bah.com](mailto:polaris@bah.com).

### Argo

Argo is simulation software provided by Booz Allen Hamilton. Argo utilizes an advanced approach to Monte Carlo simulation, achieving substantial run-time and file-size savings. Argo utilizes algorithmic, hardware-independent efficiencies that dramatically reduce run-times and streamline the resources required to perform sophisticated analysis.<sup>3</sup>

For more information, visit <http://www.boozallen.com/consulting/products/software/argo> or contact [argo@bah.com](mailto:argo@bah.com).

### Polaris and Argo via ONCE

Users covered by the NASA licenses can download Polaris and Argo through the ONCE Database at <http://www.oncedata.com>.

### ACEIT

Automated Cost Estimating Integrated Tools (ACEIT) is a Government-owned tool provided by Tecolote Research, Inc. The tool consists of a family of applications, including JACS and CO\$TAT, which support program managers and cost and financial analysts during all phases of a program's life cycle. ACEIT

<sup>2</sup> For an explanation of Polaris, visit <http://www.boozallen.com/consulting/products/software/polaris>.

<sup>3</sup> For an explanation of Argo, visit <http://www.boozallen.com/consulting/products/software/argo>.

contains application tools (database, statistical analysis, knowledge libraries, model building, risk analysis, and more) for storing and analyzing cost and technical data, developing cost and cost-risk models, sharing, and reporting cost estimates.<sup>4</sup>

For more information, visit <http://www.aceit.com> or contact [aceit\\_support@tecolote.com](mailto:aceit_support@tecolote.com).

## **CO\$TAT**

CO\$TAT is the statistical analysis package of the ACEIT application suite that has been specifically designed for the cost/price analyst. CO\$TAT is an Excel add-in that contains most of the features available in commercially sold major statistics programs. With CO\$TAT, users can rapidly move through the analysis process and develop estimating relationships. The analysis results can quickly and automatically be included directly into a cost estimate. CO\$TAT is a module in ACEIT and provides the framework to do cost regression analysis.

## **JACS**

Joint Analysis of Cost and Schedule (JACS) is an add-in for Microsoft Project that is designed to quickly create probabilistic results for schedule and costs in an integrated schedule. JACS enables the cost-loading of schedule tasks and risk events, allowing the analyst to assign probability distributions and create a holistic view of the resultant risk analysis. JACS, a module in ACEIT, is a primary JCL tool and is validated and approved for milestone reviews.

## **PRICE**

PRICE Systems, LLC, provides NASA with suite of tools that model extensive input parameters, allowing for a diverse level of estimating, from general macro-level conceptual estimating to greater fidelity in estimating as a concept matures (capable of estimating at the system and component level). PRICE cost models are based on historical project data verified and validated by extensive PRICE Research. PRICE TruePlanning is a cost estimating framework designed to reduce the time and expense required to satisfy credible, data-driven parametric estimating needs.

For more information, visit <http://www.pricesystems.com> or contact [charles.d.hunt@nasa.gov](mailto:charles.d.hunt@nasa.gov).

## **SEER**

System Estimation and Evaluation of Resources (SEER) is a commercial-off-the-shelf (COTS) parametric cost model widely used in Government for parametric hardware estimating. It is provided by Galorath, Inc. SEER project management tools provide project planning, project estimating, project tracking, and project cost management software for software, hardware and electronics systems; manufacturing; and information technology.

For more information, visit <http://www.galorath.com> or contact [charles.d.hunt@nasa.gov](mailto:charles.d.hunt@nasa.gov).

## **E.2.3. Additional Models and Tools**

There are additional models and tools available to the analyst, in addition to those identified in Table E-1. CAD continues to track estimating models and tools used across the Agency, and can provide a summary of additional tools that may be used upon request to [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov). In addition, members of NASA's estimating community who use tools not included in Table E-1 are invited to contact CAD to discuss dissemination of, or communications regarding those tools across the community.

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<sup>4</sup> For an explanation of ACEIT and components of the ACEIT suite, visit <http://www.aceit.com>.

## E.3. Models and Tools Summary

A more detailed summary of the models and tools available to all NASA estimators is available in Table E-2. Any questions or suggestions for updates or additions should be addressed to CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

**Table E-2. Estimating Models and Tools**

Tool/Model Name	POC	Abstract
<b>Category: NASA-Sponsored Models and Tools</b>		
Project Cost Estimating Capability (PCEC)	<p>MSFC Andy Prince <a href="mailto:andy.prince@nasa.gov">andy.prince@nasa.gov</a></p> <p>NASA Headquarters Charles Hunt <a href="mailto:charles.d.hunt@nasa.gov">charles.d.hunt@nasa.gov</a></p>	<p>The Project Cost Estimating Capability (PCEC) is an initiative sponsored by CAD and Marshall Space Flight Center (Engineering Cost Office) to provide robust and consistent analytical capability to the NASA cost and schedule communities. PCEC is based on parametrics and is intended to be NASA's one-stop shop for cost and schedule estimating capability.</p> <p>Historical NAFCOM functional capability will be replaced by PCEC framework. These include WBS templates, Cost Estimating Relationship (CER) statistics, weight-based CERs, multivariable CERs, learning curve reports, systems test hardware cost, schedule estimating, and time phasing. Other capabilities (to include the NASA Instrument Cost Model (NICM) and QuickCost) will migrate towards integration within the PCEC framework. Historical, current, and future research capabilities will also be incorporated into the PCEC framework.</p> <p>PCEC Interface will facilitate the use of the PCEC Library information (e.g., inserting CERs, building Work Breakdown Structures) for creating estimates. It will also automate redundant estimating processes. The interface is an Excel add-in. PCEC access is available upon request via CAD at <a href="mailto:hq-cad@mail.nasa.gov">hq-cad@mail.nasa.gov</a>.</p>
NASA Air Force Cost Model 12 (NAFCOM)	<p>MSFC Andy Prince <a href="mailto:andy.prince@nasa.gov">andy.prince@nasa.gov</a></p>	<p>NAFCOM is an automated parametric cost estimating tool that uses historical space data to predict the development and production costs of new space programs. It uses parametric relationships to estimate subsystem- and component-level costs for aerospace hardware, including Earth-orbiting spacecraft, piloted spacecraft, launch vehicles, upper stages, liquid rocket engines, scientific instruments, and planetary spacecraft. The model is used primarily in the early phases of a space project and estimates development and production costs at the subsystem and/or component level. <i>NAFCOM will transition into the Project Cost Estimating Capability in 2014–2015. The same functionality will be retained.</i></p>
NASA Instrument Cost Model VI (NICM)	<p>Jet Propulsion Laboratory Hamid Habib-Agahi and Joe Mrozinski <a href="mailto:jmrozins@jpl.nasa.gov">jmrozins@jpl.nasa.gov</a></p> <p>NASA Headquarters James Johnson <a href="mailto:james.k.johnson@nasa.gov">james.k.johnson@nasa.gov</a></p>	<p>NICM is a new observational instrument cost model that can estimate instrument cost by analogy or by parametric CERs at the system or subsystem levels, depending on the amount of design information available. The inputs are objective; instrument type, mass, power, data rate, and design life are some of the independent variables. The model can produce probability density functions based on both input parameter uncertainties and CER uncertainties. The tool has undergone validation. Both the expected value and the uncertainty in the stochastic PDFs have been verified.</p>

## NASA Cost Estimating Handbook Version 4.0

Tool/Model Name	POC	Abstract
Technology Cost and Schedule Estimation (TCASE) Tool	SpaceWorks Enterprises, Inc. (SEI) Jon Wallace <a href="mailto:jon.wallace@sei.aero">jon.wallace@sei.aero</a>  NASA Headquarters Marc Greenberg <a href="mailto:marc.w.greenberg@nasa.gov">marc.w.greenberg@nasa.gov</a>	The Technology Cost and Schedule Estimation (TCASE) tool generates estimated ranges of cost and schedule duration for a new technology development project. It does so by drawing analogies to historical and current project, or by means of a decision tree model trained on these data. Past performance information for nearly 3,000 technology development projects is stored in an accompanying database. The tool is specifically designed to examine technologies in the range of TRL 1 through TRL 6.
Schedule Management and Relationship Tool (SMART)	SpaceWorks Enterprises, Inc. (SEI) Jon Wallace <a href="mailto:jon.wallace@sei.aero">jon.wallace@sei.aero</a>  NASA Headquarters Arnold Hill <a href="mailto:arnold.a.hill@nasa.gov">arnold.a.hill@nasa.gov</a>	The Schedule Management and Relationship Tool (SMART) combines analogy-based and parametric methods in a schedule estimating tool for unmanned spacecraft projects. The tool utilizes high-level technical and programmatic characteristics to determine a spacecraft's likely development schedule duration. It incorporates several previously developed, third-party schedule estimating relationships (SERs) for comparison.
Phasing Model	NASA Headquarters Charles Hunt <a href="mailto:charles.d.hunt@nasa.gov">charles.d.hunt@nasa.gov</a>	The Phasing Model generates Phasing Estimating Relationships (PERs) that can be used to help the analyst estimate annual funding for a mission, given a cost and schedule estimate. The relationships developed by the Phasing Model are based on historical data and do not necessarily represent "optimal" phasing. The time period for the PERs is System Requirements Review (SRR) to Launch, and the content can include two options: Option 1: Total project excluding launch Option 2: Spacecraft and instruments only The Phasing Model can be used to support, assess, and/or defend budgets, and is also a good starting point for analyzing cost & schedule ramifications.
Schedule Estimating Relationship Risk Analysis (SERRA)	NASA Headquarters Charles Hunt <a href="mailto:charles.d.hunt@nasa.gov">charles.d.hunt@nasa.gov</a>	The SERRA model is designed to estimate high-level schedules early in a project's life cycle. Top-level design (Phases A–C) and manufacturing (Phase D) durations are calculated with parametric equations based on technical inputs. SERRA allows the analyst to: <ul style="list-style-type: none"> <li>• Obtain a point estimate for design and manufacturing duration.</li> <li>• Calculate schedule S-curve by specifying distributions for technical inputs.</li> <li>• Assess a range of missions, including planetary, launch vehicle/unpiloted, and Earth-orbiting.</li> </ul>
Quantitative Techniques Incorporating Phasing and Schedule (QTIPS)	NASA Headquarters Charles Hunt <a href="mailto:charles.d.hunt@nasa.gov">charles.d.hunt@nasa.gov</a>	The QTIPS model is designed to analyze cost and schedule implications for changes to a baseline schedule. It allows the user to assess the following scenarios: <ul style="list-style-type: none"> <li>• The cost impact when a program schedule grows.</li> <li>• The cost impact when a program schedule shrinks.</li> <li>• The cost and schedule impact when a program incurs an annual budget cost cap.</li> </ul>

## NASA Cost Estimating Handbook Version 4.0

Tool/Model Name	POC	Abstract
QuickCost	<p>Joe Hamaker <a href="mailto:jhamaker@galorath.com">jhamaker@galorath.com</a></p> <p>NASA Headquarters Charles Hunt <a href="mailto:charles.d.hunt@nasa.gov">charles.d.hunt@nasa.gov</a></p>	<ul style="list-style-type: none"> <li>QuickCost estimates the cost and schedule of scientific missions (including the spacecraft bus, instruments, launch services, ground station, and MO&amp;DA). The model requires only a few top-level independent variables (the dry mass, power, data rate, apogee, pointing accuracy, design life, ATP date, number of instruments, and percentage of new designs). It provides a prediction interval around the estimate and any specified confidence level.</li> </ul>
One NASA Cost Engineering (ONCE) Database	<p>NASA Headquarters</p> <p>Eric Plumer <a href="mailto:eric.plumer-1@nasa.gov">eric.plumer-1@nasa.gov</a></p> <p>James Johnson <a href="mailto:james.k.johnson@nasa.gov">james.k.johnson@nasa.gov</a></p>	<p>The One NASA Cost Engineering (ONCE) database is a secure Web-based application containing all completed Cost Analysis Data Requirement (CADRe) submissions for easy retrieval and faster data analysis. Access is securely provided for NASA users through the Agency Identity Management &amp; Account Exchange (IdMAX) system. ONCE provides enhanced insight and management of historical cost and technical data, which is helping to advance cost estimating practices and analysis across the Agency. The ONCE database is located in the ONCE Portal at <a href="http://www.oncedata.com">http://www.oncedata.com</a>.</p> <p>Beginning in 2014, the ONCE Portal also included a Model Portal for NASA's cost estimating tools and cost models. Examples of models and tools available via the ONCE Model Portal (and as shown in Table E-1) include the NASA Phasing Model, TCASE (Technology Cost and Schedule Estimation), Polaris, ARGO, and ACEIT (which includes JACS), all of which are available for easy download for users with access. ONCE also has a new Library section that includes all original CADRes as well as the CADRe source documents, NASA New Start Inflation tables, and the NASA Cost Symposium presentations from 2006–2014.</p>
Resource Data Storage and Retrieval (REDSTAR) Library	<p>MSFC</p> <p>Mary Ellen Harris <a href="tel:(256)544-2320">(256) 544-2320</a></p>	<p>The REDSTAR Library is a NASA-owned (MSFC Engineering Cost Office) and controlled repository containing over 35,000 documents related to spacecraft cost, technical, and programmatic information. The physical library is located at SAIC's Research Park Odyssey Drive facility in Huntsville, AL.</p>

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Tool/Model Name	POC	Abstract
Category: Models and Tools with NASA-Provided Licenses		
Polaris	Booz Allen Hamilton Eric Druker <a href="mailto:polaris@bah.com">polaris@bah.com</a>  <a href="http://www.boozallen.com/consulting/products/software/polaris">http://www.boozallen.com/consulting/products/software/polaris</a>	Polaris is program analysis software provided by Booz Allen Hamilton. Polaris integrates cost, schedule, and risk artifacts into a single model, enabling better project performance through real-time simulations. Polaris integrates cost estimates, schedules, and risk registers into a single analytical model that provides a cohesive view across all three project control functions. Polaris is a primary JCL tool and is validated and approved for milestone reviews.
Argo	Booz Allen Hamilton Eric Druker <a href="mailto:argo@bah.com">argo@bah.com</a>  <a href="http://www.boozallen.com/consulting/products/software/argo">http://www.boozallen.com/consulting/products/software/argo</a>	Argo is simulation software provided by Booz Allen Hamilton. Argo utilizes an advanced approach to Monte Carlo simulation, achieving substantial run-time and file-size savings. Argo utilizes algorithmic, hardware-independent efficiencies that dramatically reduce run-times and streamline the resources required to perform sophisticated analysis.
Automated Cost Estimating Integrated Tools (ACEIT)	Tecolote Research, Inc. Stephen Sekeres <a href="mailto:aceit_sales@tecolote.com">aceit_sales@tecolote.com</a>  <a href="http://www.aceit.com">www.aceit.com</a>	ACEIT is an integrated suite of analysis tools for the desktop. Similar to how Microsoft Office provides a suite of applications to automate office functions, ACEIT provides a suite of applications to automate cost estimating and analysis. ACEIT has several applications focusing on the functions within the cost estimating environment.
CO\$TAT	Tecolote Research, Inc. Stephen Sekeres <a href="mailto:aceit_sales@tecolote.com">aceit_sales@tecolote.com</a>	CO\$TAT is the statistical analysis package of the ACEIT application suite that has been specifically designed for the cost/price analyst. CO\$TAT is an Excel add-in that contains most of the features available in commercially sold major statistics programs. With CO\$TAT, users can rapidly move through the analysis process and develop estimating relationships. The analysis results can quickly and automatically be included directly into a cost estimate. CO\$TAT is a module in ACEIT and provides the framework to do cost regression analysis.
Joint Analysis of Cost and Schedule (JACS)	Tecolote Research, Inc. Stephen Sekeres <a href="mailto:aceit_sales@tecolote.com">aceit_sales@tecolote.com</a>	Joint Analysis of Cost and Schedule (JACS) is an add-in for Microsoft Project that is designed to quickly create probabilistic results for schedule and costs in an integrated schedule. JACS enables the cost-loading of schedule tasks and risk events, allowing the analyst to assign probability distributions and create a holistic view of the resultant risk analysis. JACS, a module in ACEIT, is a primary JCL tool and is validated and approved for milestone reviews.

## NASA Cost Estimating Handbook Version 4.0

Tool/Model Name	POC	Abstract
SEER for Hardware, Electronics, & Systems (SEER-H)	Galorath Incorporated Brian Glauser <a href="mailto:bglauser@galorath.com">bglauser@galorath.com</a>  <a href="http://www.galorath.com/DirectContent/SEERforHardware2.pdf">www.galorath.com/DirectContent/SEERforHardware2.pdf</a>	SEER for Hardware, Electronics, & Systems (SEER-H) is a robust decision-support tool providing LCC for any size hardware project, from individual components to a variety of complete product assemblies. Using parametric algorithms, extensive knowledge bases, or user-supplied data, SEER-H can reliably and accurately estimate the total cost of ownership for new product development projects. It provides cost and pricing vision from project inception to production, including systems level, product development, production, operations and support, and disposal costs. It also provides detailed insight into the risks, uncertainty, and cost drivers associated with hardware development, acquisition, and integration.
SEER for Software (SEER-SEM)	Galorath, Incorporated Brian Glauser <a href="mailto:bglauser@galorath.com">bglauser@galorath.com</a>  <a href="http://www.galorath.com/DirectContent/SEERforSoftware2.pdf">http://www.galorath.com/DirectContent/SEERforSoftware2.pdf</a>	SEER-SEM is a powerful decision-support tool that estimates software development and maintenance cost, labor, staffing, schedule, reliability, and risk as a function of size, technology, complexity, and any project staffing constraints. SEER-SEM is effective for all types of software projects, i.e., new development, modification, and off-the-shelf integration projects. SEER-SEM estimates the resources and scheduling that software development requires, and it has an unparalleled capability for tradeoff and risk analysis.
PRICE® TruePlanning™	PRICE Systems, LLC Melissa Winter <a href="mailto:melissa.winter@pricesystems.com">melissa.winter@pricesystems.com</a>  <a href="http://www.pricesystems.com/pdf/PRICE_Cost-Model_H-HL.pdf">www.pricesystems.com/pdf/PRICE_Cost-Model_H-HL.pdf</a>	PRICE® TruePlanning™ is a cost estimating framework designed to reduce the time and expense required to satisfy credible, data-driven parametric estimating needs at all levels of an organization—executive, financial, and project/program estimating and management. It is the only cost estimating framework that can integrate multiple cost models—including hardware, software, IT, assembly, and program management costs—all within the same estimate. PRICE® TruePlanning™ also helps to refine the value of project cost histories within the parametric estimating process and supports the ability to integrate dynamic Work Breakdown Structure (WBS) and Cost Element Structure (CES) mapping.
PRICE® Estimation Suite (PES)	PRICE Systems, LLC Arlene Minkiewicz <a href="mailto:arlene.minkiewicz@pricesystems.com">arlene.minkiewicz@pricesystems.com</a>	Based on extensive historical cost experience gained from thousands of projects, these independent models continue to provide PRICE customers with reliable cost estimating for discrete disciplines. They do not, however, integrate with the PRICE® TruePlanning™ Framework and its Companion Applications, and cannot incorporate multiple cost models within the same estimate.

## Appendix F: Phasing of Cost Estimates

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Developing a cost estimate requires more than just determining the total cost. The estimate must also address how those costs are phased over the time period of the development, and NASA has developed tools to assist the estimator with phasing.<sup>1</sup> The phasing profile is important for budget formulation. For example, if the phasing profile for a project is constrained due to budget limitations in particular years, the result may be an increase the overall development cost due to inefficiencies of stretching out or delaying work to stay within available resources in a particular year. In addition, cost estimates and phasing profiles reflect when resources will be expended or costed, and they need to be adjusted to reflect the New Obligation Authority (NOA) that is represented by the budget requests for any particular year, as there is a lag between when funds are available for obligation and when they are costed.<sup>2</sup> Cost-phasing is therefore an important element to be considered in the budget formulation process. In a February 2010 report titled *Assessments of Selected Large-Scale Projects*, the U.S. Government Accountability Office (GAO) found that nearly 50 percent of recently assessed projects had issues due to “budgets [that did] not match the work expected to be accomplished.”<sup>3</sup> The report concluded that these funding issues are some of the primary challenges that can contribute to cost and schedule growth within NASA.

As part of a quality cost estimate, Ground Rules and Assumptions (GR&A) should cover the phasing of the cost (commonly referred to as time phasing).

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. Depending on the activities in the schedule for each year, some years may have more costs than others. Great peaks or valleys in annual funding should be investigated and explained, since staffing is difficult to manage in such variations from one year to another. Anomalies are easily discovered when the estimate is time phased. Cost limitations can also affect an estimate’s time phasing, if there are budget constraints for a given fiscal year. These conditions should be addressed by the estimate and their effects adequately explained.<sup>4</sup>

In general, there are two methodologies for time-phasing an estimate: Engineering Build-Up and Parametric. Most time-phasing will typically consist of a mix of both methodologies, which should be considered two ends of one spectrum. At one end, the engineering build-up, or bottom-up approach would be essentially a summation of a detailed resource-loaded schedule (sometimes called a bottom-up estimate), and, at the other end, a top-down approach would be essentially a parametric or heuristic of a program or high-level element.

### F.1. Engineering Build-Up Time-Phasing

An analyst who has developed a grassroots estimate generally has also developed or been provided with a schedule. In this case, the analyst can cost-load the scheduled activities to develop a phasing plan. The basic process for cost-loading the schedule is to (1) determine the key milestone with which to spread the costs, (2) estimate the percent of total effort required to complete each milestone, and (3) allocate the

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<sup>1</sup> NASA Phasing Model, available via the ONCE Model portal at [www.oncedata.com](http://www.oncedata.com) and described in a paper by presented at the 2013 NASA Cost Symposium [http://www.nasa.gov/sites/default/files/files/08\\_PERFT\\_Cost\\_Symposium\\_Final\\_TAGGED.pdf](http://www.nasa.gov/sites/default/files/files/08_PERFT_Cost_Symposium_Final_TAGGED.pdf).

<sup>2</sup> Burgess, Erik. 2004. “Time Phasing Methods and Metrics.” Paper presented at 37th Annual DoD Cost Analysis Symposium, Williamsburg, VA, February 10-13.

<sup>3</sup> GAO. 2010. *Assessments of Selected Large-Scale Projects*. Washington, DC: GAO, pp. 74–75.

<sup>4</sup> Ibid.

cost to the appropriate fiscal year by multiplying the Work Breakdown Schedule (WBS) cost element by the percentage of effort for each milestone task.

For the Engineering Build-Up method, if a project schedule has not yet been developed, there are two alternative methodologies that can be used. The first alternative is to use a schedule provided to the project by the contractor, which can be useful during source selections where a contractor is providing a cost proposal to the Government. Keep in mind that cost elements such as Government Furnished Equipment (GFE), NASA Test and Evaluation (T&E), and education and public outreach will not be on the contractor's schedule and need to be accounted for separately. The second alternative method involves using an analogy. Analogies are based on the similarity of tasks, technical parameters (e.g., mass or power), key milestones, program length, magnitude of cost, and other program/technical parameters. This method allows the analyst to select an analogous project to use as the pattern for the fiscal-year spread.

## F.2. Parametric Time-Phasing

In practice, there are three types of distributions used to approximate a program's time-phasing: Beta, Rayleigh, and Weibull. Studies have shown that cumulative project expenditures follow a Rayleigh<sup>5</sup> or Weibull<sup>6</sup> distribution quite closely. Both distributions model the linear ramp-up, peak, and exponential rampdown that are typical of most projects. Other distributions, such as the Beta distribution and 2nd- and 3rd-order polynomials, can mirror this same pattern and have been used by cost analysts to spread costs over a schedule and determine annual phasing requirements. Cost analysts at Johnson Space Center pioneered the use of this quantitative technique for NASA in the 1960s by using a Beta distribution (curve) to spread the point estimate from a parametric cost estimate over a project schedule.

Heuristics, typically expressed in percent cost for a percent time, are also commonly used. For example, several NASA studies<sup>7,8</sup> show that space systems typically *expend* 45–55 percent of their funds within the first 50 percent of time. A typical distribution (Rayleigh, Weibull, or Beta) illustrates the percentage spent and the elapsed time between two points in time. By way of illustrating the concept, if an analyst has developed an estimate of \$100 million for a satellite, without any other knowledge of funding needs, the analyst could use the rule of thumb that assumes a 60:40 Beta Curve (60 percent of the cost at the halfway mark and 40 percent for the remainder of the project). The rule of thumb for a ground-based system is 40:60. Table F-1 below illustrates three examples of Beta distributions: 50:50, 60:40, and 70:30.

Some of the NASA parametric models or other tools also offer spreading functions; however, it is recommended that the analyst examine several of them carefully prior to selecting the approach for spreading the early cost estimate.

<sup>5</sup> Lee, D., Hogue, M., and Gallagher, M. 1997. "Determining a Budget Profile from a R&D Cost Estimate." *Journal of Cost Analysis*.

<sup>6</sup> Brown, T., White, E., and Gallagher, M. 2002. "Weibull-based Forecasting of R&D Programs Budgets." *Journal of Cost Analysis*.

<sup>7</sup> Kellogg, B., Hayhurst, M., Roeum, V., and Miller, M. 2013. "Generic Cost Profiles Based on Actual Costs in NASA CADRes." NASA Cost Symposium. Pasadena, CA.

<sup>8</sup> Burgess, E., Krause, C., Sterburzel, J., and Elliott, D. 2013. "Phasing Estimation Relationships." NASA Cost Symposium. Pasadena, CA.

## 2013 NASA Cost Estimating Handbook

PDF Curve Shapes	Years	Percentatge Cost Per Year									
		1	2	3	4	5	6	7	8	9	10
50:50	1	100									
	2	50	50								
	3	21	58	21							
	4	10	40	40	10						
	5	6	26	36	26	6					
	6	4	17	29	29	17	4				
	7	3	12	22	26	22	12	3			
	8	2	9	17	22	22	17	9	2		
	9	1	7	13	19	20	19	13	7	1	
	10	1	5	11	15	18	18	15	11	5	1
60:40	1	100									
	2	60	40								
	3	31	53	16							
	4	19	41	32	8						
	5	12	31	33	20	4					
	6	9	23	28	24	13	3				
	7	6	17	24	24	18	9	2			
	8	5	14	20	22	19	13	6	1		
	9	4	11	16	19	19	15	10	5	1	
	10	3	9	14	16	17	16	12	8	4	1
70:30	1	100									
	2	70	30								
	3	45	42	13							
	4	28	42	23	7						
	5	18	38	25	14	5					
	6	12	32	26	17	10	3				
	7	9	26	25	18	12	7	3			
	8	7	21	24	18	13	9	6	2		
	9	5	16	23	18	14	10	7	5	2	
	10	4	13	21	18	14	11	8	6	4	1

Table F-1. Selected Annual PDF Cost Distributions for Selected Curve Shapes

One specific NASA phasing tool is the Phasing Model, available via the ONCE Model portal at [www.oncedata.com](http://www.oncedata.com). The Phasing Model generates Phasing Estimating Relationships (PERs) that can be used to help the analyst estimate annual funding for a mission, given a cost and schedule estimate. The relationships developed by the Phasing Model are based on historical data and do not necessarily represent “optimal” phasing. The time period for the PERs is System Requirements Review (SRR) to Launch, and the content can include two options:

Option 1: Total project excluding launch

Option 2: Spacecraft and instruments only

The Phasing Model can be used to support, assess, and/or defend budgets, and is also a good starting point for analyzing cost & schedule ramifications.

Other Government agencies<sup>9</sup> as well as NASA<sup>10,11</sup> have demonstrated distribution fitting and Phasing Estimating Relationship analysis. These phasing methodologies should only be used before detailed statements of work and schedules are created or as a macro crosscheck. It is preferable to resource load the schedule milestones and deliverables as the basis for either annual or monthly cost phasing.

The analyst also needs to be cognizant that these tools are intended to provide a spread of costs and are not to be confused with obligations and further adjustments that may need to be made to convert the costs to obligations so that long lead purchases and the execution of contracts can be accounted for. Furthermore, these tools typically provide phasing in calendar year (CY) dollars, which must be translated to Real Year (RY) dollars before being used for obligations or budgeting purposes.<sup>12,13</sup> Relating budgets (obligations) and expenditures (cost) is extensively covered in available literature.<sup>14</sup>

### F.3. Phasing Model

The Phasing Model<sup>15</sup> generates Phasing Estimating Relationships (PERs) that can be used to help the analyst estimate annual funding for a mission, given a cost and schedule estimate. The relationships developed by the Phasing Model are based on historical data and do not necessarily represent “optimal” phasing. The time period for the PERs is System Requirements Review (SRR) to Launch, and the content can include two options:

Option 1: Total project excluding launch

Option 2: Spacecraft and instruments only

The Phasing Model can be used to support, assess, and/or defend budgets, and is also a good starting point for analyzing cost & schedule ramifications. The Phasing Model is available on the ONCE Model Portal at [www.oncedata.com](http://www.oncedata.com).

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<sup>9</sup> Burgess, E. 2006. “R&D Budget Profiles and Metrics.” *Journal of Parametrics*, pp. 11–30.

<sup>10</sup> Burgess, E., Krause, C., Sterburzel, J., and Elliott, D. 2013. “Phasing Estimation Relationships.” NASA Cost Symposium. Pasadena, CA. [http://www.nasa.gov/sites/default/files/files/08\\_PERFT\\_Cost\\_Symposium\\_Final\\_TAGGED.pdf](http://www.nasa.gov/sites/default/files/files/08_PERFT_Cost_Symposium_Final_TAGGED.pdf)

<sup>11</sup> Kellogg, B., Hayhurst, M., Roem, V., and Miller, M. 2013. “Generic Cost Profiles Based on Actual Costs in NASA CADRes.” NASA Cost Symposium. Pasadena, CA. [http://www.nasa.gov/sites/default/files/files/04\\_Hayhurst\\_Cost\\_Profile\\_Briefing-2013\\_NASA\\_Cost\\_Symposium.pdf](http://www.nasa.gov/sites/default/files/files/04_Hayhurst_Cost_Profile_Briefing-2013_NASA_Cost_Symposium.pdf)

<sup>12</sup> NASA New Start Inflation Index, posted on the CAD website at [http://www.nasa.gov/offices/ooe/CAD/Publications.html#VOuu\\_Do1-gQ](http://www.nasa.gov/offices/ooe/CAD/Publications.html#VOuu_Do1-gQ).

<sup>13</sup> Whenever dollars are being spread across two or more fiscal years, the calculations must be performed in CY dollars. After the CY dollars are spread into each fiscal year, they can be inflated to RY.

<sup>14</sup> Unger, J., Gallagher, M., and White, E. 2004. “R&D Budget-driven Cost and Schedule Overruns.” *Journal of Cost Analysis*.

<sup>15</sup> More details can be found in a paper on the Phasing Model presented at the 2013 NASA Cost Symposium. [http://www.nasa.gov/sites/default/files/files/08\\_PERFT\\_Cost\\_Symposium\\_Final\\_TAGGED.pdf](http://www.nasa.gov/sites/default/files/files/08_PERFT_Cost_Symposium_Final_TAGGED.pdf).

## Appendix G: Cost Risk and Uncertainty Methodologies

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Cost risk and uncertainty exist through all phases of a project's life cycle. It is important for a cost estimator to identify and distinguish between risk and uncertainty, as they are distinct and consequential inputs to the analysis. A cost analyst must be able to defend the uncertainty and risk assessments built into the cost estimate and ensure that it is appropriately applied to the estimate. The following topics are described in this appendix:

### **G.1. Cost Risk**

#### **G.1.1. The Difference Between Risk and Uncertainty**

#### **G.1.2. NASA Cost-Risk Policy**

#### **G.1.3. Cost-Risk Management**

#### **G.1.4. Cost-Risk Assessment**

#### **G.1.5. Cost Estimating Risk as Part of the Estimating Process**

### **G.2. Cost-Risk Estimation Approaches**

#### **G.2.1. Simulation Approach**

#### **G.2.2. Analytical Approach**

#### **G.2.3. Hybrid-Based Approach**

### **G.3. Discrete Risk Analysis**

#### **G.3.1. Sensitivity Analysis**

#### **G.3.2. Program Portfolio Effect**

#### **G.3.3. Cost-Risk Output**

### **G.4. Cost Models that Address Risk**

#### **G.4.1. PRICE Systems Solutions**

#### **G.4.2. SEER**

#### **G.4.3. Project Cost Estimating Capability (PCEC) Tool**

#### **G.4.4. Automated Cost Estimating Integrated Tools (ACEIT) and JACS**

#### **G.4.5. Polaris and Argo**

#### **G.4.6. Crystal Ball**

#### **G.4.7. @RISK**

### **G.5. Example for Calculating a Cost Risk or S-Curve**

#### **G.5.1. Summary of Results**

For additional detailed information on cost-risk and uncertainty methodologies, refer to the 2014 Joint Cost and Schedule Risk and Uncertainty Handbook (CSRUH). The Joint CSRUH serves as a reference for Navy, Marine Corps, Army, Air Force, Missile Defense Agency and NASA cost analysts for incorporating risk and uncertainty within cost estimates. The handbook incorporates consideration of schedule uncertainty, risk registers, historical uncertainty in input parameters, improved risk expert

elicitation, and other recent areas of innovation. Concepts are developed using one consistent example throughout the Handbook. The Handbook web page also provides useful tools that assist with incorporating the techniques described in the Handbook into cost estimates. The handbook is available online at <https://www.ncca.navy.mil/tools/csruh/index.cfm>.

## G.1. Cost Risk

NASA employs cost-risk assessments on its space missions in order to understand risks and help ensure that resources and plans are adequate to deliver projects on time and within budget. Cost risk must be carefully and quantitatively assessed in developing and presenting any cost estimate for several reasons. First, when trade studies are conducted, a single cost estimate, such as an expected cost, may mislead the trade team by not revealing the potential for overruns. Second, at Confirmation Reviews and Authority to Proceed decision points, the cost estimate must include an appropriately chosen level of unallocated future expense (UFE) to achieve a desired confidence level. The objective of a cost-risk analysis is to produce a credible project cost cumulative distribution function (CDF, or “S-curve”) for the range of costs of the project.

There are six activities associated with developing a cost-risk assessment in order to understand the current confidence level of the project and estimate the amount of unallocated future expense (UFE) necessary to achieve a desired confidence level:

1. Determine the project's cost drivers and risks with input from the NASA P/pM and staff;
2. Develop probability distributions for the technical and schedule cost drivers;
3. Develop probability distributions for the cost model uncertainty;
4. Run the risk model;
5. Identify the probability that the actual cost is less than or equal to the point estimate; and
6. Recommend sufficient UFE to achieve the desired percent confidence level.

All NASA projects should develop plans and budgets that are based upon a quantification of risk and uncertainty that could cause the project to take longer or cost more than initially anticipated. Program Managers (PMs) should request budget amounts that reflect that information with a certain probability that the project will be completed at or below this amount (note that at Key Decision Point (KDP)-C, this probability is usually 70 percent).<sup>1</sup> Specific to cost risk, NPR 7120.5E covers program and project management's cost risk roles and responsibilities as well as program and project cost risk requirements by life-cycle phase. These roles and responsibilities include the following:

- a. Risk assessments
- b. Risk evaluations
- c. Risk mitigation
- d. Identification of margin and Unallocated Future Expenses (UFE) (formerly known as reserves)
- e. Associated oversight and approval processes

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<sup>1</sup> See NPR 7120.5E at <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>.

By adhering to these guidelines and other steps outlined in this appendix, NASA cost estimators and analysts will improve the quality and accuracy of space systems cost estimates, help to generate realistic budget plans, and provide decision makers with accurate and realistic cost data in order to better inform the decision-making process.

### **G.1.1. The Difference Between Risk and Uncertainty**

There is an important distinction between the terms “risk” and “uncertainty.” It is recognized that the taxonomy and definitions of “Risk” and “Uncertainty” have been defined by several sources, including Knight, 1921, pp. 19–20<sup>2</sup>; Fuguitt and Wilcox, 1999, pp. 140–141<sup>3</sup>; Garvey, 2000, p. 27<sup>4</sup>; and Hubbard, 2010, pp. 49–50<sup>5</sup>. Most notably, the GAO’s Cost Estimating and Assessment Guide differentiates risk and uncertainty using the following definitions (General Accountability Office, 2009)<sup>6</sup>:

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

In keeping with the spirit of the sources cited above, and for the purposes of this NASA handbook and appendix, risk and uncertainty are defined as follows:

- **Risk** is an event not in the projects baseline plan that is an undesirable<sup>7</sup> outcome (discrete risk). This definition is similar to one that one would see in a risk matrix. The event is characterized by a probability of occurring and an expected impact if the event did occur.
- **Uncertainty** is the indefiniteness about a projects baseline plan. It represents our fundamental inability to perfectly predict the outcome of a future event. Uncertainty is characterized by a probability distribution, which is based on a combination of the prior experience of the assessor and historical data.

### **G.1.2. NASA Cost-Risk Policy**

NASA’s Space Flight Program and Project Management Requirements document (NPR 7120.5E) requires that Programs and projects develop probabilistic risk-informed analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met.

In the formulation stage, specifically for KDP-B, NASA is calling for programs and projects to provide probabilistic analysis on both their cost and schedule estimates. This analysis is then used to determine a high and a low estimate for cost and for schedule. The community has identified two good candidate methodologies for producing the risk estimates and associated results: 1) complete parametric estimates of cost and schedule, or 2) complete a JCL consistent with policy. It is the viewpoint of the Office of Evaluation, and the majority opinion of the community,<sup>8</sup> that conducting a JCL at KDP-B should not be required. This is primarily because projects typically do not have detailed plans available to support an in-

<sup>2</sup> Knight, Frank H. (1921) *Risk, Uncertainty, and Profit*.

<sup>3</sup> Fuguitt, Diana; and Wilcox, Shanton J. (1999) *Cost-Benefit Analysis for Public Sector Decision Makers*. Praeger.

<sup>4</sup> Garvey, P. R. (2000). *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective*. New York: Marcel Dekker.

<sup>5</sup> Hubbard, D. W. (2010). *How to Measure Anything*. John Wiley & Sons, Inc.

<sup>6</sup> United States General Accounting Office, *GAO Cost Estimating And Assessment Guide: Best Practices For Developing And Managing Capital Program Costs*, March 2009, GAO-09-3SP [www.gao.gov/products/GAO-09-3SP](http://www.gao.gov/products/GAO-09-3SP).

<sup>7</sup> Risks can also be opportunities if the outcome of the event is a positive outcome.

<sup>8</sup> As discussed at the NASA Executive Cost Analysis Steering Group (August 2011).

depth JCL analysis, and by design, the requirement at KDP-B is intended to “bound the problem.”

Conducting a parametric estimate of schedule and cost utilizes the historical data and performance of the Agency and provides a valuable estimate of the range of possibilities. Attempting a JCL at KDP-B, for these reasons, is therefore not required; however, if a JCL were conducted at KDP-B, it would fulfill the policy requirements of KDP-B because the JCL analysis is more stringent than the KDP-B requirement.

To calculate a JCL, the project should use a rigorous process that combines its cost, schedule, and risk into a single model that can generate a probabilistic assessment of the level of confidence of achieving a specific cost-schedule goal. The rationale for conducting JCL in support of KDP-C is 1) the project's plan is well defined, and 2) this is the timeframe in which NASA is committing to external stakeholders. The Agency uses this assessment when considering its external commitment (the Agency Baseline Commitment [ABC] at KDP-C) as one means of ensuring the project has a robust plan with costs linked to schedule, where both are informed by risks.

Once a baseline is approved, NASA policy does not require a project to maintain the analysis models used to calculate the JCL. However, the Agency does utilize a variety of performance metrics to assess how well the project is performing against its plan. If these metrics show that a project's performance varies significantly from its plan, the project may need to replan, but Agency policy only requires a repeat calculation of the JCL in the event that the project requires a rebaseline. JCL analysis can provide valuable insights as a management tool; however, the only Agency requirement for JCL is at KDP-C.

In addition to the recommended probabilistic profile confidence level, a number of cost-risk-related activities are required throughout the project's life cycle.

- A high-level Work Breakdown Structure (WBS) consistent with the NASA Standard Space Flight project WBS, a schedule, and a rough order of magnitude (ROM) cost estimate and cost range
- A baseline mission concept document that includes key risk drivers and mitigation options
- A preliminary full Life Cycle Cost Estimate (LCCE) that includes UFE, along with the level of confidence estimate provided by the UFE based on a cost-risk analysis

Specifically, the relevant language from 7120.5E reads as follows<sup>9</sup>:

*Tightly coupled and single-project programs (regardless of life-cycle cost) and projects with an estimated life-cycle cost greater than \$250 million shall develop probabilistic analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met in accordance with the following requirements.*

*At KDP I/KDP C, tightly coupled and single-project programs (regardless of life-cycle cost) and projects with an estimated life-cycle cost greater than \$250 million shall develop a resource-loaded schedule and perform a risk-informed probabilistic analysis that produces a JCL. The JCL is the product of a probabilistic analysis of the coupled cost and schedule to measure the likelihood of completing all remaining work at or below the budgeted levels and on or before the planned completion of Phase D.*

The following activities are considered best practices for cost-risk analysis:

- Overarching principles: The analysis must be transparent, traceable, defensible, and timely
- Cost and schedule baseline estimates must:
  - Have a clear basis of estimate
  - Include all the cost elements and schedule activities
  - Be supported by relevant data

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<sup>9</sup> Language is taken directly out of NPR 7120.5E Section 2.4.

- All possible risks, threats, liens, uncertainties, mitigation strategies, and opportunities must be explicitly quantified, including the following:
  - Their probability of occurring
  - Their estimated cost and/or schedule consequences
- The analysis must address available annual resources
- The analysis must incorporate impacts of cost and schedule performance to date (not required for KDP-B)
- Risks must be transparently incorporated into cost, schedule, and/or both
- The Joint Cost and Schedule Confidence Level (JCL)<sup>10</sup> product documentation/model must describe the:
  - Basis for base schedule duration and logic
  - Basis for baseline cost estimates
  - Risks included and basis for probability and consequences
  - Risks excluded and why
  - Description of the JCL method used

### **G.1.3. Cost-Risk Management**

While some cost-risk methodologies can be generalized for space flight programs or even non-space flight projects, the focus and the tools discussed here apply to Category I and II major space flight projects.<sup>11</sup> The objective of cost-risk management is to continuously determine the likely rolled-up risk impact on the cost of the program/project by organizing, obtaining, and using cost-risk information.

Cost-risk management integrates the risk management process<sup>12</sup>; cost estimating; cost-risk assessment/analysis (using the identified risks in the project risk list and the cost estimate); and Earned Value Management (EVM); with procurement, source selection, cost data collection, and cost data analysis as supporting disciplines.

An integrated cost-risk assessment is performed throughout the project life cycle, enabling decision makers to manage the cost risks and analysts to continue to identify and quantify cost risks throughout the program life cycle.

The next three sections provide a summary of the three-step cost-risk management process:

- Steps needed to sufficiently identify and quantify cost risks;
- How to establish cost-risk reporting during; and
- How to manage cost risk using reported EVM and cost-risk data.

#### **G.1.3.1. Identify and Quantify Cost Risk**

The activities in this step include:

1. Identify and assess risk. Examples of risk can include items that have low Technology Readiness Levels (TRLs), components used for the first time or for new operating environments, schedules that are too short, requirements that change, etc.<sup>13</sup>

<sup>10</sup> For more information on JCL, refer to Appendix J.

<sup>11</sup> See NPR 7120.5E at <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>.

<sup>12</sup> For more information on NASA's risk management process, see the NASA Risk Management Handbook at [www.hq.nasa.gov/office/codeq/doctree/NHBK\\_2011\\_3422.pdf](http://www.hq.nasa.gov/office/codeq/doctree/NHBK_2011_3422.pdf).

<sup>13</sup> NASA Procedural Requirement (NPR) 8000.4A, Agency Risk Management Procedural Requirements, December 2008.

2. Translate risk assessment into cost impact.
3. Perform S-curve and risk-based cost analysis.

#### **G.1.3.2. Establish Cost-Risk Reporting**

The activities in this step include:

1. Develop the Request for Proposal (RFP), EVM, Data Requirements Description (DRD), and equivalent project plan requirements.
2. Evaluate EVM and Life Cycle Cost (LCC) DRDs in proposals/project plans.
3. Perform the Integrated Baseline Review (IBR).

#### **G.1.3.3. Manage Cost Risk Using Reported Data**

The activities in this step include:

1. Perform EVM performance measurement and S-curve analysis.
2. Compile end-of-contract cost-risk data for database updates, data evaluation and analysis, and cost-risk algorithm updates.
3. Maintain liens and threats list.

#### **G.1.4. Cost-Risk Assessment**

Cost-risk assessment is the process of identifying and analyzing critical project risks within a defined set of cost, schedule, and technical objectives and constraints. Cost-risk assessment balances the probability of failing to achieve a particular outcome against the consequences of failing to achieve that outcome. Assessing cost risk also allows the cost estimator to document risks in a manner that accommodates proactive management of project costs.

The purpose of cost-risk assessment is to capture uncertainty in such areas as cost estimating methodology, technical risk, schedule risk, and programmatic factors in order to go from a deterministic point estimate to a probabilistic estimate. A credible baseline estimate is the key starting point in generating a cost-risk-adjusted estimate and the development of confidence intervals. Note that a point estimate is usually based on most-likely/current-best-estimate inputs. Historically, on large-scale projects, possible impacts of risks have been addressed by establishing contingencies that were added to a base cost estimate. Contingencies were typically estimated budget allowances that were set using simple rules of thumb, such as 10 percent of the base cost.

Risk analysis provides an analytical basis for establishing defensible cost estimates that quantitatively account for likely project risks. It is important to keep in mind that this analysis should be continuously reviewed and updated as more data become available. By projecting how the future will turn out as a result of undertaking a certain course of action (or inaction), risk can be analyzed. A risk analysis, therefore, fundamentally consists of answering the following questions:

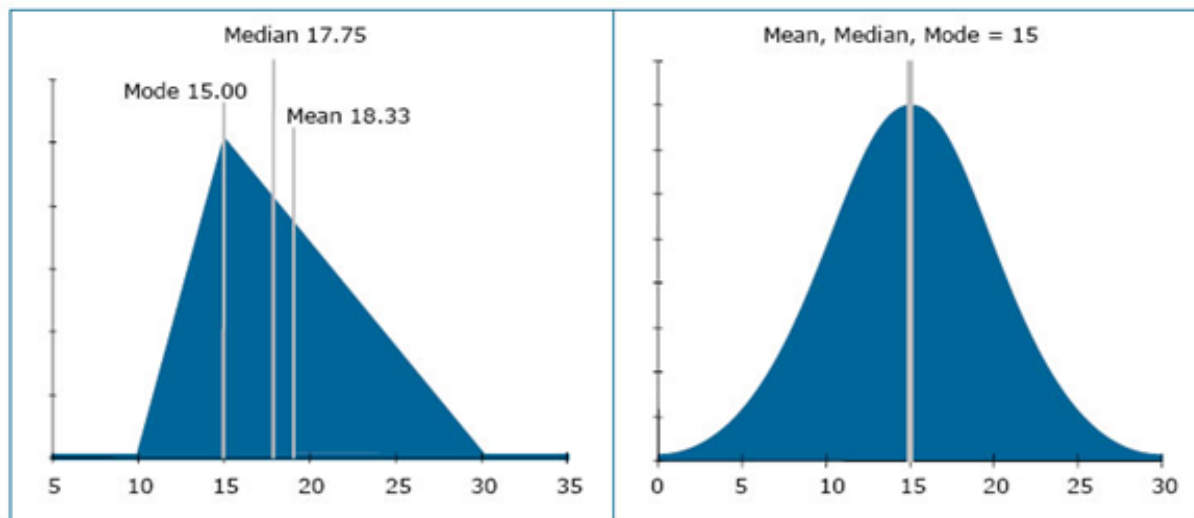
1. What can happen?
2. How likely is it that it will happen?
3. If it does happen, what are the consequences?

Risk analysis utilizes various methods of modeling, analysis, and evaluation and thus contains various types of uncertainty. In general, these uncertainties may be attributable to a number of factors that include (1) the statistical nature of data, (2) the insufficient understanding of physical and biological phenomena, and/or (3) unpredictable events (e.g., natural, biological, and human behavior). For cost

estimates, the risk stems from uncertainties encountered during the course of project development, from prelaunch through Phase F.

The cost-risk assessment process forces the consideration of cost risks by the cost estimator and the PM. This assessment provides tangible data for use as the basis for informed decisions. The estimator should not be limited in what data are reviewed (e.g., just the project risk list).

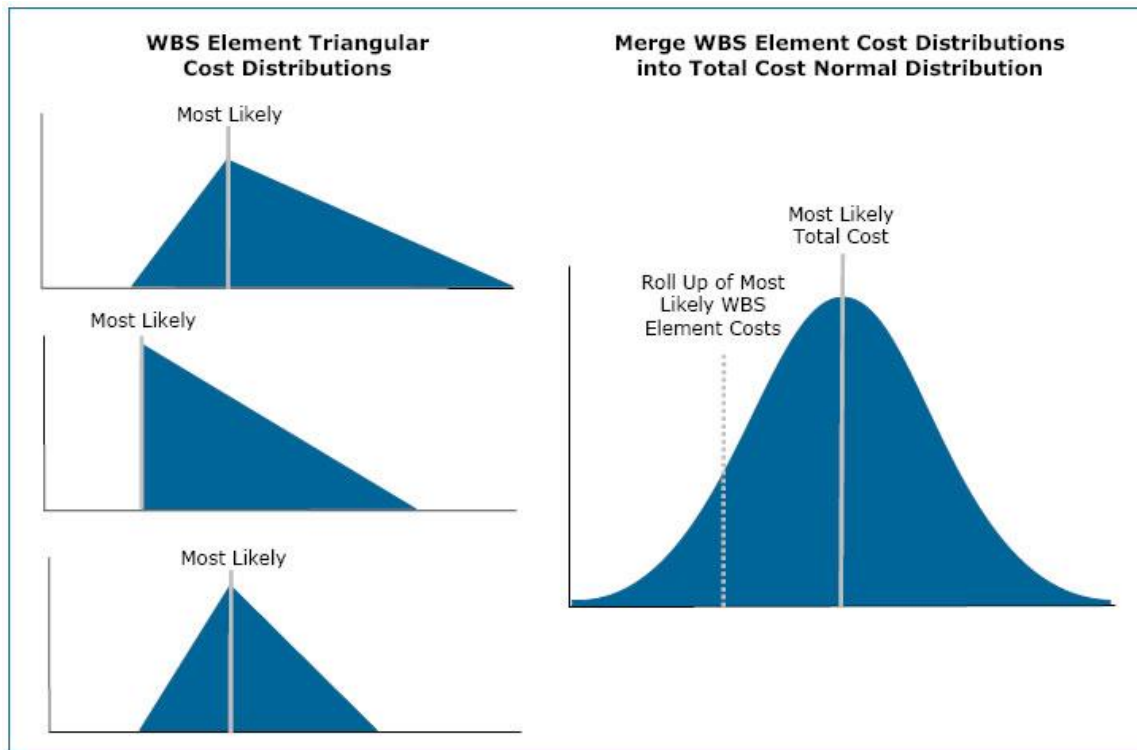
It is important to understand that when project costs are being estimated, the costs are an uncertain quantity and the point estimate is not the only possible estimate. Figure G-2 demonstrates that point estimates of individual WBS elements using triangular and normal distributions can be quantified as “most likely” (mode), “50th percentile” (median), or “expected value” (mean). The use of this terminology implies that costs are statistical in nature and defined by their probability distributions.



**Figure G-2. Statistics of Triangular and Normal Distributions**

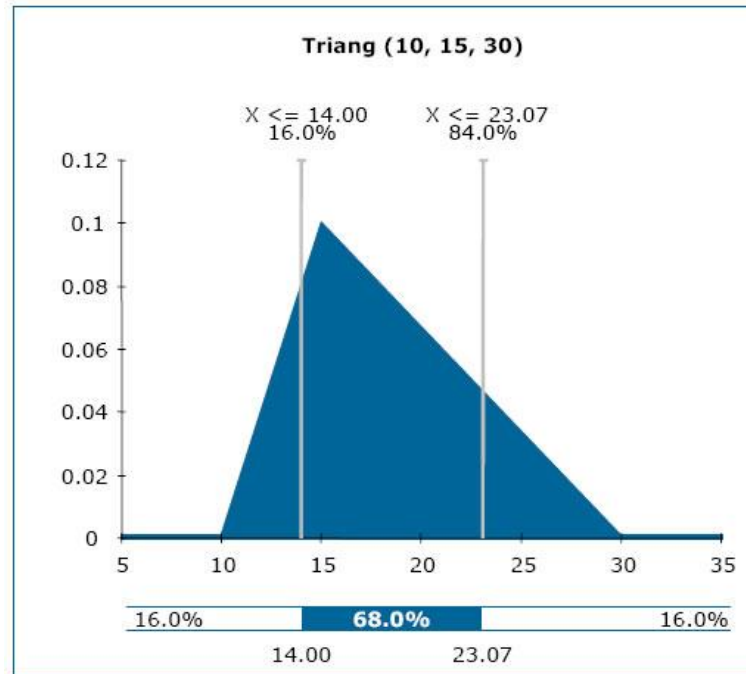
When the number of WBS elements increases, the distribution of the total cost of the WBS elements approximates the normal distribution (Figure G-3). This is known mathematically as the Central Limit Theorem. This theorem states that the average of the sum of a large number of independent, random variables with finite means and variances converges to a normal random variable.

Three of the more commonly used probability distributions for assessing risk are triangular, normal, and lognormal distributions.



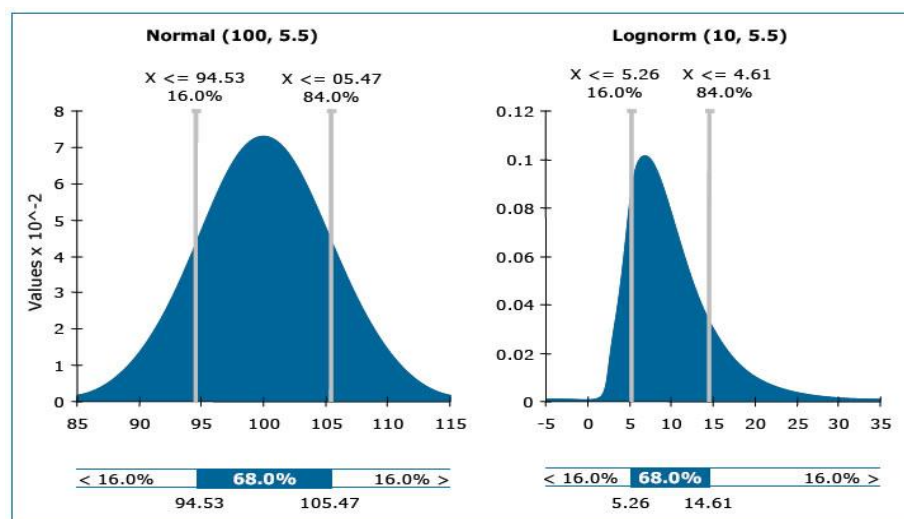
**Figure G-3. Central Limit Theorem**

As shown in Figure G-4, triangular distributions require three inputs to define (most likely, lowest, and highest). They can be determined quantitatively, for example, by using three cost estimates for a single project element to define the distribution of the range of costs for that element. They can also be determined subjectively, as when experts determine the range of possible values for a model input or risk magnitude. Note that analysts and engineers tend to overestimate best-case outcomes and underestimate worst-case outcomes. Therefore, cost analysts frequently do not treat their minimum and maximum values as the end of points of the triangular distribution. Instead, they adjust the extremes of the triangular distribution to allow for a wider range of potential outcomes.



**Figure G-4. Triangular Distribution Example**

The normal and lognormal can be used when the mean and standard deviation are known (see Figure G-5). This approach eliminates the need to specify minimum and maximum values. Sometimes the normal distribution can produce negative values that, obviously, do not make logical sense for describing cost. Furthermore, the normal distribution's inherent symmetric characteristic cannot characterize the common tendency for costs to go up rather than down over time. For these two reasons, the lognormal distribution, which cannot go below zero and is nonsymmetrical (e.g., can be right-skewed), is typically preferred over the normal distribution by many cost analysts.



**Figure G-5. Normal and Lognormal Distributions**

### G.1.5. Cost Estimating Risk as Part of the Cost Estimating Process

Cost estimating risks include economic factors such as rate uncertainties, cost estimating errors, and statistical uncertainty inherent in the estimate. Cost estimating risk is dependent upon other fundamental risk dimensions (technical, schedule, and programmatic risks), so these must all be assessed to arrive at an accurate picture of project risk.

Cost estimating risk assessment takes into account the cost, schedule, and technical risks that are then factored back into the cost estimate. To quantify the cost impacts due to risk, sources of risk need to be identified. NASA cost analysts should be concerned with three sources of risk and ensure that the model calculating the cost also accounts for these risks:

- **The risk inherent in the cost estimating methodology.** For example, if a regression-based Cost Estimating Relationship (CER) is used, it has an associated Standard Error of the Estimate (SEE), confidence intervals, and prediction intervals, any of which can be used to include cost estimating methodology risk in the estimate.
- **The risk inherent in the technical and programmatic aspects of the systems being developed.** The technology's maturity (TRLs are good indicators of this risk source), design/engineering, integration, manufacturing, schedule, and complexity, etc., fall into this risk category. Quantifying the cost impacts due to these kinds of risks is not as statistically based as CER risk (Figure G-6), which graphically displays the effects of cost estimating methodology risk and technical input risk. See Appendix D for additional information on estimating the costs of technology development.

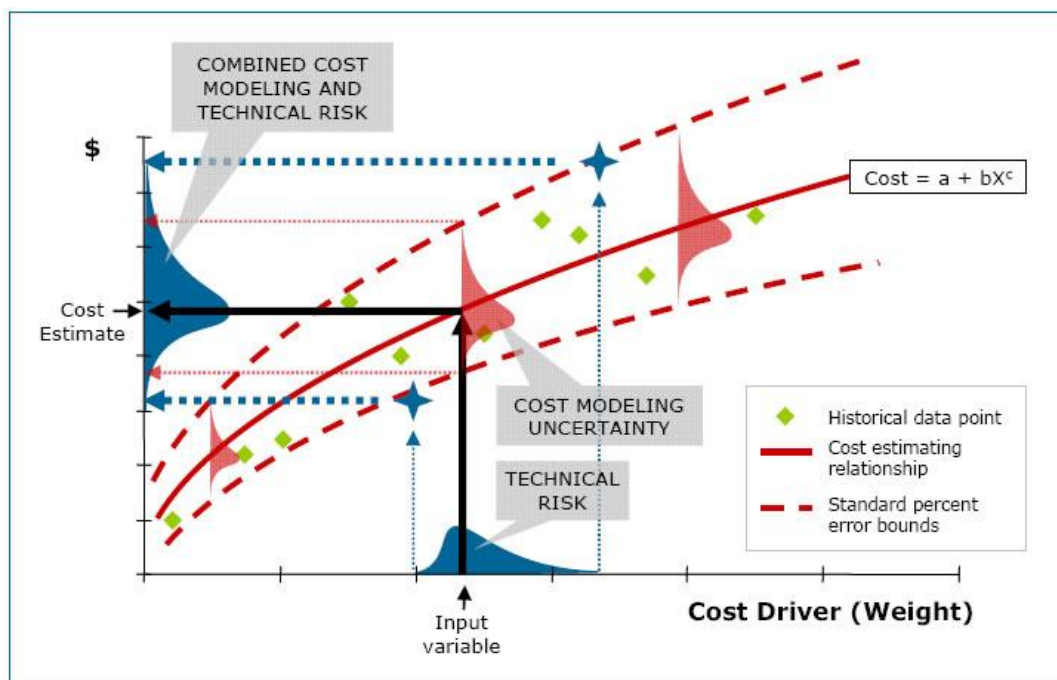


Figure G-6. Cost Modeling and Technical Input Risk

- **The risk inherent in the correlation between WBS elements.** Correlation assessment determines to what degree one WBS element's change in cost is related to another's and in which direction. For example, if the cost of the satellite's payload goes up and the cost of the propulsion system goes up, then there is a positive correlation between both subsystems' costs.

Many WBS elements within space systems have positive correlations with each other, and the cumulative effect of this positive correlation tends to increase the range of the possible costs.

Types of risk may be classified as known-knowns, known-unknowns, and unknown-unknowns. The known-knowns are the discrete risks for which likelihood and consequence are understood. The known-unknowns are discrete risk for which likelihood and consequence are not understood. Unknown-unknowns are, by definition, unknown—but they are not unknowable. The unknown-unknown risks are generally quantifiable only through subjective assessment. The potential exists for reducing the effect of this class of risk by interviewing more subject matter experts (SMEs) or waiting for additional information to become available. Lastly, for risks that are unknown and for which prior assessment is not possible, allowances can still be made for contingency.

The challenge for cost estimators and schedule analysts is to determine how best to accommodate these risks, uncertainties, and unexpected surprises without either over- or understating their effects and without negatively impacting the project budget. CADRe Part C (see Appendix A) also captures specific risks for each project, and has proven to be a valuable resource to other projects in identifying potential risks.

Even as early as Pre-Phase A, there are many risks that can and should be identified and addressed in a cost estimating risk assessment. Cost estimating uncertainty, technical input variable uncertainty, and correlation risks all need to be considered. Schedule risk can be handled outside these three types of risk by applying probabilistic activity duration risk to the critical path analysis (CPA).

Working with a wide variety of organizations that include but are not limited to technical experts, Program/Project Office (PO) staff, independent review teams, and other programmatic experts, the cost estimator should identify cost estimating risk drivers and vary the operating scenarios and input parameters through the production of comprehensive probabilistic/deterministic cost-risk and sensitivity analyses. It is the job of the cost estimator to estimate the effects of identifying, assessing, and analyzing cost estimating risk drivers (e.g., probabilistic cost-risk analysis) and varying cost drivers (e.g., deterministic cost estimating risk). The next step is to revise the LCCEs reflecting the selected variations, pointing out the relationship between the LCC and the key technical and/or operational parameter risks. Discrete technical cost estimating risk assessments involve identifying and estimating specific cost-driving technical risks.

For example, a notional new electronic component for a spacecraft might have risk in key engineering performance parameters such as dynamic load resistance, operating voltage, power regulation, radiation resistance, emissivity, component mass, operating temperature range, and operating efficiency. The project technical staff can identify these risks during a cost estimating risk assessment. Instead of probabilistic distributions and Monte Carlo simulations, however, mitigation costs for these more specific risks are estimated based on their probabilities of manifesting discrete changes in the technical parameters (e.g., increased component mass or power regulation). Justifying the value of cost estimating risk is a function of the detail specification of the three categories of risk (cost estimation, technical, and programmatic) that drive the cost estimating risk range. Cost estimating risk estimates that add, for example, 30 percent of additional costs to the point estimate have to be defensible with a cost estimating risk methodology that justifies the endpoints of individual WBS element cost estimating risk distributions, SEE regression lines, and reliable correlation coefficients.

As a project moves through the conceptual design phase, the range of feasible alternatives decreases while the definition of those alternatives increases. At this stage, there is a crucial need to identify pertinent cost issues and to adjust them before corrective costs become prohibitive. Issues and cost drivers must be identified to build successful options. By deriving a cost estimate on proposed project alternatives, a PO can determine the cost impact of the alternatives. These cost drivers feed an

increasingly detailed cost estimating risk assessment that takes into account the three cost estimating risk categories for the estimate. The point estimate and the risk assessment work together to create the total LCCE.

As a project moves through the preliminary design phase and the project definition matures, cost estimators should keep the estimate up to date with definition changes and have a full cost estimating risk assessment to defend the estimate, reduce updated estimate turnaround time, and give the decision maker a clearer picture for “what if” assessments or major decisions. The role of the cost estimator during this phase is critical. It is important to understand the basis of the estimate, from the technical baseline to the cost-risk assessment, and document and present the results of these efforts to decision makers. It is the cost estimator’s responsibility to ensure that the best possible LCC with recommended levels of UFE are based on updated cost-risk assessments in Phase B. These estimates will support budget formulation in the transition from Phase B to Phase C/D.

When conducting Phase C/D estimates, new information collected from contractor sources and from testing must be fed back into the point estimate and the risk assessment, which will create a more detailed project estimate. During this phase, the cost estimating risk assessment should be very detailed, including not only any changes in requirements or project design, but also other details provided by project technical experts, such as testing and schedule impacts. While the product is being designed, developed, and tested, there are changes that can impact the estimate and the risk assessment. It is critical to capture these changes to maintain a realistic program estimate now and in the future. During this phase, programmatic data may have just as much of an impact on the estimate and risk assessment as technical data.

## G.2. Cost-Risk Estimation Approaches

Decision makers prefer, as a general rule, lower estimates to higher ones. The reason is fairly obvious. If estimates are lower, either more projects can be developed within limited available funding or proposed projects are more appealing to funding appropriators. Cost estimating risks generally add cost to estimated project costs, so decision makers will want justification before agreeing to cost estimating risk assessments. Cost estimators need methodologies that produce cost-risk assessments that are beyond reproach. This section first covers a common cost-risk approach—the Simulation Approach—then provides an overview of two alternative cost-risk methods: the Analytical Approach and Hybrid Approach. NASA usually uses the Hybrid Approach.

### G.2.1. *Simulation Approach*

The Simulation Approach to assessing cost risk uses either a Monte Carlo or Latin Hypercube simulation to calculate numerous scenarios of a project cost by repeatedly picking random values from the input variable distributions for each “uncertain” variable and calculating the results. Typically, a simulation will consist of 2,500 to 10,000 iterations in order to reach a steady-state result. The results of the Simulation Approach include risk-adjusted estimates and corresponding statistical estimate distributions. The estimate distributions provide the decision maker with a range of possible outcomes with a minimum and maximum value. There are many good sources of information on the Simulation Approach, including most recently the Joint CSRUH<sup>14</sup> as well as the Space Systems Cost Risk Handbook (SSCRH) and the Air Force Cost Risk and Uncertainty Handbook (AFCRUH) provide an overview of the Simulation Approach.<sup>15</sup> Commercially available products such as Crystal Ball, @RISK, and the Automated Cost Estimator (ACE)

<sup>14</sup> <https://www.ncca.navy.mil/tools/csruh/index.cfm>

<sup>15</sup> SSCRH, pp. 26–29, November 2005. AFCRUH, Pages 5–6, April 2007.

module of Automated Cost Estimating Integrated Tools (ACEIT) have the capability to perform the Simulation Approach.

### **G.2.1.1. Inputs-Based Simulations**

The steps associated with the Inputs-Based Simulation Approach are described below. An alternative to the Inputs-Based Simulation method is to apply uncertainty directly to the results (cost-model outputs). By use of uncertainty distributions on the outputs, the aggregate uncertainty of both the methodology and the inputs is addressed.

#### **Step 1—Generate/Obtain Point Estimate**

The point estimate represents one possible estimate based on a given set of program characteristics. The credibility of any estimate is based on a realistic and complete technical, schedule, and programmatic baseline. The point estimate serves as the reference point on which the cost-risk analysis is based.

#### **Step 2—Quantify Cost Estimating Uncertainty**

The second step of the Simulation Approach is to quantify the probability distributions by describing the modeling uncertainty of all CERs; cost factors; other estimating methods; and, specifically, the type of distribution (e.g., normal, triangular, lognormal) as well as the mean, standard deviation, and other statistical measures. For example, if a regression-based CER is used, it has an associated SEE, confidence intervals, and prediction intervals, all of which can be used to include cost estimating methodology risk in the estimate.

There are many references to the various probability distributions that can be used to quantify cost estimating uncertainty, including the SSCRH, which provides definitions, formulas, and guidance on probability distributions. The AFCRUH provides examples and guidance on measuring cost estimating uncertainty and probability distributions. It also provides detailed guidance on measuring CER uncertainty in addition to benchmarks for statistical measures such as the CV and measurements of estimating accuracy.

#### **Step 3—Quantify Technical Risk**

Step 3 of the Simulation Approach includes developing probability distributions for the technical and schedule cost drivers. The technical risk probability distributions (e.g., normal, triangular, lognormal, or beta) quantify the cost effects due to technical risks, as well as provide the mean, standard deviation, and variance of the cost effects.

As stated earlier, the distribution commonly used to characterize technical risk is a triangular distribution, as shown in Figure G-4. The triangular distribution is fairly simple to characterize since the analyst only needs to produce three points: a reference point (sometimes called the “most likely”), a pessimistic point, and an optimistic point. A process called the Relative Risk Weighting (RRW) approach can be used to obtain and defend technical risk distributions. The subjective method of elicitation (Expert Opinion) is another approach for quantifying technical risk. At least one source provides guidance on this approach and also provides guidance on bounding subjective inputs when upper and lower limits are not available from SMEs.<sup>16</sup>

Both the cost estimating methodology and the technical cost risk distributions must be accounted for in the final cost-risk distribution. Figure G-6 shows the convolution of CER cost estimating and technical risk into the resultant cost-risk Probability Density Function.

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<sup>16</sup> AFCRUH, p. 14, April 2007.

## Step 4—Quantify Correlation

The fourth step in the Simulation Approach requires the quantification of correlation. Correlation determines to what degree one WBS element's change in cost is related to another's and in which direction. For example, if the cost of the satellite's payload goes up and the cost of the propulsion subsystem goes up, then there is a positive correlation between both subsystems' costs. Many WBS elements within space systems have positive correlations with each other, and the cumulative effect of this positive correlation tends to increase the range of the possible costs. Correlation between two elements can be a value that ranges from  $-1.0$  to  $+1.0$ . In the aerospace industry, typical pairwise correlations have typically been found to vary between  $+0.3$  and  $+0.6$ .<sup>17</sup> Correlation is a very important aspect of combining cost distributions. When using the Simulation Approach, if two WBS elements are highly positively correlated ( $0.7$  to  $1.0$ ), then random samples should also be highly positively correlated. That is, if one sample is large, then the other should tend to be large also. In the absence of correlation, then the size of the first WBS element's sample has no effect on the size of the second WBS element's sample. It is important to note that functional correlation between elements may already be accounted for in the cost model. Functional correlation exists when the factors are used to estimate costs in multiple elements. For example, if the results of a weight-based CER are used to generate a thermal control subsystem and a structure subsystem, then both elements will be functionally correlated.

Correlations between WBS elements (Step 4) must be accounted for in the combining of cost estimating (Step 2) and technical cost-risk distributions (Step 3). Commercial Monte Carlo simulation models such as @RISK and Crystal Ball contain the capability to apply correlation during the statistical summing of a project's WBS element cost-risk distributions. The correlation values are calculated between all WBS elements that are estimated using CERs and other methods. Correlation ( $r$ ) between different elements can range from low to high. For example, low:  $r = \pm 0.02$ ; mild:  $r = \pm 0.2$ ; moderate:  $r = \pm 0.6$ ; and high:  $r = \pm 0.8$ . The idea is that correlation affects the overall cost variance. Note that it is virtually impossible to get a correlation of  $0$ . Even two sets of random numbers will have some slightly positive or negative correlation. A presentation by Dr. Stephen Book, "A Theory of Modeling Correlations for Use in Cost-Risk Analysis," provides an approach that quantifies correlation values for WBS elements based on the relationship of the elements' standard error (as a percentage of their point estimate), the percentage of new technology in the element, and an assumed cost growth sensitivity factor.<sup>18</sup>

Analysts must provide the correlation values to the simulation models. These values can be derived using a variety of methods (one of which was provided in the previous paragraph). Table G-1 shows a correlation matrix for a sample ground system. In this example, logistics and facilities are highly correlated ( $r = 0.8$ ) and ground systems engineering and ground management are moderately correlated ( $r = 0.6$ ). The correlation between an element and itself is  $1.0$  (e.g., ground system software and ground system software).

<sup>17</sup> Correlation of Spacecraft Mission and Project Costs, C. Swan, S. Jarrett, JPL, July 2007 (unpublished).

<sup>18</sup> Book, S.A., "A Theory of Modeling Correlations for Use in Cost-Risk Analysis," 3rd Annual Project Management Conference, NASA, March 2006.

**Table G-1. Sample Correlation Matrix for a Hypothetical Ground System<sup>19</sup>**

Ground Systems	Integration & Test	Product Assurance	Systems Engineering	Management	Logistics	Facilities	Software
Integration & Test	1.0						
Product Assurance	0.2	1.0					
Systems Engineering	0.2	0.2	1.0				
Management	0.2	0.2	0.6	1.0			
Logistics	0.2	0.2	0.2	0.2	1.0		
Facilities	0.2	0.2	0.2	0.2	0.8	1.0	
Software	0.2	0.2	0.5	0.2	0.2	0.2	1.0

A subjective method for deriving correlation values is to develop approximate correlation coefficients between WBS elements. This can be as simple as determining whether two WBS elements are correlated by a small amount or by a large amount and whether that correlation is positive or negative. For example, if you believe two WBS elements have a small amount of positive correlation, then you would choose a correlation value of  $\approx 0.3$ . It is then necessary to follow documented procedures within the Monte Carlo simulation software to produce the desired correlations in your cost estimate.

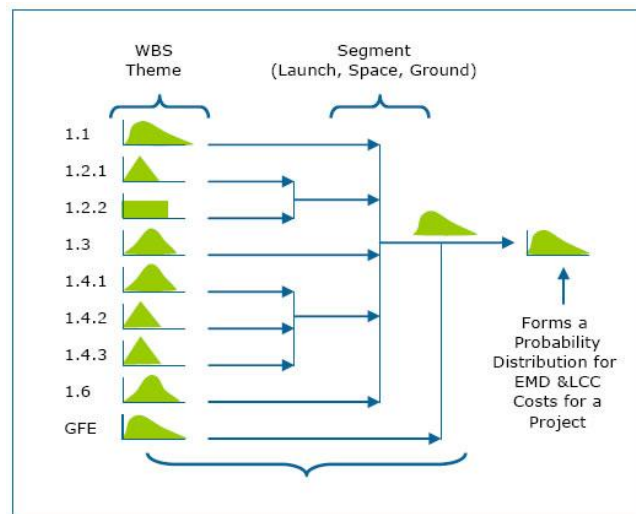
There are different types of correlation approaches that can be evaluated using @RISK, Crystal Ball (Spearman Rank), and Excel's CORREL formula (Pearson Product Moment) as well as metrics for measuring correlation adequacy.

### Step 5—Run Simulation

The cost analyst will set up and run the cost estimate in a Monte Carlo/Latin Hypercube framework (e.g., with models such as Crystal Ball or @RISK) that incorporates cost estimating, technical, and correlation risk. This will result in a cumulative distribution function from which an appropriate probability (and other points within the probabilistic range) can be easily identified.

The simulation will run iterations on the cost estimating and technical input uncertainty in conjunction with the correlation values to calculate cost-risk distributions and statistically sum all the WBS elements to arrive at a probabilistic range of the potential cost for the program. Figure G-7 illustrates the results of a statistical summation process normally performed by the simulation.

<sup>19</sup> SSCRH, p. 28, November 2005.



**Figure G-7. Statistical Summation Process Results**

### **Step 6—Assess Risk Estimates/Unallocated Future Expense**

Risk estimates represented as UFE at NASA are defined as the difference between the recommended probabilistic percentile and the “as specified” project cost (e.g., arithmetic sum of WBS element reference point/deterministic cost estimates) and represent the estimate of “risk cost.” Risk costs can be allocated downward to any level of WBS using any of the approaches that are summarized in the next step. The derivation of risk estimates for planning purposes begins with the probabilistic cost estimate range at KDP-B. As possible cost impacts due to estimation, technical, programmatic, and dependency risks are incorporated into the cost estimate, the UFE at the LCC level is identified. This UFE is the difference between the arithmetic sum of the WBS reference point estimates and the cost at the recommended probabilistic percentile.

### **Step 7—Allocate Risk Costs to the WBS**

The analyst will need to allocate the risk estimates to the lower-level WBS elements in order to move the WBS elements’ deterministic point estimates to probabilistic estimates. There are several existing methodologies to assist the analyst in allocating risk estimates that incorporate a risk dollar allocation algorithm.

#### **G.2.2. Analytical Approach**

The Analytical Approach to cost risk provides analytical alternatives for quantifying cost risk that do not require simulation. The two most common methods for conducting the Analytical Approach are the Scenario-Based Method (SBM) and the Method of Moments.

##### **G.2.2.1. Scenario-Based Method (SBM)**

The SBM is derived from a variation of sensitivity analysis. The principle strengths of the SBM are its visibility, its defensibility, and the cost impacts of specifically identified risks. The SBM specifies a well-defined set of conditions or scenarios (i.e., prime scenario/protect scenario) that would create a condition that management would like to guard against. The SBM postulates on specified scenarios that, if they occurred, would result in costs higher than the level planned or budgeted for. These scenarios do not have to represent worst cases; rather, they should reflect a set of conditions a Program Manager or decision maker would want to budget for, should any or all of those conditions occur.

These are the eight steps associated with an SBM:<sup>20</sup>

Step 1—Generate/Obtain Point Estimate

Step 2—Define the Project Performance Floor (Scenario to “Protect” Project from Cost Overrun)

Step 3—Compute Performance Floor Cost and Cost-Risk Estimates

Step 4—Assess Point Estimate Probability

Step 5—Select Coefficient of Variation (CV)

Step 6—Derive Cumulative Density Function (CDF) and Determine Confidence Levels

Step 7—Perform Sensitivity Analysis

Step 8—Allocate Risk Costs

The details on each of these eight steps are provided in the 2014 CSRUH at <https://www.ncca.navy.mil/tools/csruh/index.cfm>.

Note that there are several existing methodologies to assist the analyst in allocating risk estimates. The cost analyst must be able to allocate the risk estimates to the lower-level WBS elements in order to move the WBS elements’ deterministic point estimates to probabilistic estimates.

Other approaches such as “needs”-based allocations also exist.<sup>21</sup> This method assumes that a WBS element’s need for risk costs arises out of the uncertainty in the cost of that WBS element. A quantitative description of that need should be the logical basis of the risk-dollar computation. In general, the more uncertain the cost is, the more risk-related costs will be needed to cover a reasonable probability (e.g., 70 percent at KDP-C) of being able to complete that element of the system. This methodology also states that inter-WBS-element correlations must be taken into account to properly allocate risk estimates back to the individual WBS elements. It is also possible to time-phase risk-cost estimates.<sup>22</sup>

#### **G.2.2.2. Method of Moments Risk Assessment**

Method of Moments is a cost-risk analysis approach that allows the analyst to statistically sum WBS element costs, which are represented by probability distributions. From this, it is possible to obtain a probability distribution of total cost. Summation of WBS element costs is done not by Monte Carlo sampling, but by fitting a lognormal probability distribution to the mean and variance of total cost. Specific percentiles of the lognormal distribution of total cost can be displayed (e.g., 10th, 20th...90th, 95th). It must be noted that, due to its reliance on normal and lognormal distributions, Method of Moments can underestimate risk in certain situations.<sup>23</sup>

For more information on Method of Moments for risk assessment, refer to the 2014 CSRUH at <https://www.ncca.navy.mil/tools/csruh/index.cfm>.

<sup>20</sup> AFCRUH (pp. 43–44, 108–111, April 2007) provides an overview, associated formulas, and detailed examples of SBM. Another source is “A Scenario-Based Method for Cost Risk Analysis,” Paul R. Garvey, The MITRE Corporation, MP 05B0000023, September 2005.

<sup>21</sup> SSCRH, pp. 140–145, November 2005. AFCRUH, pp. 91–92, April 2007. Book, Stephen A., “Cost Risk Analysis: A Tutorial,” in conjunction with the Risk Management Symposium Cosponsored by the USAF Space and Missile Systems Center and the Aerospace Institute, Manhattan Beach, CA, June 2, 1997.

<sup>22</sup> AFCRUH, pp. 36–37, April 2007.

<sup>23</sup> Further information pertaining to this methodology can be found in the NAFCOM model, AFCRUH, p. 95, April 2007, and SSCRH, pp. 140–142, 156, November 2005.

### G.2.3. Hybrid-Based Approach

Another cost estimating approach combines scenario-based identification and assessment of the specific risk scenarios with probabilistic analysis of the cost-risk consequences that may occur to create a risk-adjusted cost estimate. This cost-risk assessment and analysis approach (known as the Hybrid Scenario) also provides the “common language” for cost estimators, project managers, and risk managers when they try to determine cost-risk quantification.

#### Step 1—Develop Reference Cost Estimate

To use the Hybrid Scenario-based estimating approach, the cost estimator must first develop the reference point cost estimate by using an analogy, grassroots (bottom-up), or parametric model. Then, the cost estimator must identify all the risks that pose a threat to a project, identify the likelihood of each risk's occurrence within the relevant WBS element, and assess the cost consequences of each risk. Ideally, the cost estimator will have access to engineering SMEs who, through their experience with similar project risks, can assist with risk identification, cost consequence assessment, and determination of the likelihood of these risks occurring.

#### Step 2—Develop Risk Matrix

After estimating a potential cost consequence for each risk, the cost estimator employs the traditional 5 × 5 likelihood versus consequence risk (or stoplight) matrix to illustrate low, medium, and high risks (Figure G-8).

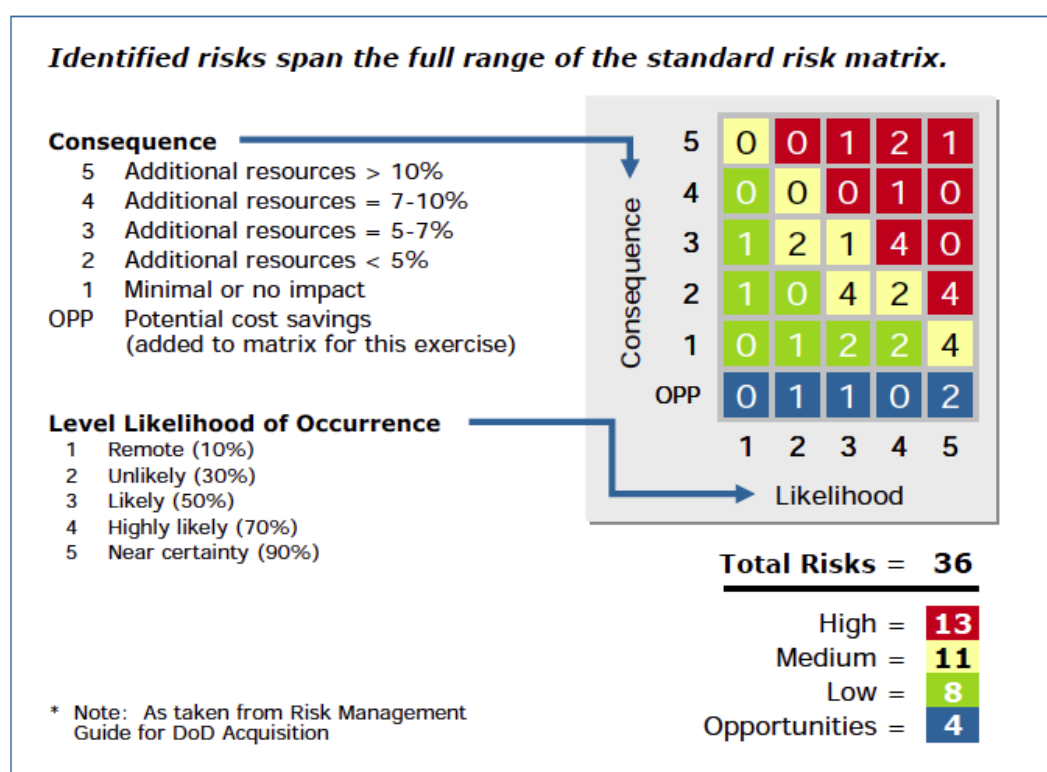


Figure G-8. 5 × 5 Risk Matrix (Also Known as a Stoplight Matrix)

#### Step 3—Run Simulation

In this step, the cost estimator uses a Monte Carlo simulation to produce a distribution of cost-risk impact that identifies confidence levels associated with each cost value in the range of a cost-risk distribution.

Using the qualitative results produced above, the cost estimator can apply a random number generator that ranges from 0 to 1 in the Monte Carlo simulation using a uniform distribution that produces random draws to simulate the likelihood of risks occurring. Each simulation's result is used to identify which risks might occur and to add the cost consequences for each identified risk with a likelihood value of equal to or less than the random number generated.

The rule for including the cost consequences is that if the random draw produces a number equal to or less than the subjective likelihood of that risk occurring, then add 100 percent of its cost consequence. Otherwise, if the random draw produces a number higher than the likelihood, its cost consequence is not added. This rule ensures that the cost consequences are included in the final distribution in accordance with the SMEs' assessments of the likelihood that those risks will occur.

For example, if the likelihood for a risk is 80 percent and its cost consequence is \$5 million, then the \$5 million would be included in the addition for each draw that was 0.8 or less. If the draw produces a likelihood of 0.9, no cost would be included for that risk because the 0.9 is higher than 0.8. For another random draw, if the likelihood of a risk were 30 percent and its cost consequence were \$10 million, then the \$10 million would be added for the number of draws that were 0.3 or less. If the draw is 0.7, then no cost consequence is included during that simulation for that risk. This process is repeated up to the total number of simulations to construct a risk consequence Probability Density Function (PDF).

This cost-risk distribution, which represents the potential dollars to be added for risk, should be matched against the WBS element using estimating methodology uncertainty distributions in an additive fashion to arrive at a combined distribution—this represents a summary cost-risk distribution. This summary distribution is useful for protecting against the risks at different confidence levels. Correlations between the WBS elements and the scenario-based cost-risk distribution would be specified to ensure an optimally credible total cost estimate distribution from which a cost estimate confidence level value can be selected for budgeting. Figure G-9 illustrates this process.

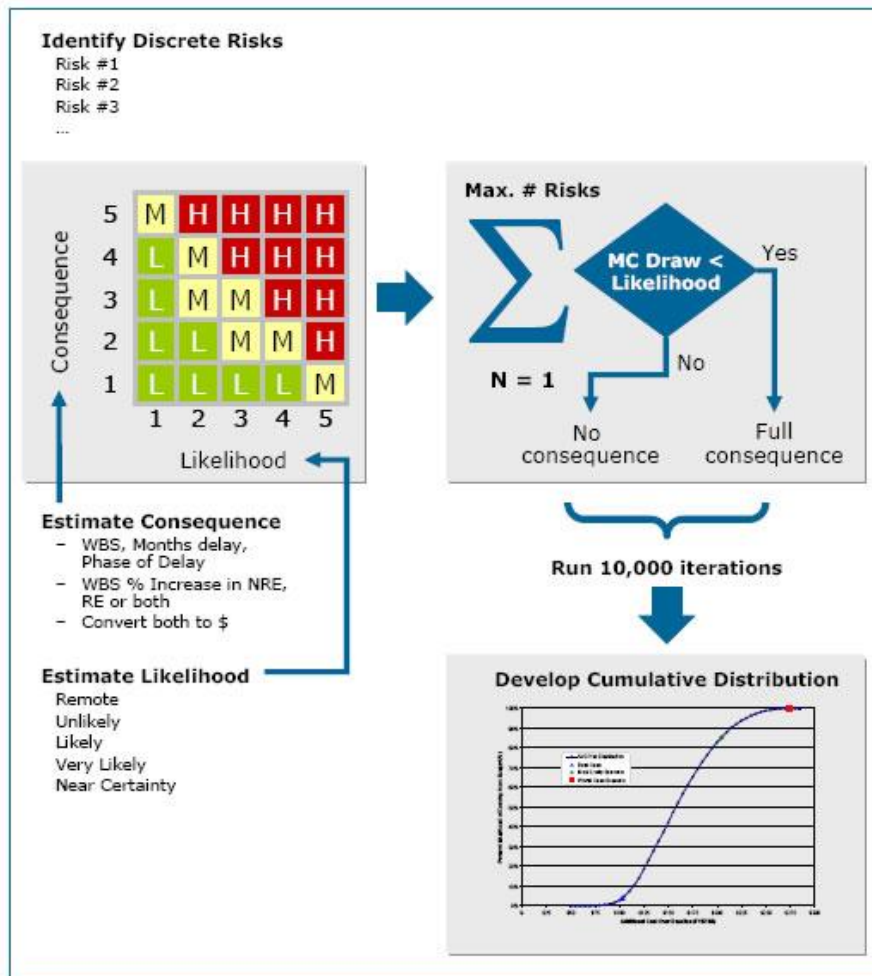


Figure G-9. 5 × 5 Matrix Cost-Risk Conversion Process Summary

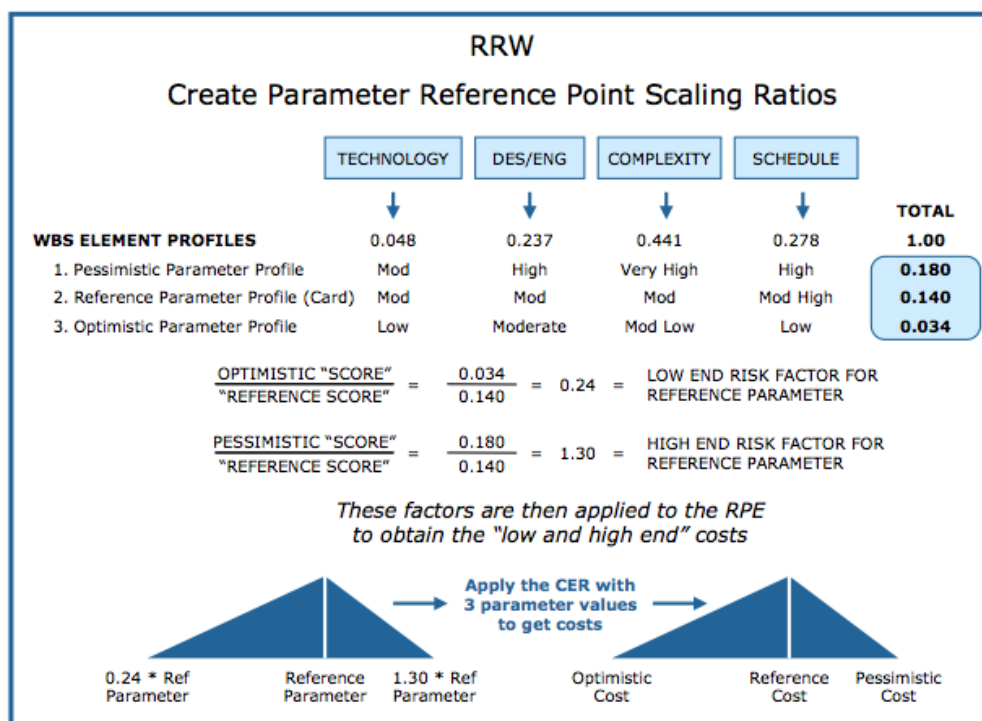
### G.3. Discrete Risk Analysis

Discrete Risk Analysis for programmatic/technical costs involves identifying and estimating specific cost-driving risks. Instead of probabilistic distributions and Monte Carlo simulations, however, the mitigation costs for these risks are estimated based on their probabilities of manifesting discrete changes in the technical parameters (e.g., increased component mass or power regulation) and cost results compared to probabilistic cost results.

A variation of assigning risk values can be used to quantify discrete risks. The discrete key engineering risks are identified and defined during the construction of the risk scenarios: pessimistic, optimistic, and reference. Each scenario has the same risks identified, and the pessimistic scenario, the worst observance of them, is hypothesized to occur. For example, the pessimistic scenario is a situation surrounding the development of the WBS element that assumes the realization of the worst conditions under each category of risk affecting the element in meeting the WBS performance expectations.

The profile or scenario for each WBS element must be written and should detail the specific, discrete engineering risks to ensure that during the risk-weighting process, the reason for a recommended confidence level for budgeting is clearly justified.

Figure G-10 illustrates this variation of the risk-weighting, which is called the Relative Risk Weighting process. This process uses the risk scores generated by the risk-rating process to define two ratios that are used as factors on the reference point cost estimate to derive a pessimistic and optimistic cost. Together with the reference point estimate, these two derived costs define that WBS element's triangular risk distribution.



**Figure G-10. Discrete Risk Analysis Using the Relative Risk Weighting Process**

The discrete major engineering risks are rated in pessimistic, optimistic, and reference scenarios to calculate relative risk scores for cost-risk triangular distribution development in the RRW process. Additionally, since the risks for each major engineering risk have been documented, it is possible to develop strategies for mitigating each of these risks and, in parallel with the RRW process, produce discrete cost-risk assessments. A cost is thus estimated for handling and/or mitigating each discrete major engineering risk to determine its specific contribution to the total cost.

### **G.3.1. Sensitivity Analysis**

Once the point estimate is developed, decision makers need to understand how sensitive the total cost estimate is to changes in the data input. Therefore, NASA recommends that sensitivity analyses be performed to identify the major cost drivers for the estimate. Sensitivity analysis is a technique used to determine how the different input ranges affect the point estimates. Significant cost drivers are those variables that, when changed in value, create the greatest changes in cost.<sup>24</sup>

<sup>24</sup> AFCRUH and SSCRH both provide guidance and examples on performing sensitivity analyses.

### G.3.2. Program Portfolio Effect<sup>25</sup>

Individual project confidence levels can roll up to higher or lower confidence levels at the program level depending on the project confidence level and the level of correlation between projects. This is sometimes called the “portfolio effect,” which is defined as the tendency for the risk on a well-diversified holding of investments to fall below the risk of most and sometimes all of its individual components.

Table G-2 presents analysis of portfolios sized with 5, 10, or 20 projects with high dispersion. The table shows assumptions of projects funded at probabilities of 50 percent, 60 percent, 70 percent, and 80 percent. The third column shows the overall portfolio confidence level of each case with the projects uncorrelated.

**Table G-2. Portfolio Probabilities for Two Levels of Correlation<sup>26</sup>**

# Projects	Project Probability	Portfolio Probability	
		No Correlation	0.25 Correlation
5	50%	38%	40%
5	60%	61%	59%
5	70%	80%	78%
5	80%	94%	92%
10	50%	32%	36%
10	60%	62%	61%
10	70%	87%	83%
10	80%	98%	96%
20	50%	24%	32%
20	60%	65%	61%
20	70%	94%	86%
20	80%	99%	98%

The fourth column shows the same, but with the projects correlated at 25 percent. Note the results in each case where the constituent projects were funded at 60 percent. The portfolio probability is near 60 percent as well. And note that if the portfolio is composed of 10 or more programs, its probability nearly doubles that of a portfolio of programs funded to 50 percent. This example indicates how modest increases in each project’s cost-risk exposure (i.e., “shaving” risk dollars by reducing each project’s probability) can lead to a significant reduction of a portfolio’s probability of meeting its funding level.

For uncertainty distributions that approximate lognormal, the median is always lower than the mean, and for that reason, funding projects at 50 percent result in weak portfolio probabilities. Funding projects at 60 percent (generally near or above the mean) bring portfolio expectations to above 50 percent. Funding projects at 70 percent or above certainly raise the probability of portfolio success but naturally require a higher level of funding.

### G.3.3. Cost-Risk Output

Decision makers want to know, if the budget is set at the estimate (or any other value), what is the likelihood of an overrun? The answer can be formed from the results of the statistical summing of the

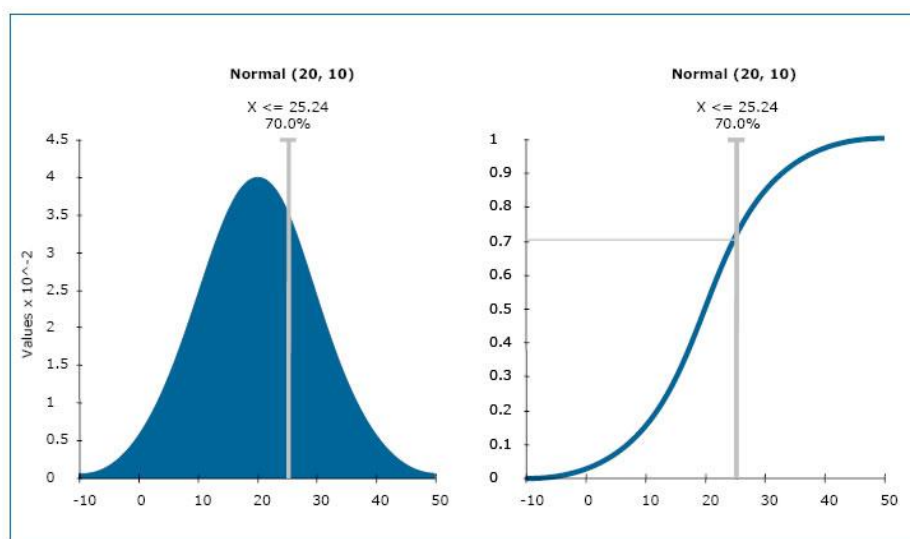
<sup>25</sup> AF CRUH, p. 45, April 2007.

<sup>26</sup> AF CRUH, p. 45, April 2007.

WBS element cost-risk distributions via an examination of the resulting S-curve or confidence level table. For example, if the budget is at the 70th percentile, there is a 30 percent chance of an overrun.

Cost-risk modeling outputs produce risk-adjusted estimates, corresponding statistical estimate distributions, and a credible project cost S-curve (the cumulative distribution function for the range of project costs). Section 2.5 of NPR 7120.5 supports the use of probabilistic cost-risk analysis to quantify uncertainties in cost estimates.<sup>27</sup> Quantifying these risks allows the estimator to address uncertainties in technical design, especially in Pre-Phase A, Phase A, and Phase B. It is also important for the estimator to address uncertainties in cost estimating methods (e.g., statistical variance in CERs) and provide decision makers with a range of cost outcomes as a function of confidence levels so that these results may be used for UFE determinations and recommendations. As the project proceeds through the life-cycle phases, the variance in the estimate should narrow (as risks gradually get retired).

Cost risk must be carefully and quantitatively assessed in developing and presenting any cost estimate. As shown in Figure G-11, the cost S-curve provides more information than a single number and can be used to choose a defensible level of risk estimates. The methods for developing a project's cost S-curve depend on the cost estimating methodology employed and the amount of risk information that the cost analyst can secure within the bounds of time and resources.



**Figure G-11. Probability Density Function (PDF) and Equivalent Cumulative Density Function (CDF or S-Curve)**

In addition to determining the S-curve, conducting cost-risk assessments contributes to the following:

1. Determining the project's cost drivers. Analyzing which input variables will have a significant effect on the final cost can help determine which design (or programmatic) parameters deserve the most attention during the project's definition and design phase.
2. Estimating the probability of achieving the point estimate. When a simulation risk analysis technique is performed using the low, most likely, and high values provided for the input variables, it can often be demonstrated that the point estimate has a less than 50-50 chance of being achieved.

<sup>27</sup> NPR 7120.5E, NASA Space Flight Program and Project Management Requirements, Section 2.5.

3. **Providing a cost range.** Establishes the low and the high end of the cost estimate with a series of low and high values of the input parameters.

Cost-risk analysis quantifies the budgets necessary for the required level of confidence. When asked how much of the dollar figure being proposed is for UFE, a good strategy is to prepare the calculation in advance, so that you can respond to that question by saying that the percentage is the amount by which the 70th percentile cost exceeds the 50th percentile  $[(70\text{th} - 50\text{th}) / 50\text{th}] \times 100\%$  and therefore can be considered UFE. Risk cost estimates should be phased in the estimate where they will most likely be needed.

## G.4. Cost Models that Address Risk

There are a number of commercially available cost modeling tools that can assist the estimator in developing realistic risk-adjusted cost estimates. Profiles of nine risk assessment software packages are presented below. Each profile highlights the software's capabilities to perform cost risk. Note that in Appendix E, there is an overview summary of many cost estimation models, including the ones discussed here. A summary of their differing capabilities is provided on Table G-3. This will aid the analyst in selecting the tool that best fits the analysis being conducted.

**Table G-3. Cost-Risk Model Summary**

Model Name	Cost/Risk Approach	Model Contact Information
True Planning	Method of Moments	www.pricesystems.com
PRICE Integrated Models & Standalone Models	Monte Carlo/Latin Hypercube	www.pricesystems.com
SEER	Monte Carlo/Latin Hypercube	www.galorath.com
Project Cost Estimating Capability (PCEC)	Excel Add-In (@RISK or Crystal Ball)	www.oncedata.com
ACEIT	Monte Carlo/Latin Hypercube	www.aceit.com
JACS: Joint Analysis of Cost and Schedule	Monte Carlo/Latin Hypercube	www.aceit.com
POLARIS	Argo (proprietary Monte Carlo simulation method)	www.boozallen.com
Crystal Ball	Monte Carlo/Latin Hypercube	www.crystalball.com
@RISK	Monte Carlo/Latin Hypercube	www.palisade.com

The PRICE Estimating Suite (PES) and SEER can evaluate cost, technical, and schedule risk. The other models do this in more limited fashion. Some models perform Monte Carlo simulation (PES, SEER, Crystal Ball, @RISK). True Planning uses the Method of Moments, which some analysts find more efficient than Monte Carlo. Because it is built within Excel, NASA's Parametric Cost Estimating Capability (PCEC) tool is able to add in Crystal Ball and @RISK. Various approaches for estimating correlation between elements are provided by the six models. All the models produce reports and chart outputs. PCEC is available free of charge. Site licenses for True Planning/PES and SEER are available for NASA Centers. ACEIT is available from NASA Headquarters. Users of Crystal Ball and @RISK would currently need to purchase site licenses (two in the case of @RISK). Therefore, model cost can be a factor in tool selection. Contact information is also provided for each model. The analyst should use a model that is available, that best fits the project's needs, and which the analyst is comfortable with.

### G.4.1. PRICE Systems Solutions

PRICE Systems Solutions<sup>28</sup> consists of two sets of parametric cost estimating models: the legacy PES, which includes PRICE H and PRICE S models, and True Planning, which includes True H and True S. In addressing risk, PES uses Monte Carlo simulation and Latin Hypercube, while True Planning uses the Method of Moments.

<sup>28</sup> For more information, visit <http://www.pricesystems.com>.

#### G.4.1.1. Cost-Risk Approach

PES assigns one of four possible probability distributions to the cost element input parameters selected for risk analysis (normal, triangular, beta, and uniform). The selection of the distribution then determines the additional data that are required to satisfy the particular distribution that is chosen. PES then employs one of two possible sampling techniques for the simulation: Monte Carlo or Latin Hypercube.

PES outputs include a graphical portrayal of the resultant probability distribution function and the cumulative distribution function. They also include a tabular listing of all input parameters identified for risk analysis, along with the probability distribution and parameters for the distribution; figures of merit for the random sample, including mean, standard deviation, coefficient of variation, and mean standard error; as well as results for every fifth percentile of the output cumulative distribution function. It is also possible to export the inputs and outputs for additional analysis outside the model.

#### G.4.1.2. Correlation

Correlation in PES is addressed through a series of checkboxes that establish a dependency between total mass and structure mass with and without the electronics mass and also interelement dependency. This approach ensures that parameters for the selected elements move in the same direction.

True Planning employs the Method of Moments methodology. It assigns triangular distributions to model element input parameters that are selected for risk analysis. These distributions are then combined to form a resultant lognormal distribution.

Interelement correlation is based on user input and the relationship of cost elements to each other. The user selects the correlation to be none, very loose, nominal, tight, very tight, or total, with corresponding numerical values ranging from 0 to 1.

The primary risk output from True Planning is a tabular listing for every fifth percentile of the cumulative distribution function of the lognormal distribution results. True Planning risk outputs also include the mean, mode, and variance for the distribution.

#### G.4.2. SEER

SEER<sup>29</sup> models capture technical input and cost estimating risk by soliciting a range of input values for most parametric inputs. These parameters require “least,” “likely,” and “most” inputs. “Least” represents the lowest reasonable value for the parameter (1 percent probability that the value would be lower than the stated least value), whereas “most” represents a 99 percent probability that the actual value will be less than the stated value. The “likely” input represents the highest probability of occurrence, the value that the estimator would enter if only a point value estimate were required. The estimator can thus specify a reasonable range for each parameter, anywhere from least certain to any desired degree of uncertainty. The range does not need to be symmetrical, but it should reflect the estimator’s best judgment based on technical inputs as to the reasonable range for the parameter value.

For each parameter where “least,” “likely,” or “most” is specified, SEER constructs an input distribution. The lowest cost input forms the lower bound, the highest cost input forms the bound, and the 50 percent point is defined by a Project Evaluation and Review Technique (PERT)<sup>30</sup> mean of the “least,” “likely,” and “most” values.

<sup>29</sup> For more information, visit <http://www.galorath.com>.

<sup>30</sup> PERT is a method to analyze the involved tasks in completing a given project, especially the time needed to complete each task, and identifying the minimum time needed to complete the total project.

### G.4.2.1. Cost-Risk Approach

For each parameter where a range of values is required, SEER will select the appropriate confidence level value for each parameter and calculate a result.

Rollup work elements aggregate several lower-level hardware and/or software items in the WBS. Sums (at the selected confidence level of the lower-level elements) can be displayed, but the sum does not generally capture the summation of the underlying distributions. A Monte Carlo technique is used to calculate uncertainty distributions for rollup work elements.

### G.4.2.2. Integration with Other Approach/Tools

SEER models incorporate basic risk-analysis features but can also provide inputs to more sophisticated risk-analysis tools. SEER can be used together with ACEIT. When using SEER models with ACEIT, entering the SEER 50 percent and 90 percent confidence level estimates for an individual work element and using a lognormal distribution in ACEIT will normally allow it to produce a good approximation of the SEER risk distribution at confidence levels above 50 percent. Galorath is also developing an interface with Crystal Ball to allow automated, sophisticated risk-analysis capabilities.

### G.4.2.3. Correlation

At the individual work element level, confidence levels represent fully correlated results. Each parameter includes a range of values and is evaluated at the same probability. In SEER, the Risk Tuner feature allows the estimator to specify different confidence levels for different categories of parameters, thus capturing varying degrees of correlation.

At the rollup level, Monte Carlo results are calculated for full correlation and no correlation. The estimator can use these endpoints to interpolate for varying degrees of correlation between the work elements.

### G.4.2.4. Reports and Charts Summarizing Cost-Risk Results

SEER models provide textual and graphical representations of risk at the work element and rollup levels. Risk analysis reports display a table of values at varying confidence levels (1 to 99 percent for individual work elements, 10 to 90 percent for rollups). Risk charts display the CDF for the selected domain (cost, work effort, schedule, software defects).

### G.4.3. Project Cost Estimating Capability (PCEC) Tool

The Project Cost Estimating Capability (PCEC)<sup>31</sup> is a NASA cost model that was initially released in 2014. PCEC is a framework that will replace NAFCOM as the standard NASA capability for estimating the cost of new space flight hardware systems during concept exploration and refinement. PCEC consists of an Excel-based architecture that combines a user interface running Visual Basic for Application (VBA) with WBS and CER libraries. This structure provided a high degree of flexibility and openness while reducing the resources required for software maintenance, thus allowing more effort to be put into improving NASA models and estimating capabilities. The PCEC modeling construct is envisioned to adapt to the new estimating needs of the NASA cost community. In particular, PCEC is intended to

- Address all elements of the NASA Standard WBS as defined in NPD 7120.5E.
- Change the focus of the NASA investment portfolio from automation centric to research centric.

<sup>31</sup> For more information on PCEC, see the presentation from the 2014 NASA Cost Symposium at [http://www.nasa.gov/sites/default/files/files/05\\_PCEC\\_2014\\_Cost\\_Symposium\\_TAGGED.pdf](http://www.nasa.gov/sites/default/files/files/05_PCEC_2014_Cost_Symposium_TAGGED.pdf).

- Create an environment that addresses the diverse estimating and analysis requirements across NASA.
- Enable the entire NASA cost community to have ownership and add value to an Agency-wide capability.
- Emphasize good analysis as a critical component of credible cost estimating (problem-driven analysis versus tool-driven analysis).

#### **G.4.3.1. Cost-Risk Approach**

PCEC incorporates estimating risk through the PCEC complexity generator CERs, which have a power equation form:

$$Y = aX_1^{b1}X_2^{b2} \dots X_n^{bn}$$

The CERs are calculated using transformed Ordinary Least Squares (OLS). The natural logarithms of the dependent variable and independent variables are calculated, and then OLS is applied to the transformed data. In other words, OLS is applied to the logarithmic-transformed model. The estimation error for the log model is a normal distribution, with mean equal to zero and standard deviation equal to the standard error of the model.

#### **G.4.3.2. Correlation**

PCEC incorporates correlation in its risk module. The user can assign any correlation value to any WBS-element pair that is chosen. Percent underestimated versus the actual correlation and number of iterations is shown in Figure G-12.

In PCEC, the systems-level element costs are calculated as functions of the hardware costs. Once risk for all the hardware elements has been calculated, risk for the systems-level elements is calculated, incorporating correlation and estimating uncertainty. Because the systems-level element costs are calculated as functions of hardware cost, technical risk for the hardware elements is incorporated implicitly.

#### **G.4.3.3. Reports and Charts Summarizing Cost-Risk Results**

PCEC provides the following reports:

1. PDF and CDF Reports
2. Risk Statistics and Allocation Reports

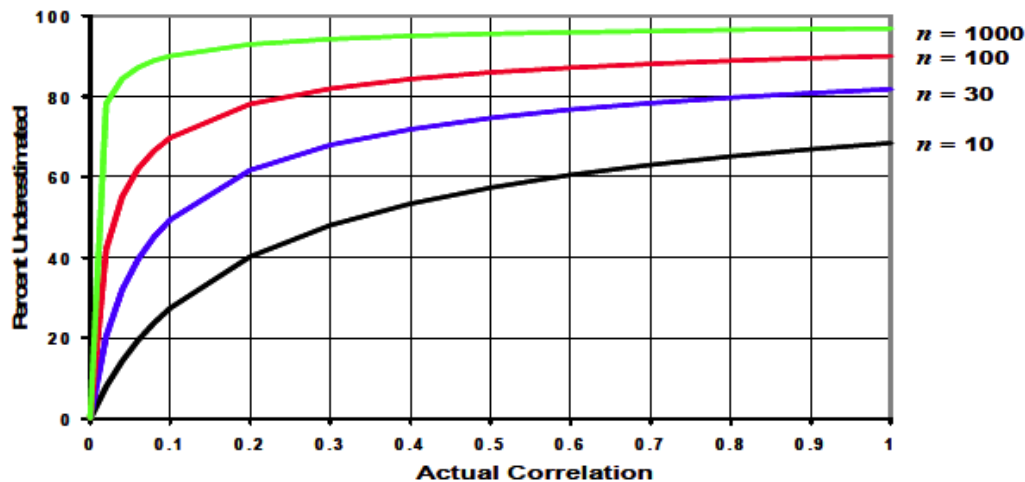


Figure G-12. Effect of Correlation on Estimates

#### G.4.4. Automated Cost Estimating Integrated Tools (ACEIT) and JACS

ACEIT<sup>32</sup> is a Government-funded, special-purpose software program specifically developed for cost analysis. It automates the primary tools and techniques of the cost analysis trade such as WBS structures, inflation, learning curves, time-phasing, Cost As an Independent Variable (CAIV), cost-category reports, documentation, what-if analysis, and risk analysis. It provides a capability that allows the estimator to conduct a risk analysis on the cost, schedule, and technology uncertainty in a cost estimate. Joint Analysis of Cost and Schedule (JACS) is an add-in for Microsoft Project that is designed to quickly create probabilistic results for schedule and costs in an integrated schedule. JACS enables the cost-loading of schedule tasks and risk events, allowing the analyst to assign probability distributions and create a holistic view of the resultant risk analysis. JACS, a module in ACEIT, is a primary JCL tool and is validated and approved for milestone reviews.

##### G.4.4.1. Cost Estimating Risk

The Automated Cost Estimator (ACE) module of ACEIT allows an analyst to specify risk distributions for any element within the model. This allows a user to explicitly specify the uncertainty distribution associated with CERs. For any element in the ACE model, a user can specify the bounds around the point estimate. The bounds for each of these distributions can be specified via low and high values or via statistical metrics (standard deviation, adjusted standard error, coefficient of variation). ACE treats the point estimate as the most likely value (except for lognormal, where it is treated as the median) and uses the distribution information as the bounds for the simulation process. Upon completion of the calculation, ACE provides the confidence level of the estimate result as well as the estimate itself.

##### G.4.4.2. Technical Input Risk

In addition to cost estimating uncertainty, ACE allows an analyst to specify uncertainty on any input cost driver. To do this, an analyst specifies the cost estimating uncertainty for the CER and then also specifies a distribution for the input parameters. During the simulation process, ACE will first determine the value of the input parameter based on its distribution information. Once this is determined, ACE uses the input parameter value to calculate the equation and determine a cost result based on the uncertainty specified for the CER. In this manner, the uncertainty of the technical inputs is included with the cost estimating

<sup>32</sup> For more information, visit <http://www.aceit.com> or contact [aceit\\_support@tecolote.com](mailto:aceit_support@tecolote.com).

uncertainty for a specific cost element. Figure G-13 shows the difference when risk is based on the inputs, or the CER, or both.

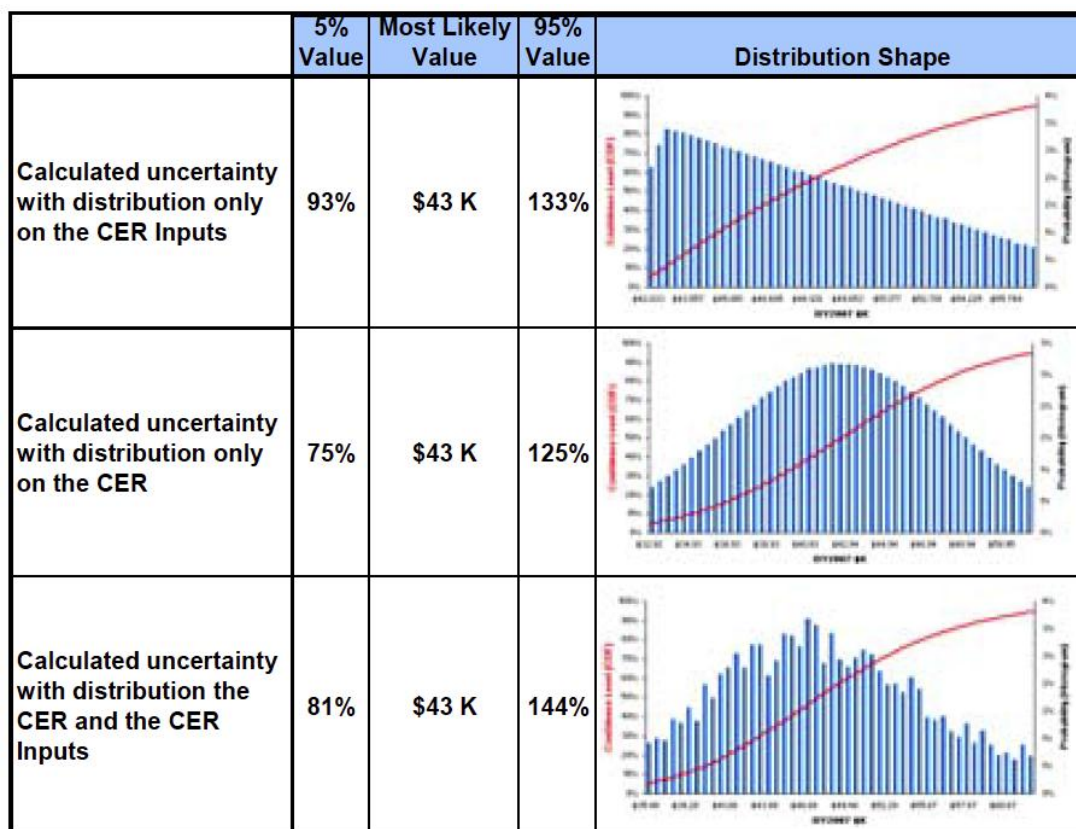


Figure G-13. ACEIT Technical Risk Input Screen

#### G.4.4.3. Correlation

ACE incorporates a correlation technique similar to that of the Lurie-Goldberg algorithm for creating a set of variables that match a supplied correlation matrix.<sup>33</sup> ACE provides tools to assist the analyst with entering a single correlation vector. Once the desired rows are in the group, the analyst enters the vector values into a Strength Column and the entire correlation matrix is determined.

#### G.4.4.4. Simulation Process

ACE uses a Latin Hypercube simulation method to derive aggregate distributions based on specified distributions for WBS elements and their associated interactions (both through the CERs and their inputs). The Latin Hypercube method requires a lower number of iterations than the Monte Carlo method. This technique ensures that the entire range of each variable is sampled.

#### G.4.4.5. Reports and Charts Summarizing Cost-Risk Results

ACEIT provides numerous reports that show the risk analysis and range from statistics to charts and graphics. Users can quickly create graphical results to see the PDF and S-curves or to compare the risk analysis results for two options.

<sup>33</sup> J. Price, C/S Solutions, "An Implementation of the Lurie-Goldberg Algorithm in Schedule Risk Analysis," 2002 SCEA National Conference.

ACEIT incorporates three risk reports: Tornado, Spider, and Variance Analysis. These reports will allow a user to obtain a deeper understanding of what cost elements and/or input parameters are driving the overall risk analysis. Examples of the Tornado and Spider charts are shown in Figure G-14.

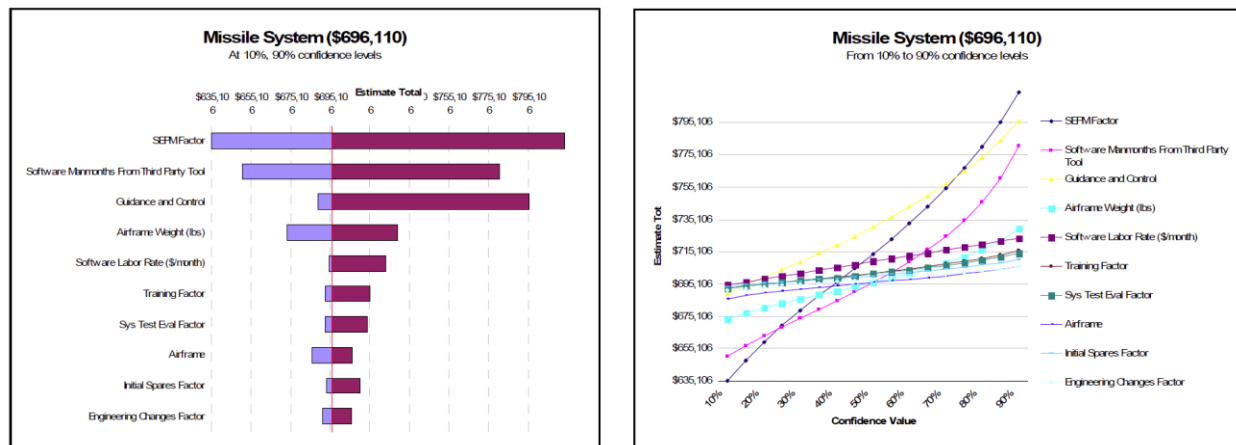


Figure G-14. Future ACEIT Cost-Risk Output Reports

#### G.4.5. *Polaris and Argo*

Polaris is program analysis software provided by Booz Allen Hamilton. Polaris integrates cost, schedule, and risk artifacts into a single model, enabling better project performance through real-time simulations. Polaris integrates cost estimates, schedules, and risk registers into a single analytical model that provides a cohesive view across all three project control functions. Polaris is a primary JCL tool and is validated and approved for milestone reviews.<sup>34</sup>

Argo is simulation software provided by Booz Allen Hamilton. Argo utilizes an advanced approach to Monte Carlo simulation, achieving substantial run-time and file-size savings. Argo utilizes algorithmic, hardware-independent efficiencies that dramatically reduce run-times and streamline the resources required to perform sophisticated analysis.<sup>35</sup>

#### G.4.6. *Crystal Ball*

Crystal Ball<sup>36</sup> is a suite of analytical software applications that enhance Microsoft Excel usage. By introducing analytical approaches such as simulation, optimization, and time-series forecasting into a spreadsheet, Crystal Ball increases the accuracy and ease of forecasting and risk analysis. Excel spreadsheets contain single-point estimates. Crystal Ball allows a range to be put around these values so all intermediate values can be accounted for. These ranges are represented by probability distributions. Crystal Ball uses Monte Carlo simulation to generate scenarios (see Figure G-15).

<sup>34</sup> For an explanation of Polaris, visit <http://www.boozallen.com/consulting/products/software/polaris>.

<sup>35</sup> For an explanation of Argo, visit <http://www.boozallen.com/consulting/products/software/argo>.

<sup>36</sup> For more information, visit the Oracle Crystal Ball website at <http://www.oracle.com/us/products/applications/crystalball/overview/index.html>.

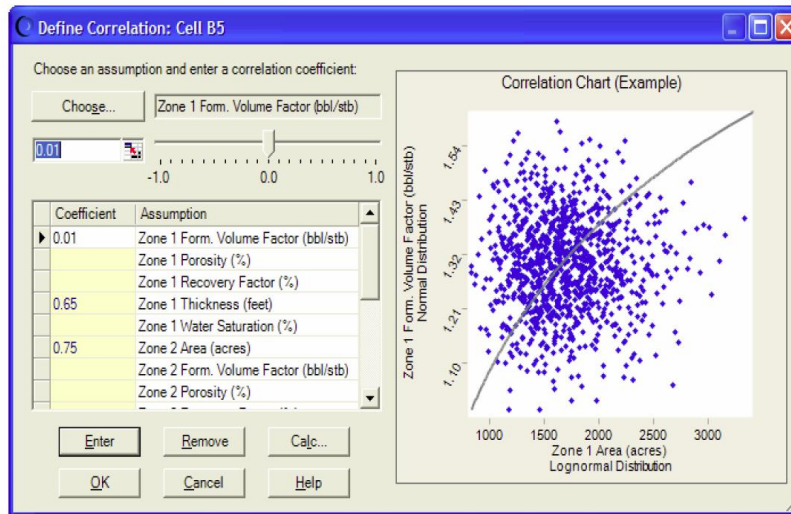


Figure G-15. Crystal Ball Cost-Risk Output Screen

#### G.4.5.1. Cost-Estimating Risk

The Crystal Ball sensitivity chart is an approach for pinpointing the drivers of uncertainty within a forecast. Generated during the simulation, this chart describes which of the uncertain factors have the greatest impact on the bottom line, with the factors at top exerting the greatest influence.

#### G.4.5.2. Cost-Risk Approach

The Crystal Ball simulation will provide answers such as “what is the most likely cost,” “how likely is the baseline estimate to be overrun,” “what is the cost-risk exposure,” and “where is the risk in this project” because it takes into account the uncertainty around project costs. Crystal Ball simulations move from a deterministic, or static, analysis to a probabilistic macro view that recognizes and compensates for uncertainty, risk, or variation (Figure G-16).

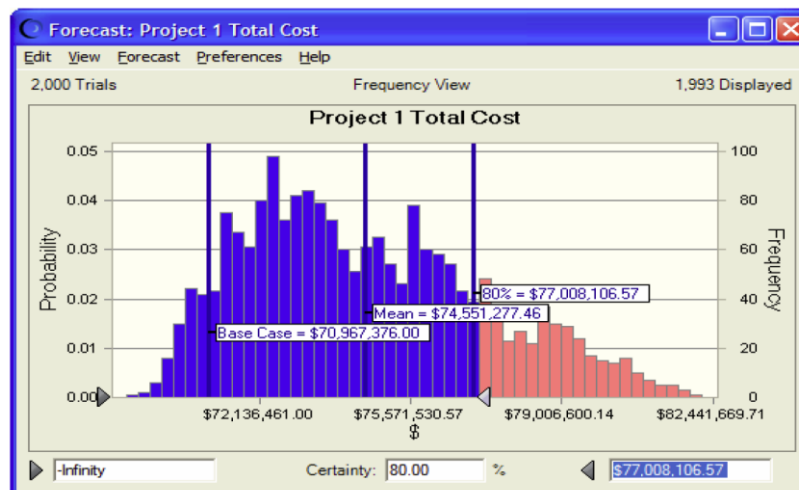


Figure G-16. Crystal Ball Cost Estimating Risk Output Screen

#### G.4.5.3. Correlation

Crystal Ball does correlation to account for cost elements that have a positive influence on each other.

#### G.4.5.4. Reports and Charts Summarizing Cost-Risk Results

Crystal Ball has many reporting and chart options. Charts used during the simulation include assumption, forecast, overlay, trend, and sensitivity. After a simulation is run, results can be exported into an Excel spreadsheet displaying the data created from the simulation results.

#### G.4.7. @RISK

@RISK<sup>37</sup> uses Monte Carlo simulation and an Excel spreadsheet to display possible outcomes and their likelihood. This information allows the user to judge which risks to take and which ones to avoid. @RISK can help the user select the best strategy based on available data.

#### G.4.6.1. Cost-Risk Approach

@RISK comes with a distribution viewer that allows the user to preview various distributions before selecting them. A user can also set up distributions using percentiles as well as standard parameters. Furthermore, a user can use historical data and @RISK's integrated data-fitting tool to select the best function and parameters.

@RISK also provides Sensitivity and Scenario Analyses. The Sensitivity Analysis can be used to rank the distribution functions in the user's model according to the impact they have on outputs. Outputs are displayed with a Tornado diagram.

#### G.4.6.2. Reports and Charts Summarizing Cost-Risk Results

@RISK provides a wide range of graphs for interpreting and presenting results. Histograms and cumulative curves show the probability of different outcomes. Overlay graphs can be used to compare multiple results, and summary graphs can be used to see risk over time. @RISK also allows the generation of a one-page, ready-to-print report of statistical results and graphs.

#### G.4.6.3. Integration with Other Approaches/Tools

@RISK is compatible with Excel versions 2000 through 2010. It is important to note that @RISK includes no direct cost estimating capability. A cost analyst must have a working estimate with cost distributions for each element in the WBS as input data before using @RISK. A recommended best practice is for the analyst to output a point estimate from his or her cost estimation tool of choice into Excel and then define the cost distributions for each element of the WBS to take advantage of the simulation capabilities.

### G.5. Example for Calculating a Cost Risk or S-Curve

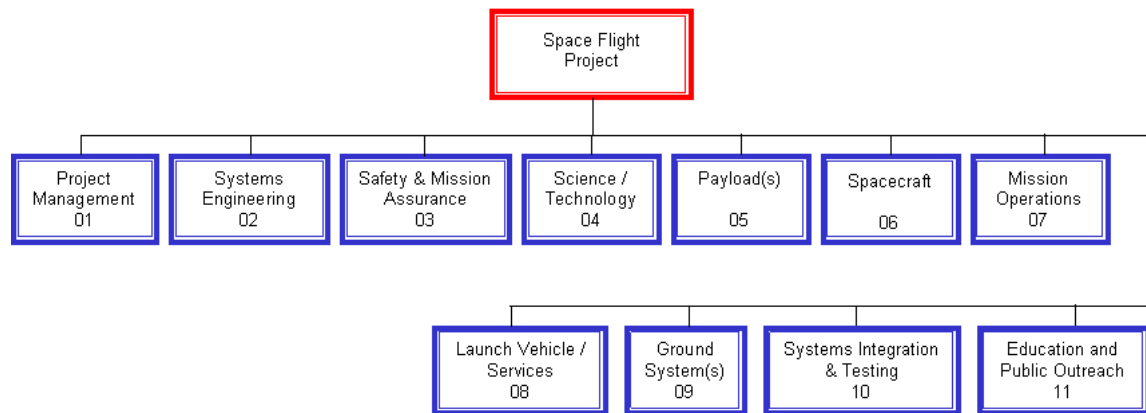
If the analyst is performing his or her own cost-risk analysis in Microsoft Excel, the following example<sup>38</sup> illustrates how to produce a cost-risk estimate (S-curve) using the standard NASA WBS for a typical space flight mission. Any of the existing, commercial simulation tools (such as Crystal Ball, @RISK, or ACE) can be used. The example here was done with @RISK.<sup>39</sup>

1. The first step is to identify the project flight system WBS that will be modeled by the Monte Carlo simulation (Figure G-17).

<sup>37</sup> For more information on @Risk, visit the Palisade website at <http://www.palisade.com/risk/>.

<sup>38</sup> Sample S-Curve Analysis, David Connor, JPL, August 2011.

<sup>39</sup> Use of @RISK in this example should not be taken as an endorsement. It met the requirements of the analysis and was readily available.



**Figure G-17. NASA Standard Level 2 WBS Elements for Space Flight Projects<sup>40</sup>**

2. For each individual WBS element, define a distribution that models the cost.
  - a. Find the mean and standard deviation for each of the WBS elements. These values can be determined from statistical analysis of historical actual mission data. Subsystem engineers can also estimate these costs with the various tools that have been described in this handbook. Table G-4 shows the values used for this illustrative example. The column titled “Single Iteration Cost, \$M” is the most likely cost of the lognormal distribution for each WBS element. The mean and standard deviation used for these distributions are also provided.
  - b. Use these means and standard deviations to set up the probability distributions needed by the Monte Carlo program. Again, in this example, a lognormal distribution is used for the individual elements as illustrated in Figure G-18. The mean, maximum, minimum, and standard deviation for each Level 2 WBS element are also provided.

**Table G-4. Cost and Uncertainty by Level 2 WBS Element**

Level 2 WBS Elements Cost and Uncertainty				
WBS	Cost, \$M (Mean)	Uncertainty, (%)	Uncertainty, (\$M) (STD Dev.)	Single Iteration Cost, \$M
1	5.7	10%	0.57	4.7
2	3.8	10%	0.38	3.6
3	4.5	10%	0.45	4.6
4	6.2	15%	0.93	5.2
5	8.1	33%	2.67	10.9
6	98.4	20%	19.68	103/9
7	10.4	30%	3.12	7.0
8	87.0	0%	0.0	87.0
9	3.5	10%	0.35	3.7
10	8.0	30%	2.40	7.1
11	0.7	5%	0.04	0.7

<sup>40</sup> NPR 7120.5E, Appendix H, Space Flight Project Work Breakdown Structure (WBS), August 2012.

## NASA Cost Estimating Handbook Version 4.0

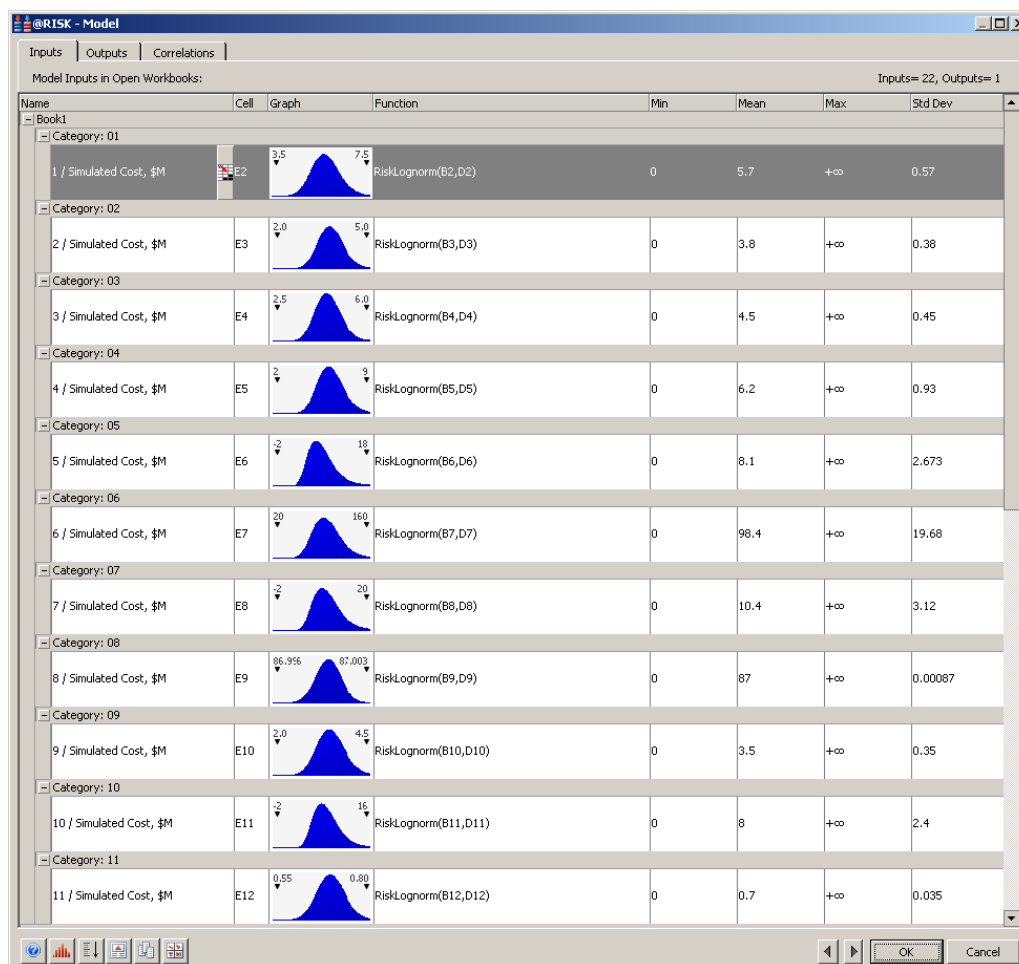


Figure G-18. WBS Distributions (Before Correlation)

3. Create a correlation matrix based on the relationship between individual WBS elements (see Section G.1.5 for a detailed discussion of correlation):
  - a. Use the @RISK analysis software to do this efficiently.
  - b. Set the level of correlation. In this example, all the elements were given a correlation of 0.6 as shown in Table G-5. Be sure to include these correlations in the simulated cost produced by the distributions.
  - c. The Monte Carlo program collects the total simulated cost produced by the distributions from each WBS element.
  - d. Note that once correlation is added to the distributions, the simulated cost will change, as well as the distributions themselves. This is illustrated in Table G-6 and Figure G-19.
4. Run the Monte Carlo simulation:
  - a. Run the Monte Carlo simulation to obtain the total simulated cost. It is advisable to use at least 1,000 iterations so a steady-state result can be obtained.
5. Produce the PDF and CDF.
  - a. The @RISK program uses the results of the Monte Carlo simulation to create the PDF and CDF (S-curve). Figures G-20 and G-21 are examples of the PDF and CDF created from the Monte Carlo results shown in the previous figure.

Table G-5. Correlation Matrix

Level 2 WBS Elements Cost and Uncertainty with Correlation				
WBS	Cost, \$M (Mean)	Uncertainty, $\pm 1$ Standard Deviation (%)	Uncertainty, $\pm 1$ Standard Deviation (\$M)	Simulated Cost, \$M
1	5.7	10%	0.6	5.4
2	3.8	10%	0.4	4.0
3	4.5	10%	0.5	5.0
4	6.2	15%	0.9	7.8
5	8.1	33%	2.7	5.8
6	98.4	20%	19.7	110.0
7	10.4	30%	3.1	8.0
8	87.0	0%	0.0	87.0
9	3.5	10%	0.4	3.3
10	8.0	30%	2.4	4.5
11	0.7	5%	0.0	0.7
<b>Total</b>				<b>241.5</b>

Table G-6. Level 2 WBS Element Cost and Uncertainty with Correlation

Correlation Matrix											
@RISK Correlations	1 / Simulated Cost, \$M in \$E\$2	2 / Simulated Cost, \$M in \$E\$3	3 / Simulated Cost, \$M in \$E\$4	4 / Simulated Cost, \$M in \$E\$5	5 / Simulated Cost, \$M in \$E\$6	6 / Simulated Cost, \$M in \$E\$7	7 / Simulated Cost, \$M in \$E\$8	8 / Simulated Cost, \$M in \$E\$9	9 / Simulated Cost, \$M in \$E\$10	10 / Simulated Cost, \$M in \$E\$11	11 / Simulated Cost, \$M in \$E\$12
1 / Simulated Cost, \$M in \$E\$2	1										
2 / Simulated Cost, \$M in \$E\$3	0.6	1									
3 / Simulated Cost, \$M in \$E\$4	0.6	0.6	1								
4 / Simulated Cost, \$M in \$E\$5	0.6	0.6	0.6	1							
5 / Simulated Cost, \$M in \$E\$6	0.6	0.6	0.6	0.6	1						
6 / Simulated Cost, \$M in \$E\$7	0.6	0.6	0.6	0.6	0.6	1					
7 / Simulated Cost, \$M in \$E\$8	0.6	0.6	0.6	0.6	0.6	0.6	1				
8 / Simulated Cost, \$M in \$E\$9	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1			
9 / Simulated Cost, \$M in \$E\$10	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1		
10 / Simulated Cost, \$M in \$E\$11	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1	
11 / Simulated Cost, \$M in \$E\$12	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1

## NASA Cost Estimating Handbook Version 4.0

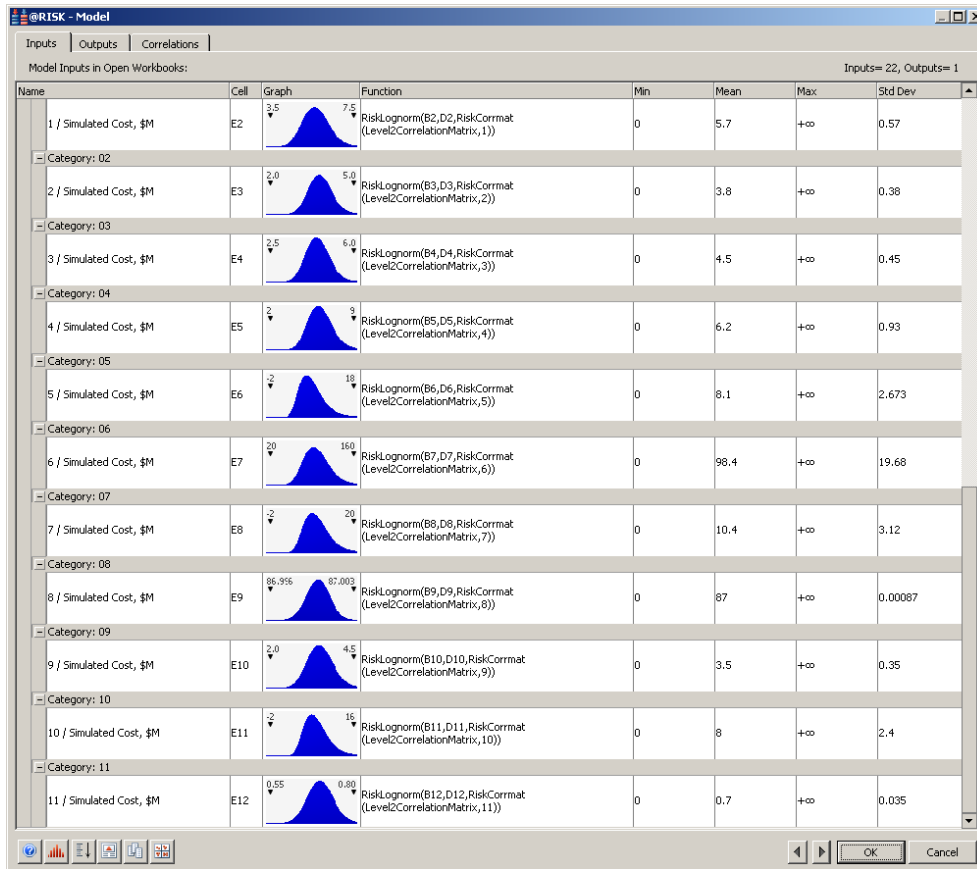


Figure G-19. WBS Distributions (After Correlation)

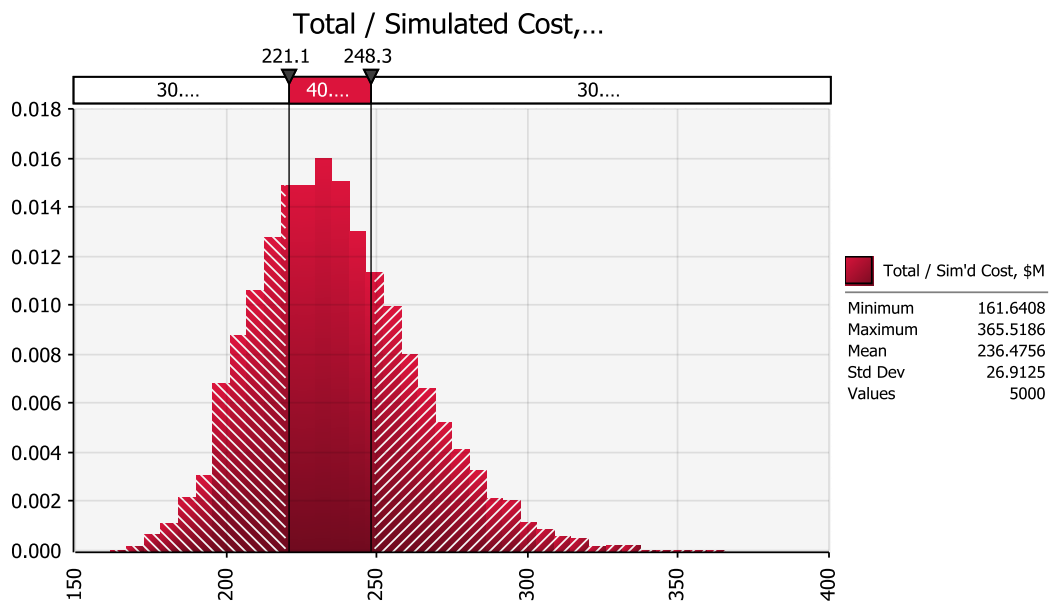


Figure G-20. Probability Density Function

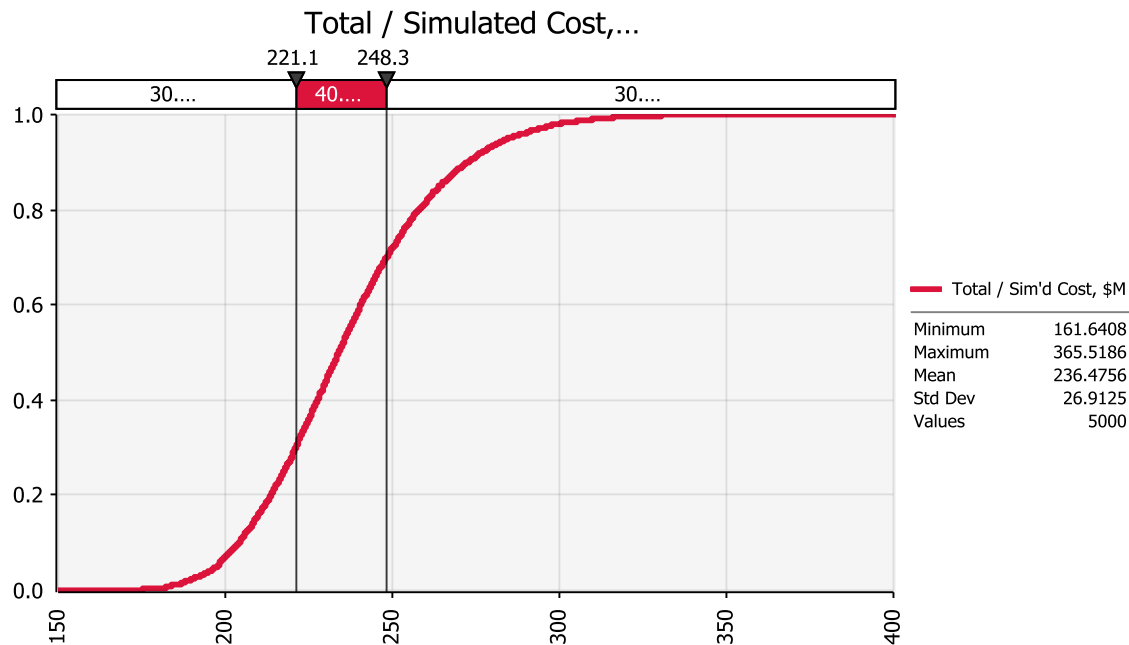


Figure G-21. Cumulative Density Function (CDF) for Total Cost (S-Curve)

### G.5.1. Summary of Results

The PDF shows the likelihood of reaching a particular cost. The first vertical line indicates that there is a 15 percent chance that the cost will be \$221 million, while the second vertical line tells us that there is an 11 percent chance that the cost will be \$248 million.

The CDF or S-curve gives an assessment of the project's cost risk. It is integral to the PDF and tells us several things. The mean or average cost is \$236 million. One standard deviation below the mean is \$209 million. One standard deviation above the mean is \$263 million. Similarly, there is a 40 percent chance that the cumulative cost will be below \$221 million and a 70 percent chance that the cost is below \$248 million.

## Appendix H: Documenting and Presenting the Results

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### H.1. Introduction

An estimate is not complete until it has been documented and communicated to stakeholders. The primary purpose of the documentation is to capture sufficient information and data that allow the reader to understand the scope and content of the estimate and allow another estimator to recreate the estimate. The documentation also supports the conclusions of the estimate and allows for updates to be made throughout the program or project's life cycle. The value of the estimate can be measured by the degree to which the stakeholders understand the estimate, use the estimate to make informed decisions, and take ownership of the estimate. This can only be accomplished by effectively communicating the results to the stakeholders, answering the questions that initiated the estimate, and bringing to light the cost drivers and risks of the system in question.<sup>1</sup>

The ability to document an estimate and clearly communicate the results is vital to establishing the analyst's credibility and, consequently, the credence of the estimate and supporting analyses. Good documentation and presentation cannot overcome a poor estimating job, but poor documentation can hurt the authority of the analysis and hinder the ability of the estimator to convince management of the data's value. Most managers are supportive of cost estimating because of its inherent importance to overall project feasibility and execution, but some view the results with a skeptical eye since cost estimating is neither a precise science nor an engineering discipline. By ensuring that proper care and thoroughness are integral to documentation and communication, cost analysts have the opportunity (and obligation) to overcome management's skepticism and transform it into constructive discussion and interaction. The key is remembering that credibility is earned, not assumed, and can be achieved only through careful documentation and communication.

The emphasis of this Cost Estimating Handbook (CEH) is on the cost and schedule aspects of a project. However, the temporal aspects are equally important, and they are mutually inseparable. Since 2009, senior NASA leaders have asked the cost/schedule/risk community to answer the following question at Key Decision Point (KDP)-C for each new major undertaking: What is the joint probability of achieving a cost that does not exceed \$XX and is completed no later than YYYY? The answer should include relevant aspects of both cost and schedule uncertainty analysis—all applicable risks must be integrated into the documentation package.

This appendix provides guidance on building a solid documentation package; developing presentations for stakeholders and management that clearly communicate the results of the analysis; and using the documentation process to perform an objective, critical assessment of the estimate.

### H.2. Documenting the Cost Estimate

The documentation process is an integral part of developing the estimate and confidence level assessment. Documenting the sources of model inputs, the rationale for model settings, and the conversations with design engineers, etc., become the Basis of Estimate (BOE) and form the foundation for communicating the analysis results to the customer and other stakeholders. Having a well-documented BOE makes it easier for the estimator to revise or update the estimate at any point in the future or for another cost analyst to modify the estimate. Good documentation establishes a credible BOE

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<sup>1</sup> For more detail on this subject, refer to the Association for the Advancement of Cost Engineering (AACE) International Recommended Practices, No. 34R-05, Cost Estimating and Budgeting—Basis of Estimate, May 2007.

that can facilitate reviews by internal organizations such as the NASA Independent Program Assessment Office (IPAO) and external reviewers such as the Government Accountability Office (GAO).

The elements of a good BOE are simple: anything that has an impact on the estimate should be documented. The easiest way to organize the information is by Work Breakdown Structure (WBS) (or Cost Element Structure [CES]) element. The following list gives examples of the types of information that should be included:

- The name and level of the WBS element.
- The type of WBS element (summation or estimating).
- The model (including version number), analogy, or factor chosen, with rationale.
- If the estimate element is a throughput, the source and rationale for the value.
- The calibration data used (if applicable).
- The source for all model inputs, including rationale and documentation to support judgment-based inputs (such as new design and complexity factors).
- Other information that influenced the estimate (e.g., project schedules, milestones, cost-sharing opportunities).
- Backup information such as Master Equipment Lists (MEL), mass properties estimates, design documentation, or conversations with design engineers or technologists (configuration/version information should be included whenever applicable).

The preferred documentation method is a narrative format augmented with tables, figures, and diagrams. While most estimation work is performed using one or more models and/or Microsoft Excel and presented in PowerPoint, both tools have drawbacks when it comes to performing the primary documentation function. PowerPoint files, model data files, and Excel files all make excellent source documents and backup material for the estimate and should be part of the documentation package. A narrative enables the analyst to bring together all of the documentation into a coherent form that can both explain the BOE and provide references and links to source material.

There are barriers to preparing good BOE documentation. Cost estimators and analysts may find documentation work to be tedious and incorrectly conclude that the results are of limited value, especially if they are still working on the project. In many cases, the analysts or estimators are already starting their next big project while completing the current one, leaving little time to prepare a detailed documentation package.

While these are explanations for not properly documenting the estimate, they are not valid reasons for deciding not to do so. Current NASA policy clearly places the cost estimator in the project approval process. While the cost community welcomes the increased visibility of the cost estimation evaluations, it also opens the community up to increased scrutiny, which emphasizes the need to ensure that estimates are credible, supportable, and defensible. Without adequate, detailed BOE documentation, this work can neither be defended nor can it provide the objective and independent cost-voice the Agency needs. An argument can also be made that by documenting assumptions while building the estimate, analysts are less prone to make mistakes and overlook inconsistencies. While this may add time to the estimating task, it may actually save time when deadlines are imminent.

### H.3. Presenting the Cost Estimate

The NASA management culture requires the ability to document the estimate in a well-organized package (combined with good presentation skills). For most studies and analyses, an important element of the

documentation of record is the presentation. Because cost estimation is an inexact science based on historical experiences and subjective judgments, it is vital that the cost estimator prepare a solid presentation package that provides the context and rationale for the estimate in a way that is clearly understood and accepted by the customer and other stakeholders.

It is beyond the scope of the CEH to develop the estimator's presentation skills. NASA offers classes in presentation skills, and every analyst should receive training. However, the CEH does provide the following guidance and recommendations on the content and format of the presentation. For example, the best approach is to develop a presentation that is clear and concise, with sufficient information to ensure that people understand how the results were obtained, but does not incorporate so much detail that the presentation gets bogged down. (Tip: Include the more detailed charts as an appendix.)

The remainder of this section focuses on the content needed to establish the estimate as credible, supportable, and defensible.

### **H.3.1. Presentation Outline**

A typical outline of an estimate presentation includes the following:

- Title Page
- Introduction/Overview/Objectives
- Approach
- Ground Rules and Assumptions (GR&A)
- Cost-Estimate Results (Point, Probabilistic)
- Validation, Sensitivities, Cost-Risk Assessment, and other Analyses
- Findings/Summary/Conclusions

#### **H.3.1.1. Title Page**

Every presentation should begin with a title page. At a minimum, the title page should contain a descriptive title, the name of the presenter, and the date of the presentation. Other information that can be shown includes subtitles; to whom the estimate is being delivered; affiliation of the presenter; contact information of the presenter; and names, affiliations, and contact information for other estimators who participated in the estimate.

#### **H.3.1.2. Introduction**

The introductory section can cover several topics including an agenda or table of contents, a roster of the estimating team (for a large effort), and an overview or description of the system being estimated. Care should be taken to clearly identify the configuration information of the system along with the description. This information should include the actual design configuration and version number. The introduction should include a description of the intended scope of the estimate, as well as a reference to the date of the source information.

#### **H.3.1.3. Approach**

The approach section describes the methods and rationale that the estimator used to perform the estimate, with any limitations from the intended scope of the estimate described. Depending upon the size and complexity of the problem, the approach section can be large or small. Typical content includes the following:

- The estimating WBS (at the appropriate level).
- A flow chart of the estimating process.
- A detailed description of all the models used, the model settings, and the use by each WBS element.
- A model calibration approach, including data used.
- A description of analogy estimates and the adjustment process used for the analysis.
- The throughput costs and sources.
- The key sources of input data used in the estimate.
- For probabilistic estimates, the assumed range and distribution of uncertainties and risks.

Because the level of detail needed to explain an estimating approach can be extensive, backup charts are often used to capture information that either is too detailed for the main body of the presentation or would not be needed for most audiences.

### **H.3.1.4. GR&A**

The GR&A capture the decisions made by the analyst (in consultation with the customer or design team) in performing the estimate. These decisions are often termed engineering judgment, analyst assumptions, or estimating ground rules. Areas addressed by the GR&A include the following:

- The assumptions about the hardware development approach and the amount of systems test hardware.
- The Base Year (BY) dollars of the estimate and inflation factors used.
- The number of flight articles produced.
- The life-cycle content of the estimate.
- The schedules and milestones.
- The contractor labor rates and fee percentage.
- The technology readiness level of key components.
- Any reserve or contingency factors.
- The identification of any elements that are absent or missing (e.g., mission operations costs).

Overlap between the GR&A and the approach section is not uncommon. Key information affecting the estimate, such as the quantities of systems test hardware or the development schedule, can be documented in either (or both) section. It is reserved to the judgment of the estimator to determine how best to present the data.

### **H.3.1.5. Cost Estimate Results**

The cost estimate should be a logical outcome of the approach taken to solve the estimating problem. The estimator must decide on how best to present the results.

- A tabular approach works well for presenting detailed subsystem or component-level costs.
- For showing the cost of several alternative concepts, bar charts make quick comparisons easy.
- Line charts or area charts are good for showing the costs phased over time.

- When showing the cost of several major elements over time, sand charts (or stacked charts) are often used.
- Pie charts are useful for illustrating the composition of a cost estimate.

There are two important criteria for designing the charts in the results section. The first criterion is the level of detail needed for the audience. Generally, the higher the level of management, the less detail is needed in the results. Also, less detail is usually required for an informational briefing versus a review. The second criterion is the point that the analyst (or manager) is trying to make. While the cost estimate itself is usually the point of the presentation, there may be secondary messages that the customer is trying to communicate. For example, the study lead for a technology demonstration mission may want the estimator to highlight the impact of technology maturation on the estimate, or a Launch Vehicle (LV) design team may want to emphasize the effect a legacy design has on reducing the cost. It is incumbent upon the analyst to take these considerations into account when developing the charts, but not become overly influenced to the point where the presentation fails to establish the credibility of the underlying cost estimate.

### **H.3.1.6. Validation, Sensitivities, Risk Assessment, and Other Analyses**

The presentation of any supporting analyses should follow the same general guidelines as the presentation of the primary estimate results. The charts should clearly state the reason for the analysis, the method and approach, any GR&A, and the results. The goal is to present an analysis that is credible, supportable, and defensible. To that end, the analyst should ensure that key details such as supporting data, rationale, and assumptions are readily apparent either in the primary presentation or in backup charts. Sensitivity plots can also be included to demonstrate which assumptions within the estimate drive the results and which allow visualization of the magnitude of variation within those assumptions.

### **H.3.1.7. Findings/Summary/Conclusions**

The final section of the presentation is an opportunity for the estimator to summarize findings or conclusions. The summary/findings/conclusion section does not need to be long—probably only a chart or two. However, it should bring the presentation to a close, provide a logical exit for the estimator, and serve to reinforce the key conclusions.

Sometimes the analyst will use the end of the presentation to present a forward work plan. The forward work plan lists tasks that the analyst has identified as necessary to either complete or improve the estimate. The analyst should be prepared to discuss a time period for completing the tasks when presenting a forward work plan.

## **H.4. Critical Assessment of the Estimate**

Good estimate documentation allows the analyst to perform a critical assessment of the estimate, either individually or with the help of other estimators. A critical assessment is vital to ensure that the estimate is credible, supportable, and defensible. The customers and stakeholders will perform a critical assessment as part of their normal reviews; therefore, by using the documentation to perform a critical assessment prior to presenting the results to customers and stakeholders, the estimator will be prepared with results that stand up under scrutiny.

The easiest approach to performing a critical assessment is to simply question every aspect of the estimate. The better the answers the analyst can provide, the more credible, supportable, and defensible the estimate. Examples of these questions include:

- Does the WBS cover everything that needs to be included in the estimate?
- Why was a particular model chosen?
- What is the basis of the model?
- What was the source of the input data?
- What is the basis of the more subjective inputs?
- How was the model calibrated?
- How were design inheritance and technology maturity handled?
- What was the source of throughput costs?
- How were uncertainty ranges established?
- Were all identified discrete risks included in the estimate?
- How was the estimate validated?
- Are there alternative approaches, methods, models, etc., that would have yielded better results?

Objectively assessing the estimate improves its credibility in four ways. First, it forces the estimator to revisit all assumptions, judgments, models, etc., in order to understand the rationale behind the estimating approach. Second, the objective assessment, especially when performed with help from other cost analysts, will identify areas in the estimate that are either missing or not well supported. Third, it provides a final sanity check to ensure that overall trends and behavior are intuitive within the estimate. Most stakeholders have the experience and intuition to expect certain logical trends within the data (i.e., subsystem X is generally more expensive than subsystem Y), and many will be quick to identify inconsistencies. Some counterintuitive trends may be correct, but the estimator needs to know how to explain them. Lastly, it helps improve the presentation by anticipating other questions that the stakeholders may ask.

By reviewing the estimate, the estimator is better prepared to defend his or her work. Identifying weaknesses in the estimate gives the estimator the opportunity to take corrective action to either fill holes or improve the quality of the estimate. In cases where the estimate is weak for a valid reason, such as lack of data, the analyst will be aware of the weakness and prepare a forward work plan to address those weaknesses. By anticipating potential questions, the analyst can make modifications to the presentation and be prepared to respond to questions from the audience.

## Appendix I: Using Performance Information to Adjust Estimates

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It is important to maintain a good project cost baseline as a forward indicator for potential cost growth. Cost estimates must be updated whenever project content changes and reconciled to the estimate baseline. By accomplishing a cost estimate on proposed program alternatives, the Project Office can determine the cost impact of the alternatives. One of the best ways a project team can update its schedule and cost estimates is to adjust these according to its own performance. Earned Value Management is recognized as a best practice for making such cost and schedule adjustments (e.g., on a monthly or quarterly basis).<sup>1</sup>

EVM is an integrated management control system for assessing, understanding and quantifying what a contractor or field activity is achieving with program dollars.

- Integrates technical, cost, schedule, with risk management.
- Allows objective assessment and quantification of current project performance.
- Helps predict future performance based on trends.

EVM provides project management with objective, accurate and timely data for effective decision-making. There are several handbooks available for the implementation of EVM.<sup>2</sup>

This appendix will be developed in more detail, but the EVM references should provide the analyst with a start for using performance information to adjust estimates. If addition information is desired, contact CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

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<sup>1</sup> EVM information available at <http://evm.nasa.gov/>.

<sup>2</sup> <http://evm.nasa.gov/handbooks.html>

# Appendix J: Joint Cost and Schedule Confidence Level (JCL) Analysis

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Joint Cost and Schedule Confidence Level (JCL) analysis is an integration of cost, schedule, risk and uncertainty. The result of a JCL analysis indicates the probability that a project's cost will be equal to or less than the targeted cost *and* that the schedule will be equal to or less than the targeted finish. The following topics are described in this appendix:

- J.1. JCL Introduction**
  - J.1.1. Purpose**
  - J.1.2. History of JCL Policy**
  - J.1.3. Requirements**
  - J.1.4. Roles and Responsibilities**
  - J.1.5. Data to Conduct JCL at KDP-C**
  - J.1.6. JCL Process Flow**
  - J.1.7. JCL Methodology and Tool Section**
- J.2. Integrated Schedule**
  - J.2.1. Developing a JCL Schedule**
  - J.2.2. Schedule Assessment**
- J.3. Cost Estimating**
  - J.3.1. Cost Loading**
- J.4. Risk Assessment**
  - J.4.1. Risk Management System**
  - J.4.2. Schedule/Cost Uncertainty**
  - J.4.3. Risk Factors**
  - J.4.4. Correlation**
- J.5. Reporting**
  - J.5.1. Cumulative Statistical Results**
  - J.5.2. Scatterplot**
  - J.5.3. Sensitivity Reports**
  - J.5.4. Advanced Results**

## Works Cited

## Acknowledgments

## J.1. JCL Introduction

Joint Cost and Schedule Confidence Level (JCL) analysis is a process that combines a project's cost, schedule, and risk into a complete picture. JCL is not necessarily a specific methodology (e.g., resource-loaded schedule) or a product from a specific tool. The JCL calculation includes consideration of the risk associated with all elements, regardless of whether or not they are funded from NASA's appropriations or managed outside of the project (e.g. a partner contribution).

A JCL identifies the probability that a given project or program cost will be equal to or less than the targeted cost AND that the schedule will be equal to or less than the targeted schedule date. There are two fundamental ways that one could generate a JCL: 1) bivariate distributions<sup>1</sup> and 2) probabilistically cost loading a probabilistic schedule (Probabilistic Cost-Loaded Schedule [PCLS]). Both methodologies will fundamentally produce a JCL; however, to fulfill the intent of the NASA JCL policy requirement, it is intended that a project or program perform the latter (probabilistic cost loading of a probabilistic schedule). Because of this, JCL, as referred to in this appendix, will effectively mean a PCLS.

The rationale for the Agency focusing in on the PCLS methodology stems from the fact that the method forces the project and the review entity to focus on the project's plan. This improves project planning by systematically integrating cost, schedule, and risk products and processes. It also facilitates transparency with stakeholders on expectations and probabilities of meeting those expectations. Lastly, it provides a cohesive and holistic picture of the project's ability to achieve cost and schedule goals and helps the determination of reserves (or Unallocated Future Expenses [UFEs]) for cost and schedule to meet a desired confidence level.

In summary, JCL helps set the foundation to answer fundamental questions: Does the project have enough funds? Can the project meet the schedule? What are the areas of risk toward successful execution of the project? What risk mitigation strategies provide the best project benefit?

### J.1.1. Purpose

A JCL number is the product of a type of process, with the intent to model the programmatic risk of the project or program plan. The purpose of the JCL is to model reality, not recreate it. As with most modeling, there are numerous ways to model any situation. The scope of this appendix does not cover all the procedural modeling techniques that can be performed, but it serves as a foundation for the expectations and understanding of NASA's JCL policy and provides insight to best practices.

It is important to note that the JCL requirement is more than just a policy requirement for an Agency Key Decision Point (KDP). It can also serve as a valuable project management tool that helps enforce some best practices of program planning and control, and it also potentially enhances vital communication to various stakeholders.

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<sup>1</sup> Garvey provides material on using bivariate distributions: Garvey, P.R., 2000, *Probability Methods for Cost Uncertainty Analysis: A Systems Engineering Perspective* (New York: Marcel Dekker).

So before implementing a JCL analysis, consider the following questions. If you can answer in the affirmative to all of them, then implementing JCL should be fairly straightforward. However, if you cannot succinctly answer them, then JCL can help!

- Are current cost, schedule, and risk integrated?
- How confident are you that the project/program will accomplish the planned work with the available funds?
- Do you know where and how your project/program risks may impact the schedule?
- Have you identified and prioritized all of the cost AND schedule drivers to your project/program?
- Can you evaluate the cost effectiveness of your risk mitigation plans?
- Can you quantify and communicate what a reduction in funding will do to the likelihood of success of your project?
- Can you assess alternative scenarios and understand how they impact confidence levels?

### J.1.2. History of JCL Policy

The following section briefly describes the history of NASA current probabilistic policy (commonly known as JCL). The intent of this section is to give the “story” behind the rationale for the current policy. The history of the current Agency probabilistic policy can be best summarized in Figure J-1. The top swim lane illustrates the project, or advocacy, analysis, whereas the bottom swim lane illustrates the independent, or non-advocacy, analysis.

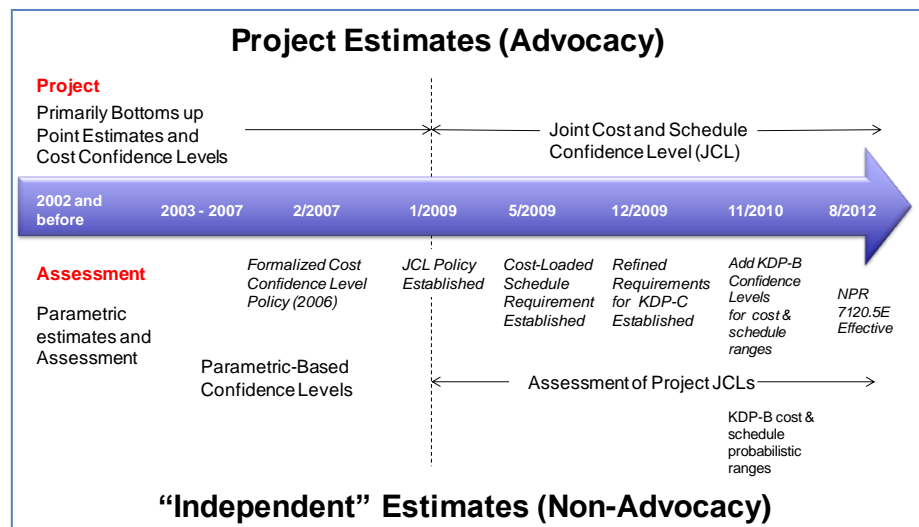


Figure J-1. JCL Policy Timeline

To understand the current situation, it is necessary to go back to 2002. Beginning in 2002, the United States General Accounting Office<sup>2</sup> (GAO) issued reports (United States General Accounting Office, 2002)

<sup>2</sup> Now known as the Government Accountability Office (GAO).

(United States General Accounting Office, 2004) that identified major causes<sup>3</sup> of cost growth including incomplete cost-risk assessment and flawed initial program planning.<sup>4</sup>

The GAO completed a detailed examination of NASA's cost estimating processes and methodologies for various programs. This report made numerous recommendations to establish a standard framework for developing Life Cycle Cost Estimates (LCCEs), which included conducting a cost-risk assessment that identifies the level of uncertainty inherent in the estimate.

Formal probabilistic estimating guidance was first mentioned in February 2006 in an e-mail from the NASA Administrator directing NASA's largest program at the time, Constellation, to budget to a 65-percent confidence level. Noted again a month later at a strategic management meeting in March 2006, "[the NASA Administrator] determined that NASA's standard practices will be to budget projects at a 70% confidence level based on the independent cost estimate...initiate a pattern of honest dealing between Program and Project Managers, HQ, the Congress, and the WH [White House], and to avoid the pattern of finger-pointing for cost overruns and schedule slips that have plagued the industry in the past." Guidance was clarified further in the spring of 2007.

Several issues arose from the initial guidance. First, the lack of formally documented policy guidance hindered effective implementation.<sup>5</sup> Second, by omitting schedule risk in the confidence statement, a vital programmatic variable was inconsistently being utilized. Last, the reconciliation process between projects and the Agency's non-advocate groups was tedious.<sup>6</sup>

In January 2009, NASA's cost estimating policy was updated to address the issues previously mentioned. Policy was inserted in the NASA governance structure<sup>7</sup> and was expanded to specify a JCL.

Though the tools, techniques, and methodologies were well understood and demonstrated in certain industries<sup>8,9</sup>, much of the analysis traditionally had not been done in the aerospace industry on highly uncertain, complex developments. NASA is continually making strides to hone the associated best practices and understanding for JCL analysis.

### **J.1.3. Requirements**

#### **J.1.3.1. Intention of Policy**

Currently, NASA is using a variety of cost analysis methodologies to formulate, plan, and implement projects. In the formulation stage, specifically for KDP-B, NASA is calling for programs and projects to provide probabilistic analysis on both their cost and schedule estimates. This analysis is then used to determine a high and a low estimate for cost and for schedule.

The community has identified two good candidate methodologies for producing the risk estimates and associated results: 1) complete parametric estimates of cost and schedule, or 2) complete a JCL

<sup>3</sup> Additional major causes of cost growth that were cited but are not addressed in this paper or directly with JCL policy include: acquisition workforce problems, "corporate-directed" actions, and competitive environment.

<sup>4</sup> Findings supported by a Booz Allen & Hamilton study for the U.S. Air Force Space and Missile Systems Center, 2002.

<sup>5</sup> Not captured in policy directives or procedural requirements (NASA governance structure).

<sup>6</sup> Project's estimates were typically done based on a project plan using detailed proposal data, grassroots estimates, and subject matter expert adjudications whereas the non-advocate probabilistic estimates were typically done parametrically using key measurable variables to "predict" cost. Reconciling the differences between these two methodologies and effectively informing the decision makers of the causality of the difference was time consuming and very difficult.

<sup>7</sup> Originally NPD 1000.5 and currently in NPR 7120.5E.

<sup>8</sup> For details on the methodology of convolving a probabilistic cost and probabilistic schedule estimate for a JCL, refer to Book, 2007, and Garvey, 2000.

<sup>9</sup> Construction, oil, and gas industries have been doing probabilistic resource analysis for some time.

consistent with policy. It is the viewpoint of the Office of Evaluation, and the majority opinion of the community,<sup>10</sup> that conducting a JCL at KDP-B should not be required. This is primarily because projects typically do not have detailed plans available to support an in-depth JCL analysis, and by design, the requirement at KDP-B is intended to “bound the problem.” Conducting a parametric estimate of schedule and cost utilizes the historical data and performance of the Agency and provides a valuable estimate of the range of possibilities. Attempting a JCL at KDP-B, for these reasons, is therefore not required; however, if a JCL were conducted at KDP-B, it would fulfill the policy requirements of KDP-B because the JCL analysis is more stringent than the KDP-B requirement.

To calculate a JCL, the project should use a rigorous process that combines its cost, schedule, and risk into a single model that can generate a probabilistic assessment of the level of confidence of achieving a specific cost-schedule goal. The rationale for conducting JCL in support of KDP-C is to help ensure that: 1) The project’s plan is well defined and risks are understood, and 2) The risk posture is acceptable for the timeframe and cost to which NASA is committing to external stakeholders. The Agency uses this assessment when considering its external commitment (the Agency Baseline Commitment [ABC] at KDP-C) as one means of ensuring the project has a robust plan with costs linked to schedule, where both are informed by risks.

Once a baseline is approved, NASA policy does not require a project to maintain the analysis models used to calculate the JCL. However, the Agency does utilize a variety of performance metrics to assess how well the project is performing against its plan. If these metrics show that a project’s performance varies significantly from its plan, the project may need to replan, but Agency policy only requires a repeat calculation of the JCL in the event that the project requires a rebaseline. JCL analysis can provide valuable insights as a management tool; however, the only Agency requirement for JCL is at KDP-C.

### J.1.3.2. Policy Summary

In summary, NASA Procedural Requirements (NPR) 7120.5E (<http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>) directs projects to generate a probabilistic cost-loaded schedule and produce a JCL for KDP-I/C<sup>11</sup> that is executable within the available annual resources. This JCL analysis will be evaluated by a non-advocacy body. The Decision Authority (DA) will determine the JCL (probability) for the associated development and life-cycle cost at which the Agency commits to deliver the program/project. It is recommended per policy that the JCL value be at 70 percent confidence for the ABC with a minimum value of 50 percent for the Management Agreement (MA), although the DA can adjust the confidence level with documented rationale.

### J.1.3.3. Policy Specifics

Specifically, the relevant language from NPR 7120.5E reads as follows<sup>12</sup>:

*Tightly coupled and single-project programs (regardless of life-cycle cost) and projects with an estimated life-cycle cost greater than \$250 million shall develop probabilistic analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met in accordance with the following requirements.*

*At KDP I/KDP C, tightly coupled and single-project programs (regardless of life-cycle cost) and projects with an estimated life-cycle cost greater than \$250 million shall develop a resource-loaded schedule and perform a risk-informed probabilistic analysis that produces a JCL. The JCL*

<sup>10</sup> As discussed at the NASA Executive Cost Analysis Steering Group (August 2011).

<sup>11</sup> Key Decision Point I or Key Decision Point C. If it is a program, then KDP-I is appropriate, and if it is a project, KDP-C is appropriate.

<sup>12</sup> Language is taken directly out of NPR 7120.5E Section 2.4.

*is the product of a probabilistic analysis of the coupled cost and schedule to measure the likelihood of completing all remaining work at or below the budgeted levels and on or before the planned completion of Phase D.*

*Mission Directorates shall plan and budget tightly coupled and single-project programs (regardless of life-cycle cost) and projects with an estimated life-cycle cost greater than \$250 million based on a 70 percent joint cost and schedule confidence level, or as approved by the Decision Authority.*

*Any JCL approved by the Decision Authority at less than 70 percent shall be justified and documented.*

*Mission Directorates shall ensure funding for these projects is consistent with the Management Agreement and in no case less than the equivalent of a 50 percent JCL.*

*When a tightly coupled program, single-project program, or project with an estimated life-cycle cost greater than \$250M is rebaselined, the JCL should be recalculated and approved as a part of the rebaselining approval process.*

*Loosely coupled and uncoupled programs are not required to develop program cost and schedule confidence levels. These programs shall provide analysis that provides a status of the program's risk posture that is presented to the governing PMC as each new project reaches KDP B and C or when a project's ABC is rebaselined.*

#### **J.1.3.4. Policy Clarifications**

There are several general areas of the policy that warrant additional clarification.

##### **J.1.3.4.1. Resource-Loaded Terminology**

The policy clearly states that the projects are required to generate a *resource-loaded* schedule. This terminology can be confusing and deserves some attention. NASA's definition of resource loading is the process of recording resource requirements for a schedule task/activity<sup>13</sup> or a group of tasks/activities.<sup>14</sup> The use of *resource loading* implies, to many people, that the tasks need to be loaded with specific work or material unit resources. This is NOT the intent of the policy. In general, the terminology of *resource-loaded* schedule can be used interchangeably with *cost-loaded* schedule. The intent of the JCL policy is not to recreate the lower level management responsibilities of understanding and managing specific resources (labor, material, and facilities) but to instead model the macro tendencies and characteristics of the project. To do this, *cost loading* a schedule is sufficient and a resource-loaded schedule is not required.

#### **Resource Loading vs. Cost Loading**

If there were two individuals who were needed to perform a task (Person A and Person B), then to resource-load each person to that task we would identify how many hours each person would put on that task and their associated labor rate. However, with regards to cost loading, we are only interested in the total effort, measured in dollars, of the entire team (Persons A and B). For a JCL, cost loading a schedule is sufficient and a resource-loaded schedule is not required.

<sup>13</sup> The terms "task" and "activity" are utilized interchangeably in this document.

<sup>14</sup> NASA Schedule Management Handbook, 2010.

#### **J.1.3.4.2. Risk-Informed**

The policy states that a project will need to perform a *risk-informed* probabilistic analysis to produce a JCL. NPR 7120.5E defines risk as “the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly, established and stated performance requirements.” Typically, from a risk-management perspective, discrete risks are identified and tracked, and mitigation plans are formulated. By *risk-informed*, the policy is stating that all appropriate discrete risks be modeled, but it is also the intent of the policy for *risk-informed* to also account for various uncertainties (that may not be discretely managed in the risk management system). Formal definitions within the context of JCL on what risk and uncertainty are will be discussed later and are summarized in the risk assessment section of this appendix.

#### **J.1.3.4.3. Life-Cycle Costs and Schedule**

It should be made clear that the scope of the JCL analysis typically includes content only through Phase D. This, by definition, is not the total life-cycle cost (as defined by NPR 7120.5E) or operational life of a project. The exact content of what is included in the costs and schedule to meet this Phase D requirement needs to be agreed upon between the project and the non-advocacy entity, as typically defined in the Terms of Reference (ToR) for the Non-Advocate Review.

#### **J.1.3.4.4. Scope**

**International/Interagency Contributions and Inter-Project/Program Risks.** With regards to International/interagency contributions and inter-project/program risks, the project is tasked to include the programmatic risk of cost and schedule impacts to the project stemming from those systems. The project should coordinate with the international, interagency, and inter-project/program entities when available, as well as coordinate with its mission directorate, to determine the adjudication and communication of the risks (ownership). Further work should be performed to determine how those risks will be incorporated and communicated in the range and JCL calculations. The non-advocacy review will have the responsibility to evaluate all aspects of the range and JCL analysis—including international/interagency and inter-project/program relationships.

**Launch Vehicle Costs.** Over the last few years of JCL policy implementation, there have been some misunderstandings on how to handle the risk associated with the launch vehicle (LV) costs in the JCL calculations. These misunderstandings dealt less with the mechanics of how to “add” the LV costs and the associated risks—as the LV costs and the risks are already captured in both the management and Agency cost commitments—but more with who should take ownership over the project life-cycle JCL analysis, which includes the LV. The issue of ownership over the project life-cycle JCL analysis (which includes LV) is discussed in the specific context of the Science Mission Directorate (SMD) missions; therefore, the following is not intended to add clarification on JCL calculations or life-cycle scope inclusion for programs/projects that fall under other NASA directorates.

In summary, the LV costs shall be included in range and JCL calculations. SMD, through its coordination with the Human Exploration and Operations (HEO) Mission Directorate and Kennedy Space Center (KSC) Launch Services Offices, will continue to be responsible for communicating the LV costs and risks to the project and for ensuring that they are integrated into the entire project scope (including LV) for the decisional PMC. The non-advocate review team shall evaluate all aspects of the JCL analysis, as well as the integrated analysis, in support of the KDP-C milestone.

### **J.1.4. Roles and Responsibilities**

This section is to help the reader understand the core roles and responsibilities when implementing a JCL. This section is divided into three areas: Data to conduct the JCL, NASA Agency roles, and project-specific roles.

#### **J.1.4.1. Primary Roles in JCL Analysis**

There are several stakeholders with direct impacts on the JCL process:

- Project managers:
  - The Project managers “own” the project advocate JCL analysis. This means that planning, developing, iterating, and presenting the results of the advocate JCL model is the project’s responsibility.
- Mission Directorates:
  - Serve as co-owners of the KDP-C Decision Memorandum, where JCL results are documented in support of external commitments.
  - Monitor project JCL status and adjudicate UFE allocation.
  - Have the ability to provide external risks to the project in support of JCL analysis.
- Office of Evaluation (OoE):
  - Independent Program Assessment Office (IPAO) supporting the Standing Review Board (SRB):
    - Facilitates SRB evaluation of a project’s JCL whenever a project is reviewed at KDP-C.
    - When requested, facilitates SRB evaluation of the project’s JCL whenever there is a Special Review or Rebaselining.
    - Provides benchmark analysis for comparing the project’s cost loading and schedule activity duration estimates.
  - Cost Analysis Division:
    - Agency JCL policy advocate.<sup>15</sup>
    - Coordinates and recommends Agency JCL policy, including derived requirements and implementation procedures.
    - Approval authority for JCL waiver requests.
    - Provides “jump start” advice and consulting support so programs and project may develop their JCLs.
    - Communicates requirements and orchestrates requisite education and training.
    - Provides access to Agency tools (e.g., Joint Analysis of Cost and Schedule [JACS] and POLARIS) and data (e.g., Cost Analysis Data Requirement [CADRe]).
- Office of the Chief Engineer (OCE):
  - Owner of NPR 7120.5E, where the JCL requirement resides.
  - Coordinates, with OoE/Cost Analysis Division (CAD), on JCL waiver requests.
  - Advises Baseline Performance Review (BPR) leadership on project performance that may lead to a rebaseline and require a new JCL per NPR 7120.5E.

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<sup>15</sup> NPR 7120.5E is available at [http://nodis3.gsfc.nasa.gov/lib\\_docs.cfm?range=1](http://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=1).

- Office of Chief Financial Officer (OCFO):
  - Serves as co-owner of the KDP-C Decision Memorandum, where JCL results are documented in support of external commitments.
  - Serves as owner of the Major Program Annual Report (MPAR), which contains JCL results and performance status, and is provided to the external stakeholder (e.g., Congress, OMB).
  - Advises CAD on waiver requests.
  - Advises BPR leadership on project performance that may lead to a rebaseline and require a new JCL per NPR 7120.5E.

#### J.1.4.2. Project-Specific Roles and Responsibilities

There are several key functions to be performed within the project; they are defined below.<sup>16</sup> Identifying roles and responsibilities early is very important to a successful JCL.

- JCL Leader: The JCL leader is the one individual responsible for coordination and integration of the JCL. This person should have a good understanding of the project plan including cost, schedule, and risk.
- Scheduler: This function is one of the most important functions in the JCL effort. This person must have intimate familiarity with the current project schedules. This person should have the expertise to construct a JCL schedule, if needed, and should be able to reach back to the technical experts.
- Estimator or Resource Analyst: This individual must be familiar with project current budget structure; cost estimates, including Basis of Estimates (BOEs); and resource plan(s).
- Risk Manager: The Risk Manager must be familiar with the current project risk management system. This person must be able to provide details supporting the risk register and should be able to reach back to the risk “owners” when needed.

Regardless how the functions get parceled out, it is important that the following fundamental questions get answered when initiating a JCL:

- Who is in charge of the JCL effort?
- Who will ultimately be responsible for the development of the model and analysis (who will run the model)?
- Who will build the analysis schedule?
- Who has access to the detailed cost data?
- Who can link the cost data to schedule tasks on the analysis schedule?
- Who can provide the risk information?
- Who can solicit and develop uncertainty data?

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<sup>16</sup> These roles are listed by responsibility. Though it is very important to have each function represented, the people-to-function ratio does not have to be 1 for 1.

### **J.1.5. Data to Conduct JCL at KDP-C**

The following section describes core informational products that will be needed to perform JCL analysis.

#### **J.1.5.1. Schedule**

Schedules should be sufficiently detailed to allow for an accurate and complete understanding of the entire task/project. Schedules perform best when they are integration focused and suitable for risk analysis. Detailed Integrated Master Schedules (IMSs) should be utilized, and they should be linked to any integration/analysis/summary<sup>17</sup> level schedule that is used to perform a JCL at KDP-C. For example, an IMS may inform an analysis level schedule, which forms the basis of the JCL model. In general, it can be difficult to perform a JCL on an IMS, and it is often recommended that schedules are appropriately summarized into an analysis schedule with the emphasis on the ability to conduct a schedule risk analysis (see the detailed discussion in J.2.1.1.). It is important to understand where discrete risks may occur in the plan and how historical uncertainty in task durations affects the plan.

#### **J.1.5.2. Cost**

The general approach to estimating costs should be consistent with Section 2 of the Cost Estimating Handbook. Some general key characteristics that must be adhered to in a JCL analysis are as follows (for more information, please see section J.1.6.3.):

- The cost estimate will need to be linked to the schedule (e.g., cost-loaded). As a note, by loading the cost estimate to the schedule, a phasing profile will be a resulting output.
- Allocated costs in the schedule will need to be characterized as time independent or time dependent (see section J.1.6.3.).
- Careful consideration needs to be made on what level of risk and uncertainty is inherently in the cost estimate (see section J.1.6.4. and J.1.6.5.).

#### **J.1.5.3. Discrete Risk List and Uncertainty Data**

The project should have a risk management system that is identifying and quantifying the known risks associated with the plan. It is important to note that the project must account for and is responsible for risks that may not be the direct responsibility of the project (e.g., the risk of an international contribution not coming in at the scheduled date). The risk list should be robust and capture as much risk as possible. Oftentimes, projects may capture only the top x number of risks; however, for a successful and informative JCL analysis, this is not desirable. Risk should be individually identified and quantified (likelihood of occurrence, cost, and schedule impact) and be mapped to an activity within the JCL schedule. CAD resources such as historical CADRe data capture historical project risks that can be helpful in ensuring a more complete risk list.

Schedule task durations and costs associated with those tasks should include uncertainty to the baseline plan. Examples of inputs to such uncertainty factors can be historical data, Subject Matter Expert (SME) opinion, or past performance data—see section J.4.2. for more details.

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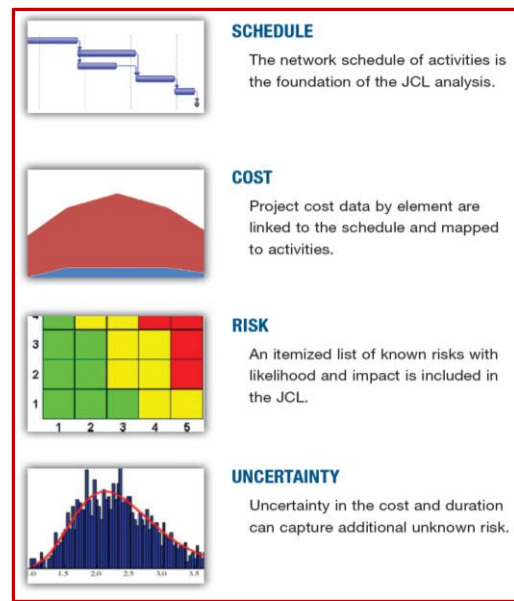
<sup>17</sup> The terms “integration,” “analysis,” and “summary level schedules” are used in the context of the JCL analysis interchangeably; however, the term “analysis schedule” is typically used to circumvent confusion. Succinctly, an analysis schedule is a logically linked schedule that is informed by the logic of the IMS; however, the detail of the schedule is rolled up to a higher level. For example, an IMS may have several activities that describe the many aspects associated with a thermal vacuum test, whereas an analysis schedule may show the test as one summarized activity.

### J.1.6. JCL Process Flow

This section mirrors the pattern of Section 3 of the Cost Estimating Handbook, but with more depth, as required by an actual cost estimator or analyst. The steps below are each amplified in sections J.2. through J.5.

In general, there are five fundamental steps in building a JCL with one prerequisite step.

- Step Zero: Identify goals for the JCL
- Step One: Build a JCL schedule/logic network (a summary analysis schedule)
- Step Two: Load cost onto the schedule activities
- Step Three: Incorporate risk list
- Step Four: Conduct uncertainty analysis
- Step Five: Calculate and view results, and iterate as required



#### J.1.6.1. Step Zero: Identify goals of JCL

As stated previously, JCL is a policy requirement, but it can also be a very valuable management tool. There are certain quality standards that must be met to satisfy policy. However, depending on goals and expectations of the JCL analysis, you may want to set up the JCL analysis to assist and be synergistic with other products and processes. When setting up the JCL process, especially the schedule, it is important to think about what questions you want the JCL to answer, who will be the primary users and beneficiaries, and what fundamental insight you want to see.

#### J.1.6.2. Step One: Schedule Network/Logic Network

The backbone to the entire JCL analysis is the schedule. Having a quality schedule with logic networking is key to a successful JCL. For more information on developing a schedule, please refer to the NASA Schedule Management Handbook.<sup>18</sup> For purposes of this illustrative example, it is assumed that your project has set up a very simple schedule.<sup>19</sup> Figure J-2 shows a simple schedule with two parallel activity streams, one with three tasks and one with two tasks, converging on a single integration task. Once that integration task is complete, the project is complete.

As you will notice, the schedule is logically linked, meaning that you can see the predecessors and successors for every task. You may also notice that the project's milestone, in this case Project End, is linked in the schedule network too. This will allow you, as you progress through the JCL steps, to understand how that milestone may ebb and flow to the left and right.

<sup>18</sup> [http://www.nasa.gov/pdf/420297main\\_NASA-SP-2010-3403.pdf](http://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf)

<sup>19</sup> Note that this example analysis schedule is extremely simplified—a high-level schedule of a typical spacecraft system will have much more detail than this.

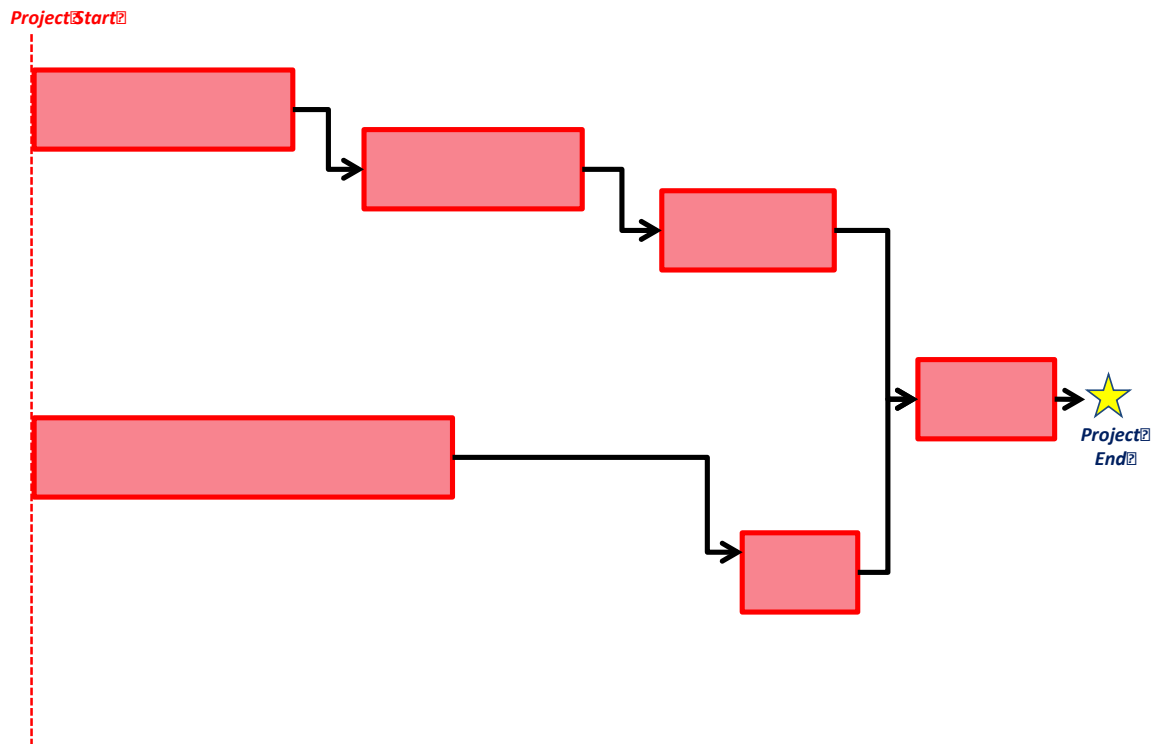


Figure J-2. Summary Schedule

### J.1.6.3. Step Two: Cost Loading the Schedule

Once a robust schedule that accurately portrays project work flow is established, the next step is to cost-load the schedule. Cost loading is accomplished by mapping cost to schedule. You want to load the cost effort for each task by how that cost (or effort) interacts with the schedule activity.

To do this, distinguish cost into two characteristics: time dependent (TD) and time independent (TI) costs.

TD costs are defined as those costs associated with effort that is based on the duration of a task. TD costs are periodic (daily, monthly, quarterly, annual) values that result in total cost as a function of total duration multiplied by the appropriate periodic value (burn-rate). Many tasks on a program/project display this behavior. Common examples are rent, utilities, facility maintenance, sustaining operations, program management, system engineering, quality assurance, other periodic fixed expenses, and other tasks which display a Level of Effort (LOE) nature.

TI costs are defined as those that are associated with the total effort to be conducted for a task irrespective of overall duration. The overall duration of TI costs are primarily a factor of three variables: 1) scope of work to be conducted; 2) productivity of the staff performing the work; and 3) achievable staffing level based on resource and fund availability. The overall duration of the task is thus determined by the effort required for its completion, and the costs are not a function of time but rather scope; while for TD elements, cost is a direct function of duration. Many tasks on a program/project display this behavior. Common examples of TI costs are materials, tests, and one-time expenses.

Figure J-3 illustrates how time dependent costs can spread over separate tasks.

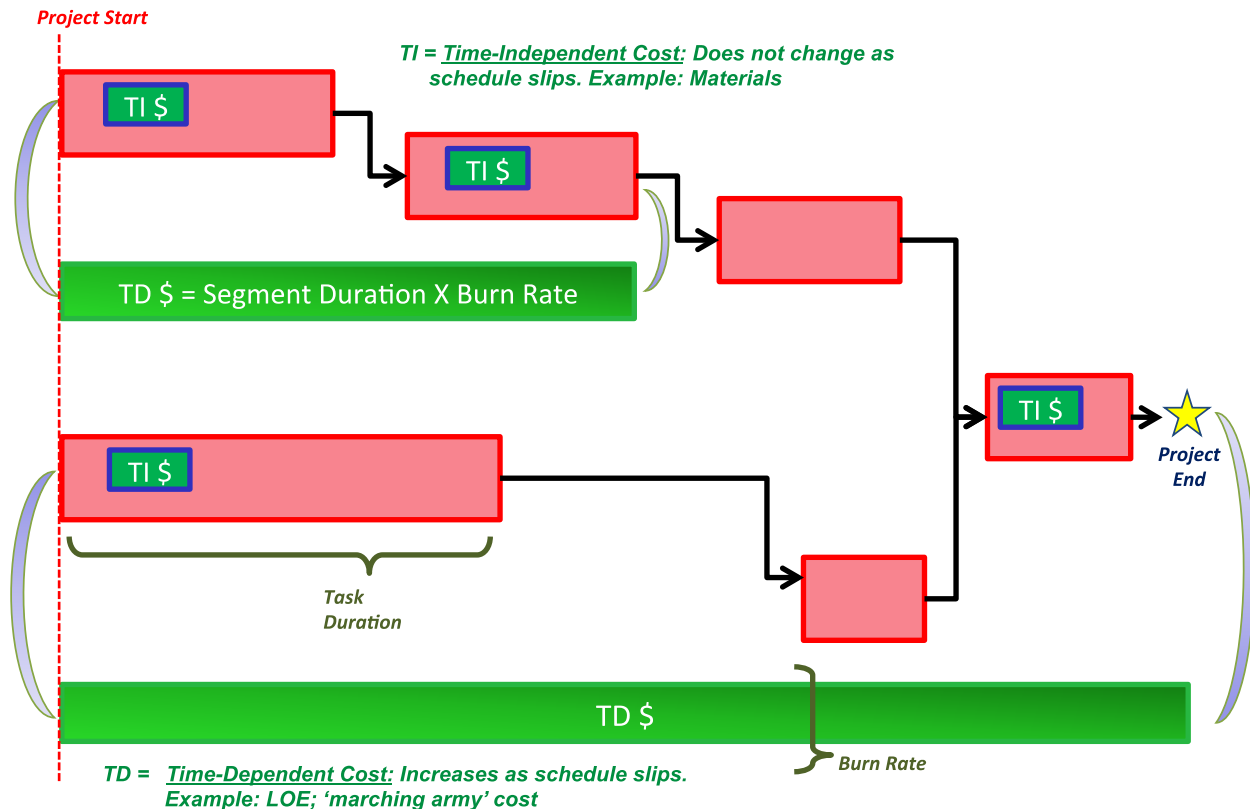


Figure J-3. Cost-Loaded Schedule

This example shows two sets of TD costs. One set expands across the entire project. This implies that there is a “standing army” of personnel that will follow the project regardless of where it is in the life cycle (i.e., project management). Another observation is that there are two tasks that do not have TI costs. This is not to imply that there are no costs associated with these tasks—in fact there are TD costs—it does show that these tasks are LOE tasks that are executed only by the TD resources or costs.

#### J.1.6.4. Step Three: Incorporate Risk List

So far, the schedule represents the baseline plan for the project (cost and schedule). All durations and cost assumptions may have risk mitigation (for costs and schedule) embedded in the plan, but risk realization from the risk management system has not been incorporated. Traditionally, NASA programs will utilize their risk management system to help populate these risk tasks; however, a JCL analysis does not have to be limited by what is currently being managed in the risk management system. For example, there may be a programmatic risk that does not “make it” in the risk management system but still is of concern to the project manager. The JCL analysis allows the project to model the programmatic consequences and expected value of these risks.

Figure J-4 demonstrates how to incorporate discrete risks into the system. From a schedule perspective, a risk event is treated the same way as a task; however, in the schedule, the risk event task only occurs *x* percent of the time as specified by the discrete risk’s probability of occurrence. Capturing risks and adding them into the schedule is introducing the first probabilistic aspect of JCL. From a static viewpoint, it looks like the risk is just a task, but when you start to run simulations, the risk event will only occur *x* percent of the time. When the risk event does not occur, the task and associated dollars will essentially default to zero; however, when the risk does occur, the task takes on the defined duration and dollar impact. The duration impact when the risk occurs can be considered the duration consequence of that

risk. You may notice that there are only TI associated costs with the risk. These costs would be the direct cost impact of the risk occurring. The duration impact of the risk affects the start date of the successor task. This impact could cause the timeframe of the TD costs on the bottom to expand. This potential expansion captures the indirect risk dollars associated with the discrete risk. When a project identifies risks for a JCL analysis, it is important that it identifies the activities the risk affects, the probability of occurrence of the risk, and the consequence (in both direct cost and direct schedule) of the risk happening.

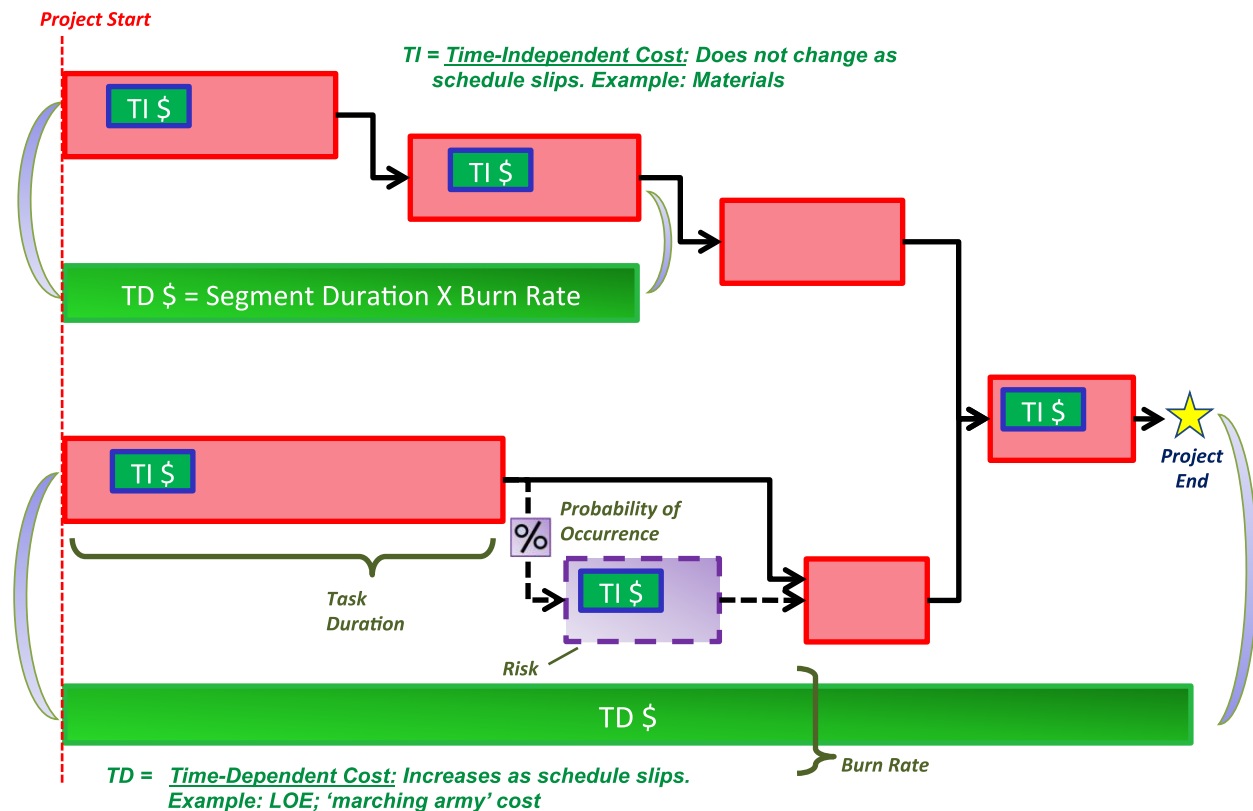


Figure J-4. Schedule with a Discrete Risk

#### J.1.6.5. Step Four: Conduct Uncertainty Analysis

Step 4 to performing a JCL is identifying and implementing the uncertainty. To this point in the JCL process, the primary driver of the JCL results is the quantitative risk assessment and the effect it has on the risk-adjusted cost and schedule. While the risk assessment provides a snapshot in time of potential future events that may cause the project to overrun, it does not account for two key facets that have the ability to drive cost and schedule.

- **Incomplete Risk Register:** Although NASA's Continuous Risk Management (CRM) process aims to create as comprehensive a risk register as possible, it is unrealistic to predict all events with the possibility to increase cost or schedule.

#### Tip:

History and experience have shown that the variance in a typical JCL model is driven significantly more by the uncertainty inputs than the discrete risks. With this said, it is essential to consider uncertainty when conducting a JCL analysis.

- Uncertainty in the Baseline Estimate: Disregarding risks altogether, it is impossible to predict the time or budget required to complete various segments of space-vehicle research, development, and production.

In recognition of these two facets, you or you in collaboration with your designated JCL analysts must account for uncertainty in their baseline cost and schedule plans. For the purposes of JCL, it is important to further distinguish between risk and uncertainty as they are distinct inputs to the JCL model.

For JCL analysis, risk and uncertainty are defined as the following:

Risk is an event not in the project's baseline plan that is an undesirable<sup>20</sup> outcome (discrete risk). This definition is similar to what is seen in a risk matrix. The event is characterized by a probability of occurring and an expected impact if the event did occur.

Uncertainty is the indefiniteness about a project's baseline plan. It represents our fundamental inability to perfectly predict the outcome of a future event.

For a seasoned cost or schedule risk analyst, it is clear that there is an overlap between these two terms. The indefiniteness of a project's baseline plan is partially caused by risks to the project. In traditional, inputs-based cost-risk analysis, discrete risks are not included as inputs, as they would likely cause double-counting when uncertainties in the technical inputs and cost outputs are accounted for. In JCL, analysis risks from the project's risk register are modeled alongside uncertainties applied to the baseline plan. This is done to increase the usefulness of JCL analysis to a project manager; being able to discern the effect each risk has on a project's cost and schedule allows for the development of risk mitigation plans.

To avoid double counting, special care must be taken to segregate uncertainty caused by risks already being modeled in the JCL simulation from the underlying uncertainty of the project's plan once these risks have been discounted. Although it is surely the case that this segregation can never account for all aspects of double counting, the benefit to project managers of getting to see risks outweighs the potential for slight errors in the analysis.

Typically, uncertainty is modeled using a three-point estimate. The low value represents the low extreme of uncertainty, the middle value represents the "most likely" value of the cost or duration, and the high value represents the high extreme of uncertainty. Please note, the baseline plan may not be any one of these numbers (low, middle, high) but should be within the range of low and high. Please refer to Figure J-5 for a visual representation.

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<sup>20</sup> Risks can also be opportunities if the outcome of the event is a positive outcome.



The process shown above should be considered iterative. However, at any point in the JCL iteration process, the final and key step is interpreting the results of the analysis. A more exhaustive list of possible output reports are shown in section J.5. With that said, it is important to explain briefly the most commonly used JCL chart, the scatterplot. A JCL calculation result, commonly referred to as a scatterplot, is graphically depicted as follows in Figure J-6.

## Appendix J

### JCL Analysis

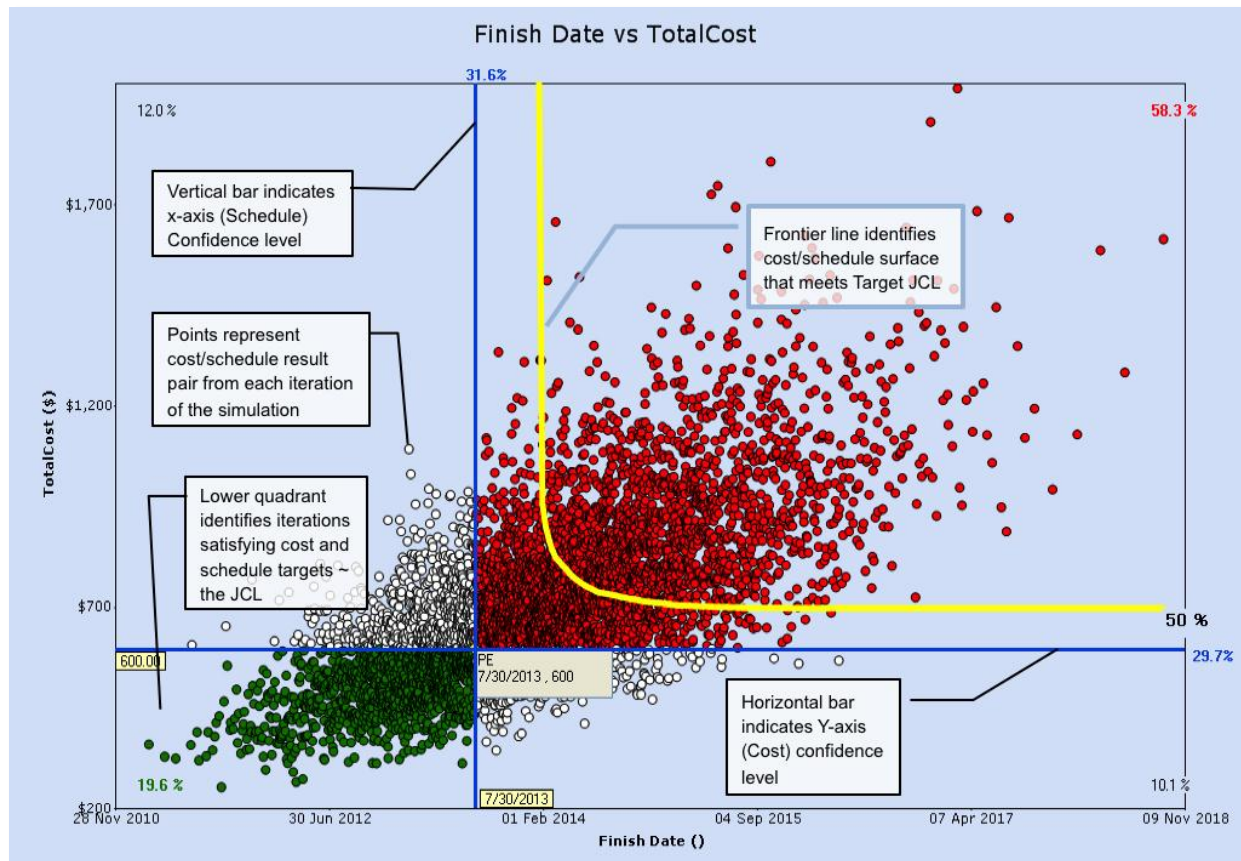


Figure J-6. Scatterplot

The crosshair can be moved to a date and cost to obtain their joint confidence. The horizontal bar of the crosshair indicates the cost confidence level whereas the vertical bar of the crosshair indicates the schedule confidence level.

The yellow line represented in this pictorial above represents the "frontier curve," or indifference curve, that specifies all the cost/schedule combinations that will meet a targeted JCL. In this example, the frontier curve represents the 50-percent JCL frontier curve. Note that the asymptotic tails shown are purely academic; it is recommended to be as close to the center of the cluster for that given frontier curve.

#### One Last Note:

The scatterplot is *only* valid for the current plan and should be considered a snapshot in time. If the project changes its baseline plan, due to factors such as a funding or schedule increase or technical challenge, this will fundamentally change the project's risk posture, and you will need to rerun the JCL. The scatterplot only illustrates protection scenarios—it does not provide guidance and should only be used as a starting point to trade off cost against schedule.

## **J.1.7. JCL Methodology and Tool Section**

### **J.1.7.1. JCL Calculation Methodology**

JCL is a broad term, and there are two broad approaches to completing a JCL: 1) bivariate independent cost and schedule distributions<sup>21</sup>, and 2) probabilistic cost-loaded schedule (PCLS)<sup>22</sup>. Both methodologies will produce a JCL; however, to fulfill the intent of the NASA JCL policy requirement, it is intended for a project or program to perform the PCLS. NASA is actively implementing PCLS to link NASA's commitment probabilistically to the project's specific plan. For a more detailed discussion on the attributes of both methodologies, please refer to Table J-1. The Agency uses the PCLS assessment method when considering its external commitment (KDP-C) as one means of ensuring that the project has a robust plan with costs linked to schedule, where both are informed by risks. With this said, the bivariate distribution method can be utilized as a cross-check to a project's PCLS analysis.

**Note:** There are several ways one could categorize the taxonomy of JCL methodologies and techniques. The authors chose, in this case, to focus on the two overarching methodologies and do not address the pros and cons of various techniques within the methodologies.

### **J.1.7.2. Tool Suites**

There are multiple tools that can be utilized to perform a JCL analysis. The Cost Analysis Division—that oversees the JCL policy implementation for NASA—recommends a set of tools to use; see Appendix E for more information. Most tools that perform probabilistic schedule risk analysis can be used to perform the basic functions needed to fulfill the JCL policy. It is important to note too that the capabilities of the industry are improving at a rapid pace.

Selection consideration should also be based on a firm understanding of current platforms. For example, what software is being used to build and maintain the schedules, or what software is being used by the cost/budget/resource analysts. Lastly, it is important to consider the familiarity of the tools at the project's Center (and of the project personnel), as well as the familiarity of the non-advocacy entity reviewing the JCL analysis.

#### **Toolsets and Licenses:**

NASA CAD currently has an Agency license agreement for two tools (ACEIT JACS and Polaris) and has provided training to Agency personnel. It is recommended that all JCL analysis be performed on one of these two tool platforms. If you are a project that wishes to utilize another toolset, please contact CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov). For details on how to obtain these tools or for more assistance on tool selection, please refer to <http://www.nasa.gov/offices/ooe/CAD/>.

<sup>21</sup> See *Probability Methods for Cost Uncertainty Analysis* by Paul Garvey for more details.

<sup>22</sup> Methodology encompasses schedule-loaded cost estimating tool.

**Table J-1. Methodology Summary**

	<b>Bivariate Independent Cost &amp; Schedule Distributions</b>	<b>Probabilistic Cost-Loaded Schedule</b>
Description	JCL developed by independently producing a probabilistic cost and schedule distribution. The distributions are combined using classical bivariate joint probability methods.	JCL developed by directly linking cost and schedule logic based on project's specific schedule and cost plans.
Detail level	Typically, less detailed.	Typically, more detailed.
Cost Methodologies	Typically, parametric but can be with analogy, SME-based, or grassroots methodologies.	Typically, detailed costs built from SME, grassroots, or proposal data.
Schedule Methodologies	Typically, parametric but can be done analogy, SME-based, or grassroots methodologies.	Typically, detailed costs built from SME, grassroots, or proposal data.
Risk/Uncertainty Methods	Risk and uncertainty inherent in parametric and analogy based data. If done by SME or grassroots methods, the risks and uncertainty would be informed by SMEs.	Risks are informed by risk management, and uncertainty is typically SME based. <sup>25</sup>
Types of Tools - Cost <sup>26</sup>	NAFCOM, PRICE, SEER, NICM, PCEC, etc.	Typically, detailed grassroots or proposal cost data stored <sup>27</sup> in either MS Excel or ACEIT.
Types of Tools - Schedule <sup>28</sup>	Schedule Estimating Relationship Risk Analysis (SERRA) Model or other user-created models if BOE is parametric, otherwise Polaris, JACS, MS Project with @RISK, or Primavera Risk Analysis Tool,.	Polaris, ACEIT, JACS, Oracle Primavera Risk Analysis Tool.
Integration Platform	Distributions can be convolved using analytical- or simulation-based tools (e.g., MS Excel, @RISK, Crystal Ball, ACEIT, MATLAB).	Scheduling tool (see above).
Life Cycle Implementation	During formulation.	Implementation at completion of formulation.
Skill Sets	Typically, cost estimating community.	Risk management, schedule, and cost/resources communities.
Data Sources	Typically, historical data from actuals and observations.	Detailed project plans, historical and SME input for risk/uncertainty.
Effort Level	Typically, low level of concentrated effort with faster turnarounds.	Typically, high level of concentrated effort from staff members with slower turnarounds.
Strengths	<ul style="list-style-type: none"> <li>Grounded in historical data and past performance</li> <li>Less labor intensive and faster turnarounds</li> <li>Community of practice well established</li> </ul>	<ul style="list-style-type: none"> <li>Forces integration of PP&amp;C silos and data products</li> <li>JCL analysis can be used to improve project plan</li> <li>Facilitates better understanding and communication of project phasing and reserve levels</li> <li>Enforces scheduling best practices</li> <li>Enforces quantification of risk realization</li> </ul>
Challenges/Issues	<ul style="list-style-type: none"> <li>Difficulty linking JCL to project plan</li> <li>Potential to double-count cost and schedule risk</li> <li>Difficult to implement after formulation</li> <li>Phasing techniques have to be implemented externally</li> <li>Parametric scheduling tools/methodologies immature</li> </ul>	<ul style="list-style-type: none"> <li>Schedule and cost BOE</li> <li>Mapping cost to schedule</li> <li>Identifying uncertainty levels</li> <li>Identifying cost behavior types (TI/TD)</li> </ul>
Recommend Uses	<ul style="list-style-type: none"> <li>Cross-check for PCLS analysis.</li> <li>Early assessments during formulation.</li> </ul>	<ul style="list-style-type: none"> <li>Rigorous analysis in preparation for KDP-C.</li> </ul>

<sup>25</sup> Best practices would encourage all uncertainty parameters to be based on historical data.<sup>26</sup> Lists are not exhaustive.<sup>27</sup> Can be stored in scheduling tool.<sup>28</sup> Lists are not exhaustive. See Appendix E for a list of available tools.

## J.2. Integrated Schedule

This section provides insight and recommendations for developing program schedules specifically for performing a JCL schedule analysis. The intent of this section is to provide guidance on JCL schedule analysis; it is not intended to provide guidance for developing an IMS. For more detail on programmatic IMS development, please reference the NASA Scheduling Handbook (NASA, 2010).

### J.2.1. Developing a JCL Schedule

Prior to developing a schedule for JCL analysis, careful consideration should be given to several important factors that will impact its purpose and analysis validity. Key factors to be considered include, but are not limited to, the following:

- The levels of schedule insight and analysis capability that are desired throughout project implementation;
- The magnitude and complexity of schedule data to be maintained and processed;
- The schedule management tools that potentially will be used; and
- The potential for accurately loading TD and TI costs to schedule tasks.

Project management should understand that the level of project insight and analysis that can be achieved is strongly dependent on the level of detail contained in the schedule. It should also be understood that detailed critical path identification and analysis, as well as detailed insight into program issues, cannot be done without properly defining analysis level tasks and applying appropriate schedule logic. Therefore, the level of schedule detail contained in the JCL schedule is important to gain adequate insight into the potential risk impacts. Oftentimes, there are numerous management tool sets available that do not allow for easy and/or accurate transfer and integration of schedule and performance data. It is crucial for achieving successful program management that tool sets that provide efficient and accurate transfer and integration of data be chosen and, where possible, mandated for all project participants.

#### Analysis Schedule Tip:

Key characteristics of an analysis schedule are that it:

- 1) Displays major work flows,
- 2) Identifies work required to support major deliverables (areas that are actively being tracked),
- 3) Identifies major cross dependencies with, or across, management responsibility boundaries, and
- 4) Has traceability and transparency to a more detailed IMS or lower level schedules.

The following options are offered as recommendations<sup>29</sup> for JCL schedule development:

- **Analysis Schedule:** For complex projects, it is recommended that projects use an analysis schedule for JCL purposes. An analysis schedule is a high-level overview of an entire program/project, where a subset of task durations is captured in a single task, similar to when viewing various details in MS Project<sup>30</sup>. Analysis schedules provide a good modeling framework

<sup>29</sup> As a third approach, schedule development uses milestone sets to reflect the major events in accomplishing all program effort. Sets of meaningful event milestones reflecting each project's scheduled effort would be used in place of detailed- or summary-level tasks. Milestone interdependencies are much more difficult to reflect accurately when using this technique. This difficulty is due to the method in which the planner/scheduler (P/S) has to account for the effort being carried out in between the milestones. In order for the analysis schedule to keep the proper time-phasing for the numerous project milestones, the P/S must either incorporate appropriate schedule lag values between each milestone or assign date constraints to each milestone included in the schedule. These practices are not conducive to sound schedule analysis. This method is not recommended and is not considered best practices but can be useful in early JCL analysis.

<sup>30</sup> It should be noted that a summary of schedule is not the same as an analysis schedule. An analysis schedule has schedule logic that "pushes" and "pulls" the summarized schedule logic.

to identify general areas and time period of critical activity sets. Analysis schedules should have traceability and transparency to the more-detailed IMS. They should display major work flows, identify work required to support major deliverables (areas that are actively being tracked), identify linkages of budgeted work to schedule scope, and provide insight into major cross dependencies with or across management responsibility boundaries.

- **Detailed IMS:** Another approach is to have the JCL schedule be the “same” as the detailed schedule—commonly referred to as IMS. This strategy provides the overall capability for integrated insight and oversight of all project work, including detailed critical path and program issue information. It should be understood; however, that while this strategy is enticing, it may not be a practical approach for the analysis schedule for JCL purposes.

While both types of schedules result in different levels of detail fidelity, if properly constructed, they both can serve as a credible foundation to the JCL analysis. Further conversation is needed when discussing the attributes of an analysis schedule versus an IMS. As with any programmatic procedures and requirements, there are many development tools to support the management and tracking of various program functions.

### J.2.1.1. IMS versus Analysis Schedule

To avoid the creation and maintenance of multiple artifacts, a project's IMS can be used as-is for performing JCL analysis. In addition to not requiring additional artifacts, using the project's IMS as the basis for the JCL model ensures risks are applied accurately to the lowest affected tasks. Another advantage to using a detailed IMS schedule is that all details of program tasks and required work are intact; hence, when performing any JCL analysis, the schedule aspects are performed at a granular level. Risks and uncertainties can be tied directly to the respective tasks, and impacts are captured within the logic of the task in the truest fashion. Table J-2 outlines a comparison of schedules.

**Table J-2. Schedule Comparison**

	<b>Integrated Master Schedule</b>	<b>Analysis Schedule</b>
Description	<ul style="list-style-type: none"> <li>• Requires risk, uncertainty, cost, schedule, slack, and margin applied to lowest affected tasks.</li> </ul>	<ul style="list-style-type: none"> <li>• High-level overview of an entire program/project</li> <li>• Subsets of tasks are captured as a single task</li> </ul>
Detail level	<ul style="list-style-type: none"> <li>• Can be cumbersome and large; can range to the tens of thousands of activities.</li> </ul>	<ul style="list-style-type: none"> <li>• Confined to a size that is manageable, leading to a greater overall perspective.</li> </ul>
Sources of data	<ul style="list-style-type: none"> <li>• Often contains contractor schedules with inappropriate constraints.</li> </ul>	<ul style="list-style-type: none"> <li>• Rollup of master schedule</li> <li>• Can lead to missed data lost in rollup</li> </ul>
Risk/Uncertainty	<ul style="list-style-type: none"> <li>• Data-driven uncertainty assigned to the lowest level, usually the task level, can be difficult</li> <li>• Uncertainty level may require the use of subjective distributional assumption since historical data may not be available</li> </ul>	<ul style="list-style-type: none"> <li>• Uncertainty is rolled up to a level that it can be reasonably assessed</li> <li>• Impact of risk may be overstated as schedule/slack/margin is rolled up.</li> </ul>
Simulation	<ul style="list-style-type: none"> <li>• May require level of granularity or magnitude of data handling that is not available in a commercial-off-the-shelf (COTS) tool.</li> </ul>	<ul style="list-style-type: none"> <li>• Simple to run on a COTS schedule risk analysis tool due to decreased complexity.</li> </ul>

Using a detailed schedule for a JCL analysis does have some drawbacks: 1) A detailed program/project schedule can be cumbersome and large. For space systems, these schedules can range to the tens of thousands of activities. Managing and maintaining JCL analysis for all of these activities can be

burdensome.<sup>31</sup> Oftentimes, an IMS is a continually updated project artifact coming from several other elements (i.e., subcontractors). This can make maintaining a lower-level schedule for JCL analysis purposes arduous. Also, contractor schedules tend to be “delivery oriented” and often include constraints on key delivery dates, tasks, or resources that can hide the true impact of risks when the schedule is run through a simulation. Performing schedule health checks on the IMS—already a best practice for scheduling—can mitigate some of these errors, but it is not possible to determine if the model is error-free until the simulation is run and results are monitored to ensure they are consistent with the inputs. 2) Assigning data-driven uncertainty at the lowest level of an IMS can be difficult. When creating an analysis schedule, the IMS is rolled up to a level at which uncertainty can be reasonably assessed (i.e., component or subsystem level). When using the full IMS, the most common methodology is to apply uncertainty at the task level. It is often necessary to use subjective distributional assumptions when applying uncertainty using the bottom-up method because historical schedule data are rarely, if ever, available at this level.

An advantage to using an analysis schedule as the artifact is that it is typically easier to gain an overall perspective of a project in a single glimpse with fewer schedule line items. Also, applying uncertainty and cost to analysis schedules is fairly simple given the limited number of tasks when compared to the project’s IMS. Simulations are also simple to run using any COTS schedule risk analysis tool due to the decreased complexity and size of the schedules.

A drawback to using an analysis schedule is that there could be a loss of schedule logic by rolling up multiple tasks into a single task. If analysis schedules are “rolled” up to too high of a level, then that can adversely affect the confidence in the JCL output results. The impact of risks will likely be overstated as schedule slack and margin, existing at the lowest level of the IMS, will be forsaken when the schedule is rolled up. Additionally, the creation of an analysis schedule for JCL means the project will have to maintain one more additional artifact throughout its life cycle if the JCL analysis is to be updated.

Regardless of approach, the goal of the schedule that supports JCL analysis is to understand how a schedule will react to risk impacts and uncertainty. Logic and constraints can have significant, adverse effects to a JCL analysis. The following sections address specific types of logic and constraints that may not affect a deterministic project schedule, but can have significant effects on the JCL analysis results. When addressing these potential pitfalls, the goal is not to change schedule logic or constraints to garner desired or positive results, but to ensure that the JCL analysis will accurately capture positive and negative changes in the schedule due to schedule logic and flow.

**For the purposes of this handbook and appendix, an analysis schedule will be the default method that is primarily referred to when addressing JCL schedules.**

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<sup>31</sup> It should be noted that when running JCL simulations, a large IMS can bog down the analysis simulation times, especially if there is a high degree of constraints and improper logic. This simulation performance may or may not be an issue when conducting a JCL as it is very dependent on tool platform.

## J.2.2. Schedule Assessment

Schedule assessment is the process of determining schedule validity and performance at a given point in time. A thorough schedule assessment using many of the techniques described in the following paragraphs should always be performed prior to establishing the IMS baseline and is essential in ensuring a quality JCL analysis. Periodic assessment is also necessary to gain assurance that the schedule continues to generate valid data and support the project's objectives throughout the project life cycle. A reliable schedule assessment checklist is an important aid that can benefit a project team or outside review team in determining schedule validity. For more information on schedules and assessments, see Appendix K and the NASA Schedule Management Handbook.

**Tip:**

Schedule health-check tools will provide metrics on the health of a project's schedule. It is important for a project to confer with the non-advocacy reviewer on the criteria or expectations.

Schedule assessment and analysis principles are the same during and after schedule development, with the exception of progress evaluation which occurs after development is complete. The following processes should be continued routinely throughout the project life cycle. As a note, a schedule health check or assessment is usually the first thing a non-advocate review team will do to a project schedule—so be prepared!

There are many tools that can be used to help a project perform a schedule assessment, including one sponsored by NASA called STAT.<sup>32</sup>

### J.2.2.1. Schedule Logic

The logic<sup>33</sup> of a schedule should be reviewed to ensure that it is complete, accurate, and realistic. Within the schedule, there should be a minimal number of tasks with no successors or predecessors identified. When these occasions do arise, valid rationale should be documented.

A thorough effort should be made to identify the tasks that may be worked in parallel with other tasks, tasks that must be worked in series with other tasks, and tasks that may be worked once another task has progressed beyond a given point. Each of these situations can be reflected with the proper use of logic relationships and lag or lead values.

A schedule logic review by project team members should focus on three specific areas. Firstly, within each logical grouping of work, the sequence of tasks/milestones should be verified. This may involve team members from different organizations, multiple project personnel from the same organization, or both. Secondly, each interface, or “hand-off,” between different work groups should be verified. And finally, the overall project phasing sequence should be validated.

It is recommended to verify that the duration for each task/activity entered is accurate and realistic based on the information provided for that task/activity. The method of verification is dependent upon the credibility of the source of the original duration information. All assumptions made in determining task/activity durations should be

**Schedule Logic Review Steps:**

- 1) Verify each sequence of tasks/milestones within each logical grouping of work.
- 2) Verify each interface or “hand-off” between different work groups.
- 3) Validate the overall project phasing sequence.

<sup>32</sup> For more information on STAT, or to acquire STAT, please refer to <http://evm.nasa.gov/handbooks.html>.

<sup>33</sup> The term “logic” is meant to represent the sequence and relationships of tasks within the schedule.

recorded. This can be an especially important consideration when later assigning resources to scheduled tasks/activities. Knowing the basis for task durations may also aid in setting risk parameters when conducting schedule risk assessments.

With each schedule task now relatively well defined, the duration for each should be verified with the task owner. All changes have to be evaluated for the impact on other related or logically tied tasks/milestones. All specific assumptions that are part of the basis for determining the duration of a task should be recorded. This should include the impact on the duration due to the experience or skill level of the resources to be assigned to each task.

### J.2.2.2. Constraints

A constraint is a fixed date assigned to control when a task starts or finishes. Caution should be exercised when using constraints because they are a significant factor in how float (slack) is calculated throughout the project schedule. While it is certainly true that there are various scheduling situations that require the use of constraints, careful thought should be given so that they are used appropriately—because their impact to the JCL analysis can prove detrimental.

Forced or fixed dates (constraints) should only be used when network logic cannot accurately depict the true sequence of work because of some external influence or an influence beyond the control of project team members. The constraint types should be reviewed carefully for accuracy and desired effect. “As Late As Possible” constraints should generally not be used in a JCL schedule. Improper and/or invalid use of constraints should be minimized due to the potential for creating misleading schedule and JCL results.

Constraints used in general schedule management, while at times may be necessary, have a drastic effect when performing a JCL. Oftentimes, constraints are placed into an IMS for management purposes. As a project progresses toward that date, the constraints are often removed or adjusted to reflect progress. In many cases, the logic is adjusted based on the progress of preceding tasks or changed to reflect newly allocated funding to allow a task to begin. Constraints may also be used to reflect milestone or project reviews slated for a specific time.

*For a JCL schedule, it is best to remove as many constraints as possible* so that the logic of the schedule will flow more naturally during a simulation. Again, the JCL is aimed at capturing the total bandwidth of a project's life cycle or phase at a single point in time. JCL tools are incapable of making “human-like” decisions when they come across a hard constraint date. JCL tools cannot look at a constraint during a simulation and factor in whether or not the task can start earlier or end sooner than it is currently slated. Therefore, when completing a JCL on a schedule with several or significant constraints, the results will be skewed based on the type of constraint used. Understanding how a schedule ebbs and flows naturally as risks materialize or mitigate gives a higher fidelity of insight to all areas of a project; however, by having constraints, those insights are altered in an unrealistic way.

For example, say there is a constraint of “Start No Earlier Than” on Task B of October 10, 2015; its predecessor Task A is planned for completion on October 1, 2011, but Task B can start as soon as Task A is completed. When a JCL iteration is run, every single iteration performed will start Task B on October 10, 2015, no matter when its predecessor finishes. This becomes especially problematic if Task A finishes after October 10, 2015, on the given iteration, because due to the constraint, Task B will still begin on the October 10. It should be noted that from a programmatic standpoint, there may be a reason why Task B cannot start until October 10 due to Task B being out in the distant future (e.g., funds availability, resource availability, etc.).

Another example of constraints unnaturally impacting a JCL analysis is a “Finish No Later Than” constraint. During the JCL calculations, no matter how the logic flow of the schedule is developed, a task

with this type of constraint will always finish on that particular date. An example of how this could negatively impact a JCL analysis is illustrated as follows. Consider a project that has a risk tied to a task with this type of constraint, with the risk impact being a 30-day delay. In the JCL analysis, this task will always show a finish date no later than indicated in the schedule, even if in logic the risk should push the tasks completion date out 30 days from its original completion date. This will skew the overall picture of the analysis to possibly reflect a project completion date to be earlier than what it should if the risk impact was reflected as modeled.

Common constraint types that can be imposed on a task include, but are not limited to, the following:

- **As Soon As Possible**—A task or milestone will finish as early as possible based on its assigned logical relationships and duration. This condition can also be described as the absence of any constraint and is deemed an acceptable constraint for JCL schedules.
- **As Late As Possible\***—A task or milestone will finish as late as possible without affecting the scheduled end date. This constraint uses total float to calculate its early finish date instead of free float. This can cause the project end date to slip.
- **Start No Earlier Than or Start On or After**—A task or milestone will start no earlier than the assigned start date. However, it can start as late as necessary.
- **Start No Later Than\* or Start On or Before**—A task or milestone will start no later than the assigned start date. However, it can start as early as necessary.
- **Finish No Earlier Than or Finish On or After**—A task or milestone will finish no earlier than the assigned finish date. However, it can finish as late as necessary.
- **Finish No Later Than\* or Finish On or Before**—A task or milestone will finish no later than the assigned finish date. However, it can finish as early as necessary. This is a useful constraint to use for a contract deliverable milestone or project completion milestone.
- **Must Start On\* or Start On or Mandatory Start**—A task or milestone will start on the assigned date. Use of this constraint overrides schedule date calculations driven by logic, possibly resulting in a date that is physically impossible to achieve.
- **Must Finish On\* or Finish On or Mandatory Finish**—A task or milestone will finish on the assigned date. Use of this constraint overrides schedule date calculations driven by logic, possibly resulting in a date that is physically impossible to achieve.
- **Deadline\***—While not listed as a constraint type, a deadline date assignment on the schedule for any task or milestone has the same results as assigning a “Finish No Later Than” or “Must Finish On.” Float (slack) calculations are from the deadline date assignments.

\*These types of constraints act as completion points in the schedule, from which the total float value is calculated.

Ideally, ***minimal use of constraints, other than As Soon As Possible, is strongly encouraged.***

Remember that constraints override task interdependency relationships. An example of where a constraint may generally have a valid purpose would be assigning a “Start No Earlier Than” on a scheduled receivable from an external source.

“Constraints” may also refer to limitations or conditions that affect the schedule. Typical examples of these situations may include test facility downtime or unavailability of specialized computer

time/equipment. These situations can be modeled through the use of calendars/assignments within the automated scheduling tool.<sup>34</sup>

### J.2.2.3. Embedded Schedule Margin

When planning out a program schedule, “margin” is added to task duration to account for future unplanned events, uncertainty, and potential risks. This schedule margin, also referred to as “reserve,” can create a negatively skewed view of a program when a JCL is completed.

One misconception to clear up is that margin is not the same as “float” or “slack”; both are calculated values based on network logic between a target start date and the earliest as possible date. Also, margin does not mean the same as lag time, which is the period of time applied to a relationship between two tasks that delays the defined relationship execution. For example, a task logically tied to another task with a finish-to-start relationship and a 5-day lag time will result in the successor task’s start being delayed until 5 days after the completion of the predecessor.

Margin is an identified and planned duration that is managed. Normally its value is a result of a schedule risk assessment or past experience/history. Margin is analogous to schedule reserve and should be managed like budget reserve. In essence, the addition of margin is done to increase the confidence of the completion date in the schedule. But when margin is left in tasks during a JCL analysis, it will reflect completion dates that are not indicative of the duration or LOE of said planned activity.

Since margin is added to duration to capture future uncertainties, it can be removed from the task duration and then modeled as uncertainty prior to running the simulation. Uncertainty can be specifically applied to task duration and is a recommended method for capturing schedule margin. By applying uncertainty rates to the task, instead of adding margin, it allows for the durations to fluctuate in a more realistic manner during a simulation, as opposed to a set margin or uncertainty value. Also, by removing schedule margin from a task’s duration, it avoids applying uncertainty twice to a task that in turn would make the task appear to have a longer duration than actually planned.

#### Tip:

When conducting a JCL analysis, identify any schedule margin that may be included in a task duration and either remove it or designate it separate from the task.

## J.3. Cost Estimating

This section will provide insight and recommendations for cost estimating as it pertains specifically to JCL. This section will only address JCL-specific topics that may not be covered under the previously mentioned best practices. So, for example, discussion on cost estimating methodologies, documentation, and general risk analysis will not be provided.

### J.3.1. Cost Loading

For the purposes of the JCL model, cost loading is the process of mapping cost estimates to elements in the schedule. Almost without exception, this is not a straightforward one-to-one function. In practice, the detail contained in the cost file can match, exceed, or be less than the detail of the schedule.

A key principle of mapping cost to a schedule is defining the characteristics of those costs as they relate to the schedule task(s). This characterization is expressed as TI costs and TD costs.<sup>35</sup>

<sup>34</sup> Note that different software tools may have different constraints or even different terminology to describe constraints.

<sup>35</sup> For further examination of determining TI from TD, see David Hulett (2011), *Integrated Cost-Schedule Risk Analysis*, Ashgate.

### J.3.1.1. Time Independent (TI) Costs

TI costs are defined as those that are associated with the total effort to be conducted for a task irrespective of overall duration. The overall duration of TI costs are primarily a factor of three variables: 1) the scope of work to be conducted; 2) the productivity of the staff performing the work; and 3) the achievable staffing level based on resource and fund availability. The overall duration of the task is determined by the effort required for its completion, and the costs are not a function of time but rather scope, while for TD elements, cost is a direct function of duration. Many tasks on a program/project display this behavior. Common examples of TI costs are materials, tests, and one-time expenses.

### J.3.1.2. Time Dependent (TD) Costs

TD costs are defined as those costs associated with effort that is based on the duration of a task. TD costs are costs that are periodic (daily, monthly, quarterly, yearly) values that result in total cost as a function of total duration multiplied by the appropriate periodic value (burn rate). Many tasks on a program/project display this behavior. Common examples are rent, utilities, facility maintenance, sustaining operations, program management, system engineering, quality assurance, other periodic fixed expenses, and other tasks which display an LOE nature.

In assessing total TD costs, an analyst must estimate two attributes: 1) the duration of the task and 2) the periodic effort required. Normally, the periodic effort is quantified in terms of a burn-rate (daily, monthly, quarterly, yearly).

Experience has shown that a majority of a project's cost will be TD rather than TI; however, the breakout of TD/TI is very dependent on the nature and acquisition strategy of the project.

### J.3.1.3. Hammock Task

Because a typical cost estimate Work Breakdown Structure (WBS) will not map one-for-one to a schedule WBS, a concept of creating a "hammock" task is often applied to the schedule.

Hammock tasks are created within JCL models when costs are to be mapped to a schedule, but the latter is significantly more detailed than the available costs. The concept is to focus on a logical section of the schedule that contains a series of tasks that are all sequentially linked via finish-to-start relationships. As illustrated in Figure J-7, the hammock task is a new task construct that is linked to the start date of the first task in this sequence and to the end date of the last task—the name comes from this anchoring to the first and last tasks, which is analogous to two trees that anchor a hammock.<sup>36</sup>

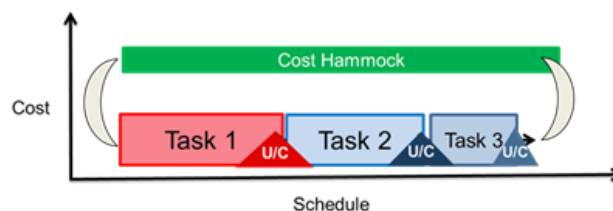


Figure J-7. Hammock Task

Consequently, when the simulation runs, this task dynamically expands or contracts depending on the behavior of the tasks under it. Hammock tasks are typically used to capture LOE segments of the schedule (e.g., project management).

<sup>36</sup> In this figure, the hammock is called a "cost hammock." Both terms mean the same thing.

## J.4. Risk Assessment

This section provides insight and recommendations for how to handle the probabilistic aspect of the JCL analysis. The probabilistic portion of JCL relies on a project's risk management system to help inform the JCL; however, this section only addresses JCL-specific topics that may not be covered under risk management best practices, as well as how to apply the identified risk management discrete risks to a JCL analysis.<sup>37</sup>

This section covers two broad topics: discrete risks and uncertainties. From a modeling aspect, a JCL is calculated by incorporating discrete risks and uncertainties. For example, if a project JCL duration and cost estimates were performed using strictly parametric (Schedule Estimating Relationship [SER] and Cost Estimating Relationship [CER]) techniques—and if it was deemed that all the types of discrete risks that could fall on the project were captured in those parametrics—then the entire JCL could be calculated using solely uncertainty techniques. On the other hand, if a project had a clear and omniscient view of all the discrete risks (and quantified general uncertainty as “risks that could occur”), then the entire JCL could be calculated using solely discrete risk techniques. In general, projects lean on using their risk management system (which is not omniscient) to capture discrete risks that are currently being watched and managed while using uncertainty to capture unknown-unknowns and scope uncertainty in the baseline plan.

### J.4.1. Risk Management System

Projects tend to include only a subset of their project-level risks or only near-term risks; however, **a robust JCL should include all of the project-level risks over the entire development phase** in order to maintain risk traceability throughout both the project risk management system and JCL model. The JCL analysis does not have to be limited by what is currently being managed in the risk management system. For example, there may be a programmatic risk that does not “make it” in the risk management system but may be of concern to the project manager.

The JCL analysis allows the project to model the programmatic consequences and expected value of such a risk. When a project identifies risks for a JCL analysis, it is important that it identifies:

- The task(s) or activities the risk will impact;
- The type of impact (e.g., a delayed start or a delayed completion); and
- The probability of occurrence of the risk and the consequence (in both direct cost and direct schedule) of the risk happening (e.g., the schedule duration impact of the risk and the costs that will be incurred if the risk occurs).

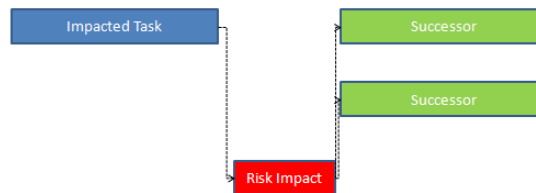
#### J.4.1.1. Identify Links to Schedule Tasks<sup>38</sup> and Types of Impacts

From a schedule perspective, a risk event is treated the same way as a task; however, in the schedule, the risk event task only occurs a certain amount of time (corresponding to that discrete risk's probability of occurrence). Capturing risks and adding them into the schedule is introducing the first probabilistic aspect of JCL. From a static viewpoint, it looks like the risk is just a task, but when simulations are run, the risk event will only occur x percent of the time. When the risk event does not occur, the task and associated dollars will essentially default to zero; however, when the risk does occur, the task takes on a duration and dollar impact.

<sup>37</sup> An excellent reference for overall risk analysis is the “Joint Cost and Schedule Risk and Uncertainty Handbook” at <https://www.ncca.navy.mil/tools/csruh/index.cfm>.

<sup>38</sup> Activities and task are interchangeable.

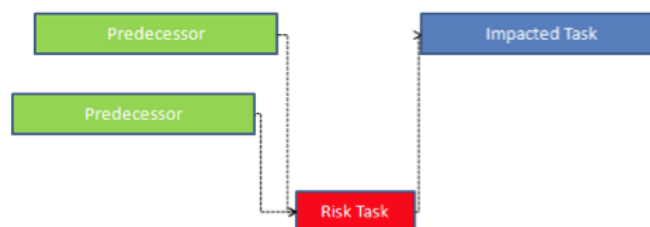
There are two general ways to identify *what* task a risk affects and *how* the risk is affecting that task. As shown in Figure J-8, the first category is risk events that cause a delay in the completion of the impacted task. These are modeled as successors to the impacted task, and the impacted task's successors are moved to the risk task as its successors. In this way, the risk task is added as an intermediate task between the impact task and its successors. For delayed completion risks, link the risk task to the task affected as a successor and ensure that the risk impacts have the same successors as the affected task.



**Delayed Completion Risk Item**

**Figure J-8. Risk Event Delays to the Completion of an Impacted Task**

As shown in Figure J-9, the second category is risk events that cause a delay in the start of the impacted task. These are basically risks that create a new effort to be conducted before the impacted task can begin. These are modeled as predecessors to the impacted task, and the impacted task's predecessors are moved to the risk task as its predecessors. In this way, the risk task is added as an intermediate task between the impact task and its predecessors. For delayed start risk, link the risk task to the task that is delayed as a predecessor, and link to the same predecessor as the affected task.



**Delayed Start Risk Event**

**Figure J-9. Risk Event Delays to the Start of an Impacted Task**

In the process of implementing risk tasks, a project may identify that a risk event can impact several tasks within the schedule. Additionally, a project may identify that many risk events impact a specific schedule task. Each of these categories required a slight variation in the approach for implementing the risk impact. The following items identify the two categories of grouping (serial, parallel) for multiple risk impacts to a schedule task.

- **Serial Impacts:** These are risk impacts that can occur independently and have a cumulative impact to the schedule task. These risk tasks are linked in serial to each other. Figure J-10 shows how having two serial impacts affecting a schedule task would be modeled in the analysis. The original successors of the impacted task are linked to the last risk impact item.

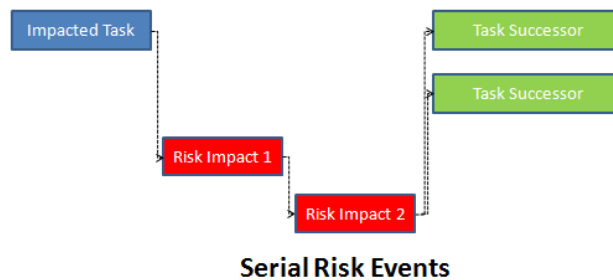


Figure J-10. Serial Impact

- Parallel Impacts:** These are risk impacts that occur independently and can be worked for resolution in parallel due to workforce and impact area. These risk tasks are implemented as parallel events. Figure J-11 shows how having two parallel impacts affecting a schedule task would be modeled in the analysis. The impacted task is linked to both risk events, and the original successors of the impacted task are linked to both risk events. In this manner when the risk events occur, the cost and schedule impact of each will be modeled in the schedule. If both risk events occur at the same time, then the schedule impact is the greater of the two, but the cost impact is cumulative.

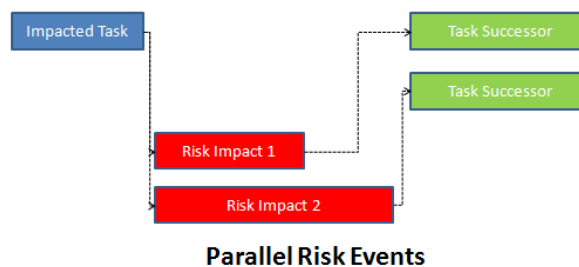


Figure J-11. Parallel Impact

#### J.4.1.2. Quantify Likelihood and Impacts

The likelihood of occurrence is typically expressed in percent likelihood of occurrence (0–100 percent)—or put simply, from a JCL modeling perspective, the percent amount of time the risk task will be “turned” on and affect the schedule. This input to a risk identified in a risk management system is commonplace, should already be part of the risks management products, and should be fairly straightforward. Most JCL tools will only support a specific value for the percent likelihood input.

The duration impact when the risk occurs can be considered the duration consequence of that risk. Typically, if there is a duration impact, this is submitted with a three-point estimate (a low value, a “most likely” value, and a high value). Along with identifying a duration impact, the project will have to also identify a “direct” cost impact for that risk. This direct cost impact could take the form of added TI costs (e.g., remanufacturing a faulty part), TD costs (e.g., risk occurs and forces overtime work), or a combination of both. These impacts are also typically captured as three-point estimates. Regardless of whether the impact is captured as TI, TD, or a combination—it should be noted that the project should only identify the direct costs associated with the risk. For example, if a risk occurs that causes a delay in the start of an integration task—hence, causing a “standing army”, or in TD costs, to accumulate—then the model, through the schedule structure, will account for the indirect costs of that risk occurring.

### J.4.1.3. Premitigation Versus Postmitigation

Properly capturing risk mitigation within a JCL model is a two-step process. First is to ensure that cost and timelines associated with the mitigation effort are captured and clearly identified within the cost estimates and Integrated Master Schedule. Since most JCL models are constructed utilizing a summary analysis schedule, it is recommended to capture all mitigation task activities into a single task activity that spans the total timeframe of the mitigation effort. The cost associated with the effort should be captured within the mitigation task accordingly in a TD and TI costing. Mitigation tasks will have uncertainty; therefore, a range estimate in terms of Min/Most Likely/Max values should be established for both cost and duration of a mitigation activity. One may also go so far as to say that a higher level of uncertainty would be applied to mitigation than other activities within the same WBS element, as mitigation of risk contains high degrees of uncertainty of success.

The second step is to capture postmitigated risk within the model. As with the current JCL model development process of capturing the likelihood of occurrence and the consequence of impact, capturing postmitigated risk is no different. The only difference is that the values for postmitigated risk are based on successful mitigation efforts and not on the likelihood and consequence of risks in their current state.

### J.4.2. Schedule/Cost Uncertainty

To this point in the JCL process, the primary driver of the JCL results is the quantitative risk assessment and the effect it has on the risk-adjusted cost and schedule. Should an analyst run a JCL simulation with just these risks, there would be a striking characteristic of the results: the coefficient of variation of both the cost and schedule risk distributions is small.

The reason for this disparity between the previously mentioned JCL model results and historical data is the omission of cost and schedule uncertainty from the JCL model. While the risk assessment provides a snapshot in time of potential future events that may cause the project to overrun, it does not account for two key facets that have the ability to drive cost and schedule.

- Incomplete Risk Register: Although NASA's Continuous Risk Management process aims to create as comprehensive a risk register as possible, it is unrealistic to predict all events with the possibility to increase cost or schedule.
- Uncertainty in the Baseline Estimate: Disregarding risks altogether, it is impossible to predict the time or budget required to complete various segments of space-vehicle research, development, and production.

In recognition of these two facets, JCL analysts must account for what is not included in the discrete risk list relative to baseline cost and schedule plans.

This section provides a working definition for uncertainty versus risk and then discusses various methods for selecting and applying cost and schedule uncertainty distributions to the JCL model, including these methods' advantages and shortcomings.

It is recognized that the taxonomy and definitions of "Risk" and "Uncertainty" have been defined by several sources, including Knight, 1921, pp. 19–20; Fuguitt and Wilcox, 1999, pp. 140–141; Garvey, 2000, p. 27; and Hubbard, 2010, pp. 49–50. Most notably, the GAO's Cost Estimating and Assessment Guide differentiates risk and uncertainty using the following definitions (General Accountability Office, 2009):

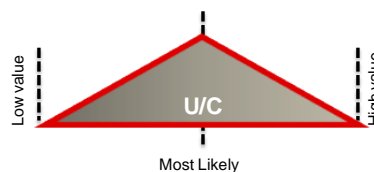
- **Risk** is the chance of loss or injury. In a situation that includes favorable and unfavorable events, risk is the probability that an unfavorable event will occur.
- **Uncertainty** is the indefiniteness about the outcome of a situation. It is assessed in cost estimate models to estimate the risk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

In keeping with the spirit of the sources cited above, and for the purposes of this handbook and appendix, and NASA JCL implementation, risk and uncertainty are defined as follows<sup>39</sup>:

- **Risk** is an event not in the projects baseline plan that is an undesirable<sup>40</sup> outcome (discrete risk). This definition is similar to one that one would see in a risk matrix. The event is characterized by a probability of occurring and an expected impact if the event did occur.
- **Uncertainty** is the indefiniteness about a projects baseline plan. It represents our fundamental inability to perfectly predict the outcome of a future event. Uncertainty is characterized by a probability distribution, which is based on a combination of the prior experience of the assessor and historical data.

In order to avoid double counting, JCL analysts must take special care to segregate uncertainty caused by risks already being modeled in the JCL simulation from the underlying uncertainty of the project's plan once these risks have been discounted.

Typically, uncertainty is modeled using a three-point estimate shown in Figure J-12. The low value represents the low extreme of uncertainty, the middle value represents the “most likely” value of the cost or duration, and the high value represents the high extreme of uncertainty. Please note that the baseline plan may not be any one of these numbers (low, middle, high) but should be within the range of low and high.



**Figure J-12. Uncertainty**

Uncertainty can be modeled, in most platforms, by percentage- or duration-based value as shown in the two examples below:

- Percentage based example: Low is 95 percent the value of the baseline plan, most likely IS the baseline plan value, and high is 200 percent the value of the baseline plan
- Duration based example: Low is based on the analogy X and is x months duration, most likely is based on average of several analogies and is x+3 month duration, and high is based on the analogy Y and is x+10 months duration

The examples above all assume a triangular distribution, but uncertainty can be modeled using other distributions including, but not limited to, normal, lognormal, Weibull, Rayleigh, PERT, or uniform. Parametric analysis can also be used to derive uncertainty distribution.

There are several factors that influence these two critical uncertainty components discussed earlier (incomplete risk lists and uncertainty in the baseline estimate):

- The complexity of the work can affect uncertainty. In general, the higher the complexity, the more uncertain the outcome becomes.

<sup>39</sup> It is important to note that “risk” and “uncertainty” are modeling constructs for JCL analysis. Within a JCL model, uncertainties *can* be modeled as risks (100 percent probability with variable impact) and risks *can* be modeled as uncertainties. As an example, risk factors approach, discussed below, can be utilized to capture both discrete risks and uncertainties.

<sup>40</sup> Risks can also be opportunities if the outcome of the event is a positive outcome.

- Underlying slack assumptions can drive uncertainty ratings. For example, if a project's tasks have a lot of "built-in" reserve to the durations, then there are more opportunity risks associated with the tasks than negative risks. Also, if a task is an analysis schedule task, then the slack assumptions at the lower level may influence the decision on how much uncertainty there is (and how to skew the uncertainty).
- The confidence level of meeting the planned task should factor into the analysis. In this case, uncertainty would be counteracting any preconceived optimistic or pessimistic bias.

It is critical that analysts invest time and thought in developing credible and appropriate schedule uncertainty distributions. At a macro level, there are three methods for selecting schedule uncertainty distributions: data-driven, SME-driven, and performance-based approaches.

#### J.4.2.1. Data-Driven Methods

**The most defensible method for selecting uncertainty distributions is through the analysis of historical data.** This analysis can be accomplished by utilizing historical analogy (either by direct comparison or by bounding possible outputs with analogies) or through utilizing parametric (cost/schedule as a function of some driving factor) data. Either approach is highly defensible but oftentimes hard to use due to a lack of data at the appropriate level. Cost and Schedule data (both raw and normalized datasets) can be accessed in ONCE.<sup>41,42</sup>

Things to consider when utilizing parametrics or historical data:

- **Were the data normalized? How?** If the data were not normalized, some simple normalization may be warranted (e.g., inflation). For normalized data, oftentimes "outlier" events will be "normalized" out. Understanding what the data constitute is very important.
- **At what level are the data, and are the data compatible with my JCL model?** As discussed, above, uncertainty metrics (whether done in absolute or relative terms) are not easily transferable from one level of fidelity to another.
- **Are the data relevant to what is being estimated?** As with all statistically driven analysis, special care must be taken so that the data are homogeneous to what is being estimated.
- **Are there enough data to support the analysis?** Sample size matters. Small samples introduce statistical bias in the estimate of population range parameters. This bias should be considered and accounted for Jarvis & Oleson, 2012.

#### J.4.2.2. Performance-Based Methods

In some cases, it is possible to use performance data to extrapolate uncertainty distributions for use in JCL models. Performance-based methods are really an offshoot of Data Driven Methods. There are countless methods by which this can be done based on the type of performance data available and the level at which the data have been captured. For example, it is sometimes easy to compare a project's most up-to-date IMS to earlier versions. This comparison provides the JCL analyst with a view for how the project's duration estimates have compared to their actuals. In this case, the distribution that best fits the growth patterns of completed tasks can be used to model uncertainty of to-go tasks. Performance-based (e.g., EVM) methods allow an analyst to develop low-level uncertainty distributions with the rigor of data-based approaches. This method is one of the best ways that data can be used to justify uncertainty

<sup>41</sup> See the paper "One NASA Cost Engineering (ONCE) Database" (Johnson, Plumer, Blandford, & McAfee, 2014), and Appendix A.

<sup>42</sup> Additional data, relating uncertainty to project's complexity, are available (Elliott & Hunt, 2014).

factors for JCL analyses. Some references on how to use performance data for uncertainty analysis include Kuo, Cyr, & Majerowicz, 2014; and Cyr & Kuo, 2012.

Things to consider when utilizing performance based inputs:

- **Past Performance:** Just like in mutual funds, past performance may not be a good indicator of the future. This is especially the case when moving from one “type” of activities to another.
- **Level of Data:** As stated previously, one needs to make sure that the level of performance-based metrics collected is the same general fidelity as the JCL model.

#### J.4.2.3. SME-Based Methods

Unfortunately, it is rarely the case that data exist to justify all the uncertainty distributions required for JCL analysis. This is particularly true when a bottom-up analysis is performed on either an analysis schedule or the project's IMS, as even the highest-level analysis schedules tend to have tasks at a lower level (component or below) than schedule data that are available. Under these circumstances, it is necessary to obtain subject matter expert judgment (SME) in order to develop schedule uncertainty metrics. This section will outline the most common method for obtaining SME inputs and converting them into triangular uncertainty distributions for use in JCL simulations. Following a discussion of several issues associated with this methodology, other approaches for using SME guidance to develop uncertainty distributions will be discussed.

Although SME guidance is generally not considered a best-practice “estimating methodology,” there are actions that can be taken to ensure that the analysis is as accurate as possible. The first step in developing SME-based distributions is identifying the experts who will provide input to the analysis. Experts should be chosen based on their familiarity with the tasks for which they are providing input. Additionally, the JCL analyst should take care to document the name, position, and contact information for each SME. This approach ensures that the analysis is traceable should any questions arise later on.

Once an expert or group of experts has been identified, the next step is to extract their inputs for the uncertainty distributions. This identification is traditionally done through the evocation of three potential durations for the task in question: The minimum duration required to complete the task, the most likely duration required to complete the task and the maximum duration required to complete the task. These durations are then modeled in the JCL analysis as a triangular distribution.

There are two issues with this method that must be accounted for in the selection of distributions: one due to the unique nature of JCL analysis, the other inherent to all SME-based judgments. Since JCL analysis models a project's risk register, if proper care is not taken in the selection of uncertainty distributions, risk can be double counted. This occurs when a SME's judgment regarding the events likely to increase or decrease the time required to complete a task contains risks that are already being accounted for in the model of the risk register. Although there is no fool-proof way to be 100% sure that no double counting is taking place, there are actions a JCL analyst can take to minimize this risk. When evoking uncertainty distributions, the JCL analyst should walk through the risk register with the SME. The SME should be asked if, in the other projects they have worked, these risks have ever been experienced. If they have, it is likely that the uncertainty distribution includes these risks. At this point, the analyst has two choices: either remove the risk from the JCL model or lower the uncertainty distribution to avoid double counting.

One risk whenever SME judgment is used to develop uncertainty distributions is the tendency for SMEs to underestimate the true uncertainty. It has been demonstrated that SMEs tend to only capture a portion of the true uncertainty in their estimate of the range of potential outcomes of an event (Hubbard, 2010). Thus, it is important that the JCL analyst compensate for this underestimation through the expansion of the distributional bounds.

One final approach for making SME-driven uncertainty estimates as accurate as possible is through obtaining multiple inputs from which a distribution can be developed. For further references, please refer to Greenberg, 2014, and Butts, 2012.

Things to consider when utilizing SME inputs:

- **Right Expertise:** It's important to get the right expert solicitation for cost and schedule uncertainties. For example, a person may be quite the expert in a technical field but may not have a good handle on the cost and schedule uncertainties of that field; whereas a recent project manager, or Center cost estimator, may not be as competent in the technical area but have a better feel for cost and schedule impacts.
- **Confirmation Bias:** Tendency to search for or interpret information in a way that confirms one's beliefs or hypotheses. For example, an SME on a given project may underestimate the negative uncertainty because they "want" the project to succeed.
- **Framing Bias:** Using a too-narrow approach and description of the situation or issue.
- **Hindsight Bias:** Inclination to see past events as being predictable.

### **J.4.3. Risk Factors**

Another method for applying risks and uncertainties in a JCL analysis is to apply risk factors to activities. These risk factors can be thought of as global risk, or uncertainties, that may apply to a large subset of the tasks. This method can be used if you feel that there are common risks to the project or uncertainties that are affecting multiple tasks. For example, performance risk or uncertainties could be applied to multiple tasks' duration and cost due to known past performance issues.

### **J.4.4. Correlation**

Correlation is essentially the degree to which two or more attributes or measurements show a tendency to vary together. The schedule logic of the JCL analysis handles functional or structural correlation; however, there are other areas in which to consider correlation.

As best practices, consider correlation for duration uncertainty distributions, the TD distributions, and the TI distributions. Adding correlation between risk can be modeled in most platforms and may be deemed to be appropriate. As guidance, there is research<sup>43</sup> indicating that a .3 correlation factor for task uncertainty distributions is appropriate and that a .6 correlation factor between cost items is an appropriate starting assumption. These guidelines are merely that; the schedule's detail and topography can affect what the true correlation is as well as a number of other factors. Remember, assuming a correlation factor of zero is still a correlation assumption.

For the latest in correlation guidance and research, please contact [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

## **J.5. Reporting**

JCL reporting can assist the project as well as facilitate communication and reconciliation with the Agency's non-advocacy entities. This section briefly describes several common JCL outputs and displays.<sup>44</sup>

<sup>43</sup> Christian Smart (2013), *Robust Default Correlation for Cost Risk Analysis*, ICEAA conference, [https://www.iceaaonline.org/awards/papers/2013\\_Risk2\\_paper.pdf](https://www.iceaaonline.org/awards/papers/2013_Risk2_paper.pdf).

<sup>44</sup> Recommended Reference: J.K. Johnson, D.M. Elliott (2013), *Understanding The Results Of An Integrated Cost-Schedule Risk Analysis*, presented at the American Institute of Aeronautics and Astronautics (AIAA) SPACE 2013 Conference & Exposition.

### J.5.1. Cumulative Statistical Results

The cumulative statistical results from an integrated cost-schedule risk analysis are most often used to calculate a desired statistical confidence level. Similar to the traditional cost s-curve, the integrated cost-schedule scatterplot represents a cumulative distribution—of cost and schedule pair values (see Figure J-13). Cumulative results displayed as scatterplots can be provided at any element level in the integrated cost-schedule risk analysis. The standard display for the cumulative statistical result is the scatterplot in most major software applications such as Joint Analysis of Cost and Schedule (JACS), Polaris, Oracle Primavera Risk Analysis (OPRA), and Deltek Acumen.

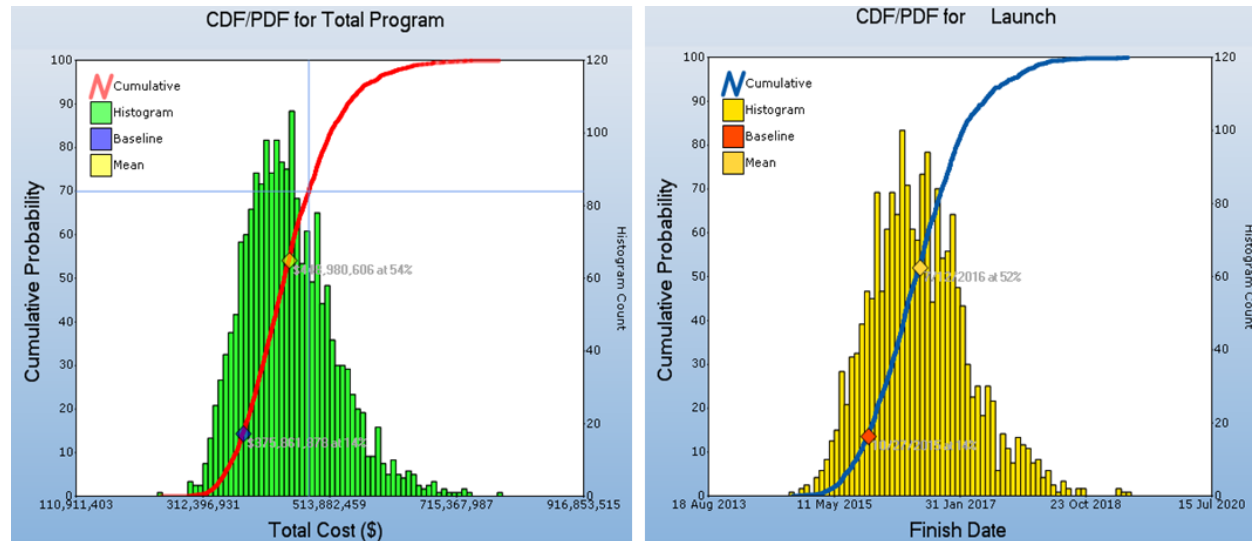


Figure J-13. Traditional Cost & Schedule S-Curves (Cumulative Distribution Function [CDF]) with Histogram (Probability Density Function [PDF])

### J.5.2. Scatterplot

A more sophisticated JCL scatterplot than was shown in the introduction to JCL in Figure J-6, is shown in Figure J-14.

The scatter plot in Figure J-14 shows iterations of cost and schedule risk analysis. Each scatterplot dot represents a specific result, or scenario, from the simulation calculation (cost and schedule). In Figure J-10, the x-axis represents the final completion date and the y-axis represents the final cost through that completion date. The scatterplot shows the simulated outcomes of the cost and schedule risk analysis. Each dot in the scatterplot represents a specific result, or scenario, from the simulation calculation (cost and schedule). The horizontal bar of the blue crosshair indicates the (Cost) confidence level, whereas the vertical bar of the blue crosshair indicates the (Schedule) confidence level. The blue-line crosshair itself reflects the project's point estimate (baseline plan) where the \$600 million project cost is at a 29.7 percent confidence level (CL) and the 7/30/2013 completion date is at a 31.6 percent CL.

Note that the CL to be at or below the point estimate's cost AND schedule is 19.6 percent, which is an estimation of a joint probability of cost and schedule. One way to visualize this joint probability is to refer to the green dots in the lower left of Figure 10. These dots represent all the scenarios that are at or below the baseline cost and schedule. In this example, if you take the green dots and divide them by the total amount of dots, you would get 19.6 percent of the dots being within cost and schedule—or put another way, 19.6 percent JCL.

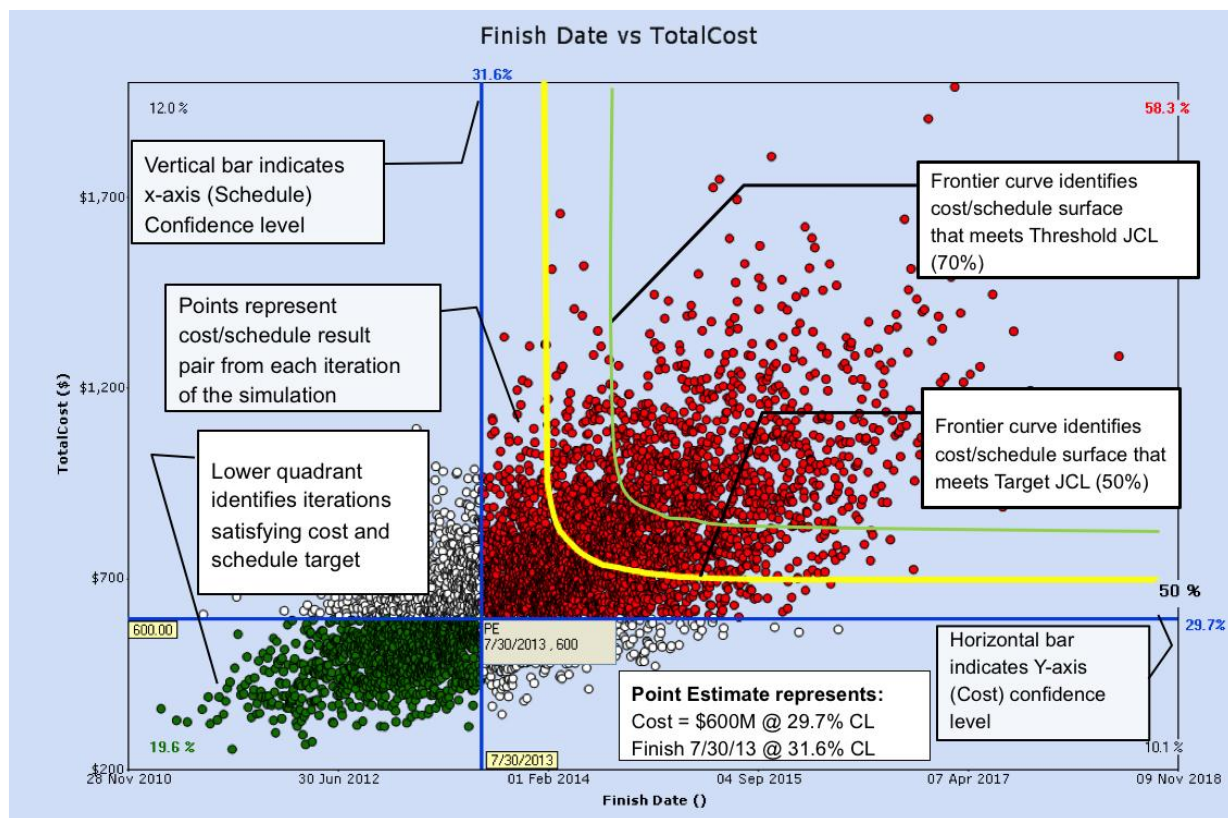


Figure J-14: JCL Scatterplot

The yellow and green lines in the upper-right quadrant of Figure J-10 represent indifference curves, or “frontier curves,” that specify all the cost/schedule combinations that will meet a specific joint confidence of cost and schedule. In this example, the yellow line represents the 50-percent JCL frontier curve while the green line represents the 70-percent JCL frontier curve. Note that the asymptotic tails on each frontier curve are purely academic—it is recommended to be as close as possible to the center of the cluster for that given frontier curve.

The frontier curves shown in Figure 10 (i.e., 50 percent and 70 percent JCL) are important references for those NASA projects/programs that need to satisfy KDP-C requirements per NPR 7120.5E. If Figure J-10 came from such a project or program, it would likely move the blue crosshair to a date and cost to obtain the Target JCL of 50 percent.

The scatterplot is ONLY valid for the current plan and should be considered a snapshot in time. If the project changes its baseline plan due to factors such as a funding or schedule increase or technical challenge, the project’s risk posture will fundamentally change, and you will need to rerun the JCL. The scatterplot only illustrates protection scenarios—it does not prove guidance and should only be used as a starting point to trade off cost against schedule.

### J.5.3. Sensitivity Reports

In addition to cumulative statistical results, the results of an integrated cost-schedule risk analysis can be expressed by illustrating the probabilistic sensitivity of elements or inputs present in the model (see Figure J-15). This is commonly done in cost-risk analysis using Tornado or Variance charts that express the relative contribution of the elements by an established metric (correlation, standard deviation, total variance, etc.).<sup>45</sup> These types of rank ordered charts are often referred to as “pareto” charts.<sup>46</sup>

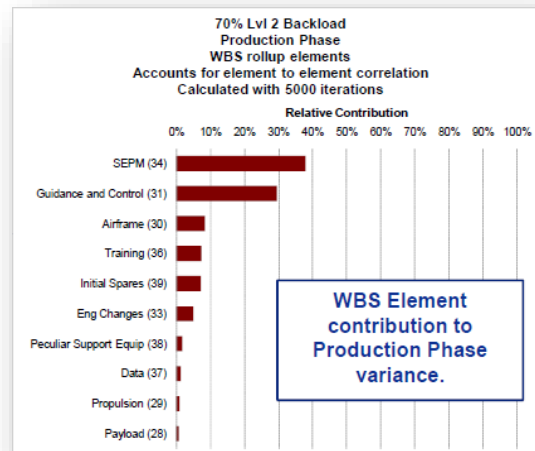


Figure J-15. Variance Analysis Charts to Determine Uncertainty Drivers (Smith, 2011)

There are a wide range of probabilistic sensitivity reports available to the analyst. Many commercial software products that can complete an integrated cost-schedule risk analysis provide multiple types of probabilistic sensitivity results, including the following:

- Duration Sensitivity: The correlation between a task's duration and the total program duration
- Cost Sensitivity: The correlation between a task's cost and the total cost of the project
- Duration-to-Cost Sensitivity: The correlation between a task's duration and the total cost of the program
- Criticality Index: The percentage of time a task spent on the critical path during the probabilistic analysis
- Discrete Risk Criticality: The probability that a risk register event will be on the critical path if it occurs

In the above sensitivity results, the critical path is defined as the path of least duration through the sequence of activities in the schedule with zero float or slack. Both the Criticality Index and the Discrete Risk Criticality can provide valuable insight into the key drivers of the probabilistic integrated cost-schedule risk analysis.

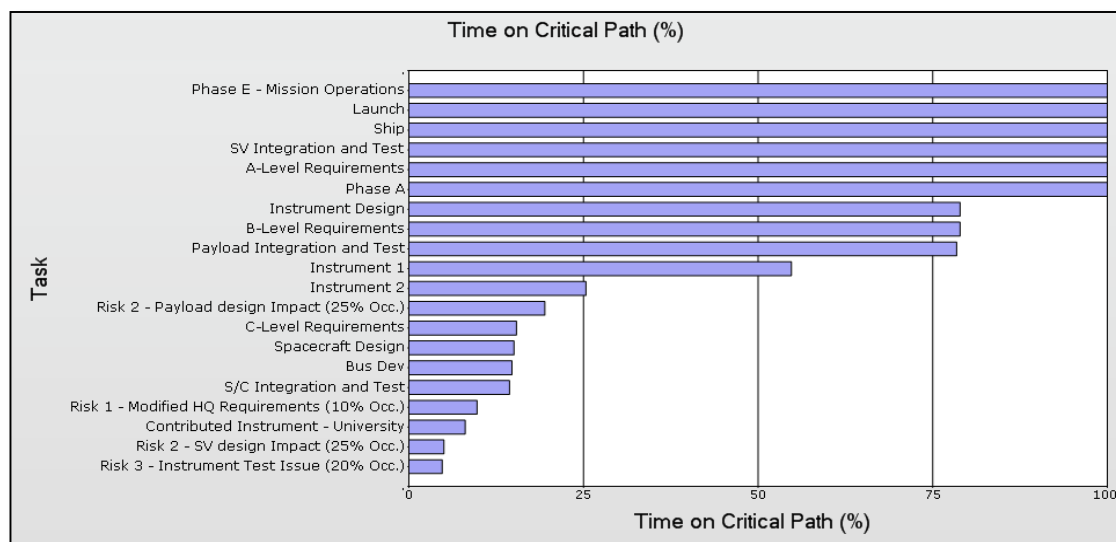
<sup>45</sup> A. Smith (2011), *Relating Tornado and Variance Analysis with Allocated Risk Dollars*, ACEIT User Workshop.

<sup>46</sup> Pareto charts are named for Vilfredo Pareto and are generally charts that contain both bars and a line graph where individual values are represented in descending order by bars, and the cumulative total is represented by the line.

### J.5.3.1. Criticality Index

Figure J-16 shows that the Criticality Index identifies tasks in the integrated cost-schedule risk analyses that are impacting the probabilistic schedule results (i.e., finish date or total duration). The Criticality Index is based on the measuring of the stochastic critical path in the integrated cost-schedule risk analysis. The stochastic critical path provides the individual task's frequency expressed as a percent time where total float, or total start float, is less than or equal to 0. This means that elements on the stochastic critical path are directly influencing the finish date or total duration of a project.

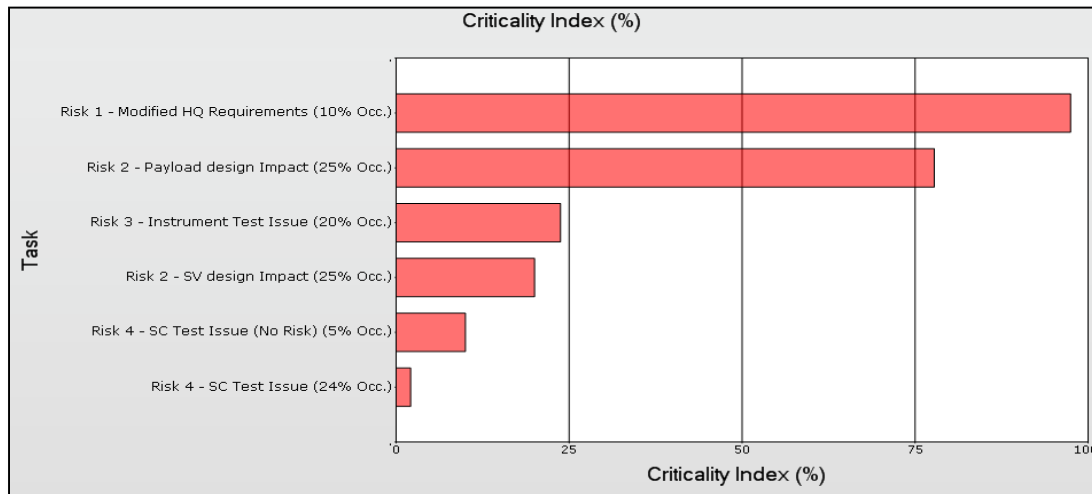
In Figure J-16, the elements are rank-ordered by the percentage of simulation iterations for which a task was on the critical path during the analysis. The key contributors to project duration and finish date are those tasks with a 100-percent Criticality Index. These tasks, regardless of how the task durations varied during the probabilistic analysis, were always on the critical path. These tasks are therefore likely to be critical to ensuring project completion on time.



**Figure J-16. Criticality Index Example Displays the Percentage of Time a Task Spent on the Critical Path**

### J.5.3.2. Discrete Risk Criticality

The Discrete Risk Criticality report is an extension of the Criticality Index and an excellent way to calculate and visualize the key discrete risk events that contribute most to the results of the integrated cost-schedule risk analysis. Discrete risk criticality is calculated as the frequency that a discrete risk appears on the critical path when it is active. Since an integrated cost-schedule risk analysis can contain a multitude of discrete risks, each with their own likelihood of occurrence and impact, it is important to analyze those discrete risks that, when active, contribute significantly to the probabilistic results. This is most directly accomplished by measuring the risks' frequency of occurrence on the critical path (see Figure J-17).



**Figure J-17. Discrete Risk Criticality Index Example Shows Risk Events Frequency on the Critical Path**

In Figure J-17, the elements are rank-ordered by a Criticality Index percent. This metric has a range from 0 to 100 percent, with elements that contribute the most and have a higher number approaching 100 percent. The calculation of the Criticality Index for any discrete risk event in the model is expressed as follows:

$$\text{Criticality Index percent} = \frac{\text{Number of Iterations where Total Float} \leq 0}{\text{Total Number of Iterations}}$$

The integrated cost-schedule risk analysis can provide valuable insight for project managers and others with meaningful probabilistic sensitivity results such as the Critical Index and the Discrete Risk Criticality. All too often, projects focus on a deterministic critical path and do not consider the effects of risks or uncertainty not directly linked to the deterministic critical path. By analyzing and illustrating the stochastic critical path, and by expressing all key elements with frequency values, additional drivers can often be highlighted that have not been previously considered.

### **J.5.4. Advanced Results**

Advanced results from the integrated cost-schedule risk analysis can provide enhanced insight into more than just the cumulative results or key drivers. A key advantage of the integrated cost-schedule risk analysis is the ability to generate statistical results over time. By developing a functional relationship between cost, schedule, and risk, the integrated cost-schedule risk analysis offers the ability to view and analyze results in a time-phased manner. In particular, an integrated cost-schedule risk analysis that uses either a cost- or resource-loaded schedule as its foundation can offer significant advantages for understanding the risk results over time.<sup>47</sup>

The Milestone Overlay and Annual Cost Uncertainty results are both advanced results that display the probabilistic results from an integrated cost-schedule risk analysis in a temporal context. Both the Milestone Overlay and Annual Cost Uncertainty are unique and advanced in that they are not readily available from all commercial software applications that perform integrated cost-schedule risk analysis.<sup>48</sup>

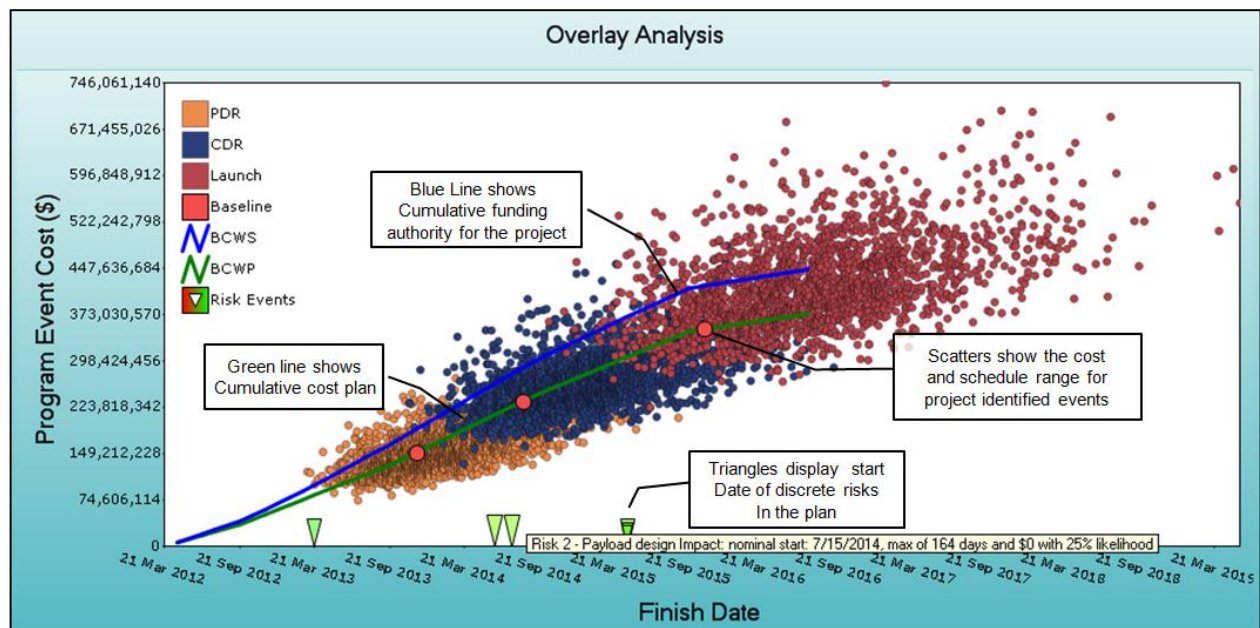
<sup>47</sup> Hulett, *Integrated Cost-Schedule Risk Analysis*.

<sup>48</sup> Joint Analysis of Cost and Schedule (JACS), by Tecolote Research, and Polaris, by Booz Allen Hamilton, both offer these outputs standard for analysts.

### J.5.4.1. Milestone Overlay

The Milestone Overlay is an advanced result that can display multiple XY scatter plot results for any number of predetermined milestones or key tasks. This result is essentially a combination of multiple cumulative scatterplots for selected milestones or key tasks in the integrated cost-schedule risk analysis. The flexibility of an integrated cost-schedule risk analysis easily supports this implementation by calculating and displaying the cost/schedule pair values for multiple elements or tasks on the same scatterplot.

Figure J-18 shows a Milestone Overlay result for an example project. In this example, multiple scatterplots are shown and color-coded. Scatterplots for Preliminary Design Review (PDR), Critical Design Review (CDR), and Launch are identified and plotted together against an X-axis of Finish Date and a Y-axis of Total Cost. The integrated cost-schedule risk analysis is able to produce scatterplots of any identified or preselected milestone or task. The Milestone Overlay can combine these together to produce a result that shows the risk to each milestone or task over time.



**Figure J-18. Milestone Overlay Advanced Result Example Displays the Scatter Plots for Milestones (PDR, CDR, and Launch) Over Time**

The baseline dates and costs for PDR, CDR, and Launch are shown as red circles in Figure J-18. These red circles mark projects' planned dates and costs for these important milestones. In each case, the red dot can be measured and contrasted against its corresponding scatter plot. Budget lines are also present, representing the Budgeted Cost of Work Scheduled (BCWS) and Budgeted Cost of Work Performed (BCWP) and providing further insight into the initial available resources over time.<sup>49</sup>

The Milestone Overlay also allows plotting of the discrete risk events and their occurrences over time. Individual risks are highlighted by triangles and annotated above in Figure J-18. By plotting multiple scatterplots over time in comparison to planned milestones dates and costs, the Milestone Overlay can

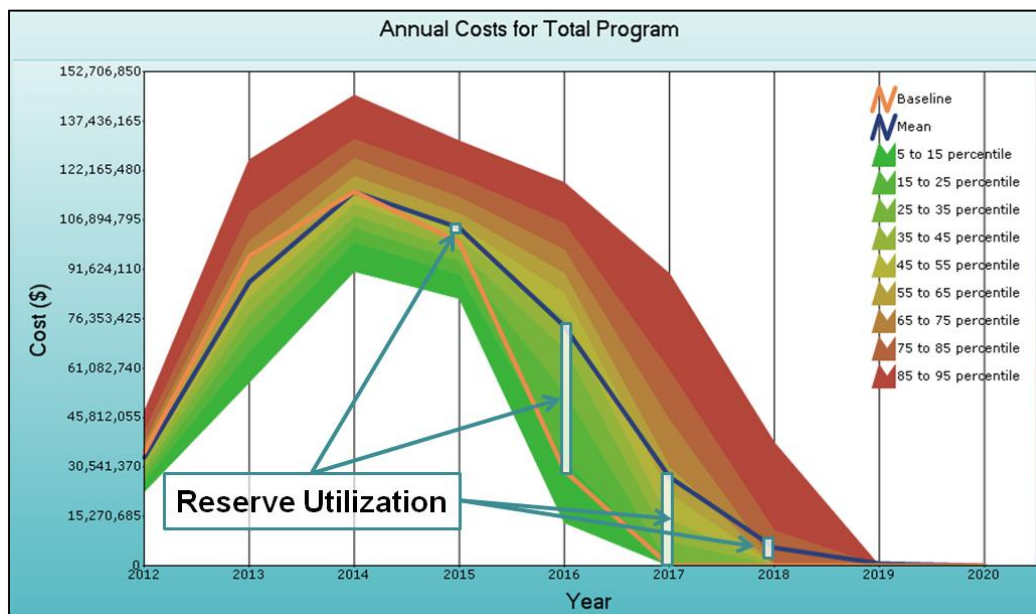
<sup>49</sup> BCWS and BCWP are common in EVM analysis. BCWS is the sum of the performance budgets for all work scheduled to be accomplished within a given time period. BCWP is the value of completed work expressed as the value of the performance budget assigned to that work.

provide a time-phased view of the cumulative results for multiple events and tasks. Including additional data such as the available budget and discrete risk events further enhance a project's understanding of the integrated cost-schedule risk analysis results over time.

### J.5.1.2. Annual Cost Uncertainty

The cost- (or resource-)loaded schedule approach to conducting an integrated cost-schedule risk analysis provides additional advancement to analysts that need to compare the annual cost risk to available resources. The Annual Cost Uncertainty results can display the probabilistic results for cost over time and allow for easy comparison to budget data. The key aspect of the Annual Cost Uncertainty result is that it can display the cost risk statistical results by a specified time period (e.g., fiscal year). Approaches have existed previously for calculating and displaying the cumulative cost uncertainty for the same budget comparison purpose.<sup>50</sup> By calculating and viewing the statistical results in an annual time-phased manner, analysts can identify particular time periods that may require reserve utilization and/or contain a significant amount of risk.

An integrated cost-schedule risk analysis that is developed using a cost- (or resource-)loaded schedule approach allows the analyst to produce Annual Cost Uncertainty results since the cost, and probabilistic risk results, will be phased over the project schedule. Understanding these results can provide insight for analysts that need to compare the time-phased risk results with available annual budgets. In Figure J-19, the time-phased probabilistic results of the integrated cost-schedule risk analysis are displayed from the 5th to 95th percentile for the years 2012 through 2020. The years 2015, 2016, 2017, and 2018 are annotated to highlight the likelihood of reserve utilization. In these years, the available annual resources, denoted by the orange line, are significantly less than the mean statistical result from the analysis, denoted by the blue line.



**Figure J-19. Annual Cost Uncertainty Result Example Displays Cost Risk Statistics Over Time in Comparison to Available Annual Resources**

<sup>50</sup> K. Cyr (2007), "The Constellation Confidence Level Estimate," *NASA Cost Symposium*.

Figure J-20 shows another example of such a display. The multi-colored bars represent the dollars needed by year for various confidence levels. The blue represents a low confidence level whereas the red represents a very high confidence level. The black lines represent the budget for each year. So, for example, the first year's (2011) budget is \$120 million, and its associated confidence level is well below this project's objective of 80 percent confidence level. The Gantt chart on the bottom of the figure provides similar analysis but by duration confidence for various summary tasks. Analysis such as this is helpful to determine whether the project's funding profile is in harmony with the probabilistic results from the JCL model. In this example, it appears that the funding for 2016 is not adequate (~10 percentile) for this project's specific risk posture.



**Figure J-20. Annual Phasing Example**

The creation of advanced results such as the Milestone Overlay and Annual Cost Uncertainty offer unique insight into the statistical results over time. The Milestone Overlay illustrates schedule milestone drift and allows for analysis of milestone or key event completion. This is an advanced approach to understanding the cumulative results from a scatterplot and offers added insight with the inclusion of an annual budget and the timing of discrete risk events. The Annual Cost Uncertainty result also provides added insight into the results of the integrated cost-schedule risk analysis by displaying the statistical results from the 5th to 95th percentile for an identified time period, such as each fiscal year.

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- James Taylor—Smith and Associates
- The former Constellation Program Office Cost Analysis Group

# Appendix K: Schedule Estimating Relationship (SER) Development and Model Inputs

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There is a fundamental relationship between project schedule behavior and project cost behavior. Understanding this relationship is essential to the cost estimator. The following topics are described in this appendix:

- K.1. Background**
- K.2. NASA Experience and Usage**
- K.3. Project Schedule Analysis Methods**
  - K.3.1. Parametric Schedule Estimating**
  - K.3.2. Analogy Schedule Estimating**
  - K.3.3. Engineering Build-Up/Grassroots Schedule Estimating**
- K.4. SER Data, Databases, and Models**
  - K.4.1. NAFCOM Model**
  - K.4.2. NICM Model**
  - K.4.3. QuickCost Model**
  - K.4.4. Schedule Estimating Relationship Risk Assessment (SERRA)**
  - K.4.5. Schedule Management and Relationship Tool (SMART)**
- K.5. Schedule Data**
- K.6. SER Research**
- K.7. SER Example Using SERRA**

## K.1. Background

There is a fundamental relationship between project schedule behavior and project cost behavior. Understanding this relationship is essential to the cost estimator. While this cost and schedule relationship seems intuitive to those in project management, it is often difficult for an estimator to quantify or model for the purposes of analysis. To complicate matters further, there is a distinction between the relationship of cost and schedule and the correlation between cost growth and schedule growth. The former (relationship of cost and schedule) is not always obvious, whereas the latter (correlation of cost growth and schedule growth) is mostly self-evident. For example, it is widely observed in a multitude of programs and projects that schedule growth usually leads to cost growth. In addition, the integrated master schedule needs to correspond to cost estimates to ensure that enough resources can be applied to activities to complete them within the expected duration. This should be done before the project schedule is finalized so that the relation between accurate cost and schedule estimates can be verified.

Ascertaining specific values of correlations for a particular project is a challenge. As with Cost Estimating Relationships (CERs), there are quantifiable relationships between the schedule and other project factors

and influences. Schedule Estimating Relationships (SERs) can likewise be used to estimate durations of schedule events much like CERs are used to estimate a particular price or cost.

SER is a technique used to estimate schedule duration by connecting an established relationship with one or more independent variables to the duration time of an event. If an independent variable (driver) demonstrates a measurable relationship with schedule duration, an SER can be developed. While relatively simple in concept, the ability to get accurate and meaningful data that can be used to quantify a relationship between an independent variable and schedule duration can be difficult.

This appendix provides a basic overview of NASA schedule estimating. Additional information on the subject is available in the NASA Schedule Management Handbook.<sup>1</sup>

## K.2. NASA Experience and Usage

NASA's SER experience has been confined to the project level (spacecraft, vehicle, and major element), where analysis of aerospace projects moving from major milestones can be accomplished without the influence of lower-level distortions. This high-level analysis has yielded statistical data and some observable trends. A transition from study to implementation has begun recently with analysts using SERs, schedule data, and models to complete schedule risk analyses on programs and projects.

While CERs can be directly used in project cost estimation, SERs do not have the same direct applicability to schedule estimation as their cost counterparts. For example, while requirements affect both cost and schedule, changes in requirements do not affect both cost and schedule estimates equally. In many cases, this is primarily because of the immaturity of SER usage within NASA and the estimating community. SERs, for the most part, are not as well publicized or used for schedule estimation. This means that many analysts may not know that SERs exist or know whether they are applicable to their particular program or project. Schedule estimation itself is also relatively new at NASA, and conducting a risk analysis on schedule, where an SER would be used, is still not a common type of analysis performed by programs or projects. Nevertheless, the new policies regarding high and low estimates of cost and schedule, as well as a greater push to understand schedule, have led to an increase in the amount of schedule analyses completed at the Agency.

CERs and SERs share similarities. Although CERs do not typically have schedule as an input, the same *factors* usually drive project CERs and SERs. These factors could be technical, such as mass and power, or they could be programmatic, such as funding stability and international partnerships. This speaks to the fundamental and intuitive notion of the common relationship between cost and schedule within an effort, since the same factors are often used to estimate both cost and duration.

## K.3. Project Schedule Analysis Methods

Parametric, analogy, and bottom-up estimating methodologies used in cost estimating are also applicable to schedule estimating. Estimating methods for schedule can be built using historical datasets, comparison to analogy, or detailed grassroots analysis. Estimating schedule durations can be extremely useful at both a high summary level or at the low activity level. The development of SERs, models, and logically linked schedules is a key component of schedule estimating. The level of detail selected will influence all of these key components. The selection of the schedule estimation method is tied to the relationship between cost and data availability, estimate purpose, data maturity, and program maturity levels. See Appendix C for more details.

### K.3.1. Parametric Schedule Estimating

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<sup>1</sup> [http://www.nasa.gov/pdf/420297main\\_NASA-SP-2010-3403.pdf](http://www.nasa.gov/pdf/420297main_NASA-SP-2010-3403.pdf)

Estimating schedule using a parametric approach involves the same fundamentals as estimating cost. Schedule duration data and independent variables are collected to conduct data analysis and determine if there are statistically significant relationships present to produce a SER. SERs can contain many of the same independent variables as CERs but could also be based on different datasets, normalization techniques, or analysis methods.

### **K.3.2. Analogy Schedule Estimating**

The analogy method for schedule estimating focuses on comparing the estimated duration with actual schedule data of similar missions. As with the analogy method for cost, careful consideration should be given to selecting the analogies. Any adjustments, deviations, or differences should be clearly identified and documented.

### **K.3.3. Engineering Build-Up/Grassroots Schedule Estimating**

Using a detailed engineering build-up estimate to develop a schedule estimate is a common technique employed by program managers all over the world. A highly detailed and logically linked schedule is the standard product generated by this schedule estimation method. As with cost estimating, grassroots estimating for schedule requires the same strong attention to detail to be successful. Analysts should continue to be careful when differentiating between a build-up schedule estimate and a given detailed schedule plan. Both may employ the engineering build-up/grassroots approach; however, there are significant differences. The former reflects an attempt to capture the entire work effort to analyze durations and the program plan. A build-up schedule estimate, similar to cost, is an attempt to predict the actual (i.e., actual duration/actual finish date.) The latter reflects the result of a detailed project plan and may contain significant constraints, optimism, or undocumented assumptions. The plan duration and plan finish date from a given detailed schedule plan are attempts to organize future work with the goal of delivering on time.

Collected data need to be normalized. Normalization involves analyzing the raw data and making adjustments for consistency. The inconsistencies that may be found in a dataset include changes in dollar values over time (inflation); learning or cost improvements for organizational efficiency; and, if more than one unit is being produced, the effects of production rates on the dataset being analyzed.

When analyzing a dataset, normalization considerations should include adjustments for the cost (currency, Base Year), size and weight, complexity or mission, frequency, and mission platform (crewed, robotic).

## **K.4. SER Data, Databases, and Models**

The underlying data that support the development and use of SERs are just as important as the data that support the development and use of CERs. The challenge at NASA is that these data are not as well recognized or available as similar cost data. Fortunately, recent efforts have begun collecting, organizing, and using schedule data to develop SERs for NASA analysts. This will result in the creation of new schedule estimating tools, as well as the expansion of existing cost models into the schedule estimating arena. Existing cost estimating models and tools such as the NASA Air Force Cost Model (NAFCOM<sup>2</sup>) also contain schedule data and SERs that can be used effectively, if the purpose and utility of the results are understood by the analyst. Refer to Appendix E for a summary of Agency-provided, as well as NASA-licensed models and tools. The following sections describe several of the SER-related tools used by the NASA community.

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<sup>2</sup> See the NAFCOM version 2011 Help file, located under "Process-Based Schedule."

### **K.4.1. NAFCOM Model**

NAFCOM is perhaps the most widely used cost modeling tool that can provide schedule output to the user. Three levels of schedules are generated by NAFCOM: system level by stage, stage level by subsystem, and subsystem level by process. The term “stage” refers to a major element of a launch vehicle estimate, as in a two-stage or three-stage launch vehicle. Earth-orbiting and planetary missions typically do not have stages, so this level of the Work Breakdown Structure is not used. The process-based view inside of NAFCOM provides estimated average schedules at the process level for each subsystem and system integration element. The user can click on any of these process bars and view a further breakdown of the processes required to develop and produce the hardware element. Summary schedules are also provided in NAFCOM at the major system element level, broken out by subsystem and system integration element, and at the complete system level, broken out by major system element. The schedule is estimated using the launch year (provided by the analyst on the Global input screen) as the end date. The model uses a combination of cost and technical parameters to estimate the schedule durations for each of the subsystems and system integration elements. In the current model version, users cannot alter schedule durations or determine schedule penalties or benefits—only average schedules are provided.

The NAFCOM-process-based schedule results are primarily useful as a crosscheck of the project schedule assumptions across the major milestone events. The utility of these NAFCOM schedule estimates and their results can be seen as a part of the wider context of schedule metrics that provide comparison to project planning and assumptions. Since the results provided by NAFCOM are average schedules, they are best used as a crosscheck at a high level against the program plan. This is much like other professional scheduling rules of thumb anchored by technical experience. The schedule metric informs project managers about how their baseline plan compares to the historical data at a high level. Schedule metrics, such as those from NAFCOM, can be used to compare against the results of project planning efforts (outputs), as well as assist technical experts during the buildup of an initial estimate. NAFCOM also provides a schedule database that can be used to better understand the schedule data for particular programs and projects. Figure K-1 provides an example schedule output from the NAFCOM model at the subsystem level.

#### **PCEC replacing NAFCOM**

At the time of publication, NAFCOM is still heavily used by the NASA cost estimating community. However, NAFCOM users are in the process of transitioning to the Project Cost Estimating Capability (PCEC), which contains additional information and tools. PCEC incorporates NAFCOM models, as well as models developed by various NASA Centers and directorates. Since most users at this time are more familiar with NAFCOM, this handbook will continue to reference it. The expectation is that the functionality provided to users by NAFCOM and referred to here will continue with PCEC. See Appendix E for additional information on PCEC.

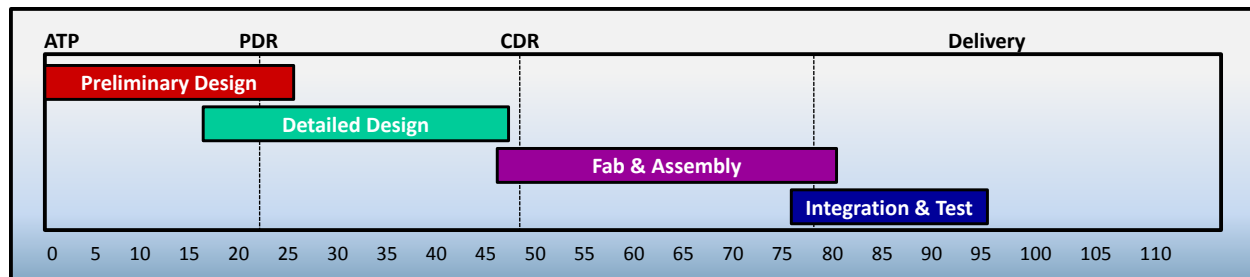


Figure K-1. An Example Schedule Output from NAFCOM at the Subsystem Level

Questions about NAFCOM should be directed to Andy Prince at [andy.prince@nasa.gov](mailto:andy.prince@nasa.gov).

#### K.4.2. NICM Model

Another NASA modeling tool that contains schedule data and SERs is the NASA Instrument Cost Model (NICM).<sup>3</sup> The NICM, which is available via the ONCE Model Portal at [www.oncedata.com](http://www.oncedata.com), focuses specifically on instrument estimation and contains a large database of many different types of instrumentation. This database includes schedule data, and there is a component within NICM for estimating schedule duration using SERs. The NICM approach to calculating duration from SERs is unique in that cost is an input to the SER equation. In this way, NICM SERs establish a functional link between the calculated cost of an instrument and its schedule duration. In addition to utilizing Cost As an Independent Variable (CAIV), NICM relies on the mission type and instrument subtype in the SER equation. Figure K-2 shows the NICM model schedule equation.

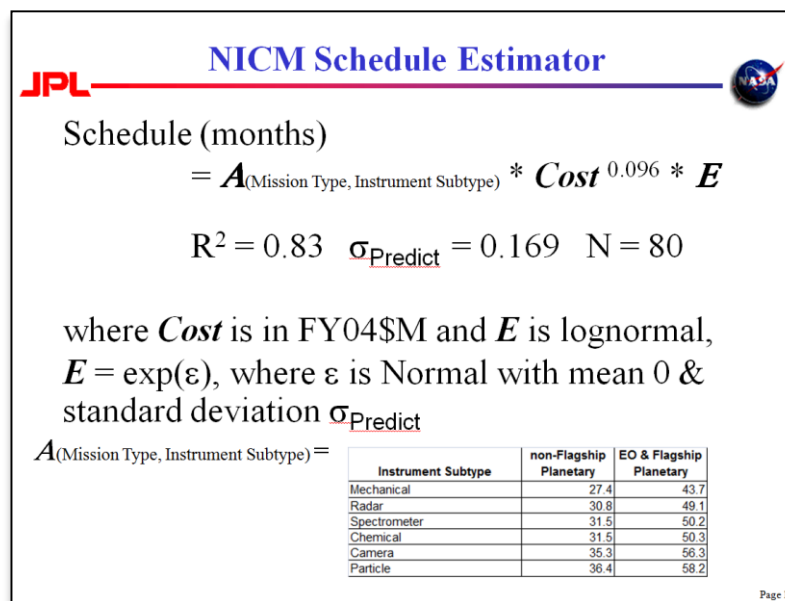


Figure K-2. NICM SER Information

Analysts with questions about using the NICM for SER capability should contact Joe Mrozinski of the NICM development team at the Jet Propulsion Laboratory (JPL), at [jmrozins@jpl.nasa.gov](mailto:jmrozins@jpl.nasa.gov).

<sup>3</sup> NICM version VI, Jet Propulsion Laboratory, May, 2014. For more information, see Appendix E.

### K.4.3. QuickCost Model

The QuickCost<sup>4</sup> model developed by Joe Hamaker also contains a schedule database and SERs. The QuickCost schedule database contains duration data on satellites, engines, module and transfer vehicles, and experimental vehicles (X-vehicles). SERs are available primarily for satellites. QuickCost will calculate duration for X-vehicles and module and transfer vehicles, but this relies upon the SER developed for satellites with additional calibration. QuickCost SERs focus on providing duration results for Phases C and D, omitting duration for Phases A and B. Analysts seeking to use QuickCost for its SER capability should contact Hamaker for more information.<sup>5</sup>

### K.4.4. Schedule Estimating Relationship Risk Assessment (SERRA)

The SERRA modeling tool also contains a database and SERs that can be used to conduct schedule risk analysis.<sup>6</sup> The SERRA SERs leverage the NAFCOM database of technical dependent factors with the explicit intent of generating NAFCOM-like SERs. SERRA can provide SERs and data on planetary, Earth-orbiting, and launch vehicle/human-exploration missions. SERRA was developed for NASA by SAIC and contains data on approximately 80 past projects. The available SERs can provide results for both Phase B/C and D and can provide a good crosscheck at a system level.

SERRA also provides schedule risk analysis through two components: technical uncertainty of inputs to the SER, and the error inherent in the SER regression. The underlying statistics of the SERRA SERs and additional information can be provided by CAD. The SERRA model is available at no cost for NASA Government distribution through the NASA Cost Analysis Division (CAD). Questions about SERRA should be directed to CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov). Sample schedule inputs and outputs for SERRA are provided in Figure K-3 along with a tabular output shown in Figure K-4.

	Units	Low	Most Likely	High
Development Start Year	1961+	2010	2010	2010
Engineering Mgmt	6 to 100	25	50	75
Dry Weight	lbs	2208.8	2761	3236.2
Max Data Rate	kbps	5800	5800	5800
Number of Instruments	1 to 12	1	1	1
Manufacturing Methods	6 to 100	25	25	50
Test Approach	25 to 75	50	50	50
Design Life	months	36	36	36
Great Observatory Class	yes/no		no	
Off-The-Shelf Bus	yes/no		yes	
Comm Satellites	yes/no		no	
Military Mission	yes/no		no	

Figure K-3. SERRA Schedule Model Inputs

<sup>4</sup> QuickCost 5.0, Joseph Hamaker, Ph.D., 2011.

<sup>5</sup> [jhamaker@galorath.com](mailto:jhamaker@galorath.com). For more information on QuickCost, see Appendix E.

<sup>6</sup> SERRA User Guide, SAIC, August 2010. For more information about SERRA, see Appendix E.

Outputs of Lognormal:				Outputs of Normal:			
	Design	Manuf	Total		Design	Manuf	Total
Mean	16.8	32.1	48.9	Mean	16.8	32.1	48.9
Median	14.9	28.5	45.7	Median	16.8	32.1	48.9
Mode	11.7	22.6	39.9	Mode	16.8	32.1	48.9
$\sigma$	8.8	16.5	18.7	$\sigma$	8.8	16.5	18.7
5th	6.6	12.9	24.9	5th	2.3	4.9	18.1
10th	7.9	15.3	28.5	10th	5.5	10.9	24.9
20th	9.9	19.0	33.5	20th	9.4	18.2	33.2
30th	11.5	22.1	37.7	30th	12.2	23.4	39.1
40th	13.2	25.2	41.6	40th	14.6	27.9	44.2
60th	16.9	32.3	50.2	60th	19.1	36.3	53.7
70th	19.3	36.8	55.5	70th	21.5	40.8	58.8
80th	22.6	42.9	62.4	80th	24.3	46.0	64.7
90th	28.0	53.1	73.4	90th	28.1	53.3	73.0
95th	33.5	63.4	84.0	95th	31.3	59.3	79.8

Figure K-4. SERRA Schedule Model Tabular Outputs

### K.4.5. Schedule Management and Relationship Tool (SMART)

The Schedule Management and Relationship Tool (SMART) combines analogy-based and parametric methods in a schedule estimating tool for unmanned spacecraft projects. The tool utilizes high-level technical and programmatic characteristics to determine a spacecraft's likely development schedule duration. It incorporates several previously developed third-party schedule estimating relationships (SERs) for comparison. SMART was developed by SpaceWorks Enterprises, Inc. (SEI) and is available via the NASA ONCE Model Portal at [www.oncedata.com](http://www.oncedata.com).

## K.5. Schedule Data

Raw schedule data used to develop SERs can be found in various locations. The schedule data are spread across the Agency, and analysts can expect to expend some effort during data collection.

Fortunately, recent efforts to consolidate and organize the data have made this job somewhat easier. The Cost Analysis Data Requirement (CADRe) data and the One NASA Cost Engineering (ONCE) database are excellent data sources for collecting duration information, at [www.oncedata.com](http://www.oncedata.com). Examining prior research from the Aerospace Corporation as well as the Air Force Cost Analysis Agency (AFCAA) and the National Reconnaissance Office (NRO) can also provide the analyst with previously created schedule databases for SER development.

## K.6. SER Research

In 2009 and 2010, NASA CAD commissioned MCR, LLC, to enhance and upgrade the database of satellite and payload schedules, focusing on the time required to move from one development milestone to the next. This work builds upon a previous database developed under a joint AFCAA/NRO task organized by the NRO Cost Analysis Improvement Group (CAIG). This research resulted in the creation of many individual SERs and a large database of schedule information for the Department of Defense (DOD), NASA, and NRO missions.

The resulting unclassified spacecraft database for satellite SER development contains 247 data records and is segregated by mission type. The resulting unclassified payload database contains 519 data records and is also segregated by mission type.<sup>7</sup> The data are further segregated by the various

<sup>7</sup> NRO Cost Group (NCG) Data Books—an ongoing collection from Government and industry, 1995 to present.

hardware vendors and identified by agency sponsor (e.g., DOD, NRO, or NASA). Parameters for mission design life (DL), end of life (EOL) date, and failure cause are included in the database to allow additional analysis of actual versus estimated plots that may suggest a relationship between the probability of premature failure and schedules that are less than the estimated schedules predicted by the SERs.

The research itself developed SERs for the time between spacecraft and instrument development milestones, including Authorization to Proceed (ATP), Preliminary Design Review (PDR), Critical Design Review (CDR), Integration and Test (I&T), Payload Delivery (DEL), First Launch Availability (FLA), and others as supported by the data. Figures K-5 and K-6 summarize the spacecraft SER and instrument SER types, respectively.

SER #	Duration	Dataset Used
<b>Authority to Proceed (ATP) to First Launch Availability (FLA) SERs</b>		
1	ATP-FLA	NASA only – All Spacecraft (SC)
2	ATP- FLA	NASA only – Planetary SC
3	ATP- FLA	NASA only – Non-Planetary SC
<b>System Requirements Review (SRR) to FLA SERs</b>		
4	SRR- FLA	NASA only – Planetary SC
5	SRR- FLA	NASA only – Non-Planetary SC
<b>Beginning of System Test (BST) to FLA SERs</b>		
6	BST- FLA	NASA only – Planetary SC
<b>ATP to End of System Test (EST) SERs</b>		
7	ATP-EST	NASA only – All SC
8	ATP-EST	NASA only – Non-Planetary SC
<b>ATP to Ship Date (SD) SERs</b>		
9	ATP- SD	NASA only – All SC
10	ATP- SD	NASA only – Non-Planetary SC

**Figure K-5. NASA Spacecraft SER Types Developed by MCR**

SER #	Duration	Dataset Used
1	ATP-DEL	Total Unclassified Database
2	CDR-DEL	Total Unclassified Database

**Figure K-6. Instrument SER Types Developed by MCR**

The SERs were developed using three statistical methods: (1) Ordinary Least Squares (OLS), (2) Minimum Percentage Error–Zero Percentage Bias (MPE-ZPB or ZMPE), and (3) Errors in Variables (EIV) regression.

The resulting SERs' goodness-of-fit statistics that were developed under this task, in general, are poorer fit statistics (as expressed by error residuals, degrees of freedom, and  $R^2$ ) than would be found in CERs. The criteria for selecting recommended SERs were thus relaxed for this research to include SERs with a standard error of 40 percent and  $R^2$  at or above 50 percent.

The two primary SER drivers that were collected and used in SER development were dry mass and beginning of life (BOL) power. The primary driver of schedule is the size of the program as measured by complexity. Both dry mass and BOL power are often used as proxies for measuring this complexity. In general, the higher a spacecraft mass and the more power it requires, the more complex it is. Another driver that is often seen in SERs is DL. Longer DL often necessitates more testing to ensure that the spacecraft lasts as long as advertised. In order to consider the "newness" of the spacecraft, an indicator variable for block change/new design was also collected in the research. This allows the analyst to distinguish from follow-on spacecraft and spacecraft undergoing major changes that could result in

significant design challenges. Two additional metrics were collected to capture the amount of diversity present in the spacecraft development process: the number of mission types and the number of distinct payloads.

Quality metrics are calculated for each SER to provide the user with an understanding of the likely accuracy of estimates based on that SER. These quality metrics depend on the values of the drivers in the database alone and not on any probabilistic assessment of the expected growth of the drivers of the particular SER involved. Therefore, during a typical risk analysis, the user should consider probable growth in the drivers, which can help account for estimating the a posteriori value of schedule duration using a priori values for schedule drivers.

Figure K-7 shows an example SER for ATP to FLA for a planetary spacecraft using ZMPE.

The complete research report, results, and Excel database are available from CAD upon request.

Applicability: All Unmanned NASA Planetary Space Vehicles			
Method: Estimation of Time from ATP to First Launch (mos) vs. Dry Mass (lbs) and IMINT / Remote Sensor			
<b>Estimating Relationship:</b>			
$Y = 5 + 0.581 * X1^{(0.785)} * (0.286)^{D1}$			
Y = Time from ATP to First Launch (mos)			
X1 = Dry Mass (lbs)			
D1 = IMINT / Remote Sensor			
<b>REGRESSION METHOD:</b>			
Constrained Optimization of SER coefficients:			
Minimized standard error with zero bias constraint			
<b>SIGNIFICANCE TESTS:</b>			
SER Form $Y = a + b(X1)^c * d^{(D1)}$			
	Coef	Value	Significance
	a	5.24	-3.41E-02 significant
	b	0.58	-1.44E-02 significant
	c	0.79	5.93E-01 significant
	d	0.29	5.91E-01 significant
<b>SER STATISTICS:</b>			
% Standard Error (Multiplicative Error)	34.7%	# Observations	30
Pearson's Correlation Squared ( $R^2$ )	54.7%	# Coefficients	4
Bias %	0.0%	Deg. Of Freedom	26
<b>FIT RESULTS:</b> Reasonable fit to data. Reasonable standard error. Zero Bias.			

Figure K-7. SER for ATP to FLA of Planetary Spacecraft Using ZMPE

## K.7. SER Example Using SERRA

The following example shows how an analyst can use programmatic data and a SER to estimate schedule duration. In this example, the analyst is tasked to perform a parametric schedule estimate. The analyst has reviewed preliminary program summaries and selected the planetary spacecraft mission type from SERRA since these most closely match the current program.

The analyst collects the following technical and programmatic data from the Project Office<sup>8,9</sup>:

- Mission Type = planetary spacecraft
- Schedule Start (StartYr) = 2011 (schedule start Base Year is 1960)
- Engineering Management (StreamEM) = 25 (few design changes, Skunk-Works approach)
- Satellite Dry Weight (DryWt) = 1,800 pounds
- Maximum Data Rate (MaxData) = 256 kilobytes per second

<sup>8</sup> The model variable names are provided in parentheses next to the input parameter name.

<sup>9</sup> Both engineering management and funding availability are based on scales of 0 to 100.

- Number of Instruments (NumInst) = 8
- Funding Availability (FundAvail) = 50 (some infrequent delays possible)
- Mission Design Life (DesignLife) = 24 months from launch to end of mission (includes transit time)
- Power Source: Radioisotope Thermoelectric Generator (RTG); (1 = no RTG, 0 = RTG)

The Engineering Management input describes the level of design changes, experience of the design team, and environment of the design effort, as follows:

- 0—Minimum design changes with design team, making maximum use of highly efficient Skunk Works approach with Integrated Product Teams (IPTs), rapid prototyping, design to cost, etc.
- 25—Few design changes using a highly efficient Skunk Works approach with IPTs, rapid prototyping, design to cost, etc.
- 50—Moderate design changes with an application of advanced design methods, including concurrent engineering, tailored specifications, minimum reporting, etc.
- 75—Dedicated design team dependent on some technology advances that encounter significant requirements changes
- 100—Distributed design team dependent upon major technology advances and experiencing frequent major requirements changes

The Funding Availability input reflects the appropriate anticipated funding availability. Choices for Funding Availability include the following:

- 25—Funding is assured; no delays
- 50—Some infrequent delays possible
- 75—Funding is constrained; delays likely

The appropriate equations in SERRA for estimating planetary mission schedule phases are as follows:

#### Schedule Duration (ATP to CDR)

$$Start\_CDR\_Dur = 0.759 FundAvail^{0.420} StartYr^{0.337} DesignLife^{0.229} StreamEM^{-0.393} RTG^{0.599}$$

#### Schedule Duration (CDR to Delivery)

$$CDR\_Delivery\_Dur = 5.279 TechnicalRating^{0.065} StreamEM^{-0.824} StartYr^{0.613} RTG^{0.376}$$

$$\text{Where } TechnicalRating = (DryWt - 100) / 4000 + (NumInst - 1) / 12 + MaxData / 256$$

It is important to realize for log-transformed regression that a “no” input translates to a value of 1.0 and a “yes” input translates to a value of 2.71828. StreamEM is a yes/no input based on a streamlined engineering management approach (yes, in this case). Also for these SERs, the input for the year of schedule start is normalized by subtracting 1960 from the year of start. The RTG input is yes/no as well, and since this spacecraft is not powered by an RTG, the value input in the SER equation is 1, regardless of what other power source might be used.

The SER equations with the appropriate programmatic inputs collected above are:

#### Schedule Duration (ATP to CDR)

$$Start\_CDR\_Dur = 0.759(50)^{0.420} (2011-1960)^{0.337} (24)^{0.229} (2.71828)^{-0.393} (1)^{0.599} = 20.64$$

**Schedule Duration (CDR to Delivery)**

$$TechnicalRating = (1800 - 100) / 4000 + (8 - 1) / 12 + 256 / 256 = 2.008$$

$$CDR\_Delivery\_Dur = 5.279(2.008)^{0.065}(2.71828)^{-0.824}(2011 - 1960)^{0.613}(1)^{0.376} = 26.98$$

Thus, the estimate development phase **(ATP to CDR) duration is 21 months**, and the estimated manufacturing phase **(CDR to delivery) duration is 27 months**.

## Appendix L: Estimating the Cost of Construction of Facilities (CoF) and Ground Support Equipment (GSE)

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Estimating facility costs is a specialized type of cost estimating.<sup>1</sup> The acquisition and development of real property is governed by Federal statute, with additional guidance and requirements levied in Office of Management and Budget (OMB) Circulars, such as A-11 and A-94. NASA directives and requirements, largely found in the NASA Online Directives Information System (NODIS) as part of the 8800 series of directives, also provide useful information.

The estimator should work closely with the Center facilities organization to ensure that estimates are complete and in compliance with these statutes and directives. This appendix provides estimating techniques and rules of thumb that were developed for application at the Kennedy Space Center (KSC). The techniques can be used as examples to assist the estimator in collecting and analyzing local data and as estimating tools and references appropriate for use at each respective installation.

The following topics are described in this appendix:

- L.1. CoF and GSE Overview**
  - L.1.1. COF Types and Affected Ground Support Equipment**
- L.2. Facility Funding Types**
  - L.2.1. Non-CoF Funding**
  - L.2.2. Facility Planning and Design (FP&D) Funding**
  - L.2.3. Phasing of Funds**
- L.3. Estimating CoF and GSE Projects**
  - L.3.1. Conceptual Parametric Estimates**
  - L.3.2. BOE**
- L.4. Historical Information**
  - L.4.1. Historical Cost and Schedule Data**
  - L.4.2. Historical Schedule Growth**
  - L.4.3. Historical Cost Growth**
- L.5. Conclusion**

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<sup>1</sup> G. C. Butts, "Accurate Estimates in Less Than a Minute," presented at the AACE International Conference, Las Vegas, NV, 2006.

## L.1. CoF and GSE Overview

It can be difficult to estimate costs for CoF and GSE due to many factors, including numerous variations of types, sizes, unique features, site location, site conditions, economic conditions, and local infrastructure capability. Federal law and NASA Facility Project Requirements, including NASA Procedural Directive (NPD) 8820.2D, dictate a rigid budget process for CoF projects that requires that CoF funding requests be submitted years before the design has been completed or final requirements are known. Figure L-1 captures the funding process. For more specific details on NASA policy and the CoF process, refer to NPD 8820.2D at [http://nodis3.gsfc.nasa.gov/lib\\_docs.cfm?range=8](http://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=8).

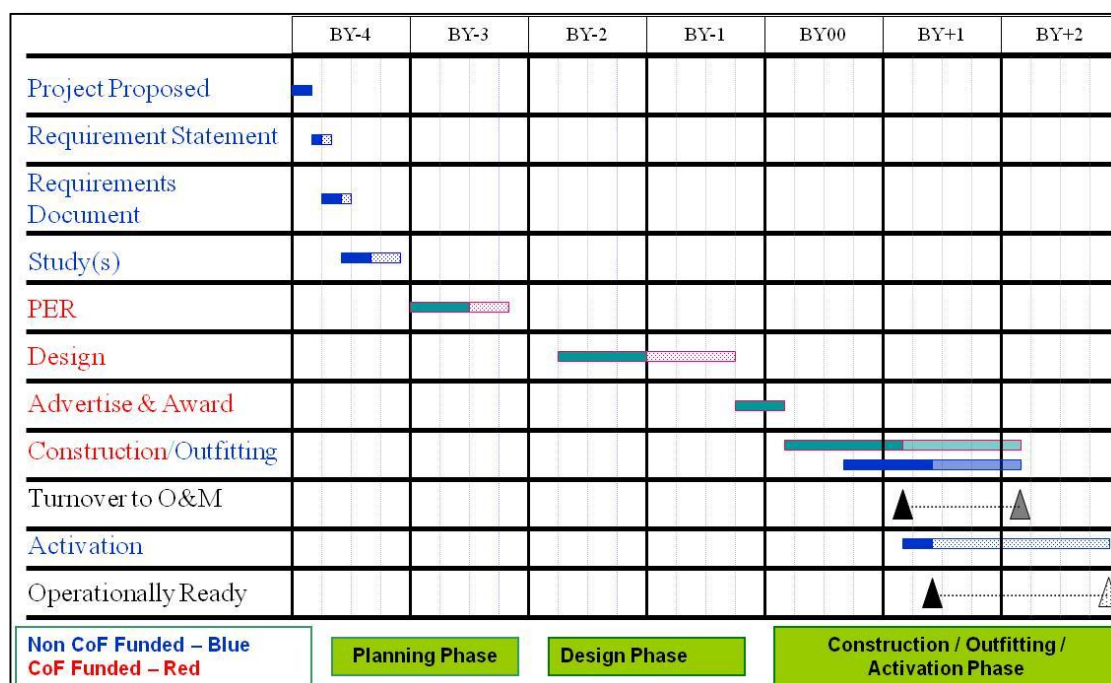


Figure L-1. The CoF Funding Process

### L.1.1. COF Types and Affected Ground Support Equipment

Congressional authorization and appropriations are required for the funding of revitalization projects, construction of new facilities, acquisition of related collateral equipment, environmental compliance design of facility projects, and advanced planning for future facility needs. Preliminary Engineering Reports (PERs) are required for each type of facility need. This includes site investigation and sufficient preliminary design to fully develop project scope, assess risks, identify construction complexities, and provide a realistic cost estimate prior to inclusion in the NASA budget submission to the OMB.

Here are details on these projects:

- Revitalization projects—Substantial renewal and upgrade work of the physical plant to meet current and future needs, thereby extending its useful life (e.g., a facility project that extends the useful service life beyond the original design life).
- Construction of new facilities—The erection or modification of real property required to support a new capability, including additions, sidewalks, parking lots, driveways, and upgrades. This includes alterations to existing facilities that change the original purpose of the facility (e.g., remodeling a warehouse, or portion thereof, into office space).

- Collateral equipment—Includes building support equipment and large, substantially affixed equipment/property that is normally acquired and installed as a part of a facility project and includes the following:
  - Building-support equipment. Common types of building-support equipment are situated within the facility (e.g., elevators, transformers, compressors, heaters, ventilators, and air conditioners). It also includes systems and subsystems, such as electrical, plumbing, pneumatic, fire-protection, fire-suppression, control and monitoring systems.
  - Large, substantially affixed equipment/property of any type. Other than building-support equipment, this type of equipment/property is built in such a way that the installation costs including building envelope modifications, special foundations, and utility service exceed \$300,000.<sup>2</sup> Noncollateral equipment, when acquired and used in a facility or a test apparatus, can be severed and removed after erection or installation without substantial loss of value or damage to the premises where installed.<sup>3</sup>
- Environmental Compliance—Environmental concerns are becoming a larger factor in the overall process, and this trend is only expected to grow. Failure to consider environmental issues will impact a project's schedule and, therefore, its budget.
  - All CoF projects require an environmental analysis.<sup>4</sup> Many of these projects require an Environmental Assessment (EA), which typically takes from 3 to 8 months to perform. Major projects generally require an Environmental Impact Statement (EIS). These typically take 1 to 3 years to complete but can run much longer if there are substantial objections from the community.
- Advanced Planning—Front-end planning to define project requirements using comprehensive planning tools such as the Project Definition Rating Index (PDRI), team building, and other techniques.

**CAUTION:**

It is critical for project success that the correct color of money is allocated!

## L.2. Facility Funding Types

There are three basic types of funding required for facility construction:

- Research & Development (R&D);
- CoF ; and
- Facility Planning and Design (FP&D)

Under NASA policy, most CoF projects will require some type of non-CoF funding for activation and non-collateral equipment.

Most facility construction and renovation projects require multiple funding types for completion.

Demolition funding is unique: it can sometimes be CoF- or non-CoF-funded depending on the specific circumstances. For example, if an entire building is to be demolished, it can be done with CoF funding even though items in the building may be classified as R&D. However, if, for example, the demolition is for something initially built with non-CoF money, then non-CoF funding could be used for demolition. Table L-1 gives examples of CoF and non-CoF items.

**Rule of Thumb:**

Items that can easily be moved are usually R&D. Items that cannot be easily moved are usually CoF.

<sup>2</sup> NASA Facility Project Requirements, NPF 8820.2F Appendix A, paragraph A-23.

[http://nodis3.gsfc.nasa.gov/lib\\_docs.cfm?range=8](http://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=8)

<sup>3</sup> NASA Facility Project Requirements, NPF 8820.2F Appendix A, paragraph A-86.

[http://nodis3.gsfc.nasa.gov/lib\\_docs.cfm?range=8](http://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=8)

<sup>4</sup> 14 CFR Part 1216 ([http://www.access.gpo.gov/nara/cfr/waisidx\\_00/14cfr1216\\_00.html](http://www.access.gpo.gov/nara/cfr/waisidx_00/14cfr1216_00.html)) and NPR 8820.2F paragraph 1.3.16.7.

## L.2.1. Non-CoF Funding

Non-CoF funds are used for noncollateral equipment such as furniture, carpeting, telephone systems, GSE, and Special Test Equipment (STE). Other non-CoF costs include relocation/move-in expenses and calibration.

**Table L-1. Example Comparison of CoF and Non-CoF Items**

Examples of CoF Items	Examples of Non-CoF Items
<ul style="list-style-type: none"> <li>• Building structure (foundation, walls, roof, etc.)</li> <li>• Vinyl tile and ceramic tile</li> <li>• Heating, ventilation, and air conditioning (HVAC) systems</li> <li>• Alternating current (AC) power</li> <li>• Electrical conduit</li> <li>• Fire-detection system hardware</li> <li>• Fire-suppression systems</li> <li>• Potable water</li> <li>• Wastewater systems</li> <li>• Facility gas systems (from source to facility 5-foot line)</li> <li>• Facility grounding and lightning protection</li> <li>• Cranes (including control systems and software programs)</li> <li>• Elevators (including control systems and software programs)</li> <li>• Exhaust systems</li> <li>• Cabling duct banks (power and communications)</li> <li>• Emergency power generation</li> <li>• Original finished flooring and ceiling</li> <li>• Signs (except personnel name signs)</li> </ul>	<ul style="list-style-type: none"> <li>• Activation</li> <li>• Furniture and window treatments</li> <li>• Carpeting</li> <li>• Systems furniture</li> <li>• Electronic equipment racks</li> <li>• Removable raised flooring</li> <li>• Raised flooring and Heating, Ventilation and Air Conditioning (HVAC) for raised flooring systems (equipment racks, computers, data equipment)</li> <li>• GSE</li> <li>• Hardline tubing and flexible hoses from facility 5-foot-line interface panel to GSE</li> <li>• Communication cable (including data circuits) and "end item" equipment</li> <li>• Telephones</li> <li>• Computers</li> <li>• Fire-detection software</li> <li>• Application software</li> <li>• Laboratory equipment and systems, including work benches, sinks, cabinets, and exhaust "hoods"</li> <li>• Uninterruptible Power Systems (UPS)</li> <li>• Direct Current (DC) power</li> <li>• Premise wiring</li> <li>• Operational Intercom System—Digital (OIS-D)</li> <li>• Cafeteria and kitchen equipment/furniture</li> <li>• Labor for connecting facility interfaces</li> </ul>

## L.2.2. Facility Planning and Design (FP&D) Funding

FP&D funding is a hybrid of non-CoF and CoF funding, but it must be clearly established early during Pre-Phase A Formulation.

Design is the cornerstone of any project. A good design is crucial for meeting the project's schedule, scope, and budget requirements. A poor design may not adequately cover the requirements of the project. If the drawings are incomplete, ambiguous, unclear, or open to interpretation, the contractor will interpret specifications and requirements to its benefit, increasing the number of change orders that will occur later and driving up cost.

### L.2.2.1. CoF Design Fees

In addition, 2 percent of the CCE may be required for a Preliminary Engineering Report (PER), and 2 percent may be required for a study. The Federal Acquisition Regulation (FAR) prohibits payment of more than 6 percent of the CCE for the actual design; however, the remaining 4 percent is allocated for site visits, design reviews, and other costs.

In practice, the higher the project costs, the smaller the design budget percentage should be in relation to the total cost. Consequently, the smaller the project, the larger the design budget should be in relation to the total cost. Smaller projects require a basic amount of work, including weekly meetings, site visits, and submittal review. It takes just as long to review a floor-covering submittal for a 1,000-square-foot building as for a 1-million-square-foot building, but on the larger projects, there are enough fees to cover this activity.

Engineering News Record (ENR) has proposed a new fee-determination formula in an attempt to adjust for these issues:

$$\text{Basic Services Design Fee} = 1.25/(\text{Log } C)^{1.5}$$

where  $C$  = current construction cost in dollars

Basic Services Design fee = percentage value

However, the proposed new fee-determination formula does not hold up against actual design fees negotiated at KSC. The following formula is a better fit for the average of 44 projects at KSC:

$$Y = 16.73 \times x^{0.37}$$

The formula estimates a 66 percent probability for design costs to not exceed the calculated amount. To increase the probability of not exceeding the calculated amount by 84 percent, the formula needs to be modified as follows:

$$Y = 16.73 \times x^{-0.34}$$

The calculated amounts by project costs are shown in Figure L-2.

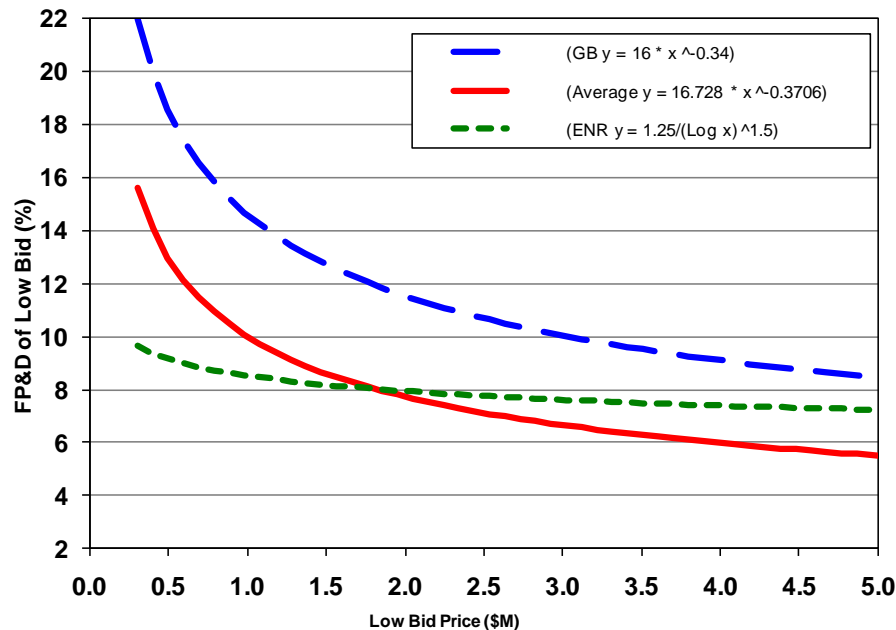
### CAUTION:

The line between CoF and non-CoF can be unclear and difficult to determine. There can be severe consequences for errors. Involve Center CoF Program Managers and Headquarters early, and document your assumptions!

### Rule of Thumb:

If the project is 10 percent non-CoF and 90 percent CoF, 10 percent of the FP&D funding will be R&D and 90 percent will be CoF funded.

**Exception:** Facility planning funding is always non-CoF funding.



**Figure L-2. FP&D Fee Calculations**

The estimator needs to remember that the relationship used to estimate FP&D fees should be applicable to the specific Center and site being evaluated.

Note that the FP&D fees for new projects are, on average, 1 percent higher than modifications to existing projects. This is attributed to the required EIS. Also, technically complex projects generally require a higher design fee than indicated in Figure L-2.

According to the *Means Estimating Handbook*, design and architectural fees range from 15 percent for small or complex projects down to 4 percent for large projects or projects involving uncomplicated or repetitive work.<sup>5</sup>

### L.2.2.2. GSE Design

The design of GSE typically costs more than normal building design costs. Historically, the range of final costs for the design of GSE has been 1 to 212 percent of the total bid, mainly due to the variety of items and quantities ordered. Only one design and 50 copies of the same item may be built; or, it is conceivable that only one unique item is ordered.

#### **Rule of Thumb:**

Normal GSE design cost is 10 to 50 percent of the total GSE cost.

#### **Rule of Thumb:**

The smaller or more unique the equipment, the higher the GSE design cost.

<sup>5</sup> *Means Estimating Handbook*, Second Edition, Reed Construction Data, 2003, p. 20.

### L.2.2.3. Design Duration

The industry average for the duration of the design phase for projects between \$500,000 and \$5 million is 8 months, but at KSC, the design phase averages 10 months due to design changes, unforeseen conditions, new requirements, etc.

A recent American Institute of Architects (AIA) survey of architecture firms determined that the average time between the award of a design contract and the award of a construction contract for a facility was about a year. However, there is considerable variation from project to project. According to the AIA survey, for commercial/industrial projects, the design phase up through contract award was less than 6 months for 40 percent of the projects, while for more than a quarter of projects, this period extended beyond a year. The size and complexity of a project are key reasons for variation in design time, but three other factors also influence design time:

- Client decision making—and whether these decisions need single or multiple approvals
- Financing and funding for the project
- Regulatory approvals—land entitlement, special-use permits, zoning, environmental issues, and historical considerations

### L.2.3. Phasing of Funds

Once the total project budget has been determined, the next step is phasing funding correctly. This is critical for project success! Unless special permission is obtained for a Limit of Government Obligation (LOGO) contract, ***all funds estimated for the contract award are required to be transferred to the Center before the contract can be awarded***, even though money may not be spent for years. Rely on your Center experts to determine optimum fund phasing, but if time does not allow, Table L-2 and Table L-3 are offered as guidelines.

**Table L-2. Typical Fund-Phasing for Small, Simple Projects with Values Less Than \$10 Million**

Item	Typical Range	Rule of Thumb	Color of \$	Year Required
Environmental Impact	1–3%	1%	FP&D	Minimum of 3 years before construction
Study	2–5%	2%	R&D	Minimum of 2 years before construction award
Design <sup>6</sup>	8–15%	10%	FP&D	Minimum of 1 year before construction award
Construction	37–83%	57%	CoF & R&D	Budget Year (BY) of award
Construction Services <sup>7</sup>	8–15%	12%	CoF & R&D	BY of award
Outfitting and Activation <sup>8</sup>	0–30%	20%	R&D	Outfitting is BY, and activation is typically 1 year after award

<sup>6</sup> See the design section for more information.

<sup>7</sup> Funding for Supervision, Inspection, Engineering, and Services (SIES) and support requests from support contractors.

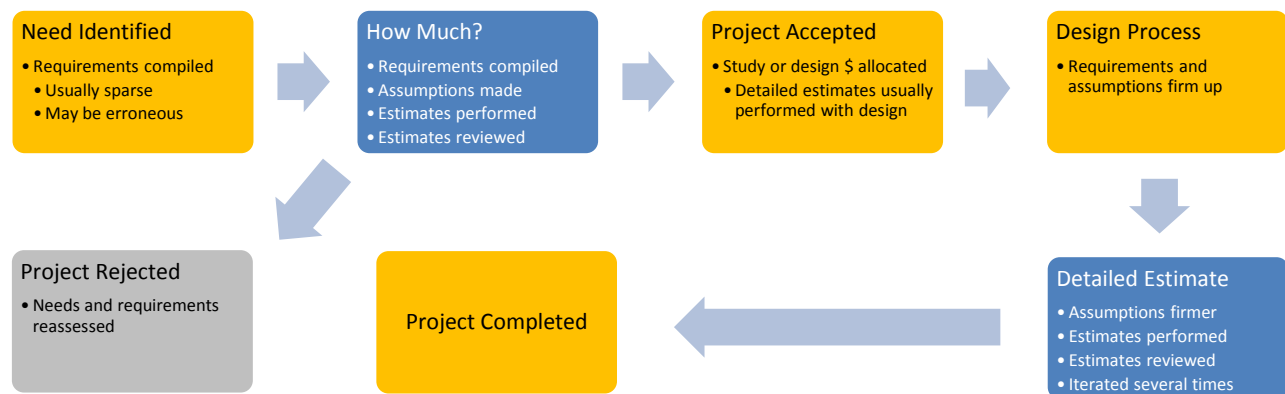
<sup>8</sup> Whatever is required to make the facility fully functional.

**Table L-3. Typical Fund-Phasing for Larger, More Complex Projects**

Item	Typical Range	Rule of Thumb	Color of \$	Year Required
Study <sup>9</sup>	1–3%	2%	R&D	Minimum of 3 years before award
Environmental Impact	1–3%	2%	FP&D	Minimum of 3 years before award
PER <sup>10</sup>	2–5%	2%	FP&D	Minimum of 2 years before award
Design	5–15%	8%	FP&D	Minimum of 1 year before award
Construction	29–71%	46%	CoF & R&D	Year of award
Construction Services	8–15%	12%	CoF & R&D	Year of award
Outfitting and Activation	0–30%	20%	R&D	Outfitting is BY, and activation is typically 1 year after award

### L.3. Estimating CoF and GSE Projects

When the need for a CoF or GSE project is identified, the first question is, usually, how much will it cost? The usual progression is similar to Figure L-3.

**Figure L-3. CoF and GSE Estimating Process**

This appendix focuses on the “How Much?” portion of Table L-3 since there are many books available that discuss the “Detailed Estimate” portion of the process.

#### L.3.1. Conceptual Parametric Estimates

Conceptual parametric estimates are typically done at the beginning of a project. Parametric estimates use comparable historical project cost data, which are adjusted to fit the known new project parameters. The costs are then escalated using a cost index to determine how much it would cost to construct the same project today. Although it sounds simple, numerous variables must be taken into account, such as changes to building codes, Americans with Disabilities Act (ADA) requirements, site-specific conditions, design changes, new security requirements, location, size, and implementation approach (competitive

<sup>9</sup> The study typically gathers requirements, examines alternatives, and prepares estimates for each option.

<sup>10</sup> The PER starts the initial phase of design.

firm-fixed price, small business set-aside, cost plus, etc.). Meticulous record keeping and a strong Basis of Estimate (BOE) are required to effectively execute this type of estimate.

### L.3.1.1. Potential Problems with Conceptual Parametric Estimates

The biggest problems encountered with conceptual estimates are the lack of defined project requirements, optimistic assumptions, or the failure of project management to acknowledge probable requirements due to the expense associated with them. Figure L-4 **Error! Reference source not found.** compares a 1974 Shuttle operations concept, left, with the reality of what was actually built, right.

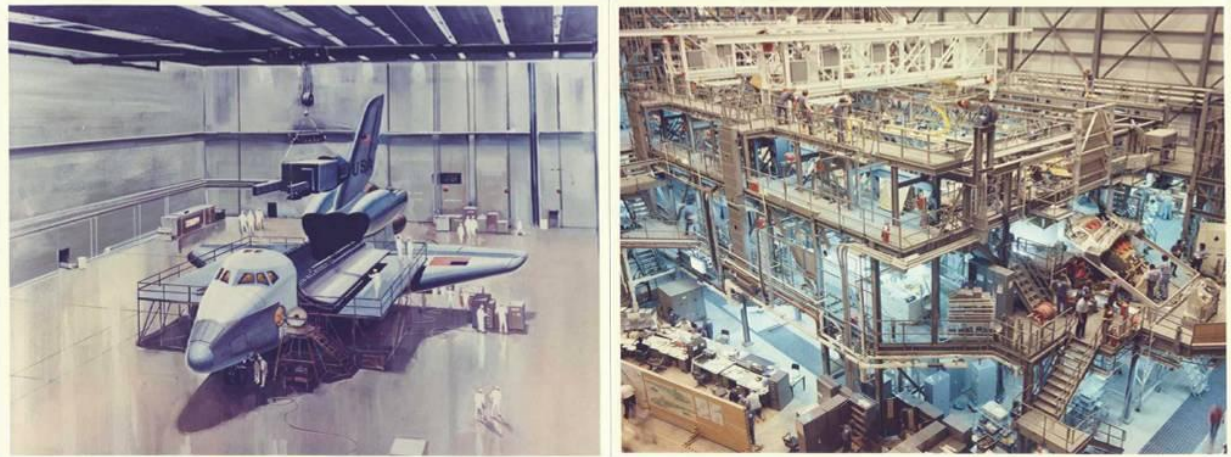
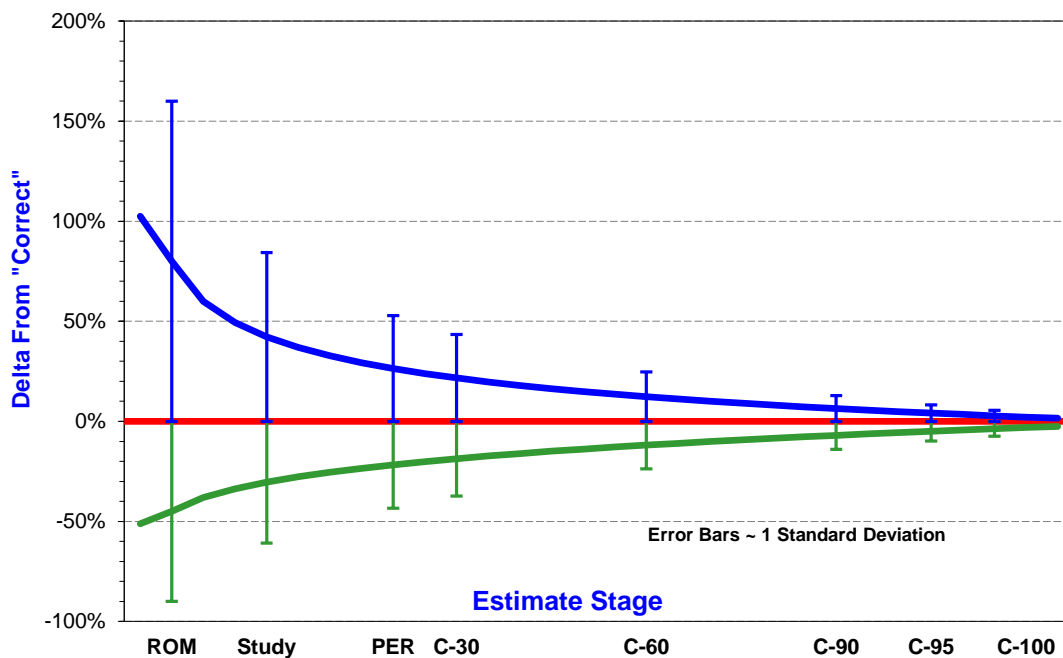


Figure L-4. Shuttle Operations 1974 Concept Versus Reality

A common, overly optimistic facilities assumption is that funds will arrive at Centers on the first day of the new fiscal year (FY). In fact, over a recent 5-year period, FP&D money showed up on average 4.6 months into the FY, and CoF funds arrived on average 7.3 months into the new FY. This issue will immediately impact costs if the project “assumes” an October 1 start. If the project deadline is fixed, the project will need to be accelerated to meet the same completion date.

The estimator should identify the level of accuracy that can be expected based on the project information given. The Standard Classification for Cost Estimate Classification System, from the American Society for Testing and Materials (ASTM), offers some guidance for this purpose.<sup>11</sup> Figure L-5 shows the expected accuracy of complex project estimates over time. Note that on the x-axis, C-30 means 30 percent complete, C-60 means 60 percent complete, etc. Routine simple projects are expected to achieve better results.

<sup>11</sup> ASTM E2516-11, ASTM Standard Classification of Cost Estimate Classification System, April 2011.



**Figure L-5. Expected Average Estimate Accuracy by Phase**

Exclusions from the estimate should be avoided. If they cannot be avoided, they must be clearly stated. Communication is critical to project success. The estimator should be aware that the project team often has a preconceived cost value for a project (usually low) at the earliest stages of scope definition. The estimator must prepare an unbiased and realistic estimate based on the scope of work to be accomplished, and the analyst should not become prejudiced by any preconceived optimism.

Another problem in using conceptual estimating methods is relying on the models or Cost Estimating Relationships (CERs) to produce an estimated value, but neglecting to adjust the calculated costs for the unique aspects of the project being estimated.

Often, the estimator fails to fully understand the basis of the historical cost information available. For example, if a historical average unit's cost value of \$100,000 per hospital bed were normalized to cover only hospital costs and not the associated costs for parking structures and related infrastructure, then the estimator would need to be aware of this and adjust the estimates accordingly.

### **L.3.2. Basis of Estimate (BOE)**

The BOE document is important for conceptual estimates because the Rough Order of Magnitude (ROM) estimate is usually used to obtain project approval and, subsequently, funding. The project's customer may have a vested interest in concealing information that may substantially affect the project cost, fearing that if the initial estimate is too high, the project may not obtain approval. However, once the project is initiated, scope creep can increase the size of the project. When new requirements are added and the project construction is delayed by the Planning, Programming, Budgeting, and Execution (PPBE) process for long periods, management will wonder why the ROM estimate was not accurate. In fact, the conceptual estimate may have been very accurate; but the project that was estimated was different from the project that was built years later. Documenting the BOE by identifying the scope of the project estimated, when it will be built, and any other assumptions and cost data used in developing the estimate can be used to defend the methods used.

## L.4. Historical Information

Many estimating methodologies discussed here require relevant historical project cost data. These methods may encompass capacity factors, parametric estimating models, unit costs, or historical project costs that can be used as a base case in the derivation of an analogy estimate. A large effort is required to gather, sort, and analyze historical project data. Both cost and design scope information must be identified and collected. It is best to collect the information at the lowest level of detail possible, since it can always be summarized later if required. After the data have been collected, it should be normalized for time, location, site conditions, project specifications, and project scope. Estimates can be prepared quickly if relevant historical project information is available. If you do not have any relevant historical information, consult the following KSC site for data: [http://www.ksc.nasa.gov/nasa-only/finance/COST\\_EST/Index.htm](http://www.ksc.nasa.gov/nasa-only/finance/COST_EST/Index.htm).<sup>12</sup>

Construction companies such as R.S. Means and Marshall & Swift, as well as the Department of Defense (DOD) and many other organizations, produce square-footage (area) costs for various common building types. However, they do not contain area costs for a specialized item, such as a new launch pad or test stand. Caution must be used since these sources typically estimate costs only to the 5-foot line of the facility, and the estimate may not include costs for activation or site-specific, NASA-specific, and infrastructure requirements that drive up costs.

### Rule of Thumb:

Assume that published area costs must be increased by 30 to 75 percent, depending on the size and type of facility for unique requirements and excluded costs.

### L.4.1. Historical Cost and Schedule Data

From initial optimism to changing requirements, NASA has historically had a difficult time meeting scheduled project completion dates within a given budget. One reason for this is that some projects develop incomplete or optimistic schedule plans. For a humorous perspective on the importance of planning, John Harvey-Jones,<sup>13</sup> chairman of Imperial Chemical Industries from 1982 to 1987, shared his insight on consequences of not going through the rigors of planning:

*Planning is an unnatural process; it is much more fun to do something. The nice thing about not planning is that failure comes as a complete surprise and is not preceded by long periods of worry and depression.*

—John Harvey-Jones MBE

### L.4.2. Historical Schedule Growth

A review of all available historical projects indicates that, on average, GSE schedules slip substantially from the awarded contract duration.

Careful data analysis indicates that for GSE projects, there is delineation between projects that are shorter than 120 days in duration and those that are longer.

<sup>12</sup> The user must be behind NASA's firewall and within the NASA Data Center (NDC) domain to access this site.

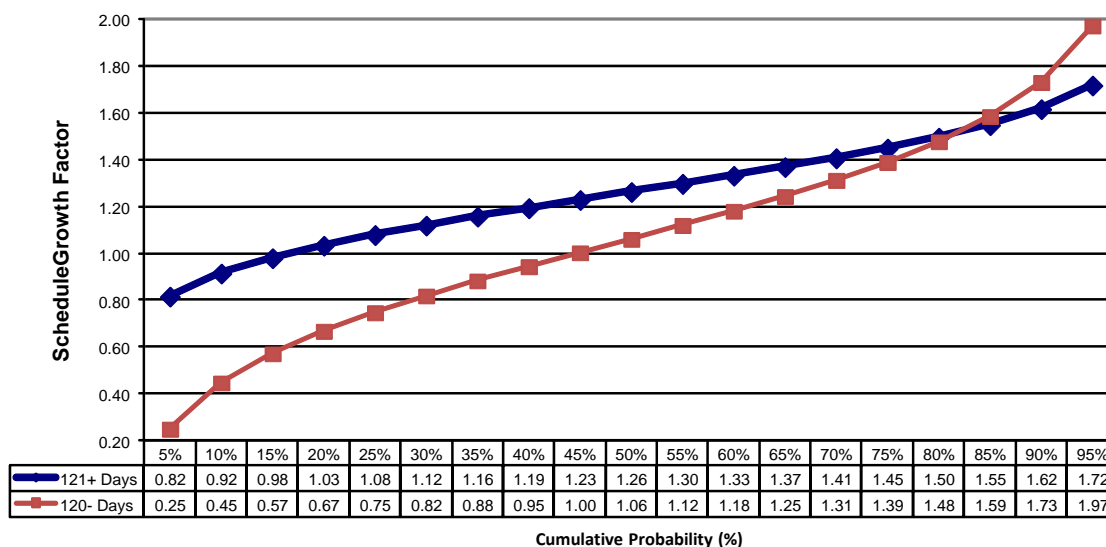
<sup>13</sup> Harvey-Jones was a Member of the Most Excellent Order of the British Empire and host of *Troubleshooter* on the BBC.

These values were calculated with the following formula:

$$\text{Project Closeout Date} - \text{Notice to Proceed (NTP) Date}^{14} = \text{Actual Days}$$

$$\text{Actual Days} \div \text{Original Contract Duration} = \text{Change in Schedule from Original}$$

Figure L-6 shows the cumulative percent probability that the schedule will slip. For CoF projects, there is a 50 percent probability that a project scheduled to be completed in 120 days or fewer will increase by 2.33 times the initial schedule. There is less than a 10 percent probability that the project will be completed on or before the originally awarded contract duration.



**Figure L-6. Historical GSE Schedule Slips**

It is important to note that these data are only for the duration of NASA-managed projects and do not include any delays for design, funding, or procurement activities. Limited anecdotal evidence suggests that these delays may be comparable.

### **L.4.3. Historical Cost Growth**

Most CoF and GSE projects increase in cost from the time of the award to the time of completion. Changes to the contract after the award are typically more expensive due to two factors: (1) lack of competition and (2) disruption to existing work processes. Contract cost growth and delta from award cost are discussed in the next section.

#### **L.4.3.1. Historical CoF Contract Cost Growth**

The majority of NASA's CoF projects incur cost growth over time. The reasons for this are varied and complex. The available data are presented here in an effort to enable better planning. The data in Figure L-7 show that for projects that are estimated at \$1 million or more, there is less than a 40 percent probability that the project will be completed for the estimated value. However, since most of NASA's CoF projects have a 10 percent contingency, the same project will have a 55 percent probability of completing the work with the allocated funding.

<sup>14</sup> NTP is similar to Authority to Proceed (ATP).

## NASA Cost Estimating Handbook Version 4.0

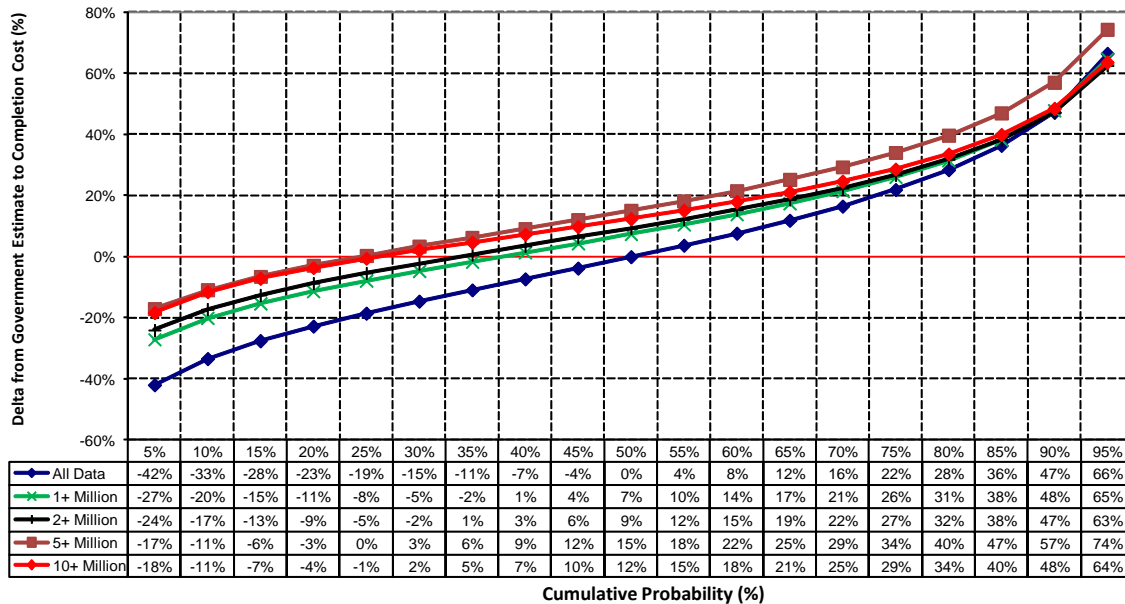


Figure L-7. CoF Estimate Growth Percentage from 100% Design Estimate at Completion

### L.4.3.2. Historical GSE Contract Cost Growth

A review of 1,286 GSE items procured for the Space Shuttle program shows that most of these items had experienced cost increases from contract award to contract closeout. How much of an increase appears to depend on the contract size. Typically, it was found that the larger the project, the higher the cost growth (see Figure L-8).

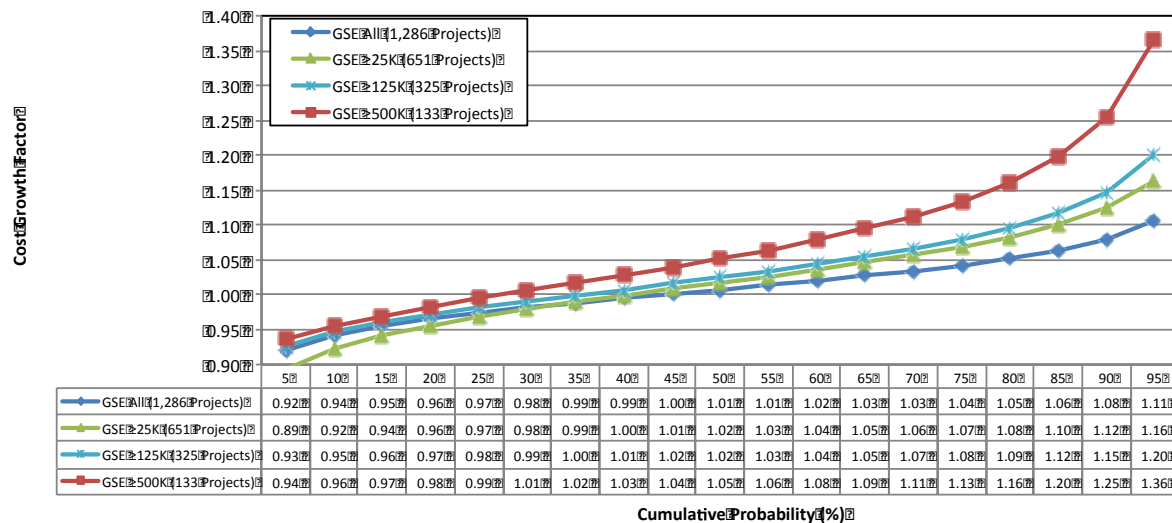


Figure L-8. GSE Historical Cost Growth Probability

Figure L-9 shows the delta from the final Government estimate and the awarded cost.

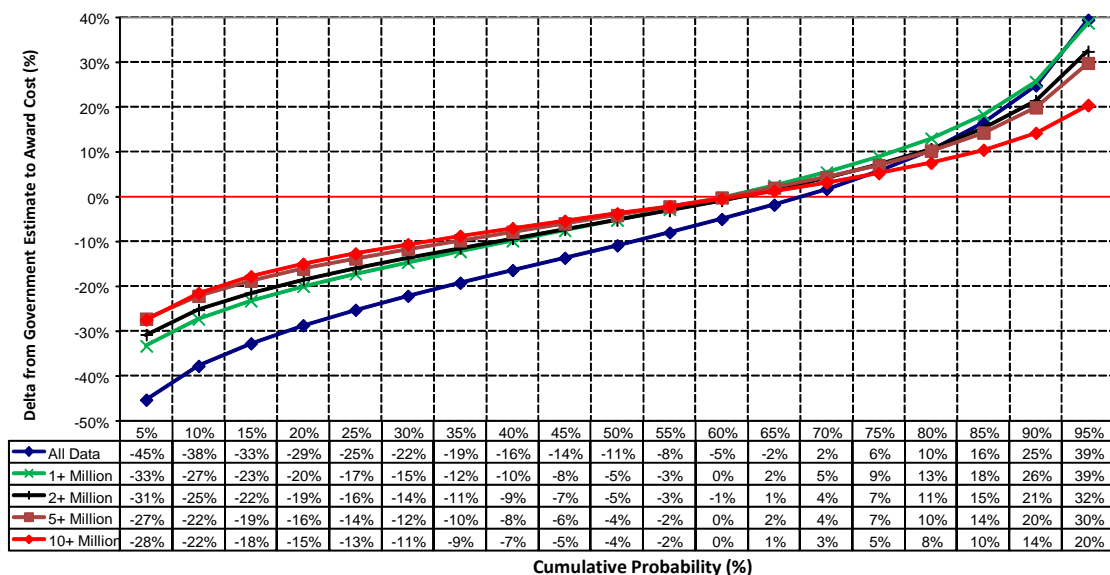


Figure L-9. CoF 100 Percent Design Estimate Delta from Award Cost

Figure L-10 shows that approximately 60 percent of all projects are awarded for the estimate cost or less.

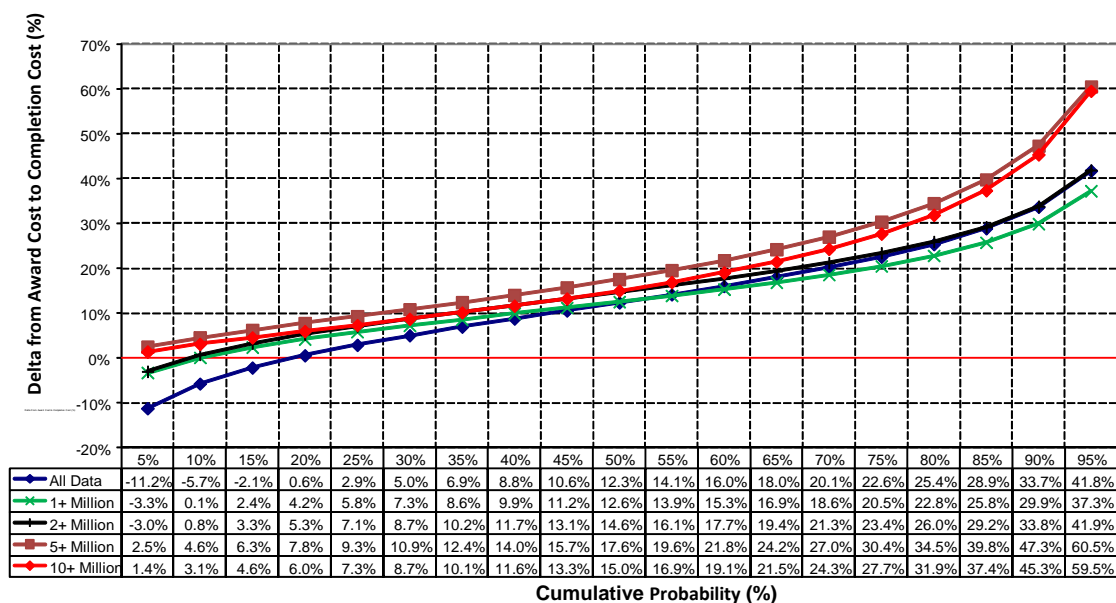


Figure L-10. CoF-Awarded Cost Compared to Completion Cost

Figure L-10 shows that approximately 90 percent of all projects increase in value from the initial awarded contract cost. Furthermore, there is a 50 percent probability that costs will increase by 12 percent or more. This increase is funded from the project contingency as well as from the delta between the estimated value and the awarded contract value.

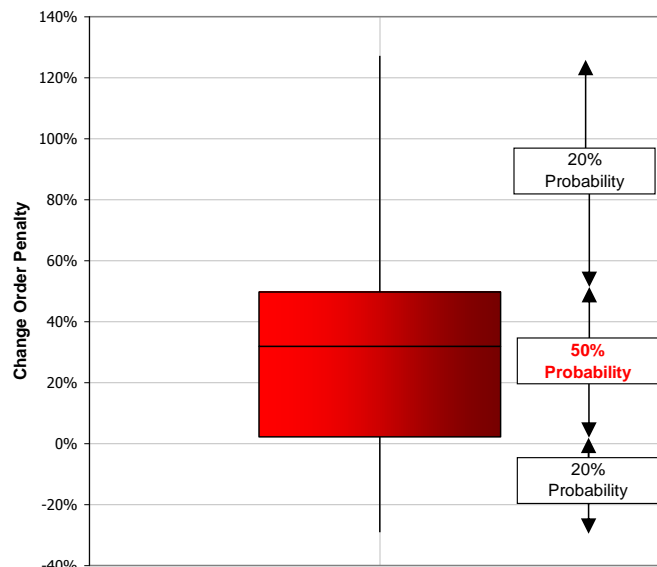
#### L.4.3.3. Other Historical Data

It is generally accepted that change orders cost more than a competitive procurement. How much more is often a subject of great debate. In an attempt to quantify probable cost impacts, historical change orders were analyzed. Approximately 6,000 change orders for 404 projects between 1987 and 2007 were

reviewed. Some records were incomplete, while other records were for very small changes. These were omitted from analysis, leaving 261 unique projects and 2,752 change orders. Here is a summary of the results:

- The average change order submitted by a contractor is 76.1 percent higher than the Government estimate for the change.
- The average negotiated price above the Government estimate is 29.7 percent higher.
- The average competitive bid for projects over \$1 million is 2.2 percent lower than the Government estimate.

Of course, averages only tell a part of the story. The box plot in Figure L-11 shows the probable change order penalty for changes over \$1 million. The chart includes the 2.2 percent delta that the low bid generally is below the Government estimate on projects costing more than \$1 million.



**Figure L-11. Historical Change Order Penalty**

Thus far, we have discussed the delta from the Government estimate for change orders. However, the total cost of the change is really larger, if you consider that 1,383 bids were 7.9 percent (on average) under the Government estimate.

## L.5. Conclusion

Analysis clearly shows that change orders cost more and that some contractors are more prone to inflated change orders than others. If change orders are planned, the Agency must budget adequately for them. The application of these concepts and the introduction of a KSC-developed model for adjusting historical estimates can be found by contacting Glenn Butts at [glenn.c.butts@nasa.gov](mailto:glenn.c.butts@nasa.gov) or the Cost Analysis Division (CAD) at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

## Appendix M: Software Cost Estimating

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Software represents a substantial portion of the cost for space systems. Estimating the cost, schedule, and effort associated with a proposed software development project is a challenging task.

Although software estimation is unique, the cost estimating process described in this handbook still applies. The primary difference between costing software and hardware or systems is that the dominant cost component is labor, therefore correctly estimating the development effort is key. The estimation methods will depend on the resources available and the level of understanding of the needs and objectives (Task 1) and the ground rules and assumptions (Task 4). A comprehensive process for software estimation is documented in Jet Propulsion Laboratory's (JPL's) Software Cost Estimation Handbook (JPL-D-26303).

Currently, NASA has agency-wide licenses for both PRICE<sup>1</sup> and SEER<sup>2</sup> estimating suites, which both include software estimation tools (see Appendix E). These two specific tools trend toward the higher side of the cost-complexity spectrum, but there are several other models available to estimate software costs. One commonly used model is the Constructive Cost Model<sup>3</sup> (COCOMO), which was developed by the Center for Software Engineering (CSE) at the University of Southern California, headed by Dr. Barry Boehm<sup>4</sup>.

This appendix will be developed in more detail, but the references should provide the analyst with the basics to help with software cost estimating. Contact CAD at [hq-cad@mail.nasa.gov](mailto:hq-cad@mail.nasa.gov).

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<sup>1</sup> <http://www.pricesystems.com/en-us/offerings/pricecostmodels.aspx>

<sup>2</sup> <http://galorath.com/products/software/SEER-Software-Cost-Estimationpr>

<sup>3</sup> [http://csse.usc.edu/csse/research/COCOMOII/cocomo\\_main.html](http://csse.usc.edu/csse/research/COCOMOII/cocomo_main.html)

<sup>4</sup> Boehm, et al, *Software Cost Estimation with COCOMO II*, Prentice Hall, 2000.

## Appendix N: Analyses for Decision Support

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In addition to developing cost estimates, NASA cost estimators conduct analysis for decision support. Analysts may provide such support for a range of customers, from projects, to institutional issues at a Center, to decision makers at NASA Headquarters. As an example, over the life of a project, there are many choices that project personnel must make. Whether these decisions take the form of a Life-Cycle Cost (LCC) analysis, an engineering trade, an architecture selection, or an affordability assessment, decision makers look to the cost estimating community to help inform these choices with data. This appendix provides details on the following six topic areas used to provide analyses for decision support:

### N.1. Sensitivity Analysis

**N.1.1. Sensitivity Analysis Overview**—A review of the steps to conduct a sensitivity analysis.

**N.1.2. Sensitivity Analysis Example**—A simple step-by-step example of how to complete and interpret a sensitivity analysis.

### N.2. Trade Studies—Includes information about the following subjects:

**N.2.1. Trade Study Analysis**—The activity of a multidisciplinary team to identify the most balanced technical solutions among a set of proposed viable solutions. Trade studies are commonly used to find the configuration that best meets conflicting performance requirements.

**N.2.2. Make-Versus-Buy Analysis**—The process of analyzing the impact of producing an item in-house or acquiring it from an external source.

**N.2.3. Lease-Versus-Buy Analysis**—The process of looking not only at financial comparisons, but also at a set of pre-established priorities.

### N.3. Affordability Analysis—The act of establishing requirements for a program or project that fit within an affordable cost goal. The top-level affordability goal flows down to tasks that will challenge requirements and perform trade studies to ensure that the goal is met.

### N.4. Cost As an Independent Variable (CAIV)—Provides highly capable systems that are affordable over the life cycle. It is essentially a planning activity establishing and adjusting program cost objectives through the use of cost-performance analyses/tradeoffs. It involves execution of the program in order to meet or reduce stated cost objectives.

### N.5. Economic Analysis (EA)—Includes information on the following subjects:

**N.2.1. EA Overview**—Provide the reasoning for initiating a project or task. The logic of the EA is that whenever resources such as money or effort are consumed, they should be in support of a specific need or objective.

**N.2.2. Future Value (FV) and Present Value (PV)**—The method of compounding money to obtain its value at a future point in time; the method of discounting money to obtain its value at the present time. How to calculate discount factors for obtaining PV.

**N.2.3. Steps for Performing an EA**—Iterative process that leads to estimating economic measures-of-merit and providing a recommendation to decision makers. Special emphasis on how to estimate and interpret Net Present Value (NPV), which is a measure of an investment's net value in today's dollars.

### N.6. Additional Resources—Documents and Web links that provide more details on the five Appendix N topics.

## N.1. Sensitivity Analysis

### N.1.1. Sensitivity Analysis Overview

As defined in section 3.1.1 of this handbook, sensitivity analysis is a technique used to treat uncertainty regarding requirements. It is used to evaluate the effects of changes in system parameters on the system cost (and/or schedule). Recall that the five steps in a sensitivity analysis are:

1. Compute the point estimate.
2. Select the elements for analysis.
3. Determine the range of values for each element selected for analysis.
4. Determine cost impact.
5. Graph or table results.

An example is provided below to demonstrate how to apply steps 1 through 5.

### N.1.2. Sensitivity Analysis Example

The office administrator is tasked to procure new bookcases for the office staff. The requirements delineate that he needs four bookcases. Each will be 7 feet high and 30 inches wide and will be constructed out of ¾-inch oak.

**Step 1: Based on the given information, he developed a point estimate of \$1,000 for these bookcases** (or \$250 per bookcase).

**Step 2: These types of tasks almost always change, so he decides to perform a sensitivity analysis against three of the requirements.**

- Wood could change to 1-inch pine or ¾-inch cherry.
- Height could range between 6 and 8 feet.
- Width could range between 24 and 36 inches.

**Step 3: Percentage changes for these three requirements changes are as follows:**

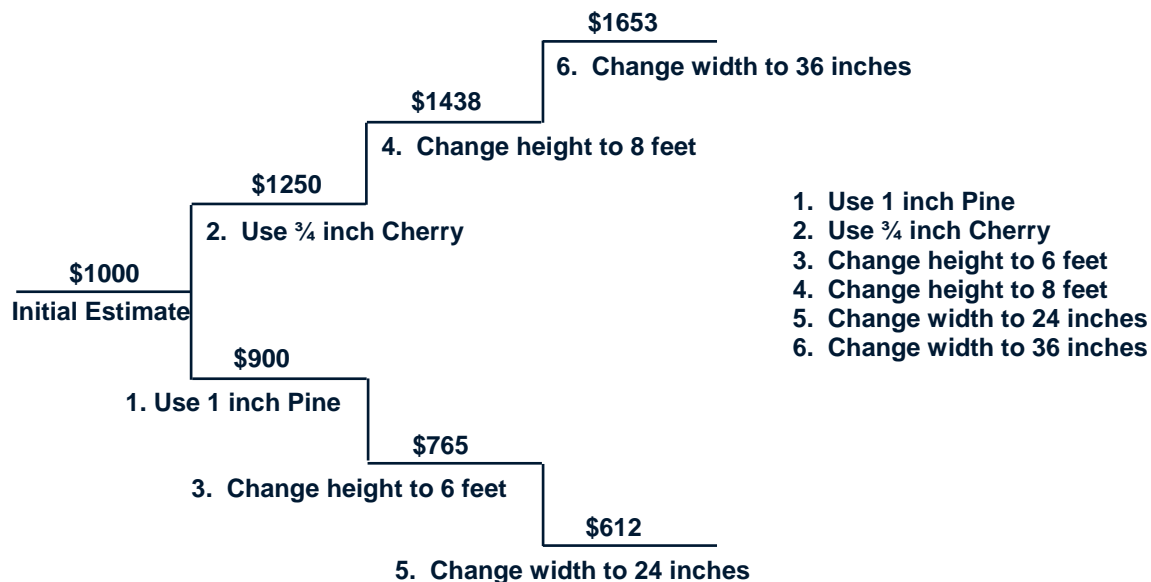
- *Use a different wood*
  - Low Value: Save 10 percent with pine
  - High Value: Additional 25 percent with cherry
- *Change height dimensions*
  - Low Value: Save 15 percent by reducing height to 6 feet
  - High Value: Additional 15 percent by increasing height to 8 feet
- *Change width dimensions*
  - Low Value: Save 20 percent by reducing width to 24 inches
  - High Value: Additional 15 percent by increasing width to 36 inches

**Step 4: He determined life-cycle cost impacts using each pair of high and low values (i.e., applied to one component at a time).**

- *Calculate new cost if different type of wood*
  - Low Value: \$900 (save 10 percent)
  - High Value: \$1,250 (additional 25 percent)
- *Calculate new cost if height dimensions are modified*
  - Low Value: \$850 (save 15 percent)
  - High Value: \$1,150 (additional 15 percent)

- Calculate new cost if width dimensions are modified
  - Low Value: \$800 (save 20 percent)
  - High Value: \$1,150 (additional 15 percent)

**Step 5: He graphed the results from Step 4. (Note that he could also table these results.)**



**Range of \$612 to \$1653 based on what-ifs**

**Figure N-1. Sensitivity Analysis of the Total Cost of Four Bookcases**

The office administrator can get many takeaways from the results depicted in Figure N-1. For example, if the budget for new office furniture were constrained to a maximum of \$1,500, he would be unable to afford four cherry bookcases that are 8 feet high and 36 inches wide (at a total cost of \$1,653). From another perspective, if the office staff had no preference about the type of wood, the office administrator could save \$100 by simply switching from oak to pine bookcases.

## **N.2. Trade Studies**

### **N.2.1. Trade Study Analysis**

Cost estimates are key inputs during cost/performance trade studies and are used to determine the most realistic and cost-effective mission architectures and system designs. The objective of a trade study is to obtain the merit of the worth (in a single figure) for each candidate and to select the one having the greatest relative value.

#### **N.2.1.1. Trade Study Steps**

The steps of conducting a trade study include the following:

1. Define the purpose.

2. State the problem.
3. Describe the selection scheme and criteria used.
4. Define the alternatives.
5. Estimate the costs and assess the performance of each alternative.
6. Determine the preferred approach.
7. Formulate recommendations.

### N.2.1.2. Trade Study Example

In Figure N-1, each parameter includes both an objective and a threshold value. Threshold values are individually set by the respective Mission Directorate process for each trade study based on the maturity or risk characteristics of the program or project under consideration. The objective value for cost in this illustration is the objective value plus 10 percent. Cost, schedule, and performance may be traded off within the range between the objective and threshold (the “trade space”) with the goal being to optimize cost and performance.

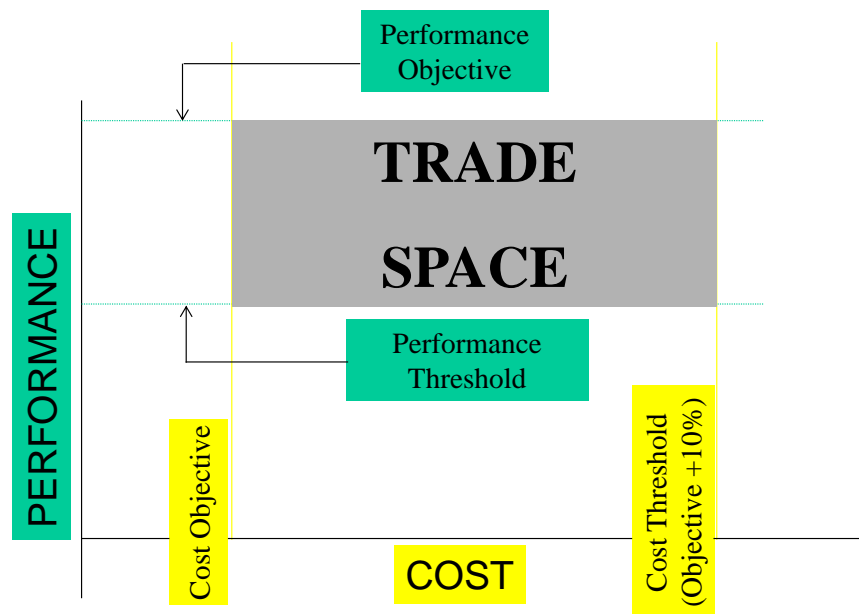


Figure N-2. Performance vs. Cost Trade Space

## N.2.2. Make-Versus-Buy Analysis

### N.2.2.1. Make-Versus-Buy Approach Considerations

Make-or-buy decisions are based on both strategic and operational assessments. The book *World Class Supply Management*<sup>1</sup> provides criteria for outsourcing, suggesting that an organization outsource all items that do not fit one of the following three criteria: (1) the item is critical to the success of the project; (2) the item requires specialized design and manufacturing skills or equipment with few qualified

<sup>1</sup> *World Class Supply Management: The Key to Supply Chain Management*, D. Burt, D. Dobler, S. Starling, 7th ed. Boston: McGraw-Hill/Irwin, 2003.

suppliers; and (3) the item fits with the organization's current or desired future core competencies. Items that meet at least one of these three criteria are considered strategic in nature and should be produced internally if possible.

At the operational level, other considerations must be assessed. Table N-1 shows other factors that may favor producing an item in-house.

**Table N-1. Operational Factors Influencing the Make-Versus-Buy Decision**

<b>Make</b>	<b>Buy</b>
Cost (may be less expensive to make the item)	Lack of in-house expertise
Desire to integrate project or organization operations	Lower Cost
Desire to employ excess production capacity	Limited production facilities or insufficient capacity
Need for control over production schedule	Desire to maintain a multiple-source policy
Desire to maintain a stable workforce	Brand preference or request by external customer
Lack of interest by qualified suppliers	Item not essential to the project or organizational strategy
Need to provide a second source	Political, social, or environmental reasons
Political, social, or environmental reasons (e.g., union pressure)	

The two most important operational factors to consider in a make-or-buy decision are the availability of production capacity/labor and cost. Once production capacity has been determined to be available, a cost assessment should be conducted. Cost elements should include all relevant costs. The desired goal of the cost assessment is to objectively compare in-house production and purchase costs. Cost elements to consider in the analysis may include those identified in Table N-2. Note that many of the "make" costs to consider are incremental. By definition, incremental costs would not be incurred if the item were purchased from an outside source. If an organization does not currently have the capacity to make the item, incremental costs will include variable costs plus the full portion of fixed overhead allocable to the item's production. If the organization has excess capacity that can be used to produce the item in question, only the variable overhead caused by production of the item is considered incremental. Therefore, with sufficient idle capacity, fixed costs are not incremental and should not be considered as part of the cost to make the item.

**Table N-2. Cost Factors in a Make-Versus-Buy Analysis**

<b>Make</b>	<b>Buy</b>
Direct labor costs	Purchase price of the part (including associated fees)
Incremental production overhead costs	Transportation costs
Delivered purchased material costs	Receiving and inspection costs
Incremental managerial costs	Incremental purchasing costs
Incremental purchasing costs	Government oversight/Defense Contract Management Agency/Verification and Validation (V&V) costs
Incremental capital costs	
Incremental inventory-carrying costs	
Incremental quality systems costs	
Opportunity cost (if applicable)	

### **N.2.2.2. Make-Versus-Buy Example**

As discussed, after consideration of strategic and operational factors, the decision to make or buy an item uses incremental analysis to determine the relevant costs. Opportunity costs must also be considered. For example, assume Company ABC uses part number V100 in several of its products. Company ABC

currently produces 10,000 of part number V100 using \$200 of direct labor, \$250 of direct materials, \$100 of overhead, and \$50 of other incremental cost per item. The purchase of parts is under review by the company's management. Purchasing has determined it would cost \$700 per unit to purchase 10,000 of part number V100 with an additional \$50 of incremental internal-purchase-related costs per part. Should Company ABC continue to make part number V100 or should it purchase the part?

Table N-3 shows the total cost to produce part number V100 is \$6 million, a savings of \$1.5 million over the purchase option, so the choice would be for Company ABC to continue to make the part.

**Table N-3. Example of Make-Versus-Buy Data**

Quantity 10,000 (K\$)	Make	Buy	Incremental Increase/(Decrease)
Direct Labor (\$0.20)	\$2,000		\$2,000
Direct Materials (\$0.25)	\$2,500		\$2,500
Incremental Overhead (\$0.10)	\$1,000		\$1,000
Incremental Misc. Cost (\$0.05)	\$500		\$500
Purchase Price (\$0.70)		\$7,000	\$(7,000)
Misc. Purchasing Cost (\$0.05)		\$500	\$(500)
<b>Total Relevant Costs</b>	<b>\$6,000</b>	<b>\$7,500</b>	<b>\$(1,500)</b>

However, assume Company ABC can use the part number V100 production space for a product that would generate \$2.5 million of additional operating income. Then the \$2.5 million in additional operating income is considered an opportunity cost and is added to the "Make" column of the analysis. With opportunity cost included, the make-or-buy analysis would generate incremental costs of \$8.5 million to make the part, \$1 million more than purchasing the part. In this case, the company would likely choose to purchase part number V100 and produce the other product (see Table N-4).

**Table N-4. Example of Make-Versus-Buy Calculation**

Quantity 10,000 (K\$)	Make	Buy	Incremental Increase/(Decrease)
Total Relevant Costs	\$6,000	\$7,500	\$(1,500)
Opportunity Cost	\$2,500		\$2,500
<b>Total Costs</b>	<b>\$8,500</b>	<b>\$7,500</b>	<b>\$1,000</b>

## **N.2.3. Lease-Versus-Buy Analysis**

### **N.2.3.1. Lease-Versus-Buy Approach Considerations**

A lease-versus-buy analysis can be performed once the decision is made to acquire an asset. This analysis is commonly used in business cases and applies most often to facilities and Information Technology (IT) projects. (See Appendix L for more information on Construction of Facilities cost estimating.) When analyzing the financial considerations under the lease-versus-buy decision process, considerations include the LCC of either leasing or buying and operating and maintaining the hardware.

The most meaningful financial comparison is the cost of lease financing versus the cost of debt financing. While comparing absolute LCC is important, it is equally critical to take into consideration fiscal budgetary constraints. While the LCC of leasing may be higher over the entire term the hardware is leased, the annual expenditures may fit better within NASA's budgetary limitations. However, the lease-versus-buy decision cannot be based purely on financial data or budgetary considerations. The decision must be made on a best value consideration. A best value selection analysis would introduce possible intangible benefits for either leasing or buying. Specific guidance on conducting these analyses is provided in the Office of Management and Budget's (OMB's) Circular A-94 ([http://www.whitehouse.gov/omb/circulars\\_a094/](http://www.whitehouse.gov/omb/circulars_a094/)).

Example factors to consider when making the decision to lease or buy include:

- Asset redeployment/disposal
- Asset tracking
- Maintenance options
- Political considerations
- Value of cancellation options
- Shortened product life cycle
- Technology refresh
- Convenience
- Ease of contracting
- Transference of residual risk

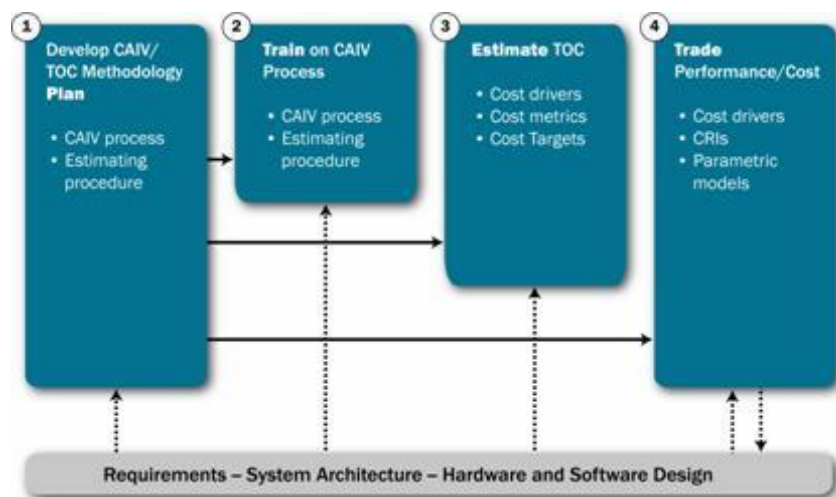
Traditionally, factors such as asset tracking and asset redeployment/disposal are considered to be advantages of leasing; however, circumstances could exist that would make these factors a disadvantage. Similarly, these types of benefits could be provided through certain procurement vehicles. It is critical to be aware of all competing purchase alternatives to leasing as well as the legislative and policy directives that guide leasing.

### N.3.1. *Determining Affordability*

#### N.4. Cost As an Independent Variable (CAIV)

### N.4.1. Steps in the CAIV Approach

engineers and NASA managers so that CAIV is applied accurately and consistently. CAIV is tied closely to the existing parametric estimating process within the NASA Centers and its cost analysis support contractors.



### Figure N-3. CAIV Process Tailored to NASA

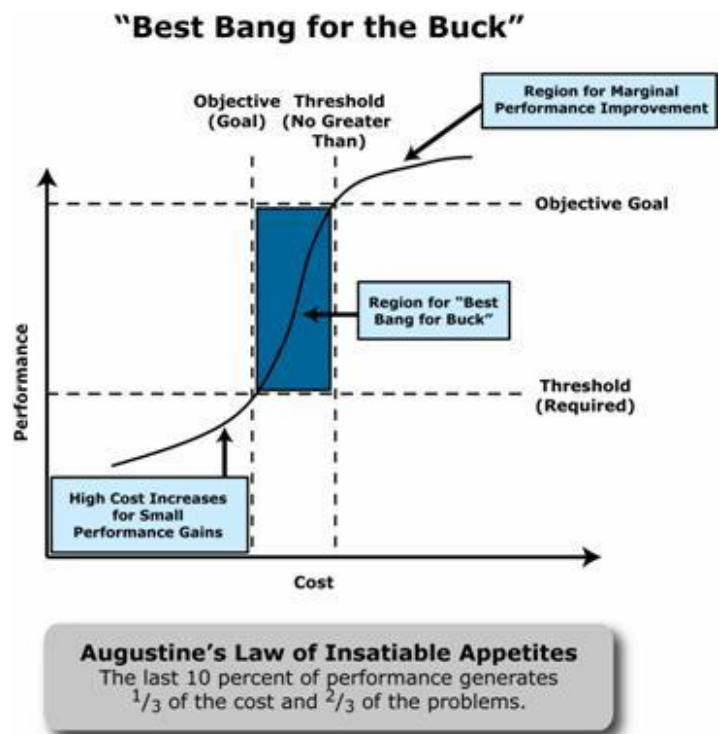
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**Step 3** uses a program's cost baseline and holds that variable (cost) constant while allowing identified cost drivers to be manipulated to see their effect on cost. A hierarchy of affordability metrics can be derived from this baseline as an outcome of the CAIV and consists of the following:

- **Cost Targets**—Absolute values of cost, with a probability dimension, for specific programs, phases, contracts, or activities. An example of a cost target would be to procure the Crew Exploration Vehicle (CEV) for a total acquisition cost of \$9 billion (in CY 2013 dollars), including all Government and contractor expenses. Cost targets can be expressed as a range of values that bound the “trade space”; the boundaries can be defined as follows:
  - **Threshold Cost**—The absolute highest cost allowable for an element if overall program-estimated LCC goals can be achieved. Breaching the threshold cost gives reason to cancel the element or project.
  - **Objective Cost**—A lower cost target that would be more difficult to achieve but that could offset overruns elsewhere in the program architecture.
  - **Cost Performance Measures (CPMs)**—Measures that combine absolute cost values with relevant performance measures. Examples include dollars per mission or flight, dollars per equivalent source lines of code (SLOC) developed or maintained, and dollars per unit mass of hardware developed or produced. These measures will change over time to reflect changing requirements, evolving design, and maturation of the program.

**Step 4** integrates CAIV trades with the mainstream of systems engineering trades. When managers have a complete understanding of system-level cost drivers and the application of experience-calibrated parametric cost estimating models, they can oversee the trade process, ensuring that affordable design options are identified and objectively considered in the trade process.

Figure N-4 illustrates the overall trade space that is defined by the objective and threshold performance parameters, as well as by the objective and threshold cost values. If enough alternatives can be compared, their relationship might indicate a curve that may detect the “knee,” or point of diminishing return (i.e., where a slight performance improvement incurs an unacceptable cost increase). Initial performance-cost trades may be limited to the Key Driving Requirements (KDR) in order to focus on primary cost drivers and to validate (or challenge) the main requirements based on affordability.



**Figure N-4. CAIV Trade Space**

## N.5. Economic Analysis

This EA section includes information about the EA Methodology, PV, NPV, Return on Investment (ROI), and Internal Rate of Return (IRR).

### N.5.1. Economic Analysis Overview

Figure N-5 illustrates the simple principle behind an EA—to determine the preferred alternative among various alternatives based upon cost and benefit data.

As shown in Figure N-5, the benefit streams expected to flow from investments are typically composed of multiple components, some of which can be characterized in terms of cost savings and cost avoidance (in financial terms); others that can be quantified, but not in cost or financial terms; and still others that simply cannot be quantified. For the benefit streams that can be quantified in financial terms, the PV metric is applied to investment cash flows (costs) and cash flows from cost savings and cost avoidances (benefits) on a comparable basis with respect to timing.

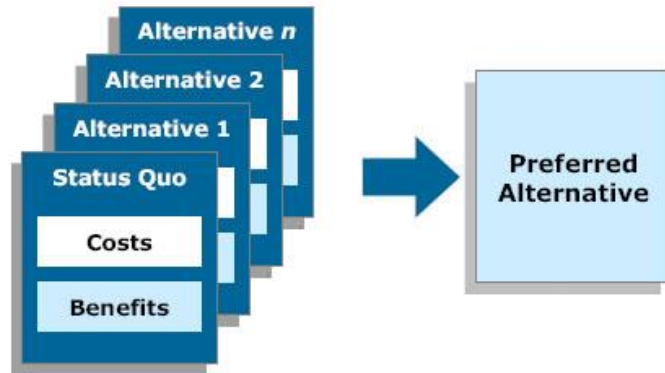


Figure N-5. Economic Analysis Objective

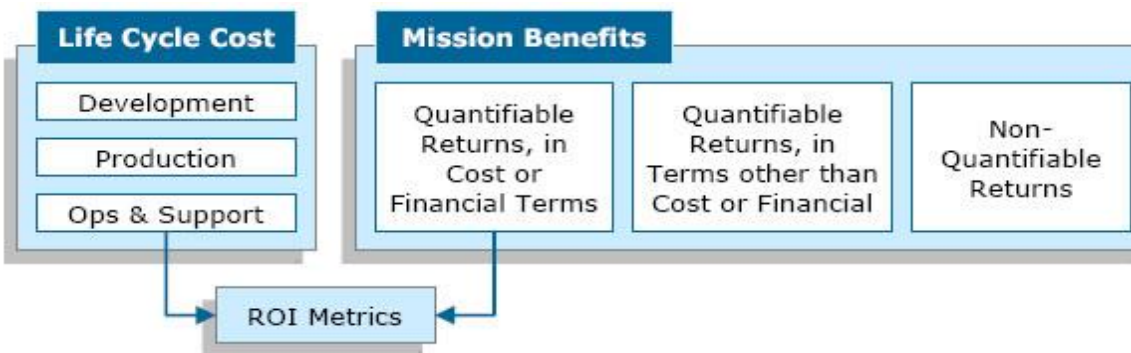


Figure N-6. Cost Benefit Analysis Framework

The development of ROI metrics, typically in the form of a ratio, can help decision makers select among investment alternatives. ROI ratios, such as savings/investment and payback ratio, can be used to identify attractive alternatives. The computation of any traditional ROI metrics can only take into account outcomes that are characterized in cost or financial terms. What is not immediately evident from Figure N-6 is the fact that the generation of an ROI metric can only result from a comparison of two or more alternatives, one of which serves as a reference point and is typically defined as the baseline or the status quo alternative.

Financially quantifiable benefits and ROI metrics should not be all that leaders rely upon when selecting alternatives for NASA. To paint the complete picture, the contribution to effectiveness of quantifiable, nonfinancial benefits and the contribution to effectiveness of typically non-quantifiable benefits should be measured using decision framework techniques such as the Analytic Hierarchy Process (AHP) or the

Multi-Attribute Utility Theory (MAUT). These decision framework techniques bring structure to complex problems where multiple alternatives need to be considered across a range of goals and objectives. They also help to develop stakeholder buy-in, facilitate an understanding of the project complexities, and shed light on the decision-making process. The techniques establish a structure that articulates and prioritizes the goals and objectives that different alternatives are expected to meet, while providing a mechanism to develop normalized scores of effectiveness.

The quantification of financial benefits, the development of ROI metrics, and the measurement of the effectiveness of nonfinancial benefits and non-quantifiable benefits serve the overall objective of making a sound recommendation in an EA. Table N-5 summarizes two types of EAs.

**Table N-5. Types of Economic Analyses**

Different EA Types	Description
<p>Analysis of Alternatives (AOA)</p> <p>Level of Effort: <i>Requires a large team, may take many months to accomplish, and addresses the full Life-Cycle Cost Estimate (LCCE)</i></p>	<p>Compares the operational effectiveness, suitability, and LCCE of the most promising of several conceptual alternatives that appear to satisfy established capability needs. Two major components of an AOA are a cost-effectiveness analysis and a cost analysis. An AOA's analysis and conclusions are then typically used to justify initiating an acquisition program. An AOA also examines mission threat and dependencies on other programs. Many times, an AOA cannot quantify benefits. For example, there is no agreed-upon monetary value for what a human life is worth. In this case, a cost-effectiveness analysis is more appropriate. A Cost Estimation and Analysis (CEA) is conducted whenever it is unnecessary or impractical to consider the dollar value of the benefits. This happens when the various alternatives have the same annual monetary benefits. Both the AOA and CEA should address each alternative's advantages and disadvantages and the associated risks and uncertainties of how these might influence the comparison.</p>
<p>Economic Analysis (EA)</p> <p>Level of Effort: <i>Requires a large team, may take many months to accomplish, and addresses the full LCCE</i></p>	<p>This is a conceptual framework for systematically investigating problems of choice. Posing various alternatives for reaching an objective, it analyzes the LCCE and benefits of each one, usually with a ROI analysis. PV is also an important concept. Since there is time value to money, it is necessary to determine when the expenditures for the alternatives will be made. The EA expands cost analysis by examining the effects of the time-value-of-money on investment decisions. After cost estimates have been generated, they must be time-phased to allow for alternative expenditure patterns. Assuming equal benefits, the alternative whose PV cost is least is the most desirable because it implies a more efficient allocation of resources.</p>

## **N.5.2. Future Value and Present Value**

The PV metric captures the time-value-of-money by adjusting through compounding and discounting cash flows to reflect the increased value of money when invested.

### **N.5.2.1. Calculating Future Value**

Compound interest occurs when the interest charged (or received) over a period is based upon the balance of principal and interest of the previous period. The Future Value (FV), representing the total amount received or repaid, is based on compound interest for a single payment or receipt. FV is calculated as  $PV(1+i)^n$  where  $i$  is the interest rate and  $n$  is the number of years from the date of initiation for the project. Another way to describe this calculation is that FV equals the product of a single payment or receipt (PV) and compound interest factor,  $(1+i)^n$ .

Compound interest is the preferred method to depict the value of money accumulated (or paid) over time. For example, suppose you had \$909.09 today (PV) and invested it at an annual interest rate of 10 percent. Because this PV of \$909.09 accumulates \$90.91 of interest over a year, you would collect \$1,000 in one year (FV). You can calculate this FV as:

$$FV = PV \times \text{Compound Interest Factor} \quad (\text{Equation N-1})$$

$$FV = PV (1 + i)^n \quad (\text{Equation N-2})$$

$$= \$909.09(1 + 0.10)^1 = \$1,000$$

But what if you decided to withdraw the money in 5 years, not 1 year? Assuming the interest rate remains fixed at 10 percent, your FV would become:

$$FV = \$909.09(1 + 0.10)^5 = \$1,464$$

In this case, \$909.09 was “invested” at an interest rate of 10 percent to become “worth” \$1,464 just 5 years later. It becomes apparent, therefore, that time-value-of-money, depicted as compound interest, can have significant impacts on the FV of a principle deposit or investment.

### N.5.2.2. Calculating Present Value

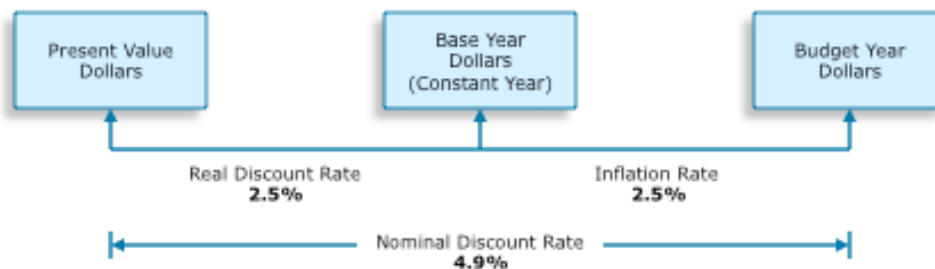
To determine the PV of money, a discount rate must be applied to costs. There are two different types of discount rates:

- Real discount rate is adjusted to eliminate the effects of expected inflation and used to discount constant-year dollars or real benefits or costs.

$$\text{Nominal Discount Rate} - \text{Expected Inflation Rate} = \text{Real Discount Rate}$$

- A nominal discount rate is adjusted to reflect inflation used to discount then-year dollars or nominal benefits and costs.

Figure N-7 illustrates this relationship between PV, base-year, and budget-year dollars.



**Figure N-7. Present Value, Base-Year, and Budget-Year Cost Relationships**

Budget-year dollars incorporate the effects of inflation and adjust for the time-value-of-money—the concept that a given amount of money is worth more today than in the future due to inflation. Base-year dollars are adjusted for the time-value-of-money, and PV dollars have the effects of inflation and time-value-of-money removed.

Real and nominal discount rates are provided by the OMB in Circular No. A-94. The rates are updated each calendar year and can be found at [http://www.whitehouse.gov/omb/circulars/a094/a94\\_appx-c.html](http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html).

Discounting translates projected cash flows into PV terms using specified discount factors. As illustrated in Figure N-8, the **discount factor** is equal to  $1/(1 + i)^n$  or  $(1 + i)^{-n}$  where  $i$  is the interest rate and  $n$  is the number of years from the date of initiation for the project. Figure N-9 provides an example of how discounting is applied.

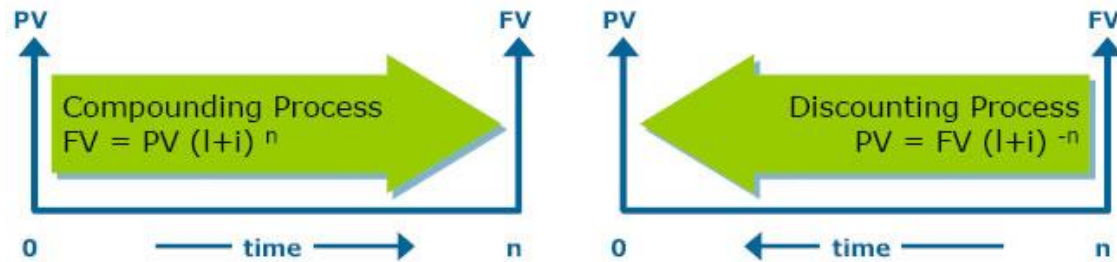


Figure N-8. Compounding and Discounting

Costs are in Budget Year Dollars					
	2006	2007	2008	2009	2010
<b>Total Annual Outlays</b>	<b>\$250,000</b>	<b>\$256,000</b>	<b>\$262,144</b>	<b>\$268,435</b>	<b>\$274,878</b>
E-O-Y Discount Factor	0.9533	0.9088	0.8663	0.8258	0.7873
Present Value	\$238,322	\$232,642	\$227,098	\$221,686	\$216,403
Cumulative Present Value	\$238,322	\$470,965	\$698,063	\$919,749	\$1,136,151

0.9533 =	0.9088 =	0.8663 =	0.8258 =	0.7873 =
$1 / (1+4.9\%)^1$	$1 / (1+4.9\%)^2$	$1 / (1+4.9\%)^3$	$1 / (1+4.9\%)^4$	$1 / (1+4.9\%)^5$

4.9% Nominal Discount Rate  
End of Year Discount Factor

TOTAL OUTLAY
<b>\$1,311,457</b>
NPV
<b>\$1,136,151</b>

Figure N-9. Example of Discounting

### N.5.2.2.1. End-of-Year and Middle-of-Year Discount Factors

The two most common discounting conventions used to evaluate Federal expenditures are end-of-year (EOY) and middle-of-year (MOY). This section provides descriptions of EOY and MOY factors associated with these discounting conventions.

#### End-of-Year (EOY) Discount Factor Calculation

The EOY discounting convention is where a payment is administratively placed at the end of the discount period. This is appropriate where you know the timing is closer to the end of a year. When using the EOY method for a specific payment, include justification in the source and derivation of costs section.

To determine the EOY discount factor, the right side of the PV formula (Equation 2) can be broken down into two parts: (1) the FV (e.g. the total amount of money in a savings account after 5 years) and (2) the discount factor (e.g. the factor that adjusts the FV to PV). This slight variation to Equation N-2 is depicted in Equation N-3.

$$PV = FV * \frac{1}{(1+i)^n} \quad (\text{Equation N-3})$$

where:

$$\text{Discount Factor} = \frac{1}{(1+i)^n} \quad (\text{Equation N-4})$$

Substituting:

$$PV = FV * \text{Discount Factor}$$

(Equation N-5)

Offering a more detailed examination of the previous example, Equation N-3 reveals how the FV of your car (\$10,000) is “discounted” to a PV of \$6,209.21. Equation N-4, an excerpt of Equation N-3, represents the EOY discount factor (for converting any FV to its respective PV). Given an interest rate of 10 percent over a period of 5 years, the discount factor can be calculated as:

$$\text{Discount Factor} = \frac{1}{(1 + 0.10)^5} = 0.6209$$

Substituting the given values into Equation 5 produces the same solution produced from Equation N-3:

$$PV = FV * \text{Discount Factor}$$

$$PV = \$10,000 * 0.6209 = \$6,209$$

It becomes apparent, therefore, that time-value-of-money, depicted as a discount rate, can have significant impacts on the PV of a principle deposit or investment.

#### Middle-of-Year (MOY) Discount Factor Calculation

The MOY discounting convention is used where a payment is administratively placed at the middle of a discount period. This is accepted by OMB as an approximation of continuous payments or payments evenly spread throughout a year. OMB guidance advocates the use of midyear discount factors, which have the advantage of providing greater accuracy than end-of-year factors. When outlays of funds are spaced evenly throughout a year, midyear discounting is considered an acceptable approximation for continuous discounting. When outlays are not spaced evenly, and the precise timing of outlays is unknown, midyear discounting minimizes the potential error. This is the preferred method of discounting and should be the default method. Built-in formulae for most spreadsheets do not support MOY, so formulae must be constructed as described later.

It is not uncommon to depict expenditures to occur at mid-year. The method for calculating midyear discount factors is based on the following formula:

$$\text{Discount Factor} = \frac{1}{(1 + i)^{n-0.5}}$$

(Equation N-6)

Applying the MOY convention to our car example (instead of the EOY convention), the discount factor increases slightly from 0.6209 to 0.6512 as shown:

$$\text{Discount Factor} = \frac{1}{(1 + 0.10)^{(5-0.5)}} = 0.6512$$

Note that in order to calculate realistic EOY and MOY discount factors, it is necessary to have the most current discount rates and an accurate Period of Analysis.

As described in Step 5 of the EA Process (in the next section), applying the appropriate discount factor to future cash streams is essential to putting all alternatives on a level playing field. Discounting converts future cash flows from FVs to PVs that can then, and only then, be used for comparing and ranking alternatives.

#### **Common EOY and MOY “Cash Flows”**

A new project typically requires an initial capital investment at the beginning of year 1 (at time = 0). Investments may need to continue for several years (e.g., EOY 1, 2, and 3). Salvage value and disposal cost (at end-of-service life) also tend to occur at EOY. Therefore, it is necessary to apply EOY discount factors to these types of cash flows.

These three exceptions aside, remaining project expenditures, such as project operations cost or building maintenance expenses, are typically depicted as MOY cash flows. Therefore, MOY discount factors should be applied to these cash flows.

### N.5.3. Steps for Performing an Economic Analysis

As described in section 3.6.1, the seven steps for performing an EA are:

1. Prepare statement of objective.
2. List assumptions and constraints.
3. Identify alternatives.
4. Identify and estimate benefits and costs.
5. Rank alternatives using economic measures-of-merit.
6. Perform sensitivity and risk analyses.
7. Prepare results and recommendation (documentation).

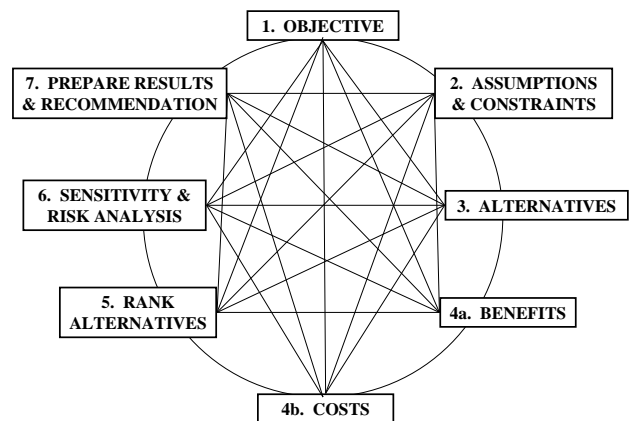


Figure N-10. Steps for Performing an EA

Although this section will review these steps in series, the EA process is most often an iterative one (see Figure N-10). There are many interrelationships among the steps in the process. Rather than performing each step in order to completion, the steps may be revisited during the analysis.

#### N.5.3.1. Prepare Statement of Objective (Step 1)

It is difficult to solve a problem if you do not know what the problem is. The need to perform an EA usually stems from an existing problem, changing threat, or changing mission. The statement of the objective should clearly define and quantify, to the fullest extent possible, what we are trying to accomplish. The statement of the objective should not assume a specific means of achieving the desired result and cover two areas: (a) describe the problem and requirement, then (b) define the objective.

**The Problem and Requirement.** You usually get this information from a boss who tells you to go fix a problem. The analyst may be at a disadvantage because the “real problem” as seen by higher headquarters may not be obvious to the team assigned to do the study.

A project is usually proposed to correct a deficiency. Deficiencies that might prompt a project include:

1. A need for a new functional requirement due to a new mission or mission change.
2. A space shortage.
3. An engineering deficiency.
4. An environmental, health, safety, fire protection, or security problem.
5. A trend of excessive operations and support costs.
6. Functional inadequacy. For example, fielding a new system where it did not fit the size or capability of support facilities or storage areas.
7. An inefficient condition, including inefficient use of energy or space.

Often a project identified to meet one requirement may be expanded to meet others. For instance, a facility addition designed to accommodate space storage requirements may also correct structural deficiencies or increase energy conservation.

**The Objective Statement.** THIS IS THE MOST IMPORTANT STEP and involves both the decision maker and analyst. Both must understand why the EA is being performed. Also, be sure to include all key functional people at this time. Consider using functional area persons, experts, academia, and the like.

A good objective statement should consist of three parts:

1. The product or service to be provided,
2. The measurement system, and
3. The selection criteria.

The product or service to be provided is exactly what will be provided, manufactured, produced, procured, or delivered. First, consider the mission or function desired. Although it does not seem very well defined yet, it is only because the alternatives more readily define the product or service. The wording of the objective statement is critical. Be specific enough to include the problem to be addressed, yet broad enough to pick up all feasible alternatives. Be careful not to word the objective statement to lead toward any one alternative.

The objective should be stated in quantifiable terms to the greatest extent possible because it is easier to compare and rank alternatives if you can compare apples to apples or numbers to numbers. Second, performance measurement criteria need to be established so that the relative costs and benefits of each alternative can be compared and related directly to the objective.

The measurement system is that standard by which the product or service to be provided will be measured. It can be stated in terms of a standard, regulation, or building code, or a goal against which the results of the selected problem solution can be measured. You must be able to measure the output in order to determine the attainment of the goal.

The selection criteria may include financial and nonfinancial comparisons such as Net Present Value (NPV), Equivalent Uniform Annual Worth, Savings Investment Ratio, Benefit/Cost Ratio, or decision analysis scores and may become the basis for your recommended decision methodology.

### N.5.3.2. List Assumptions and Constraints (Step 2)

It is important to list constraints that each alternative must meet to weed out infeasible alternatives early. List only those assumptions that are absolutely necessary because the more assumptions, the more chances to introduce uncertainty into the study. Finally, identify any limitations in the scope of the study such as limited timeframe or personnel to perform the study.

**Assumption #1: Economic Life.** The first and commonly foremost assumption required in every EA is that of each alternative's economic life. Economic life is defined as the period of time over which the benefits from an alternative are expected to accrue (i.e., we receive the use or benefit of an alternative). It is commonly equal to the years associated with operating and support. Each alternative has its own economic life. The economic life of a given alternative is usually the shortest of the physical life, mission life, or technological life.

- *Physical life* is the estimated years that an asset can physically be used to accomplish the function for which it was intended.
- *Mission life* is the estimated years over which the need for the asset is anticipated.
- *Technological life* is the estimated years a facility, piece of equipment, or automated information system will be used before it becomes obsolete due to changes in technology.

**Assumption #2: Period of Analysis.** Another important assumption is described as the Period of Analysis. The Period of Analysis starts from the year the first costs are incurred for each alternative and ends in the last year costs are incurred for that alternative. Since it includes disposal costs, the Period of Analysis may extend for some number of years beyond the end of economic life.

**Other Assumptions.** Although listed as the second step in the analysis process, the formulation of assumptions is, in reality, continued through every phase. Care must be taken not to oversimplify the scenario and thereby distort the analysis too much from practical consideration. Assumptions are used to help:

- define the study problem
- establish alternatives
- provide means for treating unknown or difficult-to-quantify elements
- perform calculations
- report study results

The formulation of assumptions is an integral part of an EA. It is accomplished whenever and wherever required, and, in fact, may be necessary when determining the original objective of the analysis.

The following items, by nature of their uncertainty, qualify as assumptions:

- Any future events
- Future economic assumptions
- Inflation factors
- Costs and benefits
- Projected workload
- Estimated economic life
- Changes to requirements

**Constraints.** In all phases of the business community, public or private, managers operate in an environment of restrictions, limiting what they can and cannot do. Whether the restrictions are “outside” constraints or self-imposed, they must be considered prior to developing possible courses of action.

Constraints such as the size or range of the manager’s “operating area” are dependent upon total organizational freedom as well as the decision maker’s position within the organization. There may be constraining organizational policies or procedures. There may be budgetary, funding, or personnel considerations. The manager may be limited to a specific amount of working area. There may be restrictions caused by production deadlines or other time-related considerations. Whatever their particular characteristics, these external constraints or barriers are beyond the control of the analyst or manager and provide boundary limitations for alternative solutions to a particular problem.

Constraints are things you know about but do not have the power to change. Sometimes all you can do is ask the imposing authority for relief or exemption. You must list all constraints because they are conditions that bind the analysis and influence the generation of alternatives.

Some constraints might be:

- |                               |                                     |
|-------------------------------|-------------------------------------|
| • budget                      | • milestones                        |
| • funding                     | • schedules                         |
| • operations                  | • deadlines                         |
| • organization                | • cost apportionments               |
| • facilities                  | • production rates                  |
| • personnel strength ceilings | • manning factors                   |
| • working area                | • NASA Center or NASA-wide policies |

### N.5.3.3. Identify Alternatives (Step 3)

There is normally more than one way to achieve a goal or objective. Each is an alternative—a different means to fulfill the need. All reasonable ways of satisfying the objective should be documented and discussed. Innovative and improved ways of doing business should be actively sought. As a minimum, each of the following alternatives must be considered:

- Do nothing or status quo (the existing way of meeting the objective)
- Modification of existing assets. This may include renovation, conversion, upgrade, expansion, or other forms of improving existing assets or services.
- Leasing or privatization
- New acquisition

Each alternative solution has its own mix of costs and benefits. One method may require a multitude of personnel while another may require a large capital investment. The number of alternatives is usually limited only by the creativity and thoroughness of the problem solver.

In the development of alternatives, the search can be either random or systematic. Examples of the random approach include the familiar brainstorming or “thinking outside the box” creativity. The random method of search will probably uncover, to a greater extent than the systematic method, a new technology breakthrough alternative.

The systematic approach of identifying alternatives is more difficult but much preferred because of its thoroughness. This is the planned effort that uses some amount of advance information. The analyst sits down and formulates a survey to ask experts about the best solution to a current problem. The systematic approach of identifying alternatives seeks to gain information from a broad source of people so that the best possible solution can be advanced.

The search for alternative solutions to an existing problem (or for replacements for current solutions) definitely should not overlook the current way of doing things. This assumes, however, that the current method is feasible and valid. At the very least, the current alternative is a standard against which to compare new possibilities.

There are, however, a number of factors in generating alternatives that may limit the range or variety that can be developed. These may be inherent biases preventing the analyst from considering certain aspects or possibilities, or there may be resource limitations that force a halt before all concepts are pursued. Some limiting factors are:

- Routine pressure of normal activities
- Tradeoffs between time and the effort expended and probability of new alternatives or additional data
- Precedence of past actions
- Nature of the organization
- Scope of the analysis (feasibility study versus detailed project report)
- Forced deadlines limiting the analysis time
- Specific lists of alternatives from higher levels of management

#### Challenges in Quantifying Benefits

Quantification of benefits can sometimes be an extremely difficult task. The reason is that benefits or effectiveness tend to have intangibles, as well as a number of different measures for the more tangible, quantifiable components.

In most cases, there is no common denominator like dollars in the case of costs. One way to address such a situation could be to rank the returns according to a hierarchy of values so that a more rational choice of alternatives can be made. Even if a benefit cannot be quantified, it should be documented and described in the EA.

These are not valid reasons to limit the search for alternatives. Be aware of their existence, deal with them by working around them, and try not to let them artificially constrain the number of alternatives.

#### N.5.3.4. Identify and Estimate Benefits and Costs (Step 4)

As described in the EA overview, costs must be viewed from the perspective of the Federal Government as a whole—not solely from the perspective of the organization for which the analysis is being done. Thus, project initiatives commonly have economic impacts that ripple beyond what is “owned” by the program itself. For example, a proposed technology demonstration initiative has the potential to divert funds away from three other NASA initiatives, improve the safety of U.S. citizens, improve the future effectiveness of two active NASA missions, and lead to reduced carbon-based emissions (environmental benefits). This same initiative could also lead to dramatic profits for Private Company X, but since those profits would not fall directly under the purview of the Federal Government, they should not be part of a Government EA.

**Identify and Estimate Benefits.** Benefits are the outputs of each alternative. They are what the Government expects to receive for the resources expended. They include measures of utility, effectiveness, and performance, and should be related to the objective. All benefits to the Federal Government should be included. In order for the analyst to avoid double-counting benefits or costs, they must be mutually exclusive.

Many benefits, described in many ways, are relatively easy to quantify. These include:

<u>Quantifiable Benefit</u>	<u>Examples</u>
Reduced Resource Requirements:	Personnel, Training, Maintenance, etc.
Improved Data Entry:	Reduced Staff Time, Reduced Error Rates
Improved IT Usage:	Storage and Retrieval, Distributed Processing
Improved Operating Performance:	Reduced Error Rates, Better Quality and Productivity
Cost Avoidance:	Eliminate Future Staff Growth, Need for Equipment
Cost Savings:	Reduced Budget, No Impact on Mission Effectiveness

Other benefits are nearly impossible to quantify in terms of dollars. Some typical *non-quantifiable benefits* include:

- Greater versatility
- Improved decision making
- Better presentation of information
- Fulfillment of operating requirements
- Improved timeliness
- Improved morale

So, the purpose of the benefit analysis is to present (to the appropriate decision maker) an orderly, comprehensive, and meaningful display of all returns expected for each alternative. In general, the following should be considered:

- A systematic procedure should be used to establish types of output;
- All benefits or returns should be identified and recorded for each of the alternatives under consideration; and
- A quantitative evaluation should be devised, if possible, for each type of output.

Benefits analysis can be rather subjective because judgments and priorities come into play. Nevertheless, benefits should be quantified whenever possible. Such measurements will vary from monetization of improved air quality to precise quantities of physical output to ranking and weighting each benefit. Verbal descriptions can often be transformed into numbers.

**Example: Valuation of Benefits (Intangibles).** A simple technique of ranking and weighting is described in this section. The general process is to first identify each benefit or decision criteria and each feasible alternative in a matrix. Then, for each benefit, assign a weight based on how important the attribute is to the overall objective. (Note: A higher number for weight shows greater relative importance.) Next, rank each alternative (again, a high number is best) based on how well the alternative satisfies the objective. For each benefit and alternative, multiply the weight by the rank to determine the weighted rank. Add the weighted ranks for each alternative. The alternative with the largest sum is the preferred alternative based on benefits. The benefit scores computed by this method have no measurable units and are only used for comparison of alternatives.

Consider the following example of benefits analysis. Due to a new 6-year NASA project starting up in fiscal year 2015, 450 NASA employees and contractors will need to relocate to a new office building. The status quo of moving into one or more existing LaRC buildings is infeasible due to limited *existing* office space available at LaRC. Therefore, additional facility space needs to be leased or purchased. In addition, it was determined that a permanent building shall not be constructed because the project will end in fiscal year 2020.

For illustrative purposes, assume that EA Step 2 (list assumptions and constraints) results in just two feasible alternatives:

- (1) Alternative A—Lease a facility space that is 12 miles west of LaRC . Ample office space is available immediately in an existing building that would be suitable and comfortable.
- (2) Alternative B—Buy temporary buildings to be placed at LaRC. Although the acquisition effort is more involved with such a purchase (versus a lease), the purchase of five temporary buildings could be accomplished in time for the move. The buildings would be somewhat less comfortable than the leased office space. However, the buildings can be located in areas that would allow the employees to still benefit from being on the “campus” of LaRC.

After a discussion with decision makers, analysts determine that there are three primary intangible benefits associated with each alternative: Proximity (i.e., how close the office is to LaRC), Availability (i.e., when the building is available), and Comfort (e.g., furniture, lighting, indoor temperature). Decision makers indicated that proximity is the most important benefit. *Proximity* is rated three times more important than *Comfort*; *Availability* is rated twice as important as *Comfort*. These benefit ratings are valued under the “Weight” column in Table N-6.

Elicitation with decision makers continues by scoring each of the three benefits. For example, the analyst presents to decision makers the following list of possible scores with respect to Proximity:

<u>If Leasing a Building provides ...</u>	<u>then Score =</u>
Poor <b>Proximity</b>	1
Below Average <b>Proximity</b>	2
Average <b>Proximity</b>	3
Good <b>Proximity</b>	4
Excellent <b>Proximity</b>	5

As shown in Table N-6, decision makers gave the “Lease Building” alternative a “Proximity” benefit score of only 2, and they gave the “Buy Temp Buildings” alternative the highest “Proximity” benefit score of 5.

Now that the analyst has a weight and score for each benefit, she is able to complete the benefit valuation for each alternative by (a) calculating weighted scores of each benefit, then (b) summing up these weighted scores. The alternative with the higher sum of weighted scores is then considered to provide more intangible benefit. In this example, as shown in Table N-6, buying the temporary buildings has an overall higher weighted score and, therefore, provides more intangible benefit versus leasing buildings.

**Table N-6. Valuating Nonquantifiable Benefits of Leasing Versus Buying Buildings**

Benefit	Weight	Lease Building		Buy Temp Buildings	
		Score	Weighted Score	Score	Weighted Score
Proximity	3	2	6	5	15
Availability	2	5	10	3	6
Comfort	1	4	4	2	2
		<b>Sum = 20</b>		<b>Sum = 23</b>	

In this example, the interviewees “scored” leasing a building as “Below Average Proximity” (score = 2). The rationale for many of the respondents was that the building distance from LaRC would add 10–15 minutes to commute time.

Upon ranking and weighting the three benefits against each alternative, it was clear that the total benefit difference between leasing versus buying was not significant. Nevertheless, as Table N-6 indicates, buying temporary buildings within the confines of LaRC had a benefit score slightly higher than that of the “Lease Building” alternative (23 versus 20). This preference was driven by the proximity benefit of the temporary buildings.

**Identify and Estimate Costs.** There are two fundamental concepts in determining costs for each alternative. The first concept is life-cycle cost analysis. The second concept is cost estimating methods.

The following basic principles are essential for identifying and estimating costs for an EA:

- The viewpoint should reflect the total cost to the Federal Government.
- The viewpoint should include nonbudgetary and opportunity costs to Government.
- The viewpoint should document the source and derivation of all costs.

**Life-Cycle Cost.** A life-cycle cost reflects the sum of nonrecurring and recurring costs. More specifically, life-cycle cost equals the total cost of research and development, investment, operating and support, and disposal. Life-cycle cost for each feasible alternative should include all costs to the Government from beginning through termination or salvage point for the entire life of a program or project.

There are two general categories of cost: nonrecurring (one-time investment) and recurring (operational). This distinction is necessary because the timing and annual rate of costs incurred are important factors in an analysis.

**Nonrecurring Cost.** Nonrecurring cost is a one-time cost category that includes such considerations as acquisition of equipment real property, nonrecurring operation and support costs, and other such investments. It also includes:

- The cost of rehabilitation, modification, or addition of land, buildings, machinery, and equipment;
- The cost of freight, foundations, and installations required by the project;
- The value of nonrecurring services received from others, both internal and external, when the cost of these services can be measured, as well as one-time personnel costs such as separation costs or hiring costs;
- The costs of leaseholds required for the alternative; and
- Working capital, current assets on hand or on order (including inventories of consumable items and resources required for the project).

**Recurring Cost.** Recurring costs are the annual costs required to operate and maintain a program or project. This category considers personnel costs, materials consumed, operating overhead, and support services required annually.

**Cost Terminology Specific to Economic Analysis.** An EA has its own unique vocabulary of dozens of EA-specific cost language terms. Nine essential terms are defined below:

- **Depreciation:** Depreciation is an accounting convention that impacts cash flows only when an income tax structure exists. DOD components do not pay taxes, and thus tax depreciation is not applicable in DOD-owned alternatives and should not be included in an economic analysis of Government investments. Activities under the Defense Working Capital Fund are allowed to use depreciation techniques to determine the values of assets and capital recovery customer fees or surcharges on prices of products and services to customers.
- **Externalities:** This type of cost can occur when a Federal action affects others (positively or negatively) without those others paying or being compensated for that action. For example, a new Air Force program may cause a 50 percent increase in employment in and around a region. The “external” cost to that region might be dramatic increases in traffic and air pollution. Such change in traffic and air pollution can lead to longer average commuting times, decreased work productivity, increased road maintenance, increased air pollution, and a higher incidence of automobile accidents. Using various economic methods, economists publish monetized values of these secondary impacts (e.g., the cost of NOx to society is \$12,700 per ton per year). Therefore, although often difficult, it is possible to translate externalities into monetary cost impacts.
- **Incremental:** These are additional costs necessary to achieve a change in the output of a particular project (a form of differential cost). Calculating the change in cash flows from a status quo project to a more efficient project is an example of an incremental cash flow. What commonly occurs when one considers alternatives is that an alternative requires an incremental increase in capital (procurement cost) to realize an incremental decrease in operating and support costs.
- **Intangibles:** Used interchangeably with “nonquantifiable,” intangibles are those elements of the alternatives that could not be depicted in monetary terms. Examples include changes in comfort, aesthetics, flexibility, safety, or morale—all of which can be extremely difficult to translate into dollars and cents.
- **Opportunity Costs:** Value of a good or service foregone or sacrificed by use of limited resources on a less effective or less gainful project. Decisions have “opportunity cost” because choosing one thing in a world of scarcity means giving up something else. For example, a person going to college foregoes earnings that he or she would have received working a paid job for 4 years. The opportunity cost of the time spent studying and going to classes is lost earnings.

- Phase-out: Lead-time is included in an EA if an alternative involves equipment that must be developed or modified before it can be used. For such an alternative, costs must be incurred for parallel operations of the status quo while the development or modification is taking place. These costs are called phase-out costs or parallel system operating costs. They must be added to the life-cycle cost of the new or modified system.
- Sunk: These are costs that have already been incurred or were irrevocably committed prior to the beginning of the period-of-comparison. They may be mentioned in the narrative of the EA report but are not included in the cost analysis. Only costs that can be influenced by the decision maker are included in the analysis. For example, if an alternative is linked to a \$300,000 research cost undertaken prior to the decision point, the research cost is sunk and should not be included in the analysis. The \$300,000 is spent and cannot be recaptured no matter which alternative is selected.
- Terminal: Also referred to as “residual” or “salvage value,” these are costs that will be incurred because of actions taken to conclude or terminate a program. These terms refer to the expected value of existing facilities or assets (e.g., land, buildings, equipment, or automated information systems) when they are no longer being used or have reached the end of their useful lives. Terminal values should be included in the cost analysis as a reduction to the cost of the alternative to which they apply. Many factors influence estimates of these values; for example, (a) probability of continued need for product (for Government or private use), (b) appreciation, and (c) depreciation. Functional area directives often specify terminal value determination procedures. Be aware of these for your functional area!
- Wash: Also called “nondifferential costs,” wash costs are those costs that apply equally to all alternatives. They can be included or excluded and should be described in the narrative of the EA report.

The determination of the cost of each proposed investment is based on the costs of adopting the alternative. Such costs are determined after due allowances for those resources are already paid for, regardless of whether or not the alternative is adopted or if the allowances would be available for use if the alternative were adopted. To determine the cost of an alternative, all the resource implications are considered. The alternative is treated in a system context. For example, the cost (admittedly oversimplified) of adopting a new radio would include not only the cost of the radio and its development, but also the costs of training people to operate it, the total cost of maintaining the radios, and cost of the additional radios required for maintenance float replacement, combat consumption, and so forth.

Inflation must be recognized in EA by two primary methods. The first and preferred method is to exclude inflation by using “base-year dollar” estimates. The second method is to use “then-year dollar” estimates that include inflation. The inflationary impact is commonly estimated by inflation indices. These forecasted inflation factors are available through cost analysis or comptroller channels at higher headquarters. A common technique is to use factors linked to the type of appropriation funding. Examples are separate factors for Research and Development or Operations and Maintenance. If inflation factors are used, you should document their source and derivation in your report.

EA requires measuring the value of costs. The unit of measure is the dollar. To avoid distortions due to changes in the value of the dollar over time, as when the general price level changes, all estimates of costs should normally be made initially in terms of base-year dollar values—that is, in terms of the general purchasing power of the dollar in the base-year of the analysis. Projected annual costs should vary only to the extent that the required level of procured goods and services is expected to vary during the project life. For example, it would be legitimate for annual costs to reflect an increase in the anticipated amount of

repairs needed, as measured by prices in effect at the beginning of the project life, since this represents a real cost increase and not an inflationary one.

Because base-year dollar estimates are most commonly used for EAs, the numbers given are generally not budget estimates, which usually reflect some anticipated inflation.

### N.5.3.5. Rank Alternatives Using Economic Measures-of-Merit (Step 5)

Decide which alternative is the “best buy for the dollar” by ranking the alternatives. For a “best buy,” we must determine the value of the benefits and compare the costs. In comparing a number of alternatives, a relatively quick comparison and ranking can be accomplished by categorizing the choices in terms of equality of costs and benefits. The comparison of alternatives has two major purposes: (1) to highlight the key issues associated with each alternative and (2) to focus on the tradeoffs (in costs and benefits) that are available to the decision maker.

Just because a pair of alternatives meets the minimum requirement does not necessarily mean that they have equal benefits. It is not uncommon to have competing alternatives that have unequal benefits and unequal costs. Under such scenarios, the analyst may need to employ noneconomic methods in addition to economic methods.

**Selecting and Applying Preferred Economic Measures-of-Merit.** In EA, current Federal policy requires us to use specific discount rates. When you apply discount factors to base-year dollars, you are accounting for two economic or financial phenomena. First, by discounting, you are considering the “time-value-of-money”, i.e., a dollar today is worth more than a dollar in the future. Second, by using a discount rate, you are assuming an “opportunity cost of capital.” In other words, you are requiring a return on the investment of Government funds.

A number of standard financial measures are available for the evaluation of alternatives. They provide insight into different views of the same situation. The choice of what measures to use should be based on the objective of the project and is made by the analyst, reviewers, and management. Often, a number of measures are used together to present a financial picture to the decision maker. An example is using the results of Net PV, Equivalent Uniform Annual Worth, and Discounted Payback Period. Each measure contributes to the understanding of the decision situation. Common financial measures and nonfinancial measures are listed as follows:

- Net Present Value (NPV)
- Equivalent Uniform Annual Worth (EUAW)
- Savings/Investment Ratio (SIR)
- Discounted Payback Period and Nondiscounted Payback Period
- Internal Rate of Return (IRR)
- Discounted Breakeven Point and Nondiscounted Breakeven Point
- Capitalized Cost
- Incremental Analysis
- Benefit/Investment Ratio
- Benefit/Cost Ratio (BCR)
- Decision Analysis Scores

In order to determine the better alternative from an EA viewpoint, you must apply one or more of the financial measures listed above. For this lesson, you will focus on two of the measures: NPV and EUAW. Both measures require the adjustment of costs for the time-value-of-money. You will make such adjustments using cash flow diagrams.

**Cash Flow Diagrams (CFD).** Many everyday economic problems involve periodic payments and receipts of money. A cash flow diagram provides a graphic representation of such cash receipts and disbursements. Cash flow diagrams are useful for analysis because, with a simple graphic, they can depict a complex situation. Secondly, cash flow diagrams assist the analyst to select an approach for solving time-value-of-money adjustments.

**How to Construct a CFD.** These guidelines are conventions and should not be interpreted as fixed rules and regulations. A CFD is a graphical representation of current and future resource expenditures and receipts (expressed in dollar terms). The first step is the drawing of a horizontal line to illustrate the considered time period. Divide the line into equal parts symbolizing the discount (interest) periods. For EA, the usual time interval is 1 year. The time periods are then numbered chronologically. The left end point is often called “time zero or base period” and represents the time of decision. For large-scale investments that require separate budget submissions and authorizations, it is common to synchronize the analysis periods with fiscal years. For other cases it is not necessary to synchronize the periods with fiscal or calendar years.

Use vertical arrows to illustrate fund outflows and inflows. Outflows and inflows are differentiated by the direction of the arrows. Arrows may be placed either above or below the line. Use downward arrows to represent outflows, or expenditures, and upward arrows to represent inflows or receipts. With discrete payments, a separate arrow represents each separate payment. To illustrate a future equal (uniform) uninterrupted series of amounts, you have the option to draw only the first and last arrows then connect the ends of the arrows with a straight line. This is done instead of drawing a separate arrow for each discrete payment.

The location of the arrow on the time line represents also the type of discounting for that payment. The most common methods include: Beginning-of-Year, Middle-of-Year, and End-of-Year. The placement of the arrow is administrative only and need not match the exact timing of the payment. As an example, with End-of-Year discounting to approximate a steady flow throughout the year, the entire year of payments is represented by a single arrow at the end of the year. The end of one year is considered the same as the beginning of the following year.

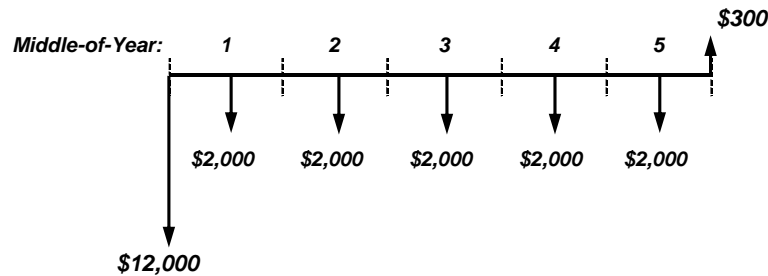
**CFD Example:** An office requires a new copy machine that will be used to produce 200,000 copies per year. One alternative is the purchase of a new copying machine. The machine will cost \$12,000 that will be paid one month after delivery. The machine would be delivered immediately. Operating and maintenance costs are estimated to be \$0.01 per copy. The copy machine will last for 5 years, at which time it will have a salvage value of \$300. An alternative is contracted service at a cost of \$0.03 per copy. The discount rate is 2.3 percent. Tabular and CFD results for each alternative are shown in Figure N-11:

$i = 2.3\%$       Copies per Year:    200,000

**Purchase Option**

Cost per copy equals: \$0.01

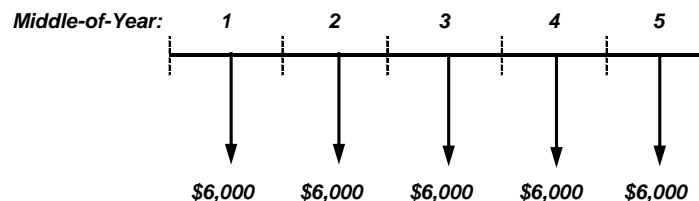
	<u>EOY 0</u>	<u>MOY 1</u>	<u>MOY 2</u>	<u>MOY 3</u>	<u>MOY 4</u>	<u>MOY 5</u>	<u>EOY 5</u>
Expenses	\$12,000	\$2,000	\$2,000	\$2,000	\$2,000	\$2,000	
Receipts							\$300
<b>Net Cashflow:</b>	-\$12,000	-\$2,000	-\$2,000	-\$2,000	-\$2,000	-\$2,000	\$300



**Contract:**

Cost per copy equals: \$0.03

	<u>MOY 1</u>	<u>MOY 2</u>	<u>MOY 3</u>	<u>MOY 4</u>	<u>MOY 5</u>
Expenses	\$6,000	\$6,000	\$6,000	\$6,000	\$6,000
Receipts					
<b>Net Cashflow:</b>	-\$6,000	-\$6,000	-\$6,000	-\$6,000	-\$6,000



**Figure N-11. Cash Flow Diagrams of Purchasing Copier Versus Contracting Copy Service**

Note that each alternative is depicted with a separate CFD. The “Purchase Option” has different EOY cash flows while the “Contract” alternative is depicted as five discrete EOY expenditures of \$6,000.

**Net Present Value**—NPV is the preferred financial measure for usage by OMB and DOD. NPV shows whether total costs are less than or greater than total benefits. However, this measure is valid only where the economic lives of all alternatives are equal. If the economic lives are not aligned and equal, then there is the inherent problem of benefit or value received from one alternative over some time that is not received from another. NPV is a popular measure-of-merit because it represents all costs and benefits reduced to a single discounted net value. This permits simple comparison of alternatives on an equitable basis.

To compare investments in terms of their NPV, all costs and receipts for each alternative are put in terms of their worth as of the date on which a comparison is to be made. (The date of comparison usually is the present or a base year.) The following conditions apply to this present worth method. Note that for these conditions, economic life is assumed to be equal to the Period of Analysis.

- Economic lives of alternatives must be finite. For example, pump A has been estimated to have a physical life of 6 years. Pump B has an estimated life of 12 years.
- Economic lives of alternatives must be equal, or else they must be placed on equal terms.

If alternatives have unequal economic lives, then three adjustments are possible:

1. Assume multiple procurements are possible for each alternative until both have the same economic life. Here we assume that the same value of benefit can be purchased again and again. This situation may be numerically correct, but may not be considered reasonable if technology is a factor. The assumption that the same benefit or value can be procured again at the same cost ignores obsolescence and new technology. As an example, if two alternatives have economic lives of 6 and 8 years, the common multiple would be 24 years, which might be unrealistic.
2. Shorten the economic life of the longer alternative. This may result in a terminal value. As an example: If two alternatives have economic lives of 6 and 8 years, use 6 years. The concern then is to determine if the alternative with 2 years remaining on its normal economic life has any salvage or terminal value.
3. Extend the economic life of the shorter alternative. This may result in additional costs, increased costs, or a degradation of benefits. For example, if two alternatives have economic lives of 6 and 8 years, force both to have 8-year economic lives.

### Depicting and Calculating NPV

For a complex situation with a number of separate payments, compute each payment as a separate equivalency back to the PV and then aggregate the amounts into an NPV. To compute NPV, follow these steps:

Step 1: Construct a cash flow diagram based upon tabular or spreadsheet data to display costs and financial benefits by year. Notate if costs are in constant-year or then-year dollars.

Step 2: Compute the PV of each annual cost and benefit. Inflows and outflows will have opposite algebraic signs.

Step 3: Sum the PV of costs and the PV of benefits to estimate NPV.

To estimate NPV, future benefits and costs must be discounted. Discount factors can be reflected in real\* or nominal terms as defined by OMB Circular A-94, Appendix C. The discount rate used depends on the type of dollars to be adjusted (see Figure N-12).

**Real Discount Rates**—Adjusted to eliminate the effects of expected inflation and used to discount Constant Year dollars or real benefits and costs. A real discount rate can be approximated by subtracting expected inflation from a nominal discount rate.

**Nominal Discount Rates**—Reflect expected inflation and used to discount *Then Year* (inflated) dollars or nominal benefits and costs.

\* in this case, "real" indicates that the effects of general inflation have been removed

**Figure N-12. Definitions of Real and Nominal Discount Rates**

NPV is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement.

For most Government-generated cost estimates, discount rates provided in OMB Circular A-94 are used to discount all cash flows. Projects with positive NPV are usually preferred. Projects with negative NPV should usually be avoided. Investment costs and cost savings are in budget-year dollars (include the

inflation and the time-value-of-money, i.e., nominal inflation rate). The PV of the sum of the difference between the initial investment costs and cost savings equals the NPV.

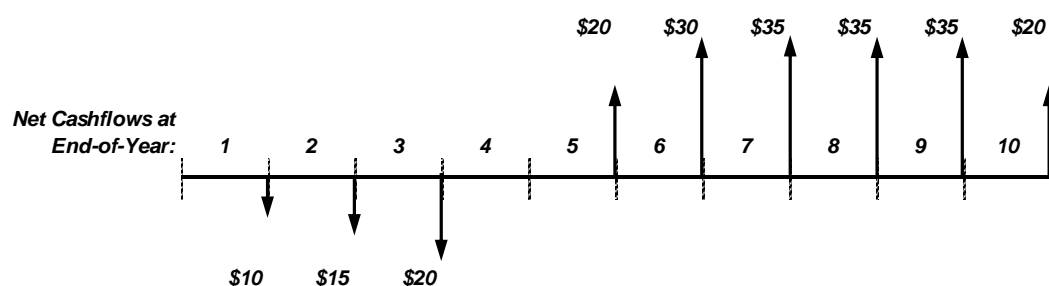
Here is an example for discounting deferred costs and benefits.<sup>3</sup> Assuming a 10-year program, the Government will commit to the stream of real (or constant-year dollar) expenditures and benefits as depicted in the CFD (Figure N-13) as follows:

$i = 7\%$

**Government 10-year Program where each Cash Flow is End-of-Year (EOY).**

Constant Year 2015 Dollars x 000,000

	EOY 0	EOY 1	EOY 2	EOY 3	EOY 4	EOY 5	EOY 6	EOY 7	EOY 8	EOY 9	EOY 10	Total
Yearly Cost	\$0	\$10	\$20	\$30	\$30	\$20	\$10	\$5	\$5	\$5	\$5	\$140
Yearly Benefit	\$0	\$0	\$5	\$10	\$30	\$40	\$40	\$40	\$40	\$40	\$25	\$270
<b>Net Cashflow:</b>	\$0	-\$10	-\$15	-\$20	\$0	\$20	\$30	\$35	\$35	\$35	\$20	\$130



**Figure N-13. Cash Flow Diagram of Government 10-Year Program**

The CFD above shows each cash flow as a net amount in each year. Real costs feeding into the net cash flow appear in column 2 of Table N-7; real benefits are shown in column 3.

The discount factor for a 7 percent discount rate is shown in column 4 of Table N-7. The PV cost for each of the 10 years is calculated by multiplying column 2 by column 4. The PV benefit for each of the 10 years is calculated by multiplying column 3 by column 4. The PVs of costs and benefits are presented in columns 5 and 6 of Table N-7.

**Table N-7. Discounted Costs and Benefits over Time**

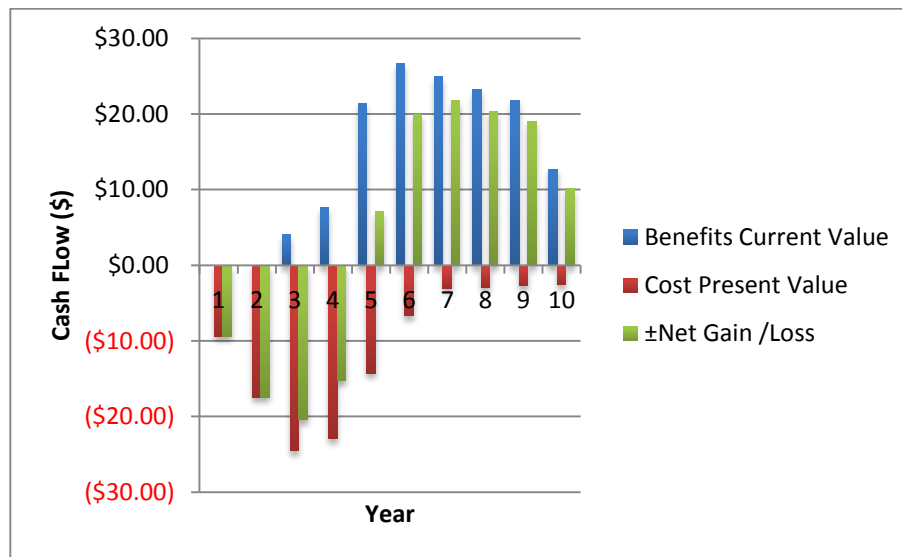
Year Since Initiation Renewal or Expansion (1)	Expected Yearly Cost (2)	Expected Yearly Benefit (3)	Discount Factors for 7% (4)	PV of Costs, Col. 2 × Col. 4 (5)	PV of Benefits, Col. 3 × Col. 4 (6)
1	\$10.00	\$ 0.00	0.9346	\$ 9.35	\$0.00
2	20.00	0.00	0.8734	17.47	0.00
3	30.00	5.00	0.8163	24.49	4.08
4	30.00	10.00	0.7629	22.89	7.63
5	20.00	30.00	0.7130	14.26	21.39
6	10.00	40.00	0.6663	6.66	26.65
7	5.00	40.00	0.6227	3.11	24.91
8	5.00	40.00	0.5820	2.91	23.28

<sup>3</sup> OMB Circular A-94, [http://www.whitehouse.gov/omb/circulars\\_a094/](http://www.whitehouse.gov/omb/circulars_a094/).

Year Since Initiation Renewal or Expansion (1)	Expected Yearly Cost (2)	Expected Yearly Benefit (3)	Discount Factors for 7% (4)	PV of Costs, Col. 2 × Col. 4 (5)	PV of Benefits, Col. 3 × Col. 4 (6)
9	5.00	40.00	0.5439	2.72	21.76
10	5.00	25.00	0.5083	2.54	12.71
<b>Total</b>				<b>\$106.40</b>	<b>\$142.41</b>

**NOTE:** The discount factor is calculated as  $1/(1 + i)^t$  where  $i$  is the interest rate (7%) and  $t$  is the year.

The sum of column 5 is the total PV of costs, and the sum of column 6 is the total PV of benefits. NPV is +\$36.01 (column 6 total minus column 5 total), which is the difference between the sum of discounted benefits and the sum of discounted costs. Figure N-14 shows this cash flow and the discounted value of the cash flow over time. Annual costs are shown in red while the annual benefits are shown in blue. The annual difference between the two is shown in green. The annual cash flow turns positive in the fifth year. The total of all the green bars is the NPV (+\$36.01).



**Figure N-14. Cash Flows and Discounted Cumulative Cash Flows over Time**

Note that an alternative way to achieve the same NPV result of +\$36.01 is to estimate the product of each *net cash flow* (see CFD in Figure N-14) with its respective discount rate, then sum up these values.

### Return on Investment (ROI)

The ROI can be maximized by:

- Minimizing costs
- Maximizing returns
- Accelerating returns

A relatively small improvement in all three may have a major impact on the overall economic return of the investment.

Figure N-15 shows that ROI is the net benefit expressed as a percentage of the investment amount.

$$\text{ROI} = \frac{\text{NPV}}{\text{PV Investment}}$$

Figure N-15. Example ROI Calculation

ROI is the incremental financial gain from an investment, divided by the cost of the investment. The ROI for a project using the data from Table N-7 equals 33.8 percent.

$$\begin{aligned}\text{PV of the investment} &= \$106.40 \\ \text{PV of the cost savings} &= \$142.41 \\ \text{NPV} &= \$36.01 \\ \text{ROI} &= \$36.01/\$106.4 = 33.8\%\end{aligned}$$

The Savings to Investment Ratio (SIR), a popular ROI metric, represents the ratio of savings to investment. In terms of the basic NPV formula, “Savings” represents PV of the cost savings and “Investment” is PV of the investment costs.

$$\begin{aligned}\text{SIR} &= \text{PV cost savings}/\text{PV investment} \\ \text{SIR} &= \$142.41/\$106.40 = 1.34\end{aligned}$$

Computing the amount of time it takes for a project to pay for itself (or return its initial investment) is another commonly used criterion for selecting among alternative courses of action. Typically, the relevant time period is expressed in terms of the number of years it takes before an investment breaks even. Assuming that one is using discounted cash flows as the basis for the calculation of the payback period, the basic question to be answered is at what point in time does the PV (cost savings) equal the PV (initial investment)? In the simplest of cases, the benefits (or returns) begin predictably at the completion of the investment phase and occur in an equal amount each time period. However, in the analyses we typically do, especially for large projects that take years to complete, benefits may begin accruing prior to completion of the investment phase and do not occur in equal annual amounts. In both simple and complex situations, the payback period in years,  $x$ , can be found with the formula below.

This formula may require solution by iteration and is likely to result in an answer that represents a fraction of a year and is found by interpolation. The mathematically correct answer to this equation can also be portrayed graphically in a form that generates a more approximate answer. An example of such a graph is shown in Figure N-16. Note that the breakeven point occurs early in 2010.

$$\sum_{t=1}^{t=X} PV(\text{Cost Savings}) = PV(\text{Initial Investment})$$



(where  $t$  = time periods in years)

**Figure N-16. Discounted Payback Period**

**Equivalent Uniform Annual Worth (EUAW).** We should also take into account the fact that alternatives may have different economic lives. When this is true, EUAW is a common economic measure-of-merit used to evaluate each alternative.

The NPV is reduced to an “average cost per benefit year” annual payment (or receipt) that can be compared with that of a competing project. This method is particularly applicable for comparison of alternatives, such as plant equipment, with unequal lives of capital investments.

All receipts and expenditures are transformed into an equivalent annual worth over the life of the project or investment. The alternative with the highest (i.e., most positive) EUAW is the most economical choice. As with NPV, the choice of the most economical alternative (based upon having the highest EUAW) assumes that all alternatives have equal nonmonetary benefits.

In addition, use of the EUAW method (rather than NPV) is required when project lifetime is either infinite or indefinite. With an infinite or indefinite life, one must still assume a specific economic life. It is not unusual for a service to be required for a period longer than the physical life of the investment. In these cases, the EUAW method assumes the automatic equal replacement of the investment and the repeating of cash flows, which results in a repetitive cycle of expenditures.

Computation of EUAW is performed in three steps:

**Step 1:** Compute the NPV of an alternative using PV techniques (for more on PV and NPV, refer to pages N-13 through N-15 and N-27 through N-29). Typically, this is calculated by estimating the sum of

the project's discounted investments, discounted Operations and Maintenance (O&M) costs, and discounted salvage value.

**Step 2:** Compute the Capital Recovery Factor (CRF) using the formula provided in Equation N-7:

$$CRF = \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (\text{Equation N-7})$$

where  $i$  is the discount rate and  $n$  is the number of years (i.e., Period of Analysis).

Note that the CRF formula changes slightly for cash flows that are MOY:

$$CRF = \left[ \frac{i(1+i)^{n-0.5}}{(1+i)^n - 1} \right] \quad (\text{Equation N-8})$$

**Step 3:** Multiply the NPV (calculated in step 1) by the CRF (calculated in step 2):

$$EUAW = NPV * CRF \quad (\text{Equation N-9})$$

**EUAW Example.** Going back to the “Lease versus Buy” building example on page N-21, the project already completed step 1 of the EUAW method by calculating NPVs for each alternative. The project assumed a real discount factor of 2.7 percent ( $i = 0.027$ ).

**Table N-8. Cash Flows and NPVs of Alternatives A and B (Example)**

<b>Alternative A - Lease Building</b>				
<b>Project Year</b>	<b>Total Cost</b> Constant FY\$15	<b>Discount Factor</b>		<b>Present Value</b> Constant FY\$15
		Type	Value	
1	-\$50,000	MOY	0.9868	-\$49,338
2	-\$50,000	MOY	0.9608	-\$48,041
3	-\$50,000	MOY	0.9356	-\$46,778
4	-\$50,000	MOY	0.9110	-\$45,548
5	-\$50,000	MOY	0.8870	-\$44,351
6	-\$50,000	MOY	0.8637	-\$43,185
<b>Total</b>	<b>-\$300,000</b>		<b>NPV =</b>	<b>-\$277,242</b>

<b>Alternative B - Buy Temporary Buildings</b>				
<b>Project Year</b>	<b>Total Cost</b> Constant FY\$15	<b>Discount Factor</b>		<b>Present Value</b> Constant FY\$15
		Type	Value	
0	-\$200,000	EOY	1.0000	-\$200,000
1	-\$30,000	MOY	0.9868	-\$29,603
2	-\$30,000	MOY	0.9608	-\$28,825
3	-\$30,000	MOY	0.9356	-\$28,067
4	-\$30,000	MOY	0.9110	-\$27,329
5	-\$30,000	MOY	0.8870	-\$26,611
6	-\$30,000	MOY	0.8637	-\$25,911
7	-\$30,000	MOY	0.8410	-\$25,230
8	-\$30,000	MOY	0.8189	-\$24,566
<b>Sub-Total</b>	<b>-\$440,000</b>			<b>-\$416,142</b>
8	\$50,000	EOY	0.8080	\$40,402
<b>Total</b>	<b>-\$390,000</b>		<b>NPV =</b>	<b>-\$375,739</b>

In Table N-8, it appears that Alternative A would be the preferred option due to it having a higher NPV (i.e., its NPV of -\$277,242 is “more positive” than Alternative B’s NPV of -\$375,739). However, the economic lives of the two alternatives are different (Alternative A = 6 years; Alternative B = 8 years), so the NPVs cannot be fairly compared for the cash flows in their present form. Calculation of EUAW for each alternative enables an “apples-to-apples” comparison. Continuing to steps 2 and 3 of the EUAW method, a CRF can be calculated for each alternative:

Alternative A only has MOY cash flows in each of 6 years ( $n = 6$ ). Therefore:

$$CRF_A = \left[ \frac{i(1+i)^{n-0.5}}{(1+i)^n - 1} \right] = \left[ \frac{0.027(1+0.027)^{6-0.5}}{(1+0.027)^6 - 1} \right] = \left[ \frac{0.03126}{0.17334} \right] = 0.18035$$

$$EUAW_A = NPV * CRF = -\$277,242 * 0.18035 = -\$50,000$$

Similar to Alternative A, Alternative B has MOY cash flows in year 1 through year 8:

$$CRF_{B1} = \left[ \frac{i(1+i)^{n-0.5}}{(1+i)^n - 1} \right] = \left[ \frac{0.027(1+0.027)^{8-0.5}}{(1+0.027)^8 - 1} \right] = \left[ \frac{0.03297}{0.23755} \right] = 0.13880$$

The NPV of Alternative B's MOY cash flows equal -\$246,142 (refer to Alternative B of Table N-8). Having this NPV and CRF for Alternative B's MOY cash flows yields the first part of Alternative B's EUAW:

$$EUAW_{B1} = NPV * CRF = -\$246,142 * 0.13880 = -\$30,000$$

Unlike Alternative A, Alternative B also has two EOY cash flows in year 0 and year 8. Therefore:

$$CRF_{B2} = \left[ \frac{i(1+i)^n}{(1+i)^n - 1} \right] = \left[ \frac{0.027(1+0.027)^8}{(1+0.027)^8 - 1} \right] = \left[ \frac{0.03341}{0.23755} \right] = 0.14066$$

The NPV of Alternative B's EOY cash flows equal -\$200,000 + \$40,402 = -\$159,598 (refer to Table N-9). Having this NPV and CRF for Alternative B's EOY cash flows yields the second part of Alternative B's EUAW:

$$EUAW_{B2} = NPV * CRF = -\$159,598 * 0.14066 = -\$22,449$$

Summing up the EUAW for Alternative B, we get:

$$EUAW_B = EUAW_{B1} + EUAW_{B2} = -\$30,000 + -\$22,449 = -\$52,449$$

In this example, leasing office space produces a slightly higher EUAW than buying temporary buildings. In other words, the average discounted annual cost to lease office space (\$50,000) is less than that to buy temporary buildings (\$52,152).

### N.5.3.6. Perform Sensitivity and Risk Analysis (Step 6)

Uncertainty is always present in economic decision making because we make assumptions in conducting the analysis and use estimates of benefits and costs. When anyone tries to estimate costs or predict future occurrences over a long time, variations are bound to occur between the estimated and the actual occurrences. It is important to analyze whether changes in assumptions, quantitative values, or priorities will affect the recommendation. Sensitivity and risk analyses can provide ranges of expected benefits and costs that may provide the decision maker better information than a single financial measure. How these variations affect the results of an EA is the heart of the sensitivity analysis.

**Sensitivity analysis.** The EA sensitivity analysis (a “what-if” exercise) tests whether the conclusion of an EA will change if a benefit, cost, or other assumed variable changes. An EA sensitivity analysis should be performed when:

- The results of the EA do not clearly favor any one alternative, or
- There is uncertainty about an assumption that can impact the estimate of costs and benefits in the EA.

During an EA, the discount rate used may play a key role in the acceptance or rejection of an alternative. Occasionally, an alternative may be economically feasible when evaluated using one discount rate but not another. An evaluation of the alternatives to indicate their relative values at varying discount rates is another useful type of sensitivity analysis. Other examples of variables or assumptions used for an EA sensitivity analysis include:

- costs or reimbursements
- performance output or benefits
- system lives or economic life
- estimation of operation-support-maintenance factors
- schedules
- other risk or unknown aspects

Once you are aware that an assumption or variable has a strong impact upon the recommendation, an in-depth evaluation should be performed. It is imperative that as high a degree of confidence as possible be established and that this degree of confidence be made clear to the analysis reviewer/approver.

Going back to our example of leasing office space versus buying a temporary building (i.e., Alternative A versus Alternative B in Table N-9), we learn that experts believe that the salvage value for Alternative B could easily increase by 50 percent or more depending on market conditions around 2020. In other words, the buildings salvage value could increase from \$50,000 to \$75,000. Incorporating this possible change into the calculations for life-cycle cost and NPV, we get:

**Table N-9. Modified Cash Flow and NPV of Alternative B (Example)**

<b>Alternative B - Buy Temporary Buildings</b>				
<b>Project Year</b>	<b>Total Cost Constant FY\$15</b>	<b>Discount Factor</b>		<b>Present Value Constant FY\$15</b>
		Type	Value	
0	-\$200,000	EOY	1.0000	-\$200,000
1	-\$30,000	MOY	0.9868	-\$29,603
2	-\$30,000	MOY	0.9608	-\$28,825
3	-\$30,000	MOY	0.9356	-\$28,067
4	-\$30,000	MOY	0.9110	-\$27,329
5	-\$30,000	MOY	0.8870	-\$26,611
6	-\$30,000	MOY	0.8637	-\$25,911
7	-\$30,000	MOY	0.8410	-\$25,230
8	-\$30,000	MOY	0.8189	-\$24,566
Sub-Total	<b>-\$440,000</b>			<b>-\$416,142</b>
8	\$75,000	EOY	0.8080	\$60,604
Total	<b>-\$365,000</b>		<b>NPV =</b>	<b>-\$355,538</b>

With a life-cycle cost of \$365,000, Alternative B still, of course, has a lower life-cycle cost than Alternative A (\$400,000). However, recall that economic measures (like NPV and EUAW), not life-cycle cost, must be used to determine the preferred alternative. Because this specific example has two unequal economic lives, NPVs for each alternative cannot be directly compared. To get a fair comparison of alternatives, we recalculate Alternative B's EUAW, now accounting for a 50 percent increase in salvage value.

The revised NPV of Alternative B's EOY cash flows equal  $-\$200,000 + \$60,604 = -\$139,396$  (refer to Table N-9). Having this NPV and CRF (calculated on page N-34) for Alternative B's EOY cash flows yields a revised second part of Alternative B's EUAW:

$$EUAW_{B2} = NPV * CRF = -\$139,396 * 0.14066 = -\$19,607$$

Summing up the revised EUAW for Alternative B, we get:

$$EUAW_B = EUAW_{B1} + EUAW_{B2} = -\$30,000 + -\$19,607 = -\$49,607$$

In this sensitivity part of the example, buying temporary buildings produces a slightly higher EUAW than leasing office space. In other words, the average discounted annual cost to buy temporary buildings (\$49,607) is less than that to lease office space (\$50,000). Therefore, the sensitivity analysis causes our preferred alternative to switch from Alternative A to Alternative B.

**Risk analysis.** In some cases, a risk analysis for an EA may be warranted. Risk analysis deals with the likelihood and expectation of possible outcomes using probability concepts. Examples of tools that can be used to perform risk analysis include expected value, probability theory, simulation techniques, and decision analysis.

### N.5.3.7. Prepare Results and Recommendations (Step 7)

The current environment is a world of congressional oversight and accounting for every dollar. In that environment, it becomes extremely important to make certain all the hard work expended to prepare an EA is properly organized and contains every element the decision maker wants to see.

The EA report should begin with an executive summary of the analysis based on the benefits and costs of the alternatives and an interpretation of the results to include a recommendation of the preferred alternative. The body of the report must include all sources of data and calculations in order to provide an auditable stand-alone document. The actual decision will be based on quantitative factors, as well as qualitative factors, such as the judgment and experience of the decision maker.

The complete analysis should now be structured to facilitate understanding on the part of the decision maker. The analyst has two courses of action:

- 1) Present alternatives in a ranking from which the ultimate course of action can be selected, or
- 2) Make a firm recommendation for the manager's consideration.

The latter is not only preferred by most decision makers, but also insures that analysis has been performed, not just data collection.

There are no strict rules governing the amount of documentation needed or what the documentation should exactly look like. Nevertheless, it is useful to see how Federal and non-Federal organizations organize and document EAs. For example, Department of Defense Instruction (DODI) Number 7041.3 (Economic Analysis for Decisionmaking) can serve as a framework to create a template for documenting an EA.<sup>4</sup>

<sup>4</sup> Department of Defense Instruction (DODI), Number 7041.3 (November 7, 1995): Economic Analysis for Decisionmaking. <http://www.dtic.mil/whs/directives/corres/pdf/704103p.pdf>

Always remember, the analyst is the honest broker and is only providing tools to support the decision maker. Decision makers are not bound by the study and its recommendations. Nevertheless, a well-executed EA with good documentation tends to steer decision makers in a better direction. Furthermore, a well-documented EA can also be invaluable for future program evaluation or for analysis of related programs.

## N.6. Additional Resources

- NPR 7120.5E NASA Program and Project Management Processes and Requirements. <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>
- NASA Systems Engineering Processes and Requirements NPR 7123.1. <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7123&s=1A>
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- R. Gregory Michel, "Make or Buy? Using Cost Analysis To Decide Whether To Outsource Public Services," August 2004, Government Finance Review. <http://www.gfoa.org/downloads/GFRAug04.pdf>
- "Build Versus Buy: Understanding the Total Cost of Embedded Design," National Instruments. <http://zone.ni.com/devzone/cda/tut/p/id/6083>
- Charles Dominick, C.P.M., SPSM, "The Make or Buy Procurement Decision," Next Level Purchasing, 2005. <http://www.nextlevelpurchasing.com/articles/make-buy-procurement-decision.html>
- "Make-or-Buy Decision," Answers.com. <http://www.answers.com/topic/make-or-buy-outsource-decision>
- "Make v. Buy: Considerations When Outsourcing To Reduce Cost," EMS Consulting Group, 2005. <http://www.emsstrategies.com/makevbuyarticle.html>
- NASA Federal Acquisition Regulation (FAR) Supplement, version 4.0, November 2004. Visit <http://www.hq.nasa.gov/office/procurement/regs/nfstoc.htm>, then go to sections 1815.407-2, Make-or-Buy Programs, and 1815.408-70, NASA Solicitation Provisions and Contract Clauses.
- NASA New Start Inflation Index (Updates on the NASA CAD Web site): [http://www.nasa.gov/offices/ooe/CAD/Publications.html#\\_VO56ojo1-gQ](http://www.nasa.gov/offices/ooe/CAD/Publications.html#_VO56ojo1-gQ)
- The Standard for Models and Simulations (NASA-STD-(I)-7009). <https://standards.nasa.gov/documents/detail/3315599>
- Cost As an Independent Variable: Principles and Implementation. <http://www.dau.mil/pubscats/PubsCats/AR%20Journal/arg2000/kaye.pdf>
- Controlling Costs—A Historical Perspective. <http://www.dau.mil/pubscats/PubsCats/PM/articles96/kausal2.pdf>
- OMB Circular A-94. <http://www.whitehouse.gov/omb/circulars/a094/a094.html>
- GAO Cost Assessment Guide. <http://www.gao.gov/new.items/d071134sp.pdf>
- An Analytical Hierarchy Process Approach to the Analysis of Quality in Telecommunications Systems. <http://ieeexplore.ieee.org/iel2/645/6841/00276672.pdf?arnumber=276672>

- NASA NPR 2830.1 NASA Enterprise Architecture Procedures—Appendix E: Approaches for Conducting Alternatives Analysis.  
[http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal\\_ID=N\\_PR\\_2830\\_0001\\_&page\\_name=AppendixE](http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_2830_0001_&page_name=AppendixE)
- Circular No. A-11, Preparation, Submission, and Execution of the Budget, OMB, August 2011.  
[http://www.whitehouse.gov/sites/default/files/omb/assets/a11\\_current\\_year/a\\_11\\_2011.pdf](http://www.whitehouse.gov/sites/default/files/omb/assets/a11_current_year/a_11_2011.pdf)
- NASA Business Case Guide for Real Property and Facilities Projects Investments, November 2010, click on Business Case Guide link at <http://www.hq.nasa.gov/office/codej/codejx/>.
- Capability Development Return on Investment for the NASA Aeronautics Program.  
<http://ieeexplore.ieee.org/iel5/10446/33170/01562857.pdf?isnumber=&arnumber=1562857>
- Chapter 12 (Economic Analysis), taken from BCF106: Fundamentals of Cost Analysis class, Defense Acquisition University (June 2009).  
[https://myclass.dau.mil/bbcswebdav/institution/Courses/Deployed/BCF/BCF106/Student\\_Materials/12%20Economic%20Analysis/Economic%20Analysis\\_Jun%2009.pdf](https://myclass.dau.mil/bbcswebdav/institution/Courses/Deployed/BCF/BCF106/Student_Materials/12%20Economic%20Analysis/Economic%20Analysis_Jun%2009.pdf)
- Economic Analysis Handbook, 2nd Edition, as published by the Defense Economic Analysis Council and the Defense Resources Management Institute.  
<https://acc.dau.mil/CommunityBrowser.aspx?id=54803>

## Appendix O: Cost Estimating References

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This appendix provides additional references that may be of use to the cost estimator. The NASA Online Directives Information System (NODIS) (<http://nodis.hq.nasa.gov/displayDir.cfm?t=NPD&c=1001&s=0>) should be the first stop for NASA policies, procedures, and guidelines.

### Additional NASA Resources

Budget Requests: <http://www.nasa.gov/about/budget/>

NASA Federal Acquisition Regulation (FAR) Supplement:  
<http://www.hq.nasa.gov/office/procurement/regs/nfstoc.htm>

NASA's Full-Cost Initiative Implementation (An Agencywide Guide):  
<http://www.hq.nasa.gov/office/oig/hq/audits/reports/FY99/pdfs/ig-99-024.pdf>

NASA Strategic Space Technology Investment Plan, NASA, December 5, 2012.

Office of Safety and Mission Assurance Technology Readiness Level Graphic:  
<http://www.hq.nasa.gov/office/codeq/trl/trlchrt.pdf>

Program Analysis and Evaluation Office (PA&E)—now the Office of Evaluation, Cost Analysis Division—*JCL Quality Standards*, Rev. 1, September 2009

The Critical Path Newsletter: <http://fpd.gsfc.nasa.gov/news.html>

NASA Technical Report Service: <http://ntrs.nasa.gov/search.jsp>

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## Appendix P: Acronyms

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AACE	Association for the Advancement of Cost Engineering
AATe	Architectural Assessment Tool—enhanced
ABC	Agency Baseline Commitment
AC	Alternating Current
ADA	Americans with Disabilities Act
AFCAA	Air Force Cost Analysis Agency
AFCRUH	Air Force Cost Risk and Uncertainty Handbook
AFRC	Armstrong Flight Research Center
AFSCN	Air Force Satellite Control Network
AHP	Analytic Hierarchy Process
AIA	American Institute of Architects
AIAA	American Institute of Aeronautics and Astronautics
AIS	Automated Information System
ANOVA	Analysis of Variance
AO	Announcement of Opportunity
AOA	Analysis of Alternatives
APMC	Agency Program Management Counsel
ARC	Ames Research Center
ASTM	American Society for Testing and Materials
ATP	Authority/Authorization to Proceed
BCA	Business Case Analysis
BCR	Benefit/Cost Ratio
BCWS	Budgeted Cost of Work Scheduled
BoE	Basis of Estimate
BOL	Beginning of Life
BPR	Baseline Performance Review
BST	Beginning of System Test
BY	Base Year
CAD	Cost Analysis Division
CADRe	Cost Analysis Data Requirement
CAIG	Cost Analysis Improvement Group
CAIV	Cost As an Independent Variable
CBA	Cost Benefit Analysis
CBE	Current Best Estimate
CBI	Confidential Business Information
CBS	Cost Breakdown Structure
CCE	Current Cost Estimate
CDF	Cumulative Distribution Function
CDR	Critical Design Review
CEA	Cost Estimation and Analysis
CEH	Cost Estimating Handbook

## NASA Cost Estimating Handbook Version 4.0

CER	Cost Estimating Relationship
CES	Cost Element Structure
CFD	Cash Flow Diagram
CFU	Cost of First Unit
CL	Confidence Level
COBRA	Complexity-Based Requirements Analysis
COCOMO	Constructive Cost Model
COF	Construction of Facilities
CONOPS	Concept of Operations
ConstY	Constant Year Dollars
COTS	Commercial Off-the-Shelf
CRF	Capital Recovery Factor
CRM	Continuous Risk Management
CSRUH	Joint Cost and Schedule Risk and Uncertainty Handbook
CurrY	Current Year Dollars
CV	Coefficient of Variation
CY	Calendar Year or Constant Year or Current Year
DC	Direct Current
DCAA	Defense Contract Audit Agency
DCF	Discounted Cash Flow
DCPLX	Development Complexities
DEL	Payload Delivery
DES	Discrete Event Simulation
DL	Design Life
DODI	Department of Defense Instruction
DPMC	Directorate Program Management Counsel
DSN	Deep Space Network
E2O	Earth-to-Orbit
EA	Economic Analysis or Environmental Assessment
EAC	Estimate at Completion
ECASG	Executive Cost Analysis Steering Group
EIS	Environmental Impact Statement
EIV	Errors in Variables
EM	Engineering Model
ENR	Engineering News Record
EOC	Elements of Cost
EOL	End of Life
EOM	End of Mission
EOY	End-of-Year
ESA	European Space Agency
EST	End of System Test
ETC	Estimate to Complete
EUAC	Equivalent Uniform Annual Cost
EUAW	Equivalent Uniform Annual Worth

## NASA Cost Estimating Handbook Version 4.0

EVM	Earned Value Management
EVMS	Earned Value Management System
ExAOCM	Exploration Architectures Operations Cost Model
FAR	Federal Acquisition Regulation
FBS	Functional Breakdown Structure
FLA	First Launch Availability
FP&D	Facility Planning and Design
FPA	Focal Plane Array
FPAM	Focal Plane Array Business-as-Should-Be Cost Model
FTE	Full-Time-Equivalents
FV	Future Value
FY	Fiscal Year
G&A	General and Administrative
GAO	Government Accountability Office
GDS	Ground Data System
GEM-FLO	Generic Environment for Modeling Future Launch Vehicle Operations
GFE	Government Furnished Equipment
GFI	Government Furnished Information
GR&A	Ground Rules and Assumptions
GRC	Glenn Research Center
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HQ	Headquarters
HVAC	Heating, Ventilation, and Air Conditioning
I&T	Integration and Test
IBR	Integrated Baseline Review
ICAM	Industrial Base Capability Assessment
ICC	Initial Operating Capability
ICE	Independent Cost Estimate
ICSAT	Integrated Cost and Schedule Analysis Tool
IdMAX	Identity Management and Account Exchange
IMS	Integrated Master Schedule
IPAO	Independent Program Assessment Office
IPT	Integrated Product Team
IR	Infrared
IRR	Internal Rate of Return
ISS	International Space Station
IT	Information Technology
JACS	Joint Analysis of Cost and Schedule
JCL	Joint Cost and Schedule Confidence Level
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KDP	Key Decision Point
KDR	Key Driving Requirement

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KPP	Key Performance Parameter
KSC	Kennedy Space Center
kWe	kilowatt-electric
LaRC	Langley Research Center
LCC	Life-Cycle Cost
LCCE	Life-Cycle Cost Estimate
LOE	Level of Effort
LOGO	Limit of Government Obligation
LSBF	Least Square Best Fit
LV	Launch Vehicle
LVCM	Launch Vehicle Cost Model
MA	Management Agreement
MADCAM	Microwave and Digital Cost Analysis Model
MAUT	Multi-Attribute Utility Theory
MCC	Mission Control Center
MCPLX	Manufacturing Complexities
MEL	Master Equipment List
MESSOC	Model for Estimating Space Station Operations Costs
MODA	Mission Operations and Data Analysis
MOY	Middle-of-Year
MPAR	Major Program Annual Report
MPE-ZPB or ZMPE	Minimum Percentage Error–Zero Percentage Bias
MSE	Mean Squared Error
MSFC	Marshall Space Flight Center
MSFC	Marshall Space Flight Center
MUPE	Minimum Unbiased Percentage Error
MW <sub>th</sub>	megawatt thermal
NAFCOM	NASA Air Force Cost Model
NAR	Non-Advocate Review
NASA	National Aeronautics and Space Administration
NCG	NRO Cost Group
NDA	Non-Disclosure Agreement
NEO	Near-Earth Object
NICM	NASA Instrument Cost Model
NODIS	NASA Online Directives Information System
NPR	NASA Procedural Requirement
NPV	Net Present Value
NRA	NASA Research Announcement
NRE	Non-Recurring Engineering
NRO	National Reconnaissance Office
NSCKN	NASA Safety Center Knowledge Now
NTP	Notice to Proceed/Nuclear Thermal Propulsion
O&M	Operations and Maintenance
O&S	Operations and Support

## NASA Cost Estimating Handbook Version 4.0

OBS	Organizational Breakdown Structure
OCE	Office of the Chief Engineer
OCFO	Office of the Chief Financial Officer
OCM	Operations Cost Model
ODC	Other Direct Costs
OIG	Office of Inspector General
OIS-D	Operational Intercom System—Digital
OLS	Ordinary Least Squares
OMB	Office of Management and Budget
ONCE	One NASA Cost Engineering
OoE	Office of Evaluation
OPRA	Oracle Primavera Risk Analysis
P/pM	Program/project Manager
P/S	Planner/Scheduler
PA&E	Program Analysis and Evaluation Office
PCC	Program Cost Commitment
PCEC	Project Cost Estimating Capability
PCLS	Probabilistic Cost-Loaded Schedule
PDR	Preliminary Design Review
PDRI	Project Definition Rating Index
PER	Preliminary Engineering Report/Phasing Estimating Relationship
PLS	Partial Least Squares
PMCM	Parametric Mission Cost Model
PMP	Project Management Plan
POC	Point of Contact
PPBE	Planning, Programming, Budgeting, and Execution
PP&C	Program Planning and Control
PV	Present Value
QTIPS	Quantitative Techniques Incorporating Phasing and Schedule
R2	Coefficient of Determination
RAM	Responsibility Assignment Matrix
RCA	Root Cause Analysis
RDT&E	Research, Development, Test, and Evaluation
REDSTAR	Resource Data Storage and Retrieval System
RFP	Request for Proposal
ROM	Rough Order of Magnitude
ROR	Rate of Return
RSAT	Risk Scenario Automation Tool
RSD	Relative Standard Deviation
RTG	Radioisotope Thermoelectric Generator
SBU	Sensitive But Unclassified
SCAT	Software Cost Analysis Tool
SE	Standard Error of Estimate
SE&I	Systems Engineering and Integration

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SEMP	Systems Engineering Management Plan
SEPM	Systems Engineering/Program Management
SER	Schedule Estimating Relationship
SERRA	Schedule Estimating Relationship Risk Assessment
SIES	Supervision, Inspection, Engineering, and Services
SIR	Savings/Investment Ratio or Systems Integration Review
SIV	Savings/Investment Ratio
SLOC	Source Lines-of-Code
SLR	Simple Linear Regression
SMD	Science Mission Directorate
SME	Subject Matter Expert
SNPPCM	Space Nuclear Power/Propulsion Cost Model
SOW	Statement of Work
SQL	Structured Query Language
SRB	Standing Review Board
SRR	Software Requirements Review
SSC	Stennis Space Center
SSCM	Small Satellite Cost Model
SSE	Sum of Squared Errors
SSR	Sum of Squared Regression
SST	Sum of Squared Total
STE	Special Test Equipment
T&E	Test and Evaluation
TBE	Technical Baseline Estimate
TCO	Total Cost of Ownership
TD	Time Dependent
TDRSS	Tracking and Data Relay Satellite System
TI	Time Independent
TOA	Total Obligation Authority
TOC	Total Ownership Cost
ToR	Terms of Reference
TRANSCOST	Space Transportation Cost Model
TRL	Technology Readiness Level
TY	Then Year
UFE	Unallocated Future Expense
UPS	Uninterruptible Power System
USCM	Unmanned Spacecraft Cost Model
VAI	Vision Analytics, Inc.
VBA	Visual Basic for Application
VHSIC/VLSI	Very High Speed Integrated Circuits/Very Large Scale Integration
WBS	Work Breakdown Structure
WYE	Work Year Equivalents
ZPB/MPE or ZMPE	Zero Percent Bias/Minimum Percent Error

## Appendix Q: Glossary

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### Analogy

A currently fielded system similar in design and/or operation to the proposed system. The cost of the proposed system is developed by taking the fielded system's data and adjusting them to account for any differences. Analogous estimates are also called comparative or extrapolated estimates.

### Analysis of Alternatives (AoA)

An AoA broadly examines multiple elements of project or program alternatives including technical risk, maturity, and costs. AoAs are intended to illuminate the risk, uncertainty, and relative advantages and disadvantages of the alternatives being considered; they show the sensitivity of each alternative to possible changes in key assumptions, and they aid decision makers in judging whether any of the proposed alternatives offer sufficient operational and/or economic benefit to be worth the cost.

### Announcement of Opportunity (AO)

A mechanism used to solicit proposals for unique, high-cost research investigation opportunities that typically involve flying experimental hardware provided by the bidder on one of NASA's Earth-orbiting or free-flying space flight missions. Scope selection through AOs can require development periods of many years and involve budgets of many millions of dollars for the largest programs. Selections are usually awarded through contracts, even for nonprofit organizations, although occasionally grants are also used.

### Baseline

The technical performance and content, technology application, schedule milestones, and budget (including Unallocated Future Expenses [UFEs]) that are documented in the approved program and project plans.

### Beta Curve

A method that can be used to spread parametrically derived cost estimates. The Beta Curve's shape can be tailored by modifying two parameters: cost fraction and peakedness.

### Business Case Analysis (BCA)

A method to aid decision makers in the comparison of alternative approaches, options, or projects. A BCA considers not only all Life-Cycle Costs (LCCs) identified by a Life-Cycle Cost Estimate (LCCE), but also other quantifiable and nonquantifiable benefits for all possible alternatives.

### Coefficient of Determination (R2)

In the context of statistical models, this is the proportion of variability in a dataset accounted for by the statistical model. In cost estimating, it provides a measure of how well cost estimates are likely to be predicted by the model. R2 ranges from 0 (no relationship) to 1 (perfect relationship).

### Compounding

The process of going from today's values, or present values (PVs), to future values (FVs).

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**Constant Year (CY) Dollars**

An analytical technique that translates a real year (RY) dollar estimate (the year expenses were realized) to a single-year value by discounting the effects of inflation. A figure expressed in CY dollars reflects the present value of a single year. Cost models are developed by normalizing actual costs to remove the effects of inflation from historical data points. Those data points are then used to develop the model. Cost estimating results are thus informed by CY values.

**Cost Analysis Data Requirement (CADRe)**

A document that captures the technical, cost, and schedule scope associated with selected project key decision points (KDPs) in a consistent format and utilizes a consistent Work Breakdown Structure (WBS). CADRe ensures the consistent capture of project data for the development of future cost and schedule estimates.

**Cost As an Independent Variable (CAIV)**

The process of examining cost drivers by holding cost independent of other technical parameters. CAIV is founded upon two primary principles: first, system costs are constrained; and second, “trade space” is the foundation for smart decisions. Trade space is the range of alternatives available to decision makers. It is four-dimensional, comprising performance, cost, schedule, and risk impacts.

**Coefficient of Variation (CV)**

A normalized measure of the dispersion of a probability distribution. The absolute value of the CV is sometimes known as relative standard deviation (RSD), which is expressed as a percentage.

**Correlation**

A statistical technique used to determine the degree to which variables are related or associated. Correlation does not prove or disprove a cause-and-effect relationship.

**Cost Benefit Analysis (CBA)**

An analytic technique that compares the costs and benefits of investments, programs, or policy actions in order to determine which alternative(s) maximize net profits. Net benefits of an alternative are determined by subtracting the present value of costs from the present value of benefits. Guidance for Cost Benefit Analysis for Government programs is provided in OMB Circular A-94.

**Cost Breakdown Structure (CBS)**

A preliminary Work Breakdown Structure (WBS) produced by a cost estimator to facilitate the generation of a cost estimate prior to the development of a project WBS. The CBS should be consistent with the NASA standard Level 2 WBS.

**Cost Driver**

Input variables for a cost estimating model that will have a significant effect on the cost estimate.

**Cost Estimate**

The result of applying quantitative techniques to calculate and forecast development, production, operation, and disposal costs within a scheduled timeframe and defined scope for a given project.

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**Cost Estimating Relationship (CER)**

A mathematical relationship that defines cost as a function of one or more independent parameters such as performance, operating characteristics, or physical characteristics.

**Cost of First Unit**

The expected or known cost of the first unit produced or delivered in a multi-unit production. In learning curve theory, this unit is expected to be the most expensive of the production and often used as the basis for adjusted cost projections of later units.

**Cost Risk**

Risk due to statistical uncertainty in the cost estimating methodology, technical parameters, economic factors, rates, and schedule, as well as programmatic and technological factors.

**Cumulative Distribution Function (CDF) (also known as “S-curve”)**

Describes the probability that a real-valued random variable,  $X$ , with a given probability distribution will be found at a value less than or equal to  $x$ . CDFs are used to specify the distribution of multivariate random variables.

**Discount Factor (also called the Discount Rate)**

The factor that is used to translate values from different time periods so that they may be combined into a single number. Discount rates are used to calculate present value (PV).

**Discounted Cash Flow (DCF)**

Refers to a cash flow summary that has been adjusted to reflect the time value of money.

**Earned Value Management/Earned Value Management System (EVM/EVMS)**

A management technique and system utilized to relate resources to schedules. Work is planned, budgeted, and scheduled in time-phased increments, producing a cost and schedule measurement baseline. The EVMS enables the evaluation of the deviation and enables the forecasting of the resulting cost and schedule performance.

**Estimate at Completion (EAC)**

The actual cost of work completed to date plus the predicted costs and schedule for finishing the remaining work. It can also be the expected total cost of an activity, a group of activities, or the project when the defined scope of work is completed.

**Estimate To Complete (ETC)**

The expected cost to complete all the remaining work for a schedule activity, Work Breakdown Structure (WBS) component, or project.

**Fixed Cost**

The costs of an activity (manufacturing, production, assembly, operation, maintenance, etc.) that do not vary significantly with the measure of the product or service output. Though these costs will be incurred regardless of the output of the system, the starting point scope of fixed costs is often determined by factors that can be controlled, such as design, capacity planning, and infrastructure scope and business process steps.

## NASA Cost Estimating Handbook 4.0

**Functional Breakdown Structure (FBS)**

A structural alternative to a Work Breakdown Structure (WBS) that can be used for estimating cost. The FBS is organized by functions that must be performed to produce a product, whereas a WBS is broken down by the end products themselves. The activities-based structure is not tied to any particular architecture because it is a listing of the needed functions, not the elements, of the architecture.

**Future Value (FV)**

A financial term that establishes the value of an asset or set of cash flows at a future point, assuming certain interest rates. FV does not include corrections for inflation. FV is used to calculate the time value of money.

**Grassroots Estimate**

The estimate generated by computing the value of labor and materials for each Work Breakdown Structure (WBS) line item. It is also referred to as “bottom-up” or engineering buildup estimating.

**Ground Rules and Assumptions (GR&A)**

A description of features that bound the cost estimates for a specified technical and programmatic scope. These allow the estimator to clearly communicate the content of the estimate to customers and stakeholders.

**Homoscedasticity**

A statistical assumption that the variance of error is constant across the data (a necessary assumption in the use of Ordinary Least Squares [OLS] regression techniques).

**Inflation**

The rise in the general level of prices of goods and services over time. Increases in inflation represent an erosion of the purchasing power of money. The inflation rate is an annualized percentage change in a price index over time.

**Interest**

A fee charged for the use of money or capital paid by a borrower to a lender as a form of compensation for the use of the assets.

**Internal Rate of Return (IRR)**

A metric used in capital budgeting to measure and compare the profitability of alternate investments. It is also known as an effective interest rate or a discounted cash flow rate of return. The IRR is the annualized effective compounded rate of return that makes the net present value (NPV) of all cash flows from a particular investment equal to zero.

**Joint Cost and Schedule Confidence Level (JCL)**

A cost and schedule condition in which there is the probability that a given project or program's cost will be equal to or less than the targeted cost and the schedule will be equal to or less than the targeted schedule for completion for a specified confidence level.

## NASA Cost Estimating Handbook 4.0

**Learning Curve**

The assumption that the more times tasks are performed, the less time will be required for each of the successive iterations, hence reducing the cost estimate. Learning curves can be calculated through several different equations. How a learning curve applies to the space sector is questionable where fewer items, rather than multiple items in a mass-production environment, are fabricated.

**Lease-versus-Buy Decision**

A specialized type of trade study that enables a decision to minimize Life-Cycle Cost (LCC) outlays by comparing the cash flows associated with each alternative and assessing the best value. This specialized Business Case Analysis (BCA) is typically applied to information technology (IT) and facilities.

**Level of Effort (LOE)**

A support activity that must be done to support other efforts. It typically involves work that must be periodically repeated. The duration is generally from the start to the finish of the effort being supported. An LOE task should never be on a project's critical path.

**Life-Cycle Cost (LCC)**

The total cost for all phases of a project or system, including design, development, verification, production, operations, maintenance, and disposal. NASA has included a detailed definition of project LCC in NPD 7120.5E. For more information, visit <http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7120&s=5E>.

**Linear Regression**

A statistical approach to modeling the relationship between a dependent variable and one or more explanatory variables. This is employed in the development and use of parametric cost estimating tools.

**Make-versus-Buy Decision**

An analysis that supports make-or-buy decisions, including both financial and strategic considerations, such as whether the element is critical to the success of the project, whether it fits into the desired future core competencies of the organization, or whether the item is so specialized that there are few or no other suppliers.

**Margin**

An allowance that is carried in budgets (now referred to as Unallocated Future Expenses [UFEs]), as well as in schedule and technical performance parameters, to provide for uncertainties and risks. Margins are typically established as a baseline in formulation and consumed as the project progresses through its life cycle.

**Model**

A representation of a system broken into its component factors, or parts, so as to mimic or behave as the actual system would, were such parts or factors to be varied and intermixed. A model is used to gain knowledge about a system without actually executing the system.

## NASA Cost Estimating Handbook 4.0

**Monte Carlo Simulation**

A class of computational algorithms relying on repeated random sampling to compute results. This simulation method is most suited to uses where there are many coupled degrees of freedom and significant uncertainty in inputs.

**Multivariate Regression**

A mathematical modeling technique that relates two or more independent variables to a dependent variable through a predetermined equation that minimizes the sum of the squared error.

**Multicollinearity**

A statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated. In this state, the coefficient estimates may change erratically in response to small changes in the model or the data, thus potentially rendering calculations of individual predictors invalid.

**NASA Research Announcement (NRA)**

A mechanism used to announce research opportunities in support of NASA's programs. Respondents prepare proposals based on their ideas, unlike proposal responses to a specific Statement of Work (SOW) issued as a part of a Request for Proposal (RFP) process. NRA proposals may result in awards of grants, contracts, or cooperative agreements.

**Net Present Value (NPV)**

The sum of the present values (a time-series of incoming and outgoing cash flows) minus the present value of the initial investment.

**Nominal Discount Rate**

The term for a real discount rate that has been adjusted to reflect anticipated inflation rates.

**Nonlinear Regression**

A statistical technique of modeling a nonlinear functional relationship in which observational data are modeled by a function that is a nonlinear combination of the model parameters and dependent on one or more independent variables.

**Normalize/Normalization**

Analysis to adjust data to a common predetermined basis. Cost data are frequently normalized to remove the effects of inflation, for example.

**Ordinary Least Squares (OLS)**

A statistical technique for estimating the unknown parameters in a linear regression model that minimizes the sum of squared distances between observed responses in a dataset and the responses predicted by the linear approximation. Where there is no multicollinearity and errors are homoscedastic and have a normal distribution, OLS is the maximum likelihood estimator.

**Organizational Breakdown Structure (OBS)**

A method of organizing costs or plans by the organizational units that perform the work. The OBS is frequently the basis for tracking fiscal performance where the Work Breakdown Structure (WBS) is used to organize the end items or work.

## NASA Cost Estimating Handbook 4.0

**Parametric Cost Estimate**

An estimate generated by methods utilizing statistical relationships between historical costs and other project variables such as a system's physical or performance characteristics.

**Payback Period**

The time required for the cumulative value of savings to equal the cumulative value of the investment. Achievement of payback is sometimes referred to as the "break-even point."

**Present Value (PV)**

The value on a given date (present) of a payment or series of payments made at other times. Future cash flows are discounted to reflect the time value of money or investment risk. PV calculations are used to provide a means to compare the cash flows of various alternatives.

**Probabilistic Cost or Schedule Estimate**

An estimate that incorporates risks, uncertainties, and Monte Carlo simulations to provide a cumulative distribution function (S-curve) of the probability of a variable with a given probability distribution being less than or equal to a value.

**Probability Density Function (PDF)**

A function that describes the relative likelihood for a random variable to have a given value. The probability for the random variable to fall within a particular region is given by the integral of the variable's density over the region. It is not negative, and its integral over the entire space is equal to one.

**Real Discount Rate**

The adjustment of a discount rate to eliminate the effects of expected inflation. It is used to discount CY dollars, real benefits, or costs.

**Regression Analysis**

An analysis that explains how the value of a dependent variable changes when any one of the independent variables is changed while the other independent variables are held constant. Linear regression and Ordinary Least Squares (OLS) regression are parametric in that the regression function is defined in terms of a finite number of parameters that are estimated from the data.

**Request for Proposal (RFP)**

A contractual document that provides a formal invitation to submit a proposal for a scope of work with the intent of forming a contract.

**Return on Investment (ROI)**

The ratio of money gained or lost on an investment relative to the money invested, which is normally expressed as a percentage. The ratio is sometimes referred to as a Rate of Return (ROR).

**Risk**

The chance of uncertainty or loss. Where there are potentially favorable and unfavorable events, risk is the probability that an unfavorable event will occur.

## NASA Cost Estimating Handbook 4.0

**Rough Order of Magnitude (ROM)**

An estimate based on an approximation without benefit of details or detailed analysis.

**Schedule Assessment**

Schedule assessment is the process of determining schedule validity and performance at a given point in time. A thorough schedule assessment using many of the techniques described in the following paragraphs should always be performed prior to establishing the IMS baseline and is essential in ensuring a quality JCL analysis. Periodic assessment is also necessary to gain assurance that the schedule continues to generate valid data and to support the project's objectives throughout the project life cycle. A reliable schedule assessment checklist is an important aid that can benefit a project team or outside review team in determining schedule validity.

**Schedule Estimating Relationship (SER)**

A mathematical relationship that defines schedule as a function of one or more parameters or factors, which may include technical parameters as well as parameters for cost. The development and use of SERs within NASA is substantially less mature than the use of CERs.

**Sensitivity Analysis**

An analytical technique used to measure the uncertainty in the output of a model relative to different sources of uncertainty in model inputs. Varying the input parameters and evaluating the changes in the outputs enables an analyst to evaluate the relationship between the inputs and outputs (testing the model) and the effects of those variations on the conclusions derived from the model.

**Simulation**

The imitation of a real-world process or system over time. The initial step requires the development of a mathematical model that represents key characteristics or behaviors of the system or process over time.

**Software Cost Estimating**

An effort that requires identical processes as the estimation of hardware, but utilizes different measures and tools.

**Then Year (TY) Dollars**

The values associated with costs or estimates in the year that they are planned or occur (also called RY dollars). These costs include any projected or experienced inflation, as opposed to CY dollars, which provide total costs from a cash flow in a single-year base (deflated or inflated).

**Time-Phased Cost**

Costs that have been allocated to a schedule or time period.

**Time Value of Money**

The value of money, including a given amount of interest earned over a given amount of time. This core concept in financial analysis enables the calculation of present value and its derivatives.

## NASA Cost Estimating Handbook 4.0

**Total Cost of Ownership (TCO)**

The total cost of an investment over a life cycle, including development, operations, maintenance, upgrades, and decommissioning.

**Trade Study**

The techniques utilized to compare alternatives as part of the decision to select the preferred alternative(s). These studies may range from formal Analyses of Alternatives (AoA) to informal quantitative analyses.

**Technology Readiness Level (TRL)**

A common scale that describes the maturity of a technology, which is utilized as an input in planning development efforts. Many cost and schedule estimation models utilize TRL as an input parameter.

**Unallocated Future Expense (UFE)**

Funding that is provided to accommodate the realization of risk and uncertainty associated with a cost or schedule estimate. These funds may ultimately be distributed to mitigate the risk, to make the product work, or to accommodate cost or schedule growth, but, because not all risks or uncertainties will be realized, initial allocation of funds to particular WBS elements would be premature. UFE is established by exercising probabilistic techniques.

**Uncertainty**

The indefiniteness about the outcome of a situation. There is uncertainty about both favorable and unfavorable events. The uncertainty must be understood in order to assess risk.

**Value Engineering**

A systematic effort to improve the value of goods or services utilizing an examination of the function. Value can be increased by either improving the function or reducing cost while preserving basic functions.

**Variable Cost**

Costs that change in proportion to the activity of the effort. The concept is useful in forecasting the impact of performance when planned baselines are not achieved.

**Work Breakdown Structure (WBS)**

A means of organizing all project or program components into a product-oriented structure that can be used to establish work packages for project cost and schedule baselines.

**Wrap Rate**

In NASA cost estimating language, major relatively fixed-cost components such as project management, systems engineering, and safety and mission assurance are referred to as wraps. The components of the wrap rate will vary from model to model. In many parametric cost models, the cost of these elements is calculated as a function of the cost of the hardware and software.